THE ELEMENTS

OF

PHYSICS.

BY THOMAS WEBSTER, M.A.

OF TRINITY COLLEGE, CAMBRIDGE;
FELLOW OF THE CAMBRIDGE PHILOSOPHICAL SOCIETY, AND SECRETARY TO
THE INSTITUTION OF CIVIL ENGINEERS.

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PREFACE.

In the work which is now brought before the public it has been my endeavour to set forth a scheme of that part of Natural Philosophy, which is generally included in the term Physics, on a plan calculated to lead the student regularly through the various subjects, and to engender the habit of systematizing and of arranging his knowledge. It has been my especial aim in the following pages to familiarize the student with processes, reasonings, just inferences, and inductions, rather than to present to him a collection of facts. The acquisition of a fact is but the first step in the study of nature; an inquiring mind stimulated thereby rests not until this fact is referred to its proper place in the system of the universe, so that the mutual relation subsisting betwixt it and all other facts is exhibited. The student thus acquires by degrees the faculty of comparing, reasoning, and judging correctly; the acquisition and proper development of which is the chief end of mental culture.

I trust that I have, in some measure, succeeded in compiling a Treatise exhibiting, in a mathematical form, but without mathematical technicalities and symbols, the various process by which the establishment of any proposition in Physics is arrived at, and the nature of the evidence which enables us to speak with confidence of the truth of any theory; exhibiting also, what may be considered as certain, what only probable, what absolutely unknown. The sphere of our knowledge being thus defined, we shall have made some progress towards ascertaining the limits of human faculties.

I am aware that, in the preceding remarks, I have described what the following work ought to be, rather than what it is; but still I trust that it will be found useful for the purposes of general education; and that by the removal of some unnecessary obstacles, the student's progress to many of the higher departments of science will be facilitated. At all events, this attempt may perhaps stimulate others better qualified for the task to devote their talents to the preparation of similar works.

To make any proper acknowledgment of the many various sources from which I have derived assistance in the compilation of the present work, would be impossible; but I must express my deep obligations to the Élémens de Physique of Pouillet; from which valuable work I have borrowed much. The reader is referred to the annexed copious Table of Contents for the various subjects treated of in the following pages.

T. W.

London, Aug. 1837.

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THE

ELEMENTS OF PHYSICS.

CHAP. I.

INTRODUCTION—LAWS OF NATURE—PHYSICAL THEORIES—PRELIMINARY NOTIONS.

1. The circle of the natural sciences presents so vast a field of inquiry, that the limited faculties of man are rarely sufficient to embrace its whole extent. The richness of the subject demands some division of labour by which each one may according to natural inclination and opportunity assist in the advance of human knowledge; hence have arisen so many various departments in the study of nature, on the peculiar objects of some of which it may be well to premise a few observations.

The distinction which exists between an internal and an external world, that is, between the world of mind and the world of matter, will be readily recognised. Each has its peculiar department, and the internal world, or world of mind, gives rise to mental philosophy, which must never be confounded with any other branch of study, and is wholly employed in tracing the origin and succession of all those phenomena which are purely mental.

The external world may be at once divided into animate and inanimate nature. The sciences which treat of animate nature are, Zoology, which classifies the various animals of creation; Botany, which is employed about the productions of the vegetable kingdom; Anatomy, which describes and compares the structures of organized beings; and Physiology, which defines the functions of the several parts and the modifications to which they are subject from external agents. Those bodies which possess the principle of life being treated of under these several departments, the celestial phenomena are resigned to the province of Astronomy. The study of inanimate nature thus restricted to terrestrial phenomena is divided into the three great departments of Geology, Chemistry, and Physics. Of these Geology, considered as including Mineralogy, treats of the external configuration of the earth, tracing the windings and indentations of its shores, the inclinations of the soil, the direction of its mountains, and the courses of its rivers; all which is sometimes called Physical Geography; penetrating the interior, it analyzes the nature of its productions, determines the positions of the different layers and crusts of the earth, and describes the alterations which have taken place and are still taking place from the action of water, of heat, and of the great energies of nature.

The distinction between Chemistry and Physics which at first may not be always quite apparent, is certain and well founded. They may meet and encroach on each other perpetually, the laws of Physics may frequently be called in to explain phenomena which belong to Chemistry, but they still have distinct provinces in the wide field of science. Among the innumerable substances which nature presents to us, some are essentially of the same character, or composed but of one kind of element or particle throughout; such are called simple substances; others being composed of more than one element are called compound substances. To recognise by analysis or decomposition what elements enter into the formation of a compound body, to determine by synthesis or recomposition what bodies will result from particular combinations, to describe the peculiar properties of each element, or of each combination of elements, are among the objects of Chemistry. Thus chemistry is a sort of inorganic anatomy, and is called animal, vegetable, and mineral chemistry, according as it is employed on one or other of these three great dominions of nature. But Physics neglects entirely the examination of the composition and decomposition of bodies, and consequently the individual laws which preside over these two classes of phenomena, laws which the chemist infers from the experiments made in his laboratory on the substances which he analyzes or recomposes. It deals with laws more general in their nature and fewer in number, which, presiding over all the changes of matter, contain and explain beforehand all the individual laws which are immediately perceptible to our senses. We are conscious that many changes are going on around us, we are acquainted with many properties of matter, we see that bodies under certain circumstances act invariably in the same manner; to explain these and similar phenomena is the province of Physics. The student of Chemistry must retire into his laboratory, and by curious and difficult art investigate the phenomena with which he deals; but the student of Physics has *his* objects ever before his eyes: the apple which falls, the water which freezes, the liquid which evaporates, the rain, hail, snow, the lightning's glare and thunder's roll, these and ten thousand other phenomena constantly going on about us are subject to laws which it is the province of Physics to unfold.

The student of Physics then, or the Physician, is concerned with all the properties of matter which have no reference to its actual composition, with all the changes of state to which matter is subject, and the laws which govern these changes, and with all the mutual actions which are going on in the world around him. The various phenomena present themselves with uniformity, similarity, and identity, according to certain laws of succession and co-existence, which it is our object to trace. These laws are derived by operations purely mental, from the facts with which our organs of sense make us acquainted; the laws are few in number, but require for a full apprehension of them an accurate acquaintance with the phenomena from which they have originated. The phenomena are almost infinite, and every day makes additions to their number, so that the illustration of the principles of Physics is brought every instant to the mind of the student who will reason and inquire for himself.

The phenomena then of nature presenting themselves as a series of facts which the mind compares and reasons from, and some appearing invariably, either succeeding each other or co-existing, there arises the irresistible conviction that they are related to each other, either as cause and effect, or as the common effect of a single cause. Of the origin of this conviction it is not our province to speak, but the truth and reality of it we cannot question; the connexion between cause and effect may be a hidden mystery, but the conviction that some connexion does exist is as firmly rooted in our mind as the conviction that order evinces design, and design intelligence. This conviction gives rise at once to the notions of law and government, so that the phenomena appear to be governed by laws; and this connexion observed in a few instances is rapidly extended throughout all nature, so that though but few comparatively of the comprehensive laws of nature have been disclosed to us, yet we are firmly convinced that all phenomena, however complex and irregular their appearance, are subject to rules as invariable as the law that a stone unsupported will fall to the ground.

2. *Laws of nature.*—A law of nature is a rule or form of words describing the mode in which things do act; the language is that a stone *will* fall to the earth, that when some facts occur others will follow. It may also be considered as a form of expression including a number of facts of like kind, or stating the relation in which they stand to

each other as causes and effects; as for instance, that all doubly refracting substances exhibit colours in a regular order; the facts are all separate, but the unity of view by which we associate them, that is, the character of generality and law arises from the relations with which our mind has invested them. Hence the law once apprehended takes in our minds the place of the facts themselves, and is said to *govern* and determine them, because it determines our anticipations of what they will be.* It is asserted that all bodies falling from the same height will acquire the same velocity; here the law is a mere form of expression, including a number of facts of like kind: again, the bulk or volume of a gas is inversely as the pressure to which it is subject, or equal volumes of all gases compressed by an equal fraction of their bulk will disengage the same quantity of heat; here the relation of cause and effect is expressed, for it is asserted that if one fact takes place another will follow.

The discovery of the laws of phenomena is in general far from easy, since there frequently exists great complication of simultaneous results. The only true source of our knowledge of nature is experience, in which term we include experiment and observation. In experiment we put into action causes and agents over which we have control, and purposely varying their combinations, notice what effects take place; in observation we simply notice facts as they occur without any attempt to influence the frequency of their occurrence, or to vary the circumstances under which they occur; these two methods constitute the whole of experience, by which is meant not the experience of one man only, or of one generation, but the accumulated experience of all mankind in all ages, registered in books, or recorded by tradition;† and this experience is the only ultimate source of our knowledge of nature and her laws. When

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* See Whewell's *Bridgewater*, pp. 7 and 301.

† Herschel, *Nat. Phil.* p. 76.

experience fails recourse may be had to analogy, whence we may obtain inductions more or less probable respecting the identity of causes; here, however, the greatest care and circumspection are requisite. After all, however, it is certain, that with our present faculties we shall never arrive at a knowledge of ultimate causes; hence we must limit our views to laws and to the analysis of complex phenomena, that is, to their resolution into simpler ones, which appearing incapable of further analysis we must consent to regard as causes.

3. *Physical Theory.*—A law having been made out or guessed at by the consideration of a great collection of facts and careful reasoning respecting them, which process constitutes what is termed the inductive philosophy, the next step is the verification of this law, that is, the determining whether this law can be considered as established; so that it, or any number such, may constitute a true physical theory. The tracing any law from its first glimmerings amidst a series of facts, to its formal enunciation, and thence to its final establishment, is one of the most interesting inquiries in which we can engage; since it would present a succession of doubts and convictions, and every variety of evidence, from the lowest presumption to the highest moral certainty. But the absolute certainty and conviction which alone can satisfy in a theory of Physics, is derived from the inverted or deductive process; it is from this alone that we can derive entire satisfaction of the truth of any theory; and we shall endeavour to make this intelligible to those who are not acquainted with the actual process leading to these conclusions.

A law having been arrived at and stated in its most general terms, must be traced out by inverted reasoning to particulars; and this process must lead, not only to those propositions whose immediate consideration led to the first discovery of the law, but also to those of which we had no previous knowledge. Any accordance between results so deduced and the facts furnished by experience, is evidence in favour of the truth of a law; but we must also deduce from it, by a series of propositions *necessarily* connected, all the phenomena in question, and this not vaguely or generally, but with the utmost precision in time, place, weight, and measure.* The development of any law so enunciated, which can only be effected by the refinements of mathematical analysis, constitutes a true theory in physics. The mathematical reasoning having brought us to the actual phenomena must do more, it must *predict* what will take place at particular times or under particular circumstances. Thus Newton, from his theory of gravitation, predicted that the earth must be flattened at the poles, and bulge out at the equator, and it was found by observation subsequent to the prediction that this is the case, and Laplace calculated very nearly the exact amount of this excess. But not to multiply instances too much, we cannot refrain from quoting the most extraordinary confirmation which has been so recently† furnished to the theory of gravitation by the return of Halley's comet. The period of this comet is about seventy-five years; from the observations made at its previous appearance the day of its return to a particular position in the heavens was predicted; and the greatest deviation between its predicted and actual return was in no case more than *four* days—according to the prediction of some mathematicians it was much less. Now when it is remembered that this error of four days was the accumulation so to speak of seventy-five years, and that one year had to be allowed for as the effect of planetary disturbances, the result is perhaps one of the most astounding which philosophy can produce. Such a prediction may well establish any theory.

There, is, however, yet a still higher species of evidence, which is furnished by what is termed, the *determination of constants;* that is, when some quantity, as the mass of a planet, which never changes, is to be calculated from the

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* Herschel, *Nat. Phil.* p. 25.

† November 1835.

ever-varying phenomena which present themselves. The determination of the mass of Jupiter has been a question much agitated by modern mathematicians. Its mass may be determined from the effects of the attractions which subsist between it and its satellites, or from the inequalities which its action produces in the motions of Juno, Vesta, and Pallas. The calculations, of the enormity of which no conception can be given, have at different periods been gone through by different mathematicians, and they give results which agree with inconceivable accuracy; the different calculations are in some cases within a one-five-hundred thousandth part of each other. And within the last few years the Astronomer Royal, Mr. Airy, has, from the elongation of Jupiter's fourth satellite, a method entirely different from some of the preceding, obtained the same value for its mass.* Than this no higher degree of evidence can be conceived; the conviction which such facts give us of the truth of a theory is complete. The preceding instances have been selected purposely from Physical Astronomy, partly on account of their grandeur, but principally because we shall have no other opportunity of adverting to them. Others furnishing similar evidence will occur hereafter.

4. *Space and Time.*—The ideas of space and of time enter into all our speculations on physical phenomena; they are probably among our earliest mental conceptions. The mind passes rapidly through the vault of heaven and beyond the utmost limits of visible bodies, and conceives no boundary beyond which spheres like our own may not revolve; thus space is as infinite in reality as it is in our conceptions. The succession of natural phenomena may give us the notion of time; spring succeeds to winter, night to day, and wave follows wave; hence the idea of time. It may also arise from the succession of which we are conscious in our thoughts; these internal phenomena are however essentially distinct from the external, in this, that they give

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* See Memoirs of Astronomical Society. 1833.

us no measure of time. Were the motions of the stars suspended, did the stream cease to flow, and the clouds become stationary, we should still have the idea of time; in the midst of this universal repose we should feel assured that time was capable of measurement and subdivision, although we had no measure of these subdivisions.

5. *Rest and Motion.*—The ideas of rest and motion are simple elementary notions, incapable of being analyzed or defined; they are suggested to us on all sides and at all times. Absolute rest and absolute motion are entirely mental conceptions; in the arrangement of the universe we know of nothing absolute, every thing is relative and conditional. Thus those objects which appear to us the most immoveable at the surface of the earth are but in a state of relative rest. The trees are at rest relatively to the mountains, the mountains are at rest relatively to the soil of the earth and the great globe itself, but trees, mountains, and globe, are all carried along together through the vast orbit of our planet, and every thing together travels in one second through ten times the space which a cannon ball would travel in the same time. But since we are principally concerned with the phenomena immediately about us, we are in the habit of considering the earth's surface as absolutely quiescent, and when we assert that a body is absolutely at rest, we mean that it is at rest with reference to some very large space with which we compare it; thus we say the trees and mountains are at rest, because they are so with reference to the earth's surface, with which we compare them. Suppose a ship to move at the rate of three miles an hour, and a person on board to walk or to be drawn towards the stern at the same rate, he would be relatively in motion with respect to the ship, yet we might very properly consider him as absolutely at rest; but on a more extended view he would be at rest only in relation to the earth's surface; for he would still be revolving round the axis of the earth, and with the earth round the sun; and, for aught we know to the contrary,

with the sun and the whole solar system he would be slowly moving among the starry worlds which surround him.

6. *Force and Matter.*—There is perhaps nothing in the whole range of science of the existence and reality of which we are more thoroughly convinced, but which is in language more inexplicable, than the notion which is conveyed by the terms force and matter. When we press our two hands together we are conscious of an effort exerted and resisted —hence the notion of force; and when we see a body in motion, we feel convinced that it is the effect of force somewhere or other exerted. A block of stone or a mass of iron are solid resisting bodies, and we are convinced that it is the exertion of force which attaches the particles of the stone and of the iron together, and keeps them fixed in their places. Were it not for this exertion of force a body would break up, and be a collection of particles placed side by side as mere dust, and our conviction that the particles are held together by what we term force, arises from the fact, that in the separation of one particle from another we are conscious of the exertion of some effort. The force then which, acting on the particles of a solid, presses them together, and gives to the whole the fixity which we know it possesses, is termed the force of cohesion; it is also termed molecular force or molecular attraction, from the opinion now very much entertained (Art. 8.) that every body consists of ultimate molecules or atoms so minute as to escape our senses except when united in great numbers by this force of cohesion; and bodies of the smallest visible bulk are made up of such an aggregation of particles. Each of these atoms is what we understand by *matter,* the conception of which seems to arise from the notion of resistance combined with extension. This resistance belongs to matter in all its states, being equally a property of the thin air and of the solid rock. Our conceptions of matter are inseparably connected with our conceptions of extension and impenetrability. By ex-

tension we understand some definite portion of space, and by impenetrability we understand the fact that one substance can exclude any other substance from the space which it occupies at any given instant. The invisible and subtile air is well known to possess this property of impenetrability, so that there is no exception in the case of this invisible matter, but in this respect it is similar to the solid matter of the universe. Thus are we brought to the well-known axiom, that two bodies cannot occupy the same space at the same time.

It appears, then, that we must consider every solid body as composed of particles which cohere and cling together by some mutual action in masses of various form and magnitude; and this fact is expressed by saying, that the particles are attracted towards each other; that is, the unknown force is in this case termed *attraction*. But the component particles, instead of being attracted towards each other, may be repelled from each other, and the force here exerted gives rise to the gaseous forms of matter. There is also an intermediate state in which neither kind of force appears to predominate, as appears in the liquid form of matter. Here, however, the force of attraction does exist in a small degree; but it may be entirely changed by the agency of heat, so that the substance will assume the gaseous state. This attraction takes place not only between the particles of the same substance, but between the particles of different substances; and it is convenient to distinguish between these two cases; hence we speak of the force of *cohesion* and of *adhesion*. Thus the particles of a drop of water are said to cohere together, but when the same drop hangs from the under surface of any body, it is said to adhere to that body. The attractions of which we have just spoken, and which take place only at insensible distances, must be carefully distinguished from that general attraction which takes place at all sensible distances, and of which we shall speak in treating of gravity.

Hence these attractions are considered to result from what are termed molecular forces, or those special forces which the molecules of bodies exert on each other, and it is from the modifications of these internal forces that the three forms of matter, namely, solid, liquid, and gaseous, arise.

The evidence on which the hypothesis of the existence of these molecular forces and of the molecular constitution of matter, rests, is strictly speaking mathematical evidence of the highest kind. We know from the discoveries of Newton that there are facts, the existence of which would never have been suspected but from mathematical reasoning and calculation; and the labours of Laplace have led to similar results in the present instance. But the observed facts and known phenomena also furnish considerable presumption of the truth of this hypothesis, as we shall have repeated opportunities of remarking in the course of this work. Independently however of all hypothesis, there are certain properties inseparable from any of the three states in which bodies exist, and to which we shall proceed in the following chapter.

CHAP. II.

DIVISIBILITY—ATOMIC THEORY—COMPRESSIBILITY—POROSITY—ELASTICITY—DILATABILITY.

7. *Divisibility.*—All bodies which possess sensible extension may be divided into several parts, and these again may be subdivided into particles more or less small, and so on to an extreme degree of minuteness; but whether or not bodies are infinitely divisible is a question which, owing to the imperfection of our senses, cannot be determined by direct experiment. The argument in favour of the infinite divisibility of matter is derived from mathematical reasoning; for a line or surface admits of division without limit; hence, however small the particles of any body may become, each of them, since it possesses surface or extension, is, mathematically speaking, susceptible of still farther division. But though substances may not in the mathematical sense be infinitely divisible, they are divisible physically, with our present imperfect means, to an astonishing degree of minuteness, and we have certain evidence of a divisibility in which the particles exist in a state of subdivision infinitely less than the powers not only of our senses assisted by the finest instruments, but almost of our conceptions and imaginations. The ingenious Wollaston obtained, for astronomical purposes, platinum wire, the diameter of which did not exceed the 18,000th of an inch; and the thinness of the gold in the very fine gilt threads of embroidery is almost beyond belief. What can be more incredible,

and yet a more decisive proof of the minuteness of matter, than that derived from the sense of smelling? There is taken from certain animals a substance termed musk, which will continue for years to send forth a strong odour without any apparent diminution in bulk. If a grain of iron be dissolved in nitro-muriatic acid and mixed with 3137 pints of water, some portion of the iron may, by proper chemical tests, be detected in every part of the liquid. This experiment proves the grain of iron to have been divided into more than 24,000,000 of parts; and if the same quantity of iron were still farther diluted, its diffusion through the whole liquid might be proved by appropriate processes.* But the vegetable kingdom presents us with a species of fungus, whose cellules must, according to Professor Lindley, be developed at the rate of more than 66,000,000 in a minute;† how can we conceive the minuteness of the matter which is almost instantaneously developed into these? But the animal kingdom affords the most striking instances of the divisibility of matter. Animalcules have been discovered whose magnitude is such that a million of them does not exceed a grain of sand. Their bodies are organized, they move about with exceeding rapidity, eat, drink, and derive nutrition, evidently exercising a digestive apparatus. They have also circulating fluids; if then a globule of their blood bears the same proportion to their whole bulk, as a globule of our blood bears to our magnitude, what power of imagination can conceive any adequate idea of its minuteness?

8. *Atomic Theory.*—The advocates of this theory suppose each body to be composed of ultimate particles or atoms, which are infinitely hard and indivisible. The evidence for this theory rests on the discoveries of modern chemistry, and especially on the researches of Dalton, from which it appears that substances, by their combining in simple and invariable proportions, give rise to the varieties of com-

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* Turner's *Chemistry*, p. 2.

† Prout's *Bridgewater*, p. 24.

pounds; thus the composition of bodies appears to be fixed and invariable, and every compound substance, so long as it retains its characteristic properties, always consists of the same elements united together, in the same proportion. Sulphuric acid, for example, is always composed of sixteen parts of sulphur, and twenty-four of oxygen; water is formed of one part of hydrogen, and eight of oxygen; and were these elements united in any other proportion, some new compounds, differing from sulphuric acid and water, would be the product. And the same is true of all other substances, however complicated, and at whatever period produced; thus marble, whether formed ages ago by the hand of nature, or recently by the chemical geologist,* is always composed of the same elementary substances. Such being the observed fact in the constitution of all compounds, the assumption that all bodies are composed of ultimate atoms, the weight of which is different in different kinds of matter, serves at once to explain all the phenomena of chemical union; and this mode of reasoning is, in the present case, almost decisive, since the phenomena do not appear explicable on any other supposition.† The phenomena of crystallization, as we shall see presently, furnish very strong evidence in favour of the preceding theory.

In connexion with this and the preceding article, we cannot refrain from quoting the opinion of the immortal Newton, in whose destiny it was to exhibit, or at least to indicate, the principal phenomena of the universe. After a brief review of the different energies which are in action,‡ he says, 'All these things being considered, it seems probable to me, that God, in the beginning, formed matter in solid, massy, hard, impenetrable, moveable particles; of such sizes and figures, and with such other properties, and in such proportion to space, as most conduced to the end for which he formed them, and that these primitive parti-

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* Sir James Hall.

† Turner's *Chemistry*, p. 225.

‡ *Optics*. Book III. Qu. 31.

cles being solids are incomparably harder than any porous bodies compounded of them; even so very hard as never to wear or break in pieces; no ordinary power being able to divide what God himself made one, in the first creation. While the particles continue entire, they may compose bodies of one and the same nature and texture in all ages; but should they wear away or break in pieces, the nature of things depending on them would be changed. Water and earth composed of old worn particles and fragments of particles, would not be of the same nature and texture now with water and earth composed of entire particles in the beginning. And therefore that nature may be lasting, the changes of corporeal things are to be placed only in the various separations and new associations and motions of these permanent particles; compound bodies being apt to break, not in the midst of solid particles, but where those particles are laid together and only touch in a few points.'

9. *Compressibility.*—The term compressibility is used to express the property which all bodies have in some degree, of being reduced to a less apparent size or volume. Every one is sensible of the existence of this quality in sponge or Indian rubber, and the diminution of the apparent bulk of most substances is familiar to every one. The *apparent* volume is essentially different from the *real* volume, which is the space that the elementary particles would exactly occupy, supposing them to be in actual contact. A substance so constituted would be perfectly hard, and consequently absolutely incompressible; that is, it could not be reduced to a smaller size. No such substance is however known to exist in nature. The diamond and manufactured steel, gold and platinum, water and mercury, have all an apparent volume, which admits of a diminution the same in kind, though widely different in degree, as the sponge and Indian rubber. When a substance is compressed, we have the same quantity of matter in a less space; this is expressed by saying, that the density of the body is increased. Thus one substance is more dense than another

when it contains the same quantity of matter in a less space, or more matter in the same space; and the fact of one body being more dense than another is indicated, as will be shewn hereafter, by the difference in the weight of equal volumes of the two substances. Thus platinum and mercury are known to be more dense than copper and water, because a cubic inch of the former substances weighs more than a cubic inch of the latter.

10. *Porosity.*—From the experimental fact that all substances may be rendered more dense, we infer the porosity of all bodies, that is, that the component particles or constituent atoms either touch each other at very few points, or, what is more probable, that they are not in contact at all; for it seems reasonable that the space by which the volume is diminished must before the diminution consist of pores. The animal and vegetable kingdoms teem with evidences of a porosity of bodies, independently of the fact of their compressibility. The mineral poison which pervades the whole frame, and the sap circulating through every part of the smallest plant, afford clear indications of this property, and we have evidence of the porosity of hard solid substances, whenever an air bubble is driven from a lump of sugar or a piece of chalk immersed in water, and in every stream which filtrates through the rocky sand stone. There is a curious semi-transparent precious stone termed the hydrophanous agate, sufficiently hard to emit sparks on being struck against steel, which when plunged in water discharges a great number of small air bubbles, becomes transparent, and receives an augmentation in its weight. On being dried it loses the water which it had imbibed, and returns to its natural opacity. The preceding quality of bodies is an immediate consequence of the theory of their molecular constitution, and the pores will be of greater or less magnitude, according to the intensity of the attractive forces to which the particles are subject. This method however of viewing the question involves refinements and considerations somewhat foreign to an elementary treatise; it

is better therefore to place it on the evidence of known experimental facts.

11. *Elasticity.*—The elasticity of substances is the quality in virtue of which they resume their former state, after either a change of volume or a change of form, when the cause to which this change was owing has ceased to act. This quality exists in very different degrees, and must be considered as resulting partly from a change of bulk, and partly from a change of form; when air is compressed by pressing down a tumbler inverted over water the elasticity arises from a change of volume, but when a steel spring is bent it results from a change of form; in general, the elasticity is connected with both these changes. A substance is considered perfectly elastic when the force of restitution is exactly equal to the force of compression; common air and all the gases possess this property nearly in perfection; hence they are termed *elastic* fluids. The elasticity of liquids is seen at once from the rebound of a stone or cannon ball from their surfaces, and from the way in which they rebound when poured from one vessel into another. When solid bodies, as two ivory balls, impinge on each other, the degree of elasticity is measured by the magnitude of the rebound after impact. The two forementioned kinds of elasticity, so to speak, though referable to the same principles, are well exemplified in the case of Indian rubber. This substance is known to be very elastic, it yields readily to compression and recovers itself immediately; here the elasticity is due almost entirely to a change of figure; for if the same Indian rubber be enclosed in a space which it accurately fills, it will resist compression with great violence. Here then the same substance illustrates the two kinds of elasticity, there is a feeble effort of recovery from a state of altered figure, and a very violent one from a state of compressibility or altered dimension. It is to this quality of bodies that we owe so much of the use of steel in the arts. Our comfort is consulted, and our carriages are preserved, by the use of springs; it is from the elasticity of a

spiral spring that our watches derive all their motion and regularity; thus furnishing an accurate measure of time.

12. *Dilatability.*—By the dilatability of a substance is meant, the quality in virtue of which it has a tendency to increase in volume without any increase in the quantity of matter. This is an essential property of elastic fluids, which by virtue of their elasticity *dilate,* as the pressure to which they are subject decreases. But it is a property of all bodies equally to change in volume under the influence of heat; all bodies dilate or expand when their temperature is raised, and contract when their temperature is lowered, and return to exactly the same volume under the same temperature. This is one of the most regular and beautiful laws of nature; at every hour both of night and day the heat varies, and all bodies at the surface of the earth participate in these variations. They are alternately in the act of dilating or contracting, and can never have the permanent dimensions which we assign to them. These constant alternations are however productive of no irregularity or confusion, for all nature experiences them equally. These alternations arise from the motion of all the constituent particles, both internal and external; hence if we learn from the porosity of bodies that their constituent particles are not in contact, we may learn from their dilatability that they are never at rest, but are continually changing their relative positions and distances. Whence we may conclude that matter, which seems to us the most inert, is the subject of ceaseless change, ceaseless activity.

CHAP. III.

HARDNESS—TOUGHNESS—DUCTILITY, &C.—FRICTION—CRYSTALLOGRAPHY.

13. In the preceding chapter we treated of certain properties which are common to all matter in whatever state it may exist; but there are some properties distinct from the preceding peculiar to solids, and closely connected with their most curious constitution, which must be briefly noticed.

The *hardness* of a solid expresses that peculiar character which gives rise to a difficulty of displacing the particles among themselves. Thus steel is harder than iron, and diamond harder than steel. There is no invariable connexion between hardness and compressibility; for the compressibility of steel and of soft iron is nearly the same, but the hardness widely different. The hardening of metals is one of the most remarkable and delicate operations in the arts; the degree of hardness is indicated by a particular succession of colours, so that the artist can see at once of what *temper* his tool is. If a body be too much hardened it becomes brittle; but brittleness and elasticity may exist together, as in glass, which is very brittle, but also highly elastic. The hardness of any solid must be carefully distinguished from its resistance to compression. The diamond is the hardest known substance, not because if it be laid on a piece of metal and hammered it will penetrate the metal rather than yield, but because it cannot be itself scraped or striated by any known substance, whereas it will striate all others. Glass, for instance, is much harder than marble, because it can scratch or striate marble, and less hard than rock crystal or diamond, because it is readily scratched by these substances. The hardness of a body is also tested by its resistance to wear; thus diamond, being the hardest known substance, can only be polished by its own dust. The degree of hardness is very different in substances whose chemical constitution is the same, but it evidently depends on their physical constitution; thus, white marble is much harder than chalk, and we have reason to believe that white marble is nothing else than chalk, whose constituent particles are in much closer contact. Softness is the opposite quality to the preceding, and a soft metal, as lead or gold, can be scratched very easily.

Toughness is very distinct from hardness, being the property in virtue of which solids will endure very heavy blows without breaking; it implies a certain yielding of parts combined with a great general cohesion and very different degrees of elasticity. Some woods are exceedingly tough, and the toughest known substances are cast iron and steel.

Malleability is that property of some metals in virtue of which they may by a blow be deprived of their figure without exerting any powerful effort to preserve it, and without fracture; thus some metals can be reduced to thin plates by hammering. Gold is the most malleable of metals, and every one must have seen the operation of making gold leaves and gold-beaters' skin, which is the skin between which the metal is hammered out into so beautiful a thinness, that two thousand are not much thicker than a sheet of paper. This property is possessed in very different degrees by other metals; some break at once like a piece of glass.

Ductility is the property which some metals possess of being drawn out into wires; it is very different from the preceding, since metals which cannot be hammered far without fracture or interruption of the continuity of the plates may be rolled or drawn out into long rods and wires. Platinum has great ductility and can be drawn into beautiful wire: one of the most striking operations of our iron works is to see enormous masses of iron reduced by a successive series of rollers into thin plates, long bars, and interminable lengths of rods and wires; a penny-piece will form a beautiful riband of twenty or thirty feet in length. The ductility of melted glass is most beautiful; the workmen will draw out most delicate threads, which lying together in pieces might be mistaken for the natural hair. That state of a body which is expressed by the term *brittleness* is entirely opposed to the preceding qualities, since some solids, as glass and iron in particular states, break on the application of the slightest force.

Tenacity is the quality by which a body resists extension or separation of parts; it is a direct proof of the attractive power of cohesion among the particles of a solid, and may be made an exact measure of it. Very accurate experiments have been made on wires, and on rods and bars of iron and wood, to determine the force with which their particles resist separation. The tenacity of iron is now a question of the greatest importance, since this metal is employed in every department; even roofs are composed of it, our walls are prevented from bulging by means of it; but its grandest application is in our ships and our bridges. Our vessels ride securely moored by iron cables, and our bridges are suspended in mid-air by iron rods and chains. If at any time the strain or tension on the chain becomes greater than the tenacity of the metal, the vessel would be abandoned to the fury of the elements, and the bridge engulfed in the chasm below.

14. *Friction.* Whenever one surface is to be moved so as to rub over another a resistance is experienced. This resistance arises from what is termed friction, and is greater or less according to the roughness or smoothness of the surfaces in contact; it appears to be occasioned by the pro-

jecting particles or irregularities of one surface inserting themselves into the corresponding interstices of the other; hence the more highly polished a surface is the less must be the friction; hence also the friction is diminished by covering the surfaces with any unctuous substance so as to prevent this insertion of the projecting points. The effects of grease in diminishing friction are so sensible that the same man can draw, without exerting a greater effort, over a greased surface, more than three times the weight he could over the one which is not greased; and the drivers of sledges in Amsterdam, on which heavy goods are transported, carry in their hand a rope soaked in tallow which they throw down from time to time before the sledge, in order that by passing over the rope it may become greased. It is friction which prevents a very heavy mass from being moved along a horizontal plane by an exceedingly small force; and it is the same resistance which hinders the foot sliding back at every step; hence it is an agent on which we are dependent every instant and in every action.

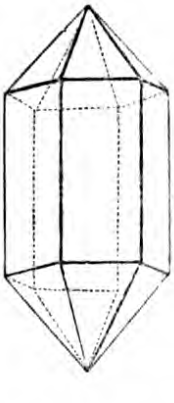
In machinery the effects arising from friction are of the greatest practical importance; the expenditure of moving power in overcoming this resistance is very great; hence every precaution is taken to diminish its effects as much as possible. The wear also which it occasions is dreadful. It is frequently taken advantage of, as when a wheel is driven round by the friction between its surface and a leather strap; a method peculiarly serviceable in many operations. It is also employed in destroying gradually a considerable velocity, or in preventing its accumulation.

Crystallography.

15. *Crystallization.* Having considered the general properties of solid bodies, we shall proceed to their internal structure and external figures. The phenomena of crystallography will shew us that they have a most curious and

intricate internal mechanism, and we shall see that all the substances usually termed crystalline are formed according to laws as certain and definite as those which preside over any department of Physics. The material particles are subject to molecular attractions, by virtue of which they become arranged in the most beautiful symmetry. The phenomena of crystallization must be considered as a certain arrangement of similar portions of matter; hence it supposes the existence of a force which compels the particles that are sufficiently near each other to seize one another, and to cohere by their suitable faces. This force, by whatever name it be called, must be considered as giving rise to a general law to which all brute and inorganized matter is subject, and which has for its object the formation and preservation of substances of this class; so that it would seem as if every species of matter may assume a determinate form, which is constantly the same when nothing interferes with the execution of these laws.

A crystal is a solid bounded by plane surfaces, disposed in a certain manner, or, according to the language of geometry, it is a polyhedron more or less regular. Many crystals are transparent, but transparency is not an essential quality of a crystal, but only its geometrical form. In all parts of the mineral kingdom we find bodies of the form of polyhedrons, some of which are exceedingly irregular; the detection of the law of formation of these irregular forms is the great object of crystallography, and one for the successful prosecution of which we are almost entirely indebted to the labours of the Abbé Haüy. Irregular crystals are very abundant, and it is in the salts that the laws of their formation are best observed. Common salt crystallizes in regular cubes, allum in octohedrons, saltpetre in long prisms; thus each salt affects a peculiar form, as may be seen in the least crystals. If a drop of water in which any of the above substance, is dissolved be placed on a glass plate, and viewed with a powerful microscope, the regular figures will be seen in the act of formation. But stones



have also their regular crystalline forms; that beautiful transparent substance called rock crystal is found in prisms of six sides terminated by summits of six faces, as shewn in the accompanying figure. Common quartz is found in crystals of the same form, but not quite so regular; the diamond is a regular octohedron, and Iceland spar or carbonate of lime appears in rhomboids. The metals also present themselves under geometric forms, native gold and silver are often found in small octohedrons, and iron and copper are sometimes formed in cubes of great regularity. But although crystals of all kinds are found in nature, still solids regularly formed are extremely rare, and we must inquire into the causes which can prevent the more frequent production of the geometric forms.

Several conditions are requisite that the products of crystallization may have all the regularity that can be desired. In the first place, the matter which is to be crystallized must be divided into its smallest particles, which we have called molecules, or atoms; in the second place, these particles must be suspended for some time in a fluid where they can move freely; thirdly, during their approach the fluid must not be agitated by any external movement; lastly, there must not exist, either in the fluid or in the containing vessel, any thing which can disturb or prevent the union of these particles. It is easy to perceive the necessity of all these conditions, and also that their co-existence will be rare. Hence we must not be surprised at the few regular crystals which exist, notwithstanding the universality of the law; almost all the minerals present very irregular masses, clearly indicating the irregularity which presided at their formation. Besides which most of them have since their formation been subject to the action of many extraneous forces, so that their primitive forms must have undergone very great alterations. By fulfilling the conditions which have just been spoken of we may easily obtain crystals of different species. If it is a salt, it must be dissolved in water; if a metal, it must be heated to the point of fusion; and if a volatile substance, it must be evaporated by heat. In these cases we see that the particles will have all the simplicity and all the mobility necessary for their freely obeying the force which must bring them together and unite them. If the water which contains the salt is slowly evaporated, so that the particles may arrange themselves according to their proper laws, very regular crystals will be formed on the sides and at the bottom of the vessel, or on a stick or piece of thread immersed in the solution, so as to serve for a point of support. In a similar manner melted metal takes a regular form as it cools; but it must not be all allowed to cool, or there will be no trace of crystallization, since all the interstices of the crystals will be filled with the superabundant matter. But just before the whole becomes solid the remaining liquid must be poured away, and the bottom of the vessel will be found to contain crystals more or less regular according as the instant seized is more or less favourable. Lead and bismuth are the best suited for this purpose, and form quadrangular prisms which are connected together by their bases. If the substance be volatile, the particles which the heat carries away being received against a cold surface take a certain arrangement; thus sulphur being volatised or sublimated crystallizes in needles or thin fine prisms applied one to the other. Such then being the general phenomena of crystallization, we shall proceed to examine the structure of crystals as they are actually presented to us in nature, and the laws which, according to the researches of Haüy, appear to exist in the construction of the irregular forms.

16. *Primitive and Secondary Forms.*—It appears that every crystal, whether natural or artificial, admits of being cleft and subdivided in certain fixed directions with much greater facility than in any other manner. These sections

of least resistance are called planes of cleavage, and their number and position depend entirely on the nature of the substance. This division having been continued in all directions where it is possible, a *nucleus* is at last obtained, and all subsequent division will only diminish the bulk without altering the form of this nucleus. The planes of least resistance or cleavage are all parallel to the planes which terminate the figure; hence if the nucleus be a cube it will continue still a cube, although by continual sections it becomes reduced to inconceivable minuteness. This nucleus or limiting form so obtained is called the *primitive form* of the crystal. Its faces are in number either equal to or double its different planes of cleavage; thus three different cleavages give a parallelopiped as the primitive form, four an octohedron or tetrahedron. Thus the primitive form or nucleus of the crystal is a solid of a constant form, whose faces follow the directions of the laminæ which form the crystals. The parallelopiped and octohedron are the most frequent primitive forms.

The *secondary forms* of crystals are those under which the crystal generally presents itself; a crystal is rarely found of the same form as its nucleus, and when the laminæ divide easily in any other direction than parallel to the existing faces, we know that the entire crystal is not of the primitive form. It appears then that every crystal may be considered as built up by the application of layers to the faces of its nucleus. Thus nature appears in every case to have started from a primitive form, and by adding successive layers of particles, whose dimensions differ according to certain laws, to arrive at the secondary form.

17. *Remarks.*—Ingenious and beautiful as this theory undoubtedly is, it must ever be borne in mind that it is at present but an hypothesis serving to guide us in our researches. The known laws of crystallography are entirely independent of any hypothesis respecting the existence of ultimate atoms, or the manner in which a crystal is built up from a primitive form. We know for certain that different sub-

stances do appear in certain definite forms, and that if a cubic or octagonal crystal be more easily divisible by laminæ parallel to its faces than in any other direction, we may continue to diminish the magnitude of the crystal, as long as the mechanical division is possible without any change of the form. But still when the assumption of the molecular constitution of bodies, combined with the preceding theory, serves so well to explain most of the known phenomena of crystals, considerable confirmation is afforded to these doctrines. The various phenomena being duly considered, little doubt can remain that all substances susceptible of crystallization consist of atoms of a determinate form. The observed facts and the reasonings from them, so long as they are independent of any hypothesis respecting the constitution of matter, cannot be disturbed, should it be hereafter proved that matter is physically infinitely divisible. But the regular form of crystals and the property of being easily divided in certain directions, indicate that the force of cohesion does not exert its power in the same degree in all the points of their particles; hence these particles seem to have certain *poles* of attraction, which, according to their greater attractive force, determine the position of the particles. This conception of polarity, which we see exemplified on a great scale in the magnetic needle, is forced upon us by the phenomena to which we have referred, and must be considered as one of the most interesting and promising speculations of modern science.*

* See Prout's *Bridgewater Treatise*, & Herschel's *Nat. Phil.* p. 239.

CHAP. IV.

EQUILIBRIUM—RESULTANTS—MACHINES—THREE LAWS OF MOTION—CENTRIFUGAL FORCE—MOMENTUM—IMPACT AND PRESSURE.

18. In the preceding chapters we have treated of those properties of bodies which depend essentially on their constitution, and which may be conceived to arise from the modifications of the internal forces to which their elementary particles are subject. We have now to consider bodies as subject to external forces, and in a state of rest or motion; and to state the laws which belong to these phenomena.

A body is in equilibrium, or at rest, when the forces which act upon it destroy, that is, counteract each other, or when they are counteracted by some resistance. Thus a body suspended by a string is in equilibrium, because the action of gravity upon it, that is, its weight, is counteracted by the tension of this string, and this again is counteracted by the resistance of the point of support. If the string is not sufficiently strong it breaks, and the body falls to the ground; if the point of support is not sufficiently firm, the body drags it down, and both fall together. Sometimes there is equilibrium where there is no fixed point and no apparent resistance; as when a fish is at rest in the water, or a balloon in the air; here, however, the weight of the fish and of the balloon is exactly counteracted by particular pressures, as we shall see hereafter.

We may assert, then, that all bodies which appear to us to be at rest are, in fact, bodies in equilibrium; for they are always subject to the action of several forces, which destroy or counterbalance one another. Two forces may be considered as equal when, being applied at the same point, or at the extremities of an inextensible line, in opposite directions, they produce equilibrium. Two equal forces will give a double force when they are added together, that is, when they act on the same side of any point and in the same direction. Thus a triple or quadruple force, and so on, may arise. If then we agree to represent a force by a number or by a line, double that force will be represented by doubling the number or the line. Now, all force may be measured by weight; hence forces of one pound, two pounds, &c., mean forces which produce the same effect as those weights would produce.

19. *Action and Reaction equal and opposite.*—When any force is counteracted, as when an immoveable obstacle is pulled by a string, or when a post sustains a weight, there is a pressure exerted in one direction which must be counteracted by a pressure exerted in the opposite direction. That each such force, or pressure, acting at any point of a body, or a machine, must be accompanied and counteracted by an equal and opposite force, or pressure, follows from the nature of equilibrium. These two equal pressures then, or forces, which co-exist at any point, are called, for the sake of distinction, the Action and the Reaction; and the preceding statement is generally referred to in mechanical science by the terms, 'the equality of Action and Reaction.'

There are several instances in which the reaction of any point may be transferred to some other point, so as to act at a mechanical advantage; the motion of a boat impelled by oars, and of a locomotive engine on a railroad or a common road, are two examples of frequent occurrence.

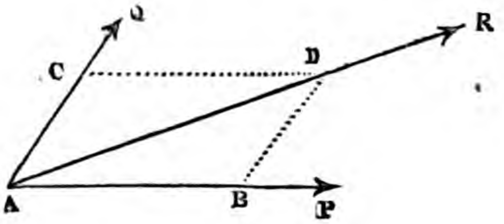
20. *Resultants.*—When several forces act at a point, we can conceive that the effect produced, that is, the pressure

exerted, might be produced by a single force; this single force, which may replace all the others without altering the effect produced, is termed the resultant of all the forces. It is a proposition of mathematics to prove that any number of forces have a single resultant, and to determine the magnitude of that resultant, and the direction in which it must act. There is no difficulty in satisfying ourselves as to the fact that the effect which is produced by a number of forces acting at a point may be produced by a single force applied at the same point. When several ropes are employed to sustain weights, or to produce motion, we see cases in which the same effect might be produced by a single rope in a proper direction; that is, all the forces exerted by these ropes may be replaced by a single force, that is, by their resultant. The forces so replaced by a single force are termed the component forces, because the whole effect is composed or compounded of their separate effects; this is termed the *composition* of forces.

In the same manner as any number of forces may be replaced by a single force, a single force may be replaced by several others. The force is then said to be resolved into others, and this operation is termed the *resolution* of forces.

21. *Parallelogram of forces.*—When the directions of two forces which act on a point make an angle with each other, the resultant of these two components has a determinate magnitude and direction, that is, its magnitude and direction may be assigned by an invariable rule. The enunciation of this rule is simple and distinct; for the proof of it recourse must be had to mathematical science. We have already (Art. 18.) said that forces may be represented in magnitude and direction by lines; if then the two forces which act on any point be represented in magnitude and direction by two lines, these lines will make an angle with each other. These two lines being considered as the sides of a parallelogram, let the figure be completed, then the diagonal of this parallelogram will represent, both in magnitude and in direction, the resultant required.

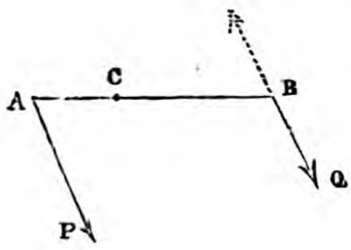
Let two forces P and Q act at the point A, the one in the direction A P, the other in the direction A Q, as indicated by the arrows. Let A B represent the magnitude of the force P, and A C the magnitude of the force Q, and complete the parallelogram A C D B by drawing B D parallel to A C, and C D parallel to A B. Join A D, then the magnitude and direction of the resultant R will be represented by A D, the diagonal of the parallelogram. Thus the point A, acted on by two forces in the directions A P and A Q, is exactly in the same case as if it were acted on by a single force in the direction A R, and whose magnitude may be represented by A D.

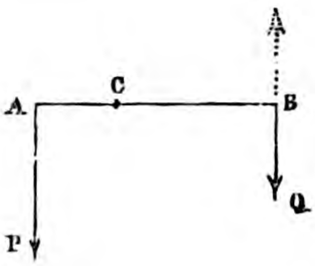


When the components are equal the resultant will bisect the angle which they make with each other, when unequal it will be nearer the greater force. If the point on which the forces act is fixed, the pressure which it sustains is the same as the resultant of the forces; if the point be not sustained, it will move in the direction of the diagonal.

In the same manner, whatever be the number of forces applied at a point, their resultant can always be found; for, first, find the resultant of any two of them by the preceding rule; and then take this resultant and another; and so on till the resultant of all the forces is found.

22. *Resultant of parallel forces.*—The forces in the preceding articles are oblique forces, that is, they have their directions inclined to each other at some angle. But when the forces have their directions parallel, they may generally be replaced by a single force, which is their resultant.





Thus if A P and B Q be parallel forces, there will be a single force passing through some point C betwixt A and B, parallel to the components, which will produce precisely the same effect. In these figures the forces act on the same side of A B, or in the same direction, but if one acted on the other side as represented by the dotted lines, there would be a single resultant, except in the case in which the two forces P and Q are exactly equal. Two equal and parallel forces acting on opposite sides of a line constitute what is termed a *couple,* which does not produce the same effect on a body as a single force; it twists a body; and any body subject only to two such forces can never be at rest.

The action of gravity presents us with an example of parallel forces on the grand scale: we shall see that bodies may be considered as having every one of their particles acted on by forces whose directions are parallel, and consequently the whole effect is the same as might be produced by a single force, or by their resultant.

23. *The Lever.*—In the preceding articles we have seen the general conditions of equilibrium for forces acting at a point; but in practice the forces can rarely be considered as acting in that manner; they are generally applied to different points on a rigid body, and tend to turn it about some axis or centre of motion. In these cases other considerations must be introduced, and as the laws are the same for all these cases, we shall state and illustrate them in their application to the simple case of the equilibrium of a lever.

The form and applications of the lever are very varied and numerous; but the simplest case is that of a straight rower pulls, is the power exerted; in all these cases, which are levers of the second kind, the power exerted is less than the resistance overcome. Hence, in levers of the first and second kind, the power acts at a mechanical advantage.

But in the third kind, in which the power acts between the weight and the fulcrum, the force exerted is greater than the resistance overcome. Thus in the common fire tongs. the hand being near the fulcrum exerts a greater force than is exerted at the surface of the substance raised. In the shears used for cutting off the wool from sheep, the hand exerts a greater force than the resistance of the substance cut. This may also be well illustrated by a person pushing at a gate near the hinge. The force which he must exert to open the gate is the greater the nearer the hand is placed to the hinge. The limbs of animals are in general levers of this class; the object being to obtain a motion through a larger space than that through which the power acts. Thus the muscle which moves the arm and hand acts near the elbow, so that the hand moves through a large space while the parts near the elbow may be considered as stationary.

The considerations of the relative space through which the power and the weight act are of the greatest importance in practical mechanics, and the proposition which is thus arrived at for all the mechanical powers, as well as for the lever, may be expressed in the following terms, 'what is gained in force is lost in velocity.' Thus in the first kind of lever, in the common poker for instance, the hand moves through a much greater space, in the same time, than the coals raised move through. In the oar, which is a lever of the second class, the hand moves through a greater space than the boat. But in the third kind of lever, as in the common fire tongs, the hand moves through a much less space than the end of the tongs, and just in the same proportion as the power exerted is greater than the resistance overcome.

24. *Machines.*—It would be foreign to our present subject to consider the various combinations which are commonly

expressed by the term mechanical powers; but as this term has been much misunderstood from incorrect views of physical principles, we shall endeavour to illustrate these principles by their applications in machines. The first question then is, what is meant by a machine; and to this we reply that a machine is any instrument designed for the modification of force; as, for the transfer of force exerted at one point to another point, or for causing a force which acts in one direction and in one manner at one point, to act in a different direction and in a different manner at another point. Thus a knife is a machine, since the power or force exerted by the hand at the handle is transferred to the substance to be cut. A pair of scissors is a machine. In all machines there are two conventional terms, the *power* and the *resistance;* by the power we mean the force whose action and direction is to be changed and modified by the machinery, and by the resistance we mean the obstacle which is to be overcome, or the work which is to be done. Thus, in cutting any thing with a pair of scissors, as we have already seen, the force which the fingers exert is the power, and the force exerted on the substance cut is the resistance; in a steam engine the elastic force of the steam is the power, the friction to be overcome, and the work to be done, together constitute the resistance. We must therefore consider a machine merely as intended to transmit power and to execute work; and the advantage derived from machinery consists in the modifications and adaptations of which a power is susceptible from this very transmission. The simple machines enable us to concentrate and divide any quantity of force which we may possess; a small force may be husbanded so as to produce all at once a prodigious effect; a large force may be subdivided so as to produce ten thousand small effects. These principles are illustrated by what is going on in every factory in the kingdom. The force of wind, water, or steam, by a continuous uniform action, sets in motion a large fly-wheel; this wheel may be employed every few minutes to lift a massive forge hammer, or it may keep thousands of smaller wheels in operation. The various motions which are going on in a single factory, all derived from one original motion, and all arising from the modifications which force and motion may receive by transmission, are objects most worthy of attentive examination.

In all the mechanical agents by which motion is transmitted, as in the lever, the pulley, the wheel and axle, and many others, it may be mathematically demonstrated, that no real power can be gained by their use, however combined. It is certain that whatever force is applied at one point can only be exerted at some other, diminished by friction and other incidental causes; but the gain arises from other sources, as the economy of time and labour, and convenience. There is another principle, that whatever is gained in the rapidity of the execution is compensated by the necessity of exerting additional force: all the combinations of mechanical art can only augment the force communicated to a machine at the expense of the time employed in producing the effect. We will illustrate this by the familiar instance of raising water by a common pump: the pump handle may be either short or long; or, which is the same thing, the person who pumps may at one time lay hold of the middle of the pump handle, and at another time at the end; and he may work the pump in either case; but when his hand is at the middle he must exert a much greater force than when it is at the end, but then his hand moves through a much less space. The advantage thus derived from a long pump handle is, that a weak man moving his arm through a long space at the end of the handle can raise as much water, that is, do as much work, as a strong man moving his arm through a less space. But unless the weak man moves his arm quicker than the strong man, he will take more time in going through his appointed space: then we see that the effect of the lever in this case may be viewed in two ways; first, either as enabling a weak man who moves his arm rapidly to do as much work as a strong man who moves his arm slowly, and thus placing them on an equality, so to speak, as mechanical agents; secondly, as enabling a weak man to do in more time what a strong man can do in less.

The real advantage then of the simple machines arises from the means which they present of employing the small power which we always possess according as it may be required. One man's effort, provided he works proportionally longer, may produce the same effect as the sudden effort of a hundred men. But it would frequently be impossible to bring together, or to concentrate, the efforts of a hundred men. Thus, at the expense of time one man may do the work of one hundred men. Again, one man may by the use of a combination of levers, such as is exhibited in the printing press, bring the types and the paper together, and press the one on to the other with a pressure which many men could not produce by any direct efforts; thus the force which he exerts at a particular point may be increased to any extent, but then it is certain that his individual effort will have been exerted through a much greater space, and it is the effort, together with the space through which the effort can be exerted, which constitutes the power of an agent. Hence we may appreciate the truth of the following proposition, that 'the power of an agent cannot be increased by the intervention of machinery, but its force may.'

25. *Power is not created, but converted.*—In the preceding article we have seen that power cannot be augmented, that is, created by the intervention of machinery, and we shall see that the same may be asserted of all the natural agents of which we avail ourselves: here there is no creation but only a conversion of power. The two natural agents of wind and water are in a state of motion by nature; we only make use of this state, and by some mechanical intervention change the direction of the motion so as to render it subservient to our purposes; we obtain a force acting in a different direction, and modified so as to suit our purposes, but we create no power. If we avail ourselves of a descending stream to turn a water wheel, we are appropriating a power which nature may appear at first sight to

be uselessly and irrecoverably wasting, but which upon due examination we shall find she is ever regaining by other processes.* The force of vapour is another most fertile source of moving power, but here it can hardly be maintained that power is created. Water is converted into elastic vapour by the combustion of fuel; if all the changes which are going on can be considered as accomplished by mechanical force, it will be almost certain that the power necessary to produce it is at least equal to that which is generated by the original combustion. 'Man therefore does not create power; but availing himself of his knowledge of nature's mysteries, he applies his talents to diverting a small and limited portion of her energies to his own wants; and whether he employs the regulated action of steam, or the more rapid and tremendous effects of gunpowder, he is only producing on a small scale compositions and decompositions which nature is incessantly at work in reversing, for the restoration of that equilibrium which we cannot doubt is constantly maintained throughout even the remotest limits of our system. The operations of man participate in the character of their author; they are diminutive, but energetic during the short period of their existence; whilst those of nature, acting over vast spaces and unlimited by time, are ever pursuing their silent and resistless career.'†

26. *Motion uniform and varied.*—In considering the different cases of the motion of a body without any reference to the cause of that motion, the rate at which the body moves occupies our attention. Some motions are slow, others rapid; these are however but relative terms, as the most rapid motion which we observe about us is slow when compared with the motion of the earth, and absolute rest when compared with the velocity of light. But the two kinds of motions with which we are at present concerned are uniform and varied motion, the latter

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* See Babbage *on Manufactures*, p. 17.

† *Ibid*, p. 18.

of which may be either accelerated or retarded, of which we shall see instances in the motion of bodies by the constant action of gravity.

The motion of a body is said to be *uniform* when it passes over equal spaces in successively equal intervals of time, and *varied* when the spaces corresponding to successive and equal portions of time are not the same. If the spaces passed over in equal portions of time become successively larger and larger, the motion is said to be accelerated, and if smaller and smaller, it is said to be retarded. Thus, suppose we have a clock which beats seconds, and observe any body which moves in a straight line, if during the interval of every successive beat it passes over one foot, in sixty beats, or in one minute, it will have passed over sixty feet; the motion then of this body is uniform. But if having passed over one foot in the 1st second, it passes over more than one foot in the 2nd second, and still more in the 3rd, and so on, the motion of that body is said to be accelerated; and if it pass over less than one foot in the 2nd second, and still less in the 3rd, and so on, the motion is retarded. The *velocity* of a body is the space passed over in a given time, as in one second; hence when one body is said to have a greater or a less velocity than another, we mean that a greater or a less space is passed over in the same portion of time. Now *one second* is always taken as the unit of time, and all motion is measured by the space which is or would be passed over in this time. Thus if a person travel four miles an hour, his velocity is $\frac{4\times5280}{60\times60}=5.86$, or nearly six feet per second.

The motion of bodies is generally referred to three fundamental laws, which were first established by Newton, and which, having been the basis of mechanical philosophy from his time to the present, will require to be considered in some detail.

27. *First law of motion.*—'A body in motion, not acted on by any force, will move on in a straight line with a uniform velocity.'

Our first impression respecting the motion of bodies is that there exists in motion some tendency to self-destruction, or some disposition continually to retard itself, as if from a kind of inertness in matter; for all the bodies which we see in motion are observed to move more and more slowly, losing their velocity by different degrees till the whole is exhausted, and the body is reduced to a state of rest. But it is clear that in common cases much of the retardation is owing to external causes, as friction and the resistance of the air, for in proportion as these impediments are removed the motion continues longer. A ball rolled along the ground is speedily stopped, but if it be rolled along a sheet of ice, the motion will continue for a very long time. The time during which a pendulum will continue in motion depends so essentially on the resistance of the air, that in an exhausted receiver a pendulum may be made to swing for several days. From these and similar instances we are led to infer that *all* the retardation arises from the action of external causes; hence if these could be entirely removed the motion would go on uniformly, the velocity continuing undiminished for ever. The motion will also be in a straight line, for whenever this is not the case it will be seen to be the result of some constraint. We may conclude therefore that motion is naturally uniform and rectilinear.

It appears then that a body has no natural tendency either for a state of rest or a state of motion. It is entirely passive. If it be at rest, it remains at rest; if it be in motion, it continues moving. In the former case, the slightest force which solicits it to move, if not opposed by an equivalent force, is obeyed; in the latter case, the slightest obstacle which retards it takes away something from its velocity; and, if such action continue, will finally extinguish the whole motion.

The law that a body is thus indifferent to rest and motion is called the *law of inertia;* it may be illustrated in many well-known instances where any change takes place suddenly in the state of things composed of several parts. When a coach is suddenly stopped by any violent concussion, as being upset, the passengers and luggage will be thrown violently forward. The passengers and luggage being bodies unconnected with the coach are affected by the law of inertia, and go on with the motion they had before, though the vehicle is stopped. A person sitting in a carriage is thrown back when the horses suddenly increase their speed, and thrown forward when they are suddenly stopped; hence, by observing in which direction this effect takes place, a person put blindfolded into a carriage may by reflection discover whether he is riding forwards or backwards, that is, whether he is placed with his face or his back to the horses. If a vessel containing water be pushed violently along the table the water dashes up behind, and if its motion be suddenly stopped the water dashes up in front. The illustrations of this law are infinite; the reasoning on which we have founded it could not of itself be considered conclusive, but when it is viewed in connection with those which have to follow, its truth cannot possibly be doubted.

28. *Motion not perpetual.*—Since in all material contrivances, however perfect, there is some resistance to motion from the constant retarding force of friction, as well as from other incidental causes, no machine can go on working for an indefinite time without a constant supply of force. This supply is administered in a watch or clock when they are wound up, and there is some similar source in every machine which goes for any length of time; this may be carefully concealed, as in automatons, but it must exist. In the water wheel this supply is furnished by the perpetual descent of the water; in the windmill by the constant action of the air; and these supplies may be perpetual, as will be seen when we come to consider the beautiful and harmonious compensations which exist in these as well as every department of nature. In the steam engine the elasticity of the vapour is called into play by the continued agency of fire, and similarly in all other cases. Now as the smallest perpetual subtraction constantly repeated would

exhaust the largest quantity, so the smallest perpetual resistance uncompensated would finally destroy any original motion. And if in all the combinations of matter there is some resistance, the doctrine that motion, if undisturbed, is endless, leads immediately to the conclusion, that a motion actually perpetual is practically impossible.*

As the terms motion and perpetual have occurred together in the preceding remarks, it may be as well to say a few words on the sense in which the phrase *perpetual motion* is generally understood. The perpetual motion which is here shewn to be practically impossible is widely different from that in the search after which so many have squandered their lives and fortunes; the perpetual motion is theoretically absurd. We cannot here confute in general terms the notion of the possibility of this scheme, but a familiar instance of what is meant by it, added to the principles already laid down, will be sufficient for the present. A fall of water will turn a wheel and work pumps; these pumps *might*, supposing there were no leakage, friction, and other retarding causes, just pump all the water back again to the height from which it had descended, but more than this could not be done. The water could not be raised the millionth part of an inch higher, nor could the wheel do the least work besides. Now the believers in perpetual motion fancy that it can pump the water back again, and by the intervention of machinery *do some work besides.*

29. *Combined motions.*—The motion of a body cannot take place in more than one direction at the same time; a body cannot at the same instant have two or more motions of translation; hence, if the circumstances are such that a body might move in more than one direction, we are certain that these motions will be combined into one. Suppose for instance that a person walks across a ship as the ship is sailing on its regular course, he can go but in one direction; again, if a ball be rolled along a table in one direction as the table is being moved in some other direc-

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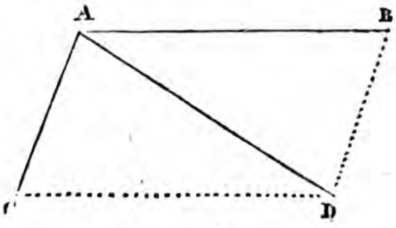
* Whewell's *First Principles*, Art. 9.

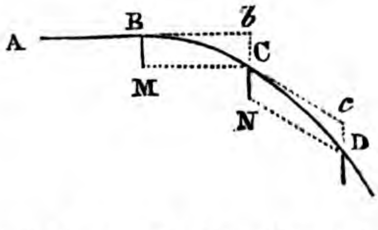
tion, this ball can have but one motion compounded of these two. The law of the composition of motions is simple and invariable. The motion of a body may be represented in velocity and direction by a straight line; if then the motion of a body consist of two combined motions, such that, separately, they would be represented in magnitude and direction by the two sides of a parallelogram, this combined motion will be expressed by the diagonal. Thus at the same instant let there be communicated to a body at A two velocities, such that with one the body would describe the line A B and with the other the line AC in the same time, then completing the parallelogram A C D B, the actual motion will be along A D, the diagonal of the parallelogram.



30. *Second law of motion.*—'When any force acts upon a body in motion, the change of motion which it produces is in the direction and proportional to the magnitude of the force which acts.'

The body is now supposed to be already in motion, and to be subjected to the action of some force; now since the effect of this force will be to produce another motion, this must be compounded with the former, and the second law of motion asserts that the motion produced is precisely the same in amount as would be produced were the body at rest; so that the new motion is combined with the previous motion in such a way that both produce their full effects parallel to their own directions.

Thus, suppose a body considered as a point to be moving in the direction A B, with such a velocity that it may describe A B uniformly in one second. Then by the first law of motion it would in the next second describe B *b* in the same straight line equal to A B. But when it comes to



B let a force in the direction BM begin to act, and act uniformly upon it for one second; the force being of such a magnitude that it would in one second cause the body to describe BM from rest. Then, at the end of one second from the time when the body is at B, it will be found at C, MC and *b*C being equal and parallel to B*b* and BM. If when the body comes to C the force were to cease to act, it would go on moving in the direction and with the velocity which it has at C. Similarly we may find the effects of other forces, and the consequence will be that we shall have a series of points, as C, D, which is the path in which the body will move, and these being near each the path will be curvilinear.

If this law were not true, and we still suppose the earth to revolve on its axis, a body struck north or south would deviate either to the east or west, neither of which is found to be the case; a stone let fall from the top of a tower would not fall at its base; the ball thrown up by the hand as a person walks along, or rides on a coach, would not return into the hand, but would fall behind. When a man standing on a galloping horse leaps over a hoop placed across his course, he does not leap forward, for this would carry him on to the horse's neck, or beyond his ears, but merely jumps up, and, being carried on according to the law of inertia (Art. 29), is, in conformity with this second law of motion, brought down to his proper place, just as if he and the horse had not been in motion.

The phenomena which may be adduced in illustration of the preceding laws, are exceedingly varied; but we shall see that both laws are applied in their explanation. Rectilinear motion does not exist, but we have no doubt of the truth of the first law, because we see that the change from the rectilinear course is due to some extraneous force.

The motions of the planets, and the rotation of the earth, are the really satisfactory proofs of the truth of the first and second laws of motion; the agreement of the results of complicated mathematical investigations founded on the supposed truth of laws, with actual observed phenomena, is the most convincing test of the truth of any laws. This is the evidence which we have already spoken of (Art. 3), and no one can doubt of the truth of these laws, when the mathematical calculations founded upon them enable us to predict, to half a second, the time at which Jupiter, twenty years hence, will be on the meridian. Every actual proof of the first law involves the truth of the second; the oscillations of the pendulum afford a direct proof of both of them.

31. *Centrifugal Force.*—The effort which a body moving in any curve or round a centre, as when a stone is swung round at the end of a string, makes at every instant to recede from the centre, or to break the string, is the immediate consequence of the first law of motion. If left to itself at any instant, it would move on in a straight line, or fly off in a tangent; that is, the direction of its motion would be that of the tangent to the curve at the instant when it was left to itself. Thus we see the dirt from a coach wheel flying off in all directions; for each particle preserves the direction which it had the instant at which it left the wheel. Whenever a body moves in a curvilinear path it must be deflected from the rectilinear path by some force, and the centripetal force, or force requisite for this purpose, may be supplied in different ways. If a stone be whirled round at the end of a string, the tension of the string is the centripetal force. The moon revolves about the earth, and the mutual attraction betwixt them, or the gravity of the moon to the earth, is the force which retains her in the orbit. If this centripetal force cease at any instant the body immediately flies off from the centre, because it flies in a tangent. Thus it appears that there is no such force as centrifugal force otherwise than as the immediate result of the first law of motion.

The tendency of revolving bodies to recede from the centre is illustrated by many phenomena. If a pair of common tongs be suspended by a cord from the top and made to turn by the twisting or untwisting of the cord, the legs will separate from each other with a force proportioned to the speed of rotation, and will again collapse when the turning ceases. This is the principle of the *governor*, of such universal application in the regulation of machinery. The governor may be described as a pair of tongs loaded with heavy balls at the ends, so that their opening may be more energetic. They are made to revolve by being attached to some part of the machinery; if the machinery goes too fast their speed is increased, they consequently fly farther from the centre, and by their motion may cut off the supply of steam or water, or whatever is the moving power; on the contrary, should the machinery go too slow they collapse, and by this motion may be made to turn on a greater supply of power. Thus by taking advantage of the simplest laws of nature the supply of power in an enormous manufactory may be always exactly proportioned to the demand.

The application of these principles to the figure of our earth and the other planets is too interesting a topic to be passed over in silence. We know that if a ball of soft clay be made to revolve rapidly about an axis, it ought and will bulge out in the middle, where the centrifugal force is greatest, and become flattened at the top and bottom. Now this same thing may have happened to our earth; we know from actual measurement that it bulges out by about thirteen miles in the middle, that is, its equatorial diameter is twenty-six miles longer than its polar diameter;* the inference which may be drawn therefore is, that our earth has been brought into this form by a rotation about its axis. Thus we have presumptive evidence of this rotation, and when from the assumption of this rotation we proceed to calculate what its force ought to be, and determine that it ought to be just as we know it is, we are firmly established in the conviction of the truth of our principles. The same

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* The measurements given by Mr. Airy, in the Encyclopædia Metropolitana, are,

Equatorial diameter	7,925·648 miles,
Polar diameter	7,899·170
Difference of diameters	26·478

evidence is furnished by the forms of Jupiter and Saturn; they revolve much quicker than our planet, and consequently bulge out much more.

32. *Third law of Motion.*—'When a force of the nature of pressure produces motion, the velocity produced is proportional to the force.'

The two preceding laws, as we have seen, cannot be established directly by experiment, they are so connected together that any experimental proof of one presupposes the truth of the other; their complete confirmation must therefore be considered as derived from the accordance of results, calculated on the supposition of their truth, with observed facts; but this third law may be established by direct experiment. For the details of these experiments we must refer to Mr. Whewell's Treatises on Mechanics, to which we are indebted for nearly every thing which is here stated respecting these laws. We shall now endeavour to shew its meaning and applications.

A given pressure will produce less velocity in a large than in a small portion of matter, that is, the greater the quantity of matter the less effect does a given pressure produce. This effect of the quantity of matter in diminishing the velocity impressed upon any substance is termed the *inertia* of the body. Since the velocity produced in a body is less as the inertia is greater, the inertia is sometimes spoken of as a resistance to motion impressed upon the body; now the effect of inertia is not to prevent but only to diminish the motion impressed. Thus, if a small weight be suspended by a string we can, by a small push, give it a considerable velocity; but if a larger weight, that is, a greater quantity of the same matter, as, for instance, a large block of stone, be suspended by a rope, the same push would scarcely produce a perceptible motion, though the friction would be altogether inconsiderable. But though, in such a case, a very small motion would be produced, there would be really *some* motion, however small were the force, and however large the mass to be moved, if the motion were not resisted by something besides the mere inertia of the body, as, for instance, friction on a fixed obstacle. This is sometimes illustrated by saying that a person walking or leaping on the earth's surface moves the whole globe of the earth by the pressure of his feet. And this is mathematically true, but the velocity of the earth is as much less than that of the person upon it as its weight is greater; so that so far as the world of sense is concerned, it is the same as if it did not exist. A very large quantity of matter may, however, be put in motion by a very small force, practically as well as theoretically, by continued or repeated action. Thus a large weight suspended by a string may be put into perceptible motion by the breath, if we blow at intervals answering to the oscillations of the string, so that the small impulses may all assist and not counteract each other.

But when the quantity of matter is the same, the effect produced, or the motion communicated, will depend on the magnitude of the force. Thus if we blow violently against a small body suspended by a string we may communicate a considerable velocity to it, and the velocity produced will depend on the force with which we blow. When a ball is impelled by the explosion of gunpowder, the force here exerted is a pressure, and the velocity produced will be proportioned to the force.

33. *Momentum.*—It appears then from the last article that in estimating the quantity of motion we must consider both the velocity and the quantity of matter in which this velocity is produced. Any force having put a body in motion and produced its full effect, remains, as it were, enclosed in the body, and the joint product of the velocity and of the quantity of matter represents the result; this joint product is termed the momentum of the body. Thus a cannon ball of one hundred ounces, moving one foot per second, has the same momentum, or the same *quantity of motion*, as a musket ball of one ounce moving with a velocity of one hundred feet per second. On these principles we may compare the effects of a battering ram and of a

cannon ball in shaking a wall; in the one case we have a large mass moving with a small velocity, in the other we have a small mass moving with a large velocity, and if the product of these is the same, the force exerted on the wall will be the same also.

From the preceding principles it follows, that if a person in a boat pull at a rope, the other end of which is fastened to a ship, both floating freely, the boat will move towards the ship and the ship towards the boat, and the velocity of the boat will be as much greater as its quantity of matter is less; so that the momenta of the two in opposite directions will be equal. Also when two bodies attract each other, they will move towards each other unless prevented. For this attraction may be considered as an invisible cord by which they pull at each other. Thus if a magnet and a piece of iron be placed on two pieces of cork and set to float on water, they will approach each other, the smaller mass moving proportionally quicker.

It follows also that the motion which exists now in the world is precisely the same as that which existed at the creation, and will continue to exist so long as the present laws of motion prevail; the term motion being confined to mean momentum in a given direction; for any amount of *relative* motion may have been extinguished. Thus every new motion communicated to a rock, or a torrent in an easterly direction, must be subtracted from the easterly motion of the earth; but when the rock is stopped by contact with the earth it loses some of its own momentum, but it communicates to the earth exactly the same quantity in the same direction.* We shall see another striking illustration of these principles in the compensation currents of the trade winds.

34. *Momentum proportional to the Pressure and Time.*— The effect of a pressure in generating motion in a given mass will evidently be greater the longer it continues to

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* Whewell's *First Principles of Mechanics*, p. 110.

act, and it will be found that the momentum produced in any time is proportional to the product of the pressure and the time. Hence we may understand the enormous effects which are sometimes produced by a small force acting continuously; as, for instance, when a small steam engine sets in motion a very large fly-wheel. This wheel acts as a reservoir of all the small pressures which have been communicated to it, and having thus concentrated them can apply them all together and at once, when some great effect is to be produced; of this we have the following instance stated by Professor Babbage, in his Economy of Manufactures:* 'In some of the iron works, where the power of the steam engine is a little too small for the rollers which it drives, it is usual to set the engine at work a short time before the red hot iron is ready to be removed from the furnace to the rollers, and to allow it to work with a great rapidity, until the fly-wheel has acquired a velocity rather alarming to those unused to such establishments. On passing the softened mass of iron through the first groove the engine receives a great and very perceptible check; and its speed is diminished at the next and at each succeeding passage, until the iron bar is reduced to such a size that the ordinary power of the engine is sufficient to roll it.'

35. *Forces require Time.*—We have seen that a small pressure acting for a long time may generate a great momentum; it appears also that a great momentum requires time to produce its effects. This is shewn by the experiment of firing a bullet through a sheet of paper hung loosely. Though the paper is so light, the great momentum of the bullet scarcely gives it any perceptible motion; the force of the bullet has not time to act on the paper. For the same reason a cannon ball may be fired through a door which swings easily on its hinges without moving it, and a bullet will pass through a pane of glass

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* Art. 20.

making a hole of its own size; in these cases the particles are carried away without having time to communicate their motion to the surrounding ones. Analagous to this is the fact, that a person may skate over ice which would not support his weight if he attempted to walk over it. Time is required for producing a fracture, and the velocity being considerable, the skater has passed from the spot before the bending has reached the point at which the ice will break.

36. *Impact and Collision.*—When a body in motion meets another body either at rest or in motion, the effect produced depends on the elasticity, on the duration of the contact, and on the relation which the masses of the body bear to each other. The action which takes place is of the nature of pressure, and consequently subject to the preceding laws of motion. The only distinction which is to be made between impact and pressure is, that impact is a pressure of very short duration. This will be apparent on considering what takes place when two bodies impinge. If an ivory ball in motion strike another at rest, they appear to separate as soon as they touch, but we know that there has been a change of form, each ball has been compressed, and this change must have occupied time, however apparently small. But were it not for the rapidity of the change we should see that the communication of motion is always gradual, and that the ball which is at rest is put into motion by insensible degrees of velocity. It is important to remember that time is necessary for the destruction of momentum, or rather of velocity, and the less the time which is employed the greater must be the effort exerted; we have already seen several instances of the effect which time has in the production of a great momentum, and it must have a corresponding effect in the destruction of momentum already generated. That the change of figure just spoken of does actually take place in impact may be made evident by the simplest experiments. Let two elastic bodies, as, for instance, two ivory balls, be covered with two

differently coloured substances, and made to impinge on each other, then the parts which are brought into contact by the impact will be stained, and a spot will be produced on each of finite magnitude. This spot could not be produced if the balls retained their globular shape; and the spots are larger as the force of impact is greater. Thus the destruction and the communication of velocity is in all cases gradual; and the time employed will depend most materially on the nature of the substance.

We may then consider impact as a pressure of short duration; increasing from nothing to a finite magnitude, and then decreasing again to nothing: hence the third law of motion is true in cases of impact; consequently experiments made on the collision of bodies may be employed to establish the third law, as was done by Wren and Newton.

37. *Sudden destruction of Velocity.*—The effects produced by impact as compared with those produced by pressure appear so enormous, that they have sometimes been referred to different principles. But the whole difficulty vanishes when the element time is properly taken into the account. In impact there is a destruction of velocity, and the effect produced depends most materially on the time employed in its destruction. This may be illustrated by the familiar example of driving a nail. If the nail be struck by a soft body it can never be driven into any obstacle, whereas a very slight blow with a hard substance will fix it at once. The difference of these effects arises from the fact that the soft body being a yielding substance its velocity is being destroyed gradually during the yielding of the body, but the velocity of the hard body is destroyed in much less time since there is very small yielding of parts. Thus it may be laid down that the force requisite for the destruction of any velocity is greater, as the time occupied in its destruction is less; and it is this force which in the above instances drives in the nail. It appears then that the hardness of the surfaces between which the impact takes

place has a most material influence on the effect produced. When the surfaces are very hard there is scarce any yielding, the velocity must consequently be destroyed in a very small time. Thus the hardness of the surfaces must be considered as the real cause of the efficacy of impact; and it is so because of the almost instantaneous destruction of velocity which takes place when the surfaces are hard. Again, if we attempt to drive a nail into a yielding board, the same principle is illustrated in the small progress which is made; the yielding takes considerable time, hence the velocity which was suddenly destroyed in the hammer is destroyed gradually at the board, so that the effect produced towards making the nail enter is exceedingly small. The preceding remarks will fully explain the surprising effects produced by a constant small impact, when the striking surfaces are very hard, and when the parts are unyielding. The preceding explains also the great advantage with which impact may be used to overcome friction. The unyielding nature of the surfaces is the very circumstance which gives efficacy to the impact. Hence we see that wedges may be driven by impact which would scarce be pushed in by any conceivable pressure.

On the preceding principles we may explain the necessity of springs for carriages which are to travel at any rate. A carriage going along at the rate of ten miles an hour meets with an obstacle; if now the carriage is perfectly stiff, so that its whole weight has to be raised suddenly over this obstacle, the shock produced on the road and wheel by the sudden change in the direction of the motion is very great indeed; but when the mass of the load is sustained on springs, the only force exerted is that which will raise the wheels and bend the springs. If roads and wheels were perfectly smooth there would be no need of springs; but this being impossible they are as necessary for the preservation of the road as for the comfort of the passengers. For the shock produced by the rapid conversion of the direction of the motion of a mass of matter from a horizontal to a vertical direction, is felt equally by the road and the carriages. These principles are of the greatest practical importance in railroads, where the velocity is great, and the surfaces are hard; and notwithstanding the degree of smoothness of the surfaces and the excellent springs with which all the carriages are furnished, the breakage of the rails and axle-trees from the above-mentioned cause is very great.

CHAP. V.

ON GRAVITY.

SECTION I.

GENERAL EFFECTS OF GRAVITY — LAWS OF FALLING BODIES — LAWS AT SURFACE OF THE EARTH — CENTRE OF GRAVITY — STABLE EQUILIBRIUM.

38. All bodies with which we are acquainted when left to themselves fall until they touch the earth, or some other body which can sustain them. This phenomenon, which takes place at the surface of the earth, at all known heights above, and depths below the surface, must be the consequence of some force residing somewhere. The natural inertness of matter, or its passive continuance in the state in which it exists, compels us to admit the existence of some force, and that peculiar force which produces these effects is termed *gravity*. Thus, gravity is the force which makes bodies fall to the earth; but this definition will convey to us a most inadequate idea of the power of this agent if we suppose it produces no other effects. It is to this that we owe many other phenomena and many other motions, to which different names have been applied. Thus, for example, the flowing of rivers, the ascent of light bodies in fluids, with many apparently contradictory phenomena, are but the effects of that same energy which we have called gravity. We may have some further idea of the way in which this force acts, by conceiving that all matter possesses the pro-

perty of attracting all other matter; we have seen instances of this attraction exerted at insensible distances, but the attraction of gravitation acts at all sensible distances, however great.

39. *Weight.*—The first and principal effect of gravity is the pressure directed towards the earth which every body exerts upon those which are placed beneath it; this pressure is usually termed weight; if my hand supports a stone, the pressure which the stone exerts upon my hand is termed the weight of the stone; hence it is asserted, that all bodies are heavy, for all fall to the earth when left perfectly to themselves. This weight is the result of the mutual attraction of the earth and the stone; the earth attracts the stone, and the stone attracts the earth; each moves towards the other (Art. 33): but, inasmuch as the motion of each is the less the greater the mass, we easily see that the motion of the earth to meet the stone, or any body which can be raised above its surface, is so indescribably small, that the motion of the stone only need occupy our attention. Hence, we never speak of the effect of the attraction of the stone upon the earth, but simply of the attraction of the earth upon the stone: but that we may have accurate conceptions on this point we must remember, that the weight of any body is really the effect of the attraction of the earth upon the body, increased by the effect of the attraction of the body upon the earth. Hence it follows, that the weight of a body is proportional to its mass; for the more particles there are in a given bulk, the greater must be this mutual attraction, that is, the weight of the body.

40. *Direction of Gravity.*—All bodies left to themselves fall to the surface of the earth, where all further progress is arrested, and the direction in which they fall, or in which gravity acts, may be observed by setting up straight rods, and watching when a body falls accurately along them. But this direction may be more readily ascertained by a plumb-line, that is, by any line hung up by one end, and

sustaining a small weight; this weight will stretch the line in the direction in which gravity acts; hence this line gives the direction of gravity. This direction is always the same at the same place, being invariably perpendicular to the surface of still water; and for all places near each other the directions are sensibly parallel, for a small extent of the surface of still water may be considered as a plane, and consequently the perpendiculars to it will be all parallel. But at places at a considerable distance from each other, as at London and Paris, the directions of gravity are inclined to each other. For the surface of still water at these places being portions of parallel spherical surfaces, or very nearly so, the perpendiculars to these surfaces at those places would, if produced, meet near the centre of the earth; and at places more distant still, as, for instance, at Paris and the Cape of Good Hope, the directions of gravity will be nearly at right angles to each other, and at our antipodes the directions are on the same line, but opposite to each other, both being towards the centre. It is generally said that the direction of gravity is perpendicular to the surface of the earth; now by this we do not mean the actual surface, such as it generally exists with its numerous inequalities, but an ideal surface, such as the earth would present were it uniformly curved like a large tract of still water, or a calm sea.

41. *Falling Bodies.*—In observing falling bodies the first thing which strikes us is the different rates of their descent. A piece of lead, or any other metal, falls very rapidly, the leaf of a tree falls very slowly; this cannot arise from the difference of the weight of two substances, for since the greater weight implies a greater number of particles, and gravity acts equally on all particles, there ought to be no difference in the descent of the two bodies. But the real cause of this apparent difference is the resistance of the air, which acts much more effectively on the extended surface of the leaf than on a smaller and heavier substance; and that this is the true

explanation the well-known guinea and feather experiment renders evident; for in this experiment a guinea and a feather reach the bottom of an exhausted receiver at the same instant. Having shewn then that all bodies fall with the same velocity, we must proceed to inquire what is this one velocity, or law, according to which the descent of every species of matter takes place; or, in other words, what relation subsists between the space which a heavy body passes over, and the time which it employs in passing over it. This relation is the law of the motion which gravity impresses on matter. The readiest apparent method of solving this question is to procure a long glass tube, exhaust the air, and allowing a body to fall from the top, to mark the point which it passes, after one second, two seconds, and so on. But we should observe here, as we may observe in the descent of bodies in the air, that at the commencement of their fall they move slowly, but their velocity augments so rapidly, that in a few seconds it is impossible to note, at all accurately, the point which the body passes at a given instant. A fall so accelerated precludes all direct observation, and recourse must be had to indirect methods, either to the inclined plane of Galileo, or to the machine of Atwood (Art. 43). We cannot, however, establish a law by direct experiment, since the errors of observation can never be altogether prevented, but we can verify an assumed law, and this is precisely what is done in treating of gravity. It is proved by observation that gravity satisfies the defined laws of a uniformly accelerated motion, as we shall proceed to shew.

42. *Uniformly accelerated Motion.*—We have just seen that the velocity of a falling body increases rapidly during its descent. Now the motion of a body is said to be uniformly accelerated when the velocity added is equal for equal times; that is, the body must receive the same addition of velocity in the 4th or 5th second as it receives in the 2nd or 3rd; when this is the case, the body is said to be acted on by a uniform accelerating force. We must con-

sider in all cases of accelerated motion, that were the action of the force to cease at any instant, the body would go on moving, according to the first law of motion, with the velocity which it then had; but, that as this force does not cease at any instant, velocity is added continuously to that already existing; the velocity added in any time being measured (Art. 26) by the space which would be passed over by the body, moving with that velocity, in the given time.

Uniformly accelerating force is measured by the velocity added in a given time, as, for instance, one second. Thus, if it should appear from observation that the velocity of a falling body receives the same addition every second, then will the force of gravity be an uniformly accelerating force, and will be measured by this quantity.

From these principles there will result the following laws:—1°. 'The velocity generated in any time by an uniformly accelerating force is proportional to the time.' 2°. 'The space described from the beginning of the motion is as the square of the time.' 3°. 'The space described by a body uniformly accelerated from rest, is half the space described in the same time with the last velocity; or, in other words, the velocity generated in one second will in the next second carry the body over double the space described in the first.'

The preceding are the laws of uniformly accelerated motion, and it remains to shew that the motion produced by gravity is subject to these laws; whence we may conclude that gravity is an uniformly accelerating force.*

43. *Atwood's Machine.*—The velocity produced by the undiminished force of gravity being much too great to be conveniently subjected to experimental examination, it

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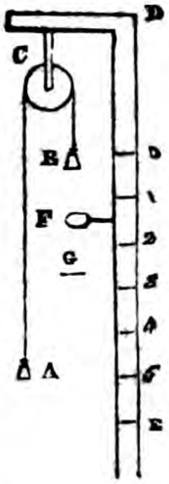
* The exact laws expressing the relation betwixt the velocity, space, time, and force, are $v = f\,t$, and $s = \frac{1}{2} f\,t^2$. In these equations f is the accelerating force, that is, the velocity added or generated in each second, and v the whole velocity generated in t seconds; also s is the space described in the same time.—See Whewell's *Elementary Mechanics*, Art. 161—164.

occurred to Atwood that all the phenomena of falling bodies might be experimentally exhibited and accurately observed, if a force of the same kind as gravity, but of much less intensity, were used; so that the motion would still be governed by the same law of gravity, while the intensity of the agent being diminished, and consequently the quantity of motion, the velocity might, even after several seconds, not have become too rapid to admit of accurate measurement. With this view Atwood suspended two equal weights, one at each end of a string, passing over a wheel, turning very easily on its axle. The equal weights are represented at A and B, and the wheel at C. These weights balance each other perfectly, and no motion can take place. To one of the weights, as to B, a slight addition is made; this was generally done by placing a small bar upon B; the bar is represented at G, and is too long to pass the ring F. This ring can be attached to any part of the graduated scale represented on D E. Suppose that B is exactly opposite the zero of the scale, and that the additional bar is laid upon it. The loaded weight will begin to descend, drawing up the unloaded weight A. The descent of the loaded weight is a motion of exactly the same kind, as of a heavy body falling freely; hence the laws of its motion will be the same; the absolute amount of velocity will be very different in the two cases, but the rate of its increase will be the same, and this is what we wish to discover.



Let us see now whether the result obtained will accord with the laws of the preceding articles. For this purpose, let the body B, being loaded, begin to descend from opposite the zero division of the scale, and let it pass by the first division in one second; then, according to the law that the space is proportional to the square of the time, it ought after two seconds to be opposite division 4, after three seconds to be opposite division 9, and so on; and the experiments with this machine shew that this is the case. We will now examine what will take place when the additional weight G acts only for a short time. Let the ring F be placed at division *one* of the scale, then the weight G will be taken off at the end of the first second, and B will continue to descend with its acquired velocity. According to law 3° (Art. 42), it ought to pass by two divisions in the next and every subsequent second; and this is found to be the case; after 2″ it will be opposite division 3, after 3″ opposite 5, and so on.

The same results may be obtained by making bodies descend down inclined planes of different heights and lengths. It was assumed by Galileo, and may be shewn to be true, for the descent of bodies down inclined planes, 'that the velocity acquired down all planes, whose perpendicular heights are equal, is the same; and equal to the velocity acquired by falling down the perpendicular height.' The time of descent down an inclined plane varies with its length, hence the motions may be made as slow as we please, and the preceding laws of accelerated motion may be verified in the case of gravity.

From these, and other far more accurate experiments, which the pendulum will give us, it appears that the laws of accelerated motion, by gravity, satisfy those of uniformly accelerated motion; hence we may conclude, that gravity at the earth's surface is an uniformly accelerating force.

44. *Law of Gravity at the Earth's surface.*—From the experiments detailed in the preceding article it appears that gravity at the earth's surface is an uniform force; and this conclusion was arrived at by shewing that gravity is in its nature such as satisfies the definitions of that kind of force. But it must be observed, that nothing has hitherto been determined respecting the intensity of this force; the experiments with Atwood's machine shew the rate by which a given quantity increases, but not the amount of that

given quantity; this must evidently be determined by observing the free motion of a falling body, when all retarding causes, as the resistance of the air, are removed or allowed for. The only accurate observations which can be made for ascertaining this point are made with pendulums, as we shall shew hereafter. By the latest experiments it appears that a body at the surface of the earth would fall in vacuo through $16\frac{1}{10}$ feet in one second; this then is the intensity of gravity. But the velocity generated in one second would in the next second carry the body over twice the space; and the space described in the first second measures the velocity generated by the accelerating force of gravity. The accelerating force of gravity is therefore said to be $32\frac{1}{5}$ feet.

45. ***Path of a Projectile.***—The course in which a ball or stone thrown by the hand moves, is at once an illustration of the laws of motion and of gravity. Did gravity not act, the ball thrown in a particular direction would continue to move in that direction until its motion was destroyed by the continued resistance of the air. But gravity constantly acting upon it, deflects it from its rectilinear path, which it bends into a curve, whose particular form may be at once determined by the simplest theoretical considerations. This curve is a portion of a parabola, with its vertex at the highest point to which the body is carried by the force of projection. If the body be projected vertically upwards, it descends in precisely the same direction, and according to the same laws as during its ascent; for the destruction of the velocity of its upward motion arises from the continued action of gravity, and this force will generate again precisely the same velocity during the descent. But if it be projected in any other direction than the vertical, it will describe a curvilinear path, which will be a portion of a parabola. The deviation of the body from this exact theoretical path, owing to the resistance of the air, is small for small velocities; but in rapid motions, as in those of a cannon or

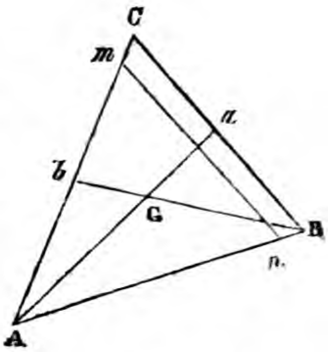
musket ball, the deviations are very great. Hence, the theory of gunnery requires many considerations which we cannot now dwell upon. If a cannon or musket ball be shot horizontally along the plain, it will, according to the second law of motion, reach the ground at precisely the same instant as a ball dropped from the mouth of the piece at the instant of its discharge. Thus, we may form some idea of the immense speed of a cannon ball, that it will travel several hundred feet while a ball dropped from the hand of a bystander falls four or five feet to the ground. From the preceding we see, that for long distances the muzzle of a gun must be elevated considerably above the level of the point which is to be hit; some allowance is made for this in the construction of rifles, and we know that these are furnished with two or three sights, to be used for different distances. The use of these has the effect of raising or lowering the breech of the piece, so that the ball has that elevation given to it which the distance of the object aimed at requires.

If a cannon ball be fired from the top of a high mountain, the distance to which it will go, before reaching the earth, depends on the force of projection, and on the height of the mountain. It is then easy to conceive a velocity, such that the ball may go many thousand miles before reaching the earth; nay, such that it will go quite round the earth without reaching the surface. In such a motion, the tendency to persevere in its rectilinear course is exactly balanced by the force of gravity, and were not the motion destroyed by the resistance of the air, the ball would go on revolving for ever. Suppose that a body is so projected, with the proper velocity, beyond the limits of the atmosphere, where there is no resistance to destroy its motion; it will go on in obedience to the laws of motion revolving for ever; it will become a satellite to our earth. And what is the Moon but such a satellite?—may not she circulate about the earth in obedience to the laws of motion and of gravity here laid down?

46. *Centre of Gravity.*—Any heavy body, whether large or small, may be considered as a collection of particles more or less minute, but indefinite in number; each of which is subject to the force of gravity. All these forces will be parallel to each other, and equal, and act in the same direction; hence they will have a resultant (Art. 22), or the whole effect will be the same as that which would be produced by a single force applied at a single point. This single force, or resultant, is the weight of the body (Art. 39), and the point at which it is applied is called the centre of gravity of the body. Every body, then, whatever be its shape or magnitude, has a centre of gravity, for all known bodies are subject to this force; and the determination of this point, for different bodies, is a very important, and often an exceedingly difficult problem. The importance of the problem arises from the simplicity which is thus introduced into all questions; since every body may theoretically be considered as a point acted on by a given force. When this point is supported, that is, when the force which acts upon it is counteracted, the body is at rest; and since this point has an invariable position in any given body, the centre of gravity of a body may be defined as the point about which a body will balance in every position. The difficulty of finding the centre of gravity arises from the irregularity of bodies. Even if their external figures are regular, we cannot be sure of the uniformity of their internal structure; they may be more dense in one part than in others; hence the actual centre of gravity cannot be always known from the theoretical determination of it. For instance, a rod will not always balance on its middle point; if one end be heavier than the other, the centre of gravity will be nearer the heavier end; the centre of gravity of a circle, or a sphere, will not always coincide with the centre of the geometrical figure. Sometimes, as in a common ring, the centre of gravity is at a point which does not lie within the material of which the ring is formed. Supposing any body, as a

straight rod, to be uniformly constituted, it will balance on its middle point, because there is on each side of this middle point a particle, the effect of gravity on which is to turn the rod in opposite directions. And these being exactly equal, the rod will be in equilibrium, when this point is sustained. We shall see, in the following article, the method which is to be pursued in the theoretical and in the practical determination of the centre of gravity of a body.

47. *Centre of Gravity of a Triangle.*—The centre of gravity in all simple figures may be found by the commonest geometrical considerations, as we shall see in the case of a triangle.



Let A B C be any triangle; draw A *a*, B *b*, bisecting the opposite sides. Now the triangle may be considered as made up of lines, each of which is parallel to the side B C, and each of which will balance on its middle point; hence the whole triangle will balance on the line A *a*; the centre of gravity, therefore, of the triangle is in this line. Similarly, the triangle may be made up of lines parallel to A C; the whole triangle will, therefore, balance on B *b*, or its centre of gravity is in the line B *b*. But it is also in A *a*; hence it is both in A *a* and B *b*, and therefore at their point of intersection, or G is the centre of gravity required. It may be proved by simple geometry, that A G = $\frac{2}{3}$ A *a*; hence, to find the centre of gravity of a triangle, we have only to draw a line from one angle, bisecting the opposite side, and to measure off from the angular point, along this line, a distance equal to two-thirds its whole length.

The practical method of determining the centre of gravity of a plain figure like the preceding, is exceedingly simple. Let it be hung up by any point, as the angular point A, for instance, and from this same point let a small plumb-line be suspended, and let A *a* be the line in which it would touch the surface; then the centre of gravity must be in this line. Similarly, if the triangle be hung up by the point B, and B *b* be in this case the direction of the plumb-line, then the centre of gravity must be in B *b*: but it is also in A *a*; it must, therefore, be at G, the point of their intersection.

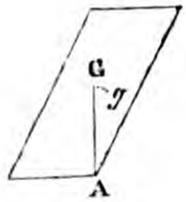
The centre of gravity of a pyramid may be found by considerations similar to the preceding. Suppose its faces are all triangles, then the whole figure may be conceived to be made up of sections, or laminæ, parallel to these faces. The centre of gravity of any of these sections can be found, and it may be shewn, as in the triangle, that the whole pyramid may balance on any of the lines drawn from any summit to the centre of gravity of the face opposite; the centre of gravity will, therefore, lie in each of these lines; and will, consequently, be at the point in which any two, or more, of these lines intersect.

48. *Conditions of a Body being at Rest.*—A body, then, will be sustained, whenever the line from its centre of gravity to the point on which it is sustained, is perpendicular to the horizon; but when a body stands on a broad base, this condition will receive some modification. In this case, the body is sustained on an indefinite number of points, and the condition now is, that the vertical from the centre of gravity must fall within the base of the body. And the preceding condition is evidently sufficient; for since this line falls wholly within the body, there will always be a line of particles affording the requisite support. This condition, then, being fulfilled, we must inquire whether the equilibrium is stable, or unstable; or whether a slight tilting of the body will be attended with a rise, or with a fall, of its centre of gravity. Hence we are led to the following—that the heights of the bodies being the same, those stand firmest whose bases are the broadest, and

centres of gravity the lowest. The following illustrations will render the preceding remarks more intelligible.

(1.)

(2.)



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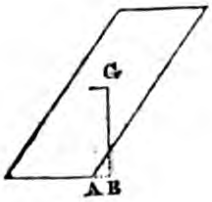
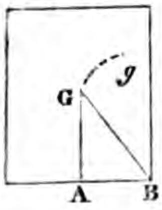


In fig. 1, the vertical drawn from the centre of gravity G falls within the base, or at A; the body may, therefore, be considered as supported on G A. Now, if this body be tilted over so as to be sustained on B, the centre of gravity will describe an arc Gg; the equilibrium is stable, therefore, for it cannot be disturbed without a rise of the centre of gravity. In fig. 2, the vertical from G falls just at the angle; the body is still supported, but the equilibrium is unstable, for if it be tilted over, so that G describes the arc Gg, the centre of gravity is lowered; the body will, therefore, upset. In fig. 3, the body cannot be sustained at all, since the vertical falls beyond the angle A, that is, without the base.

(4.)



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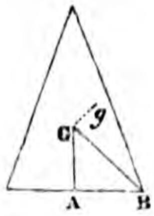

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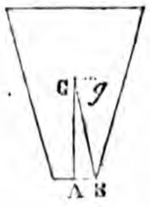
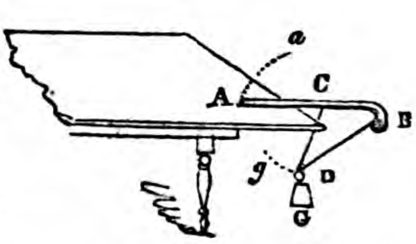


Again, in fig. 4, where the base is much broader than in fig. 1, the equilibrium is much more stable, because of this breadth of the base; for the body cannot fall over without the centre of gravity being much more raised, and the broader the base the higher must the centre of gravity be raised before the body can upset. In fig. 5, where the breadth of base is the same, but the centre of gravity is much lower, the arc G g, which must be described, is much more vertical; hence fig. 5 is much steadier than fig. 4. In fig. 6, the effects of a narrow base, and a high centre of gravity, are at once apparent; the rise of G is very small, and its path very short, so that an exceeding small tilt will overset the body.

Let a common walking stick, A B, be laid on a table: and let a heavy weight be attached to it by a string at C, being slightly pushed in, or out of the vertical, by a rod D B, then there will be equilibrium as represented in the figure. The string C D being pushed out of the vertical, no lateral motion can be given to the weight without raising the centre of gravity of the system. The end A of the stick will describe the arc A a, turning about C, and the centre of gravity would then ascend in an arc D g. But since such a motion would be attended with a rise of the centre of gravity, the position in which it is, before that rise can take place, is one of stable equilibrium; hence a small disturbance will not destroy the equilibrium.



49. *Illustrations.*—From these principles we may easily understand the various natural positions into which instinct directs us to place our limbs. In every position the centre of gravity of the body must be directly above the point of support; in ordinary cases the human body is supported on a base, whose boundaries are the lines that can be drawn joining the toes and the heels, and along the outside edges of the feet. A projection then in any part, as a load on the back, or in the arms, requires the body to be inclined so that the vertical from the centre of gravity of the compound mass may fall within this base. Hence, also, when a person would stand steadily, the feet must be set at as great a distance apart as is convenient and consistent with a ready

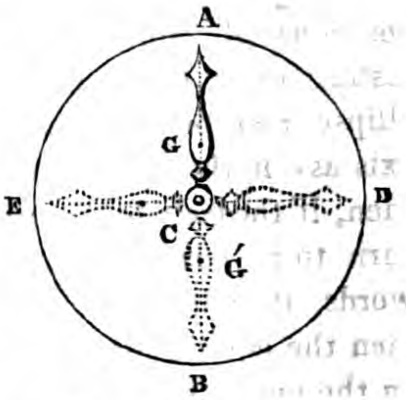
change of posture; the toes also must be turned out which adds to the breadth without sensibly diminishing the length of the base. The difficulty of walking on wooden legs is to be referred to the difficulty with which the centre of gravity can be kept over so small a base; and when the centre of gravity is raised, as by mounting on a pair of stilts, the position of the body may soon be brought into a position of unstable equilibrium.

The beautiful statues of antiquity will furnish many illustrations of contrivances on the part of the sculptors, by which the instinctive and unconscious adaptions of nature are so exactly imitated, that the statue has the same stability as the natural figure would have under the same circumstances.

In ascending a hill we appear to lean forwards, and in descending to lean backwards, but we only keep ourselves perpendicular to a horizontal plane; were our bodies to be perpendicular to the inclined surface of the soil, the vertical from the centre of gravity would fall without the base of the feet, and we could not be supported.

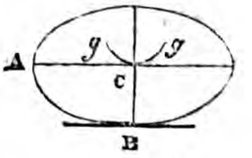
In rapid motions, the centre of gravity appears to be momentarily unsupported, or only partially supported, since the impression of a horse's hind foot may sometimes be seen upon or before the impression of the fore foot; but in these cases the weight of the animal, though unsustained, has not time to produce its effect. In general, quadrupeds move one foot on each side at the same time, so that the centre of gravity is over the diagonal of the four-sided figure formed by its feet. The motion of fowls is worth observing; they set one foot before the other so that the weight of the body is thrown directly over one leg at each step.

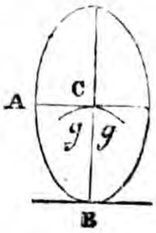
50. ***Equilibrium, stable and unstable.***—We have already seen that the only condition requisite that a heavy body should be in equilibrium, is that its centre of gravity should be sustained; but this condition may be fulfilled in differ-

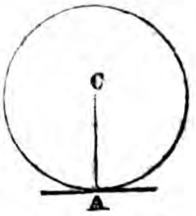


ent ways, according as the body is suspended from, or sustained on, a point of support. If an index, or hand, moving freely about its centre C, be at rest, its centre of gravity must be in the vertical line A B. There are but two ways in which the hand can rest; its centre of gravity must either be at G, above the centre C, about which the hand turns, or at G′ below it; the hand cannot rest in any intermediate position, as those indicated by the dotted lines C D, or E. Thus, there are but two positions of equilibrium. The nature of the equilibrium is however very different in the two cases; in the one it is *unstable*, in the other it is *stable*: for if, when the centre of gravity is above the point of support, the hand be moved ever so slightly from its vertical position, it will not return to that position, but will move still further to the right, or to the left, according to the side to which it is disturbed: in this case then the equilibrium is unstable: but when the centre of gravity is below the point of support, the hand, however moved, will return to its original position, or the equilibrium is stable. There is then stability in the equilibrium when the centre of gravity is below the point of support, and instability when it is above it: in all other cases there is no equilibrium at all, unless the adhesion to the axis be such as to prevent the hand from moving freely.

A body placed on a horizontal plane, and touching it but in one point, may assume divers positions of equilibrium, some of which will be stable, and others unstable, as in the preceding case. There may be others also which are termed *indifferent;* because the body, on being disturbed, makes no attempt to return to, or recede farther from, its original position, but remains in the position which we give to it. The three cases may be illustrated by the positions of equilibrium of an ellipse, and of a circle, resting on a horizontal plane. If an ellipse rest on the end of its smaller axis as C B, the equilibrium is stable; for then, if the body be disturbed, it will return to its former position, or, in other words, it will rock about B, and not turn over; here then the equilibrium is stable: but if it rest on the end of its larger axis, as C B, the least disturbance will overset it, it will recede further from its original position, it will not rock about B; here then the equilibrium is unstable. But a circle will rest on any radius as C A, and into whatever position it is brought it will stay there, shewing no disposition to move either way, that is, either back again to, or further from, the position in which it is once placed; here the equilibrium is indifferent.







In considering the preceding cases of the ellipse and the circle, we observe that the centre of gravity is in one position of the ellipse the lowest, and in the other the highest possible; that is, the line from the centre of gravity to the point of contact is in one case a minimum, and in the other case a maximum: but in the circle the distance of the centre of gravity from the supporting plane does not vary. Whenever then the supporting ray, or the line drawn from the centre of gravity to the point of contact, is a minimum, or less than the rays on each side of it, the equilibrium is stable; and whenever it is a maximum, or greater than those on each side of it, the equilibrium is unstable; and when it is neither a maximum nor a minimum, but all the rays are equal, the equilibrium is indifferent. All questions respecting the upsetting and falling of bodies, must be resolved by the preceding principles. So long as a body is in such a position that it cannot be moved without raising its centre of gravity it cannot be overturned, but where the centre of gravity would be instantly lowered by any tilting motion, the body must be upset if disturbed in the slightest degree.

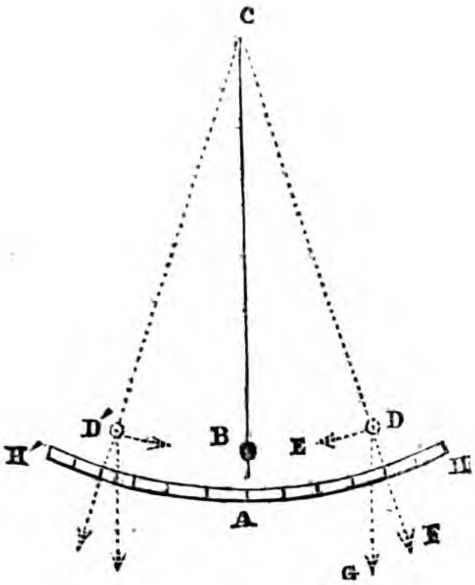
SECTION II.

SIMPLE, CYCLOIDAL, AND COMPOUND PENDULUMS—MEASURE OF TIME—INTENSITY OF GRAVITY—FIGURE OF THE EARTH—UNIVERSAL GRAVITATION.

On the Pendulum.

51. The pendulum, considered with reference either to its theory or its practical applications, is an instrument on every account worthy of a most attentive examination. Its theory affords us a most beautiful example of the dominion of mathematics over the laws to which matter is subject, and of the way in which experiment and observation, guided by mathematical research, may unfold the phenomena of nature. As a practical instrument the pendulum stands unrivalled; the observations which can be made with it are on many accounts more exact than those which can be made in any other manner, and the corrections for the errors which are inseparable from all observations, can be made with a great degree of precision and certainty; hence the evidence and knowledge which it affords us is of a higher order than can be obtained directly in any other manner.

Any body suspended from a fixed point by a string, and drawn from its position of rest, will, when left to itself, not only return to its original position, but will pass beyond it, and continue swinging about, passing and repassing its original position, until finally reduced to rest. This backward and forward motion is termed oscillating, and the body having passed from one extreme point to another is said to have performed an oscillation. A simple pendulum is supposed to consist of a heavy molecule, suspended by a perfectly flexible string without weight.



Thus, let B be a small ball, suspended by a fine string from the point C. Let the ball, or bob, as it is termed, be brought to D: being then left to itself, it will descend down the arc H A, and passing A will ascend up the arc A H′, and come into the position D′, such that the angles B C D′ and B C D are equal, or the arc of ascent equal to the arc of descent. The angular distance B C D, by which the pendulum is moved from its position of rest, is called the extent or amplitude of the oscillation; and the time which the body takes in descending or in ascending, is the time of half an oscillation, and both together, or the time of describing the whole arc, is the time of a whole oscillation. When the body is at D, let us consider the force which acts upon it, which is gravity, in the direction D G. Now this force is equivalent to two others, one in the direction D F, and the other in the direction D E (Art. 21). Of these, the former is sustained at C by the tension of the string, the latter is wholly effective in making the body move down the arc, or towards A. It will be seen that the direction and magnitude of each of these component forces changes each instant; that when the body is at A, the latter vanishes entirely. But the body in its descent having acquired a certain momentum, will lose it again by decrements equal to the increments by which it acquired it, but in the inverse order; so that the arc of ascent will be exactly equal to the arc of descent. The limb H H′ being graduated will shew the extent to which the pendulum oscillates on each side of the vertical.

If the resistance of the air, the rigidity of the string, and the friction about the point C, could be entirely removed, the pendulum, once set going, would oscillate for ever; and it continues to oscillate in proportion as these retarding causes are removed. In experiments in which great care has been taken to remove as much as possible all these retarding causes, a pendulum has gone on oscillating for several days. The preceding explanation will be sufficient to shew the way in which the motions of the pendulum are produced, but as it is impossible, without the aid of mathematics, to present an exact and entire theory of this instrument, we shall briefly state the results which the mathematical theory gives, and which observation fully confirms. In the preceding illustration the arc of vibration is a circular arc, the point of suspension being the centre of the circle, but the arc which possesses the most remarkable properties, and which is notorious in the history of mathematical science, in consequence of the discussions it has given rise to because of the pendulum, is the cycloid; and the exact laws to which we have alluded, belong to a pendulum swinging in this arc, or to the cycloidal pendulum.

52. *Laws of the Cycloidal Pendulum.*—It will readily be conceived that a body may be made to swing in any curve, the string by which it is suspended being constrained. If the string be merely tied to a point the body will describe a circular arc, but if during the motion of the body the string be prevented from being stretched straight by being constantly wound round or unwound from a curve, then may the body describe any curve. Thus, a body may

be made to swing in an arc which is a portion of a cycloid, and for which we have the following remarkable laws.

1°. 'The cycloid is an isochronous curve; that is, whatever be the length of the arc in which the body swings, or the extent of vibration, this arc will be described in the same time.'

2°. 'The time of an oscillation varies directly as the square root of the length of the pendulum, and inversely as the square root of the force of gravity.'

3°. 'The resistance of the air and friction, though they affect the extent of each oscillation, produce no effect on the time in which the oscillation is performed.'

These are the laws to which theory leads for the motion of a cycloidal pendulum; but the practical difficulties of making a pendulum oscillate in a cycloid are such, that its use is entirely superseded by the circular pendulum, that is, by a weight suspended from a point, and oscillating in a circular arc.

53. *Simple Pendulum.*—The great value of the cycloidal pendulum, could it have been practically executed, would arise from the fact of the isochronism of its vibrations; whatever was the extent of the arc in which it had swung, the time of its passing and repassing the lowest point would have been invariably the same, and we should thus have been furnished with an exact measure of time. Now, with respect to the circular pendulum, it may be shewn by mathematics, that provided the arc of vibration be small, its oscillations will be *practically* isochronous; or, in other words, the time of a body's swinging in a small circular arc will not differ sensibly from the time in which it would oscillate in a cycloidal arc. Hence we see the reason why the pendulums of all good clocks swing in very small arcs; so long as the arcs are small the isochronism of the motion is insured; hence good clocks keep the same time.

The circular or common pendulum, being thus identified with the cycloidal pendulum in the isochronism of its vibrations, is also subject to the same laws, and, consequently, the times of the oscillations of two pendulums will be as the square roots of their lengths. Suppose that three pendulums, whose lengths are as the numbers 1, 4, 9, be suspended and set swinging, then, according to the preceding law, the times of their performing each oscillation will be as the numbers 1, 2, 3, for these are the square roots of the preceding numbers. Such will be the observed fact as near as we can judge; the pendulum whose length is 1 will make two oscillations, while that whose length is 4 makes one oscillation, and will make three, while the pendulum whose length is 9 makes one. These and similar observations will enable us to verify a law, but its absolute certainty must depend on very different evidence (Art. 3), as we shall shew presently, in the case of the pendulum.

The preceding experiments will also serve to shew the uniformity and universality of the action of gravity. The times of oscillation are precisely the same, whatever be the substance of which the pendulum is composed. Balls of wood, ivory, metal, hollow, empty, or filled with any substance, will oscillate in precisely the same time, provided the length of the string be the same, and the resistance of the air be allowed for.

In the preceding we have been speaking of the simple pendulum, which may be considered as consisting of a string without weight, sustaining an indefinitely small portion of some material substance. Now, no such pendulum as this exists in nature; every string has sensible weight, and the matter suspended cannot be considered as a point; so that a pendulum is really an irregular mass, and these irregularities must be got over, or our experiments and observations cannot be depended upon. This, theory enables us to do; and much as it has hitherto done, in pointing out the laws of the simple pendulum, it has done much greater service in shewing us how to overcome the irregular combination of matter which must ever perplex calculation, and to subject any irregular mass, or compound pendulum, to the preceding laws of the simple pendulum; this we shall now endeavour to make intelligible.

54. *Centre of Oscillation.*—Any mass, however irregular in form and constitution, may be set swinging about an axis, and oscillate, as we have already described respecting the simple pendulum. But the times of the oscillations of such a mass will depend on its external figure, on its internal constitution, and on the position of the axis, that is, the point of suspension, about which it oscillates. But the small oscillations will be isochronous, or performed in the same time as we have already seen in a simple pendulum. Now there is some point in this irregular mass which moves precisely as a single particle would do, suspended by a string, whose length is equal to its distance from the point of suspension. The position of this point is called the *centre of oscillation* of the body. If all the particles of the body be supposed collected at this point, and suspended from the point of suspension by a string without weight, then will this simple pendulum oscillate in precisely the same time as the irregular mass. By the knowledge of this centre of oscillation, the calculations respecting the oscillations of a solid mass, or compound pendulum, become the same as those of a single particle suspended by an imaginary thread, and the difficult problem of a compound pendulum is at once reduced to the preceding laws of a simple pendulum.

Every mass has its centre of oscillation; but the investigation of its position is in most cases a difficult mathematical question. The point being determined, its distance from the axis, or point of suspension, is the length of the simple pendulum; hence the time of the oscillation of a compound mass is inversely as the square root of this distance. But the great practical importance of knowing this point is the remarkable relation which subsists between it and the point of suspension, and which is stated in the following terms—" The centres of oscillation and suspension are reciprocal."* Thus, if we have a bar of iron, which can oscillate about an axis placed at any point, and its centre of oscillation be determined, and at this centre another axis be placed; then if the bar be inverted and suspended on this new axis, the old point of suspension will be the new centre of oscillation. Thus the centres of suspension and oscillation are convertible. The application of this principle by Kater in the great problem of the determination of the length of the second's pendulum, furnishes one of the most beautiful instances on record of the direct application of a law, which must ever have lain hid but for the refinements of mathematical reasoning.

55. *Length of the Second's Pendulum.*—Few things probably, at first sight, may seem more easy than the determination of the length of a pendulum which oscillates in a given time, and yet it is certain that there are few problems whose direct determination presents many more insuperable difficulties. For, suppose we have a small heavy particle suspended by a thread, almost without weight, and swinging freely; suppose also, that the number of oscillations which it makes in a given time, and consequently the length of each, to be accurately known; suppose moreover, the want of flexibility in the thread, and the resistance of the air, to have been entirely removed or allowed for; and it only now remains to *measure* the length of the string. This, as will readily be seen, cannot be done with any degree of accuracy; we cannot determine the exact point of suspension, nor the exact point of the connexion of the string with the heavy particle; so that the uncertainty attendant on this operation, even when performed with the greatest possible exactness, renders some other method highly desirable. This great desideratum was furnished by Kater, by the application of the principle stated in the preceding article. We can measure with extreme accuracy between two fixed surfaces, as axes of suspension; the difficulty, then, is to obtain two surfaces, or

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* Whewell's *Mechanics*, Art. 205.

points, so related. This may be done by adjusting a moveable weight on a bar of metal furnished with two axes of suspension; the weight must be moved about until it is in a position such that the time of oscillation about either axis is precisely the same. These two axes will then have the required relation for that given mass, and, consequently, the time of oscillation being observed, and the distance between the axes being accurately measured, we have the length of the simple pendulum which oscillates in this time. It would be foreign to our purpose to attempt any description of the wonderful ingenuity displayed by Kater on many practical points in this very difficult problem; we have endeavoured to make the principle of his method intelligible, and for the rest we must refer to his own paper.*

The length of a pendulum oscillating in any time having been accurately determined; the length of the second's pendulum, that is, of the imaginary simple pendulum which would oscillate in a second of time, can be found by a simple proportion from the theoretical law (Art. 52.) of the times being inversely as the square roots of the lengths. And the length of this pendulum, as determined by Kater, in the latitude of London, in vacuo, at the temperature 62° of Fahrenheit, and reduced to the level of the sea, is 39·1386 inches. The reasons for these various statements, and the way in which the result would be affected by any variations in the circumstances to which they refer, will appear in the subsequent parts of this work.

Before closing this article, it may be well briefly to review the steps of the investigation which have conducted us to this most important determination. First, then, the mathematical theory leads to the proposition, that the times in small circular arcs are inversely as the square roots of the lengths of the pendulum; theory next leads to the position of the centre of oscillation, and to the law that the distance of this from the point of suspension is the length of the theoretical simple pendulum, which oscillates in the same

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* *Philosophical Transactions*, 1818.

time as the irregular mass; theory next leads to the remarkable proposition of the convertibility of the centres of suspension and oscillation. Then comes in observation, and determines what is the length of the simple pendulum which is made to oscillate in conformity with these theoretical laws; this length having been accurately ascertained, and also the corresponding time, we return to the theoretical law for the determination of the length which corresponds to any other portion of time, whatever may be the most practically convenient; and this being a second, it is the length of the second's pendulum which is finally arrived at.

56. *Compensation Pendulum.*—The time of the oscillation of a pendulum depends on its length, that is, on the distance of the imaginary point termed the centre of oscillation from the point of suspension; if, therefore, from any circumstance, the pendulum becomes lengthened, the time in which it swings will be lengthened too; and if it be shortened, the time will also be shortened. This is known to every one who watches a clock; a clock is observed to lose, that is, the pendulum takes too long a time to perform its oscillations—it must, therefore, be shortened; a clock gains, that is, goes too fast, or takes too little time for each oscillation—the pendulum must, therefore, be lengthened. This, every person who attends to the rate of a clock must either do or allow for at different times; that is, the pendulum must either be made of the exact length, or the quantity by which the clock is too fast or too slow must be allowed for. Now, it is impossible to make a clock go accurately true; the only true and invariable measure of time is the rotation of the earth, and, consequently, in all observatory clocks, when an error amounting only to a very small fraction of a second can be detected, there is what is termed the clock error, that is, a given quantity, which must be added or subtracted from the time as shewn by the clock, in order to give the more accurate time, as ascertained by astronomical observations. But a

pendulum being a large mass of matter, is subject to constant changes from the variations in temperature, and the expansion and contraction from this cause occasions so great a change in the position of the centre of oscillation, that no clock made with a common pendulum would be worth any thing for astronomical purposes; hence recourse is had to compensation pendulums, that is, to pendulums so constructed that an expansion or contraction of the whole mass will not alter the distance between the centres of oscillation and of suspension. This is effected by combining the different rates of expansion of different metals, so as to compensate each other. The principal part of the pendulum is the heavy weight at the end, or the bob; now it is evident that the centre of oscillation will be somewhere within this mass, and its position will consequently be affected by any change in the position of this mass. The gridiron pendulum consists of parallel bars of brass and steel, so adapted that the expansion of one elevates, just as much as the expansion of the other lowers, the centre of oscillation of the pendulum. This method of compensation is, however, almost entirely superseded by the mercurial bob, or by using a cylindrical vessel full of mercury, as the sustained weight. On the way in which the adjustments for the compensation are effected, we cannot at present enter.

57. *Measure of Time.*—One of the most important uses of the pendulum is the means which it affords us of measuring time with ease and accuracy. We have seen that if the arc through which it swings be small, its oscillations are isochronous, or performed in the same time; if, therefore, we can devise any means of counting and registering these equal intervals of time, we shall have an exact measure of time. Again, we have also stated, as a theoretical law, that the resistance of the air and the retarding cause of friction do not alter the time in which each vibration is performed; but since these are constantly acting as retarding causes, they will diminish the arc of vibration by insensible degrees, and the pendulum will finally stop. Two

points, then, must be attended to; we must devise some means for counting the number of oscillations, and some supply of force to compensate the retarding forces which are constantly acting to destroy the motion. These two ends are brought about by the machinery of a clock; all the parts of a clock, except the pendulum, are contrivances for counting, in a convenient manner, the oscillations, and registering them successively, and for administering that supply of force, without which the motion of the pendulum could not long continue. Of the way in which this register is effected, or of the very beautiful contrivances by which the supply of force is administered by the contrivance termed the dead beat scapement, it is not our province here to speak, but they are most worthy the attention of every one. On the principle of the supply of force, we may remark, that it must take place just as the pendulum is at the lowest point, or in the middle of its oscillation; for if a small acceleration be given at this point of the swing, it is equivalent to starting the pendulum with a fresh velocity; but if it be given at any other point, the isochronism will be in great danger of being disturbed. The theory of this subject is extremely beautiful, and leads us at once to the preceding important practical results.

But the question here naturally arises, how are we assured of the isochronism of our good pendulums; should the small intervals of time change in any manner, how can we possibly detect it, since these intervals are our units of time? Our only certain invariable measure of time is the period of the rotation of our earth about its axis. We are certain that this has not changed from the days of Hipparchus* to the present hour. It is by this unerring standard, then, that we can test the regularity and constancy of the intervals registered by our clocks.

58. *Variations of Gravity.*—We have hitherto considered gravity as invariable, and traced the consequences of a

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* B. C. 120.

change in the length of the pendulum; we shall now suppose the length invariable, and consider the effect on the time of an oscillation caused by a change in the intensity of gravity. The time of an oscillation (Art. 52.) varies directly as the length of the pendulum, and inversely as the force of gravity, that is, the time diminishes as the force of gravity increases, and conversely. If, then, the time of the oscillation of a pendulum be observed in London, and the *same* pendulum be carried to the Cape of Good Hope, and its time of oscillation be observed again there, and these times are equal, we may conclude that the force of gravity is the same at the Cape as at London: but if the time be greater at the Cape than at London, we must conclude that the force of gravity is less. It was suggested by Newton, from theoretical considerations on the Figure of the Earth, that gravity must *decrease* as we advance towards the equator, and *increase* as we advance towards the poles. All observations on the pendulum confirm this. The pendulum that swings exactly in one second here, oscillates more slowly at the equator, and more rapidly at the poles; the force of gravity, therefore, is diminished at one place, and increased at the other; and the second's pendulum is shorter at the equator, and longer at the poles, than in our latitude.*

Observers generally give the length of the pendulum which oscillates in a second of time as the result of their experiments. The reason for this is obvious; the only certain and invariable standard to which we can directly refer, is one of time; namely, the time of the rotation of the earth about its axis; hence, when this or any portion of it, as one second, is our unit, we have an invariable standard by which we may compare different observations. But it must particularly be remembered, that the determination of the length of the pendulum is the result of a ma-

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* The length near the equator is 39·02 inches; at latitude 79° about 39·21 inches, and at London 39·13 inches.

thematical calculation founded on observations; some things can be observed directly, and some must be calculated from indirect observations; and it is the province of analysis to predetermine what is to be observed, and what is to be calculated.

59. *Intensity of Gravity.*—The mathematical theory of the pendulum establishes a constant relation between the time of an oscillation, the length of the pendulum, and the force of gravity. Now it is the necessary consequence of this relation, that where any two of the quantities are given, the third may be found. If, then, we have a pendulum of given length oscillating seconds, the intensity of gravity may be calculated. This is the only certain mode of determining it; the experiments on falling bodies are liable to numerous inaccuracies, but the observations with the pendulum lead us at once to an exact measure of the accelerating force of gravity. If the calculation be gone through on this principle, we shall find that the force of gravity will generate a velocity of 32·2 feet in one second; and, consequently, that a body falling freely from rest would fall through $16\frac{1}{10}$ feet in the first second. The results obtained in this manner agree with those which may be obtained by Atwood's machine, and the inclined plane, to a great degree of accuracy. When pendulum observations are made with great care in different latitudes, the accelerating force of gravity is found to vary; thus it is found to be less at the equator than at the poles; it also depends on the distance of the station from the centre of the earth, being less at the summits of high mountains than at the surface of the earth. All observations which have been recorded shew that the energy of gravity is invariably the same in the same latitudes at the level of the sea; for this is the fixed surface to which every thing must be referred; at the same distance from the earth's centre, the latitude being unchanged, the same pendulum will oscillate in precisely the same time; and the experi-

ments made with this instrument are, as we have already stated, the only ones in which implicit confidence can be reposed.

60. *Figure of the Earth.*—The loftiest mountains on the surface of the globe are but most minute elevations when compared with the mass of the whole globe itself; they are much as grains of sand would be, scattered on a globe of a yard radius: similarly, the greatest depths of the ocean are but inconsiderable cavities. Thus the earth viewed in its whole extent, may be considered as sensibly regular, and may be taken as such in all our calculations. The ancient astronomers had discovered the curved figure of the earth, and the sphere immediately presenting itself as the most perfect figure, they naturally supposed the form of the earth to be spherical; and they made some attempts towards ascertaining its dimensions. The earth, however, is not spherical. Newton, from theoretical considerations, announced that it must be flattened at the poles and bulge out at the equator; and this statement has been most accurately verified within the last century by direct measurement. The simplest pendulum observations will enable us to declare that such is the case: but the important question is, as to the amount of these deviations from the spherical form. That we may weigh the celestial bodies in a balance, and determine the dimensions of the solar system, we must know accurately the form and magnitude of our own globe. This must be our base of measurement, our unit of calculation. These requisites may be supplied by observations with a pendulum; the observed times in which the same simple pendulum oscillates at the equator, and at the poles, or the observed length of the second's pendulum at these two places, will, with the assistance of mathematical calculation, enable us to determine the exact form of the earth. Of the nature of these calculations we cannot here attempt to give the least idea, but we are confident of their exactness, because entirely independent methods lead to results which differ only by exceedingly small quan-

tities from those furnished by the pendulum. The process of reasoning is nearly as follows: the earth is, both from theoretical considerations and direct observation, evidently not a sphere, but much more nearly a spheroid; that is, it has a figure slightly flattened at the poles, and elongated at the equator; the action then of gravity will be more intense at the poles than at the equator; the variations in the intensity of gravity are a matter of direct observation with the pendulum; hence we shall be able to determine how much the one axis exceeds the other, that is, what is the amount of the equatorial excess. The calculations having been gone through on these principles, it is found that the diminution of gravity at the equator is too much than, reasoning on other principles, it ought to be. But it must be remembered that no account has been taken in the preceding reasonings of the rotation of the earth about its axis, and of the consequent effect of centrifugal force near the equator (Art. 31), which will evidently be to diminish the rate of a falling body, and consequently the rate of a pendulum, or the apparent intensity of gravity. This then being properly taken into the account, the results in whatever way they are arrived at agree to a most wonderful degree of minuteness. Respecting the slight differences which do, and ever must, exist between the results of observation assisted by theory, such as those indicated in the preceding article, and the results of pure theory, such as that of Newton and Laplace, we may make the following important remarks. The lengths of the pendulums from which we deduce the intensity of gravity at different stations, are facts entirely independent of any hypothesis; the only errors which can exist here are those inseparable from observation; but the errors of pure theory are those incidental to the hypotheses which it necessarily involves; in proportion then as our means of observing improve, and our knowledge gives us more correct hypotheses, we may be sure that the results of observation and of theory will approach more and more.

61. *Unit of Length and Weight.*—It is of the greatest importance for the civil and commercial relations of life that the standards of length and of weight should be invariable, and incapable of being lost; at all events that we should have the power of verifying their exactness, and of comparing them at different epochs of time. For this purpose we must call in the assistance of the great globe itself. In the uniform rotation of the earth we have the only true measure of time, and in its dimensions we find a natural unit for the measure of space. The attraction of the earth combined with the rotation about its axis enables us, by the assistance of mathematical reasoning, and the oscillations of the pendulum, to determine another standard for the measure of space, which may at any time be verified; thus these two standards are a check on each other, and in their accurate agreement we have the most convincing proof and strongest conviction of the truth of our calculations. The length of the pendulum which oscillates seconds in the latitude of Greenwich* is the standard of British measure. If the measures were remodelled, it would be convenient to take this as the length of a yard; but as the yard was fixed long before this test was known, the length of the pendulum is expressed according to the established measure. Thus the second's pendulum at Greenwich will serve at any time to determine what the yard ought to be; and also all smaller units, as feet and inches. The standard of French measure is derived from the direct measurement of the dimensions of the earth. The meridian line of any place may be determined by astronomical observations, and any portion of the arc of this line may be measured. The ten-millionth part of the quadrant of the meridian passing through the observatory of Paris is the *metre*, or French unit of linear measure; it is equal to 39·371 English inches; and the *centimetre* is the one-hundredth part of the metre, or ·39371 English inches.

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* Greenwich is chosen being the place of the Royal Observatory.

The standard of British *weights* is the weight of a cubic inch of pure water at its maximum density (Art. 66): this is divided into 252·458 portions, called *grains;* and of the grains so determined, 7000 are a pound avoirdupois, and 5760 a pound troy. The French standard of weight is the weight of a cubic centimetre of pure water at its maximum density, and is called a *gramme;* it is about nineteen English grains.

Both the English and French standards are, theoretically speaking, equally eligible; practical convenience would lead us to prefer the pendulum standard, but practical accuracy gives the preference to the measurement of the arc of the meridian: for any minute error committed in determining the length of the pendulum, becomes multiplied by the repetition of the unit in all measurements of considerable length, performed in yards; but any error committed in the determination of the arc of the quadrant of the meridian, becomes so subdivided in the final result, that the repetition of the unit will but repeat an error which can never become sensible; this division and repetition of an error is one of the most important practical considerations in Physics, whenever quantities are to be determined with great minuteness.* The presumed permanence of the great laws of nature, which all experience irresistibly forces on our belief, is the basis of our faith in the preceding calculations: if the dimensions of the earth were to change in form or magnitude, the inch and the metre would be changed, and we could never recover their length; but then every thing about us would be changed also; the rotation of the earth would not have the same period. If the composition of water were to change, or if gravity changed its intensity, the same uncertainty and confusion would result. Thus is every thing in our most fundamental principles but conditional; and science, when it has done its best by establishing its basis on the stability of the

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* Herschel's *Study of Nat. Phil.* p. 127.

universe, has but a relative existence, and the scientific speculator is but the interpreter of nature as it at present exists.

62. *Universal Gravitation.*—Hitherto gravity has been considered only with reference to falling bodies; we have seen that it extends to all accessible heights above the surface of the earth, and far beyond; now we see no reason for drawing a line at any particular height, and asserting that there it must entirely cease; why then should it not extend to the moon? We know that the moon must be acted on by some force to keep it in its orbit; if gravity be *not* that force, there must exist some other; and besides this, gravity must cease at some inferior level, or the nature of the moon must be different from that of ponderable matter: for if not, it would be urged by both powers, and therefore too much urged, and forced inwards from her path.* It is on such reasoning that Newton is understood to have rested his law of universal gravitation; the next step was to compare the results of theory founded on this hypothesis with the known laws of gravity at the surface. For this purpose, he reasoned on his law of universal gravitation, which may be thus stated; 'Every particle of matter in the universe attracts every other particle, with a force varying inversely as the square of the distance.' Reasoning on this law, he calculated, from the effect which the earth would produce on a mass at the distance of the moon, what effect it ought to produce on a mass nearer to it, as on a falling body, and he found that the result obtained by calculation agreed with the observed laws of falling bodies. Thus was one irresistible argument furnished for the truth of his law; but his mighty mind rested not here; it pursued the same reasoning through all the universe, having extended the action of gravity from the earth to the moon, and thence to the sun, he saw it pervading the whole solar system, and recognised it as the

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* Herschel's *Astronomy*, 236.

one harmonious law of the universe. Having thus briefly indicated the principles on which the theory of universal gravitation was first established by its immortal author, we must dismiss this part of the subject; its thorough investigation belongs to the science of Physical Astronomy. It is the province of that science to trace out the steps of the Newtonian Philosophy, and to exhibit the irresistible evidence on which the law of gravitation rests. It is our humbler task to trace this law in all its details at the earth's surface, and to shew how this one universal principle pervades and influences every phenomenon.

63. *Attraction of Mountains.*—Since every particle of matter attracts every other particle, we may reasonably expect that a large mass of matter, as a mountain, will exert some sensible action on the surrounding bodies. If, for instance, a stone be let fall down a precipice by the side of a mountain, we might expect that its motion will be directed towards the centre of the mountain rather than towards the centre of the earth. But when we consider that the largest mountains are but as grains of sand when compared with the whole mass of the earth, we need not be astonished at their effects being insensible, or being almost entirely overbalanced by the general attraction of the earth. Still, however, they must, if the law of universal gravitation be true, produce some effect on the direction of a falling body; and conversely, if this deviation can be detected, we may be at once assured of the universality of this law for all matter, and that there is no Cartesian vortex round about the earth, or particular affection towards the centre, by which all bodies are constrained to descend.

The first attempt to discover, from the attraction of mountains, a proof of the universal attraction of matter, was made by Bouguer, by observing the effect of a mountain on the direction of the plumb-line. There arises a difficulty in determining whether the plumb-line has undergone any deviation; for the same cause which would change its direction, would also change the position of the surface of still water, which is the general standard by which the verticality of the line is ascertained; hence we cannot determine the question directly; for however the line may be made to deviate from the vertical, it will be perpendicular to still water, whose surface will suffer precisely the same deviation from the horizontal. Recourse must therefore be had to the stars; astronomical observations can alone give us a fixed direction for experiments of this nature. It was on the side of part of the mountain chain of Chimboraco, in Peru, which forms one of the largest mountains in the world, that Bouguer made his experiments, and notwithstanding the almost insuperable difficulties which presented themselves, he succeeded in his design, and clearly recognised a deviation of 7″ or 8″ due to the attraction of the mountain.

The most important observations which have been made on this subject were those of Maskelyne* on the attraction of Schellalion, a mountain in Scotland, which from its isolated position is peculiarly adapted for observations of this kind. The greatest care was taken by that philosopher, and he clearly established a deviation of 54″, or, nearly 1′. From this it is evident that mountains do act on a plumb-line, and produce a sensible deviation, the amount of which depends on their mass, and on the nature of the substances which compose them. These experiments were made by Maskelyne with the special view of determining the mean density of the earth, which he calculated at about 4½ times the density of water. Recent calculations have been made on this subject by Carlini, from a series of pendulum observations, and he obtains nearly the same value for the density of the earth as that obtained by Maskelyne.

64. *Experiments of Cavendish.*—We owe to Cavendish another proof of the principle of the universality of the attraction of matter upon matter, and a different determination of the mean density of the earth. This dis-

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* In 1772.

tinguished philosopher conceived the idea of having a long thin rod with small balls at each end accurately balanced in a horizontal position, by a fine thread attached to its middle point. This lever is a species of pendulum, which may oscillate backwards and forwards in a horizontal plane by the horizontal attraction of two masses, brought near its ends on opposite sides; just as the common pendulum makes oscillations in a vertical plane, from the attraction of the mass of the earth in a vertical direction. Two large masses of lead were brought near the small balls at the end of this lever when perfectly at rest, but on opposite sides, so that the effect of each would be to move the lever in the same direction; the lever will begin to move, and continue to make oscillations as long as the large masses are near the balls. This is the most unexceptionable proof of the attraction of matter on matter which can possibly be conceived; the motion of the lever is most certainly due to the attraction of the masses of lead, and the force is evidently the same in kind as that by which a body falls to the earth; the only difference in these two forces arises from the difference of the attracting masses. This fundamental fact of the attraction of the balls being established, we have only to observe the time of the oscillations, and the length of the lever, the centre of the great masses being considered as the centres of attraction. From these observations, incomparably more accurate than any which can be made on the attractions of a mountain, Cavendish determined the mean density of the earth to be about 5½ times the density of water. The density thus assigned by Cavendish is not at all greater than might be conjectured from pendulum observations. Newton had long before advanced it as a probable supposition that the density of the earth might be about five or six times that of water; and the perfect agreement of the result of many modern experiments with this conjecture, is one proof, among many others, of the wonderful accuracy and penetration of that philosopher.

65. *Concluding Remarks.*—We cannot leave this subject

without taking a brief review of the peculiar method of reasoning which is employed in the establishment of the laws at which we have arrived, and briefly stating the illustration which may be derived from the pendulum of the establishment of physical laws and theories.

The theory of the pendulum is essentially a mathematical theory; the simple pendulum is a mere hypothesis, and the laws of its motion must consequently be ascertained by analysis. Hence is obtained a relation betwixt the length of the imaginary string which sustains the oscillating imaginary particle, the time of its vibrations, and the intensity of the force to which it owes its motion, or gravity. Next, the theory of the motion of a solid mass points out certain cases in which the motions of a pendulum, such as we can make, are identical with the preceding imaginary pendulum. Thus, then, we obtain an instrument with which observations can be made, and the laws of whose motions are exactly defined by theory. The next step is to apply this pendulum in observations; here practical considerations and theory together determine what is to be observed. In the equation which theory gives, and by which it connects together the time of a pendulum's vibration, its length, and the intensity of gravity, it may at first sight appear indifferent which two of these three quantities are observed, since the third can then be calculated; but if all could practically be observed, there would be no necessity for the assistance of the mathematical theory. In this case, however, the time and length may be observed, but the force of gravity cannot: it must be calculated from the other two. Thus, we see how, in the case of the pendulum, theory and experiment are combined to obtain an accurate result. Had the intensity of gravity been determined by Atwood's machine, or in any other manner, then the length of the pendulum would be calculated from this, and the time of its vibration. But the pendulum presents far greater facilities for the determination of the intensity of gravity than any other instrument; and it is employed for this purpose in preference to all others.

Again, the pendulum furnishes us with distinct evidence of the complete truth of the laws of motion. It does not supply a separate proof for each law, but a complete verification of all three. For instance, the first law of motion asserts, that a body in motion will go on moving for ever, unless acted on by some external force; now we are convinced that a pendulum would go on swinging for ever, if the resistance of the air and friction could be entirely removed. The motion of the pendulum is in no case rectilinear, but its curvilinear motion is in exact conformity with the second law of motion, and thus the motions of a pendulum may be considered as establishing these two laws. The real conviction, however, which we have of the truth of the laws of motion results, as has been already stated, on the extraordinary agreement of long-calculated results, obtained on the supposition of their truth, with the actual observed fact. Were the laws of motion not true for the celestial bodies, the whole planetary theory and its predictions would rest on untrue hypotheses; but we have the most perfect confidence in the results, and a thorough conviction of their truth; the hypotheses, therefore, or the laws of motion on which they rest, cannot be untrue.

The pendulum, as we have already seen, furnishes us with a most sure method of ascertaining whether the predictions of Newton, and the laws of gravity at the surface of the earth, are true or false; it also furnishes us with an example of what was termed (Art. 3.) the determination of constants. We may determine any one of the three quantities, the time, the length, the force, by assuming the laws for two of them. For instance, suppose the length of the pendulum to be the constant to be determined; we know now that the time of an oscillation depends on the intensity of gravity; we know also that the force of gravity varies with the latitude; the laws of these two variable quantities being assumed, or supposed known, we may proceed to determine by calculation the constant length of the pendulum. If, on the calculations being made for the assumed time of oscillation and force of gravity at London, Paris, and the Cape, the length comes out the same, we have very high evidence of the truth of the principles which lead to such an invariable result.

In conclusion, we must call the attention of the student to the general illustration which the pendulum affords of all oscillatory movements. We shall hereafter have several instances in which the particles of bodies are said to perform oscillations that is, move backwards and forwards about some mean position, which was their position of rest. The language and laws of the oscillations of a pendulum are at once transferred to these. The motions of the particles are said to be isochronous, that is, each takes the same time to pass and repass from one extreme position to another. A most important illustration of the preceding remarks will be furnished in treating of Acoustics. The particles of any sounding body, as a bell, execute regular oscillations, or go through a periodic series of isochronous movements; when these oscillations cease, the bell ceases to sound.

CHAP. VI.

ON FLUIDS.

Section I.

GENERAL PROPERTIES OF FLUIDS—TRANSMISSION OF PRESSURE—CONDITIONS OF EQUILIBRIUM.

66. The existence of matter in its three different states depends on the relative adaptation of the forces to which the particles are subject; in solid matter the force of cohesion is very great, but the particles of fluid matter can be moved amongst each other without any sensible resistance. Fluids are generally divided into liquids and gases; in the former, the forces of attraction and repulsion seem to be very nearly balanced; but in the latter, the force of repulsion is such that the particles will recede from each other unless prevented by some extraneous force, as the resistance of the sides of the containing vessel. The attraction of cohesion does exist in some small degree amongst the particles of a liquid; for a drop of water generally assumes a form which is nearly spherical. This form is, however, considerably modified by the action of gravity, and by the attraction of the mass with which it is in contact. The particles of a liquid adhere also with different degrees of force to different solids; some cases they do not adhere at all, or the solid cannot be wetted by the liquid. These forces of cohesion and of adhesion may be measured by direct experiment; if a flat plate be brought into contact with the surface of a liquid, a greater force will be required to raise it again than is re-

quired to sustain the simple weight of the plate. The excess of this force above that which would sustain the plate, measures the force of the cohesion of the liquid, or of the adhesion betwixt it and the plate.

The distinction of fluids into liquids and gases, or inelastic and elastic fluids, is convenient, and in some cases necessary; they have, however, many common properties, and the following articles will generally apply to both. All fluids are subject to the general law of expanding by heat, and contracting by cold; but the amount of the dilatation or contraction for given changes in the temperature is very varied. Water follows a remarkable law, it contracts as the temperature decreases, but when the temperature has reached to 40° Fahrenheit, the contraction stops, and the density of the water is at a *maximum;* for if the temperature be still further reduced, the water begins to expand, and the expansion continues gradual to the freezing point; when, at the instant of solidification, a sudden and large expansion takes place. We shall return hereafter to the subject of the expansion and contraction of fluids for given changes in the temperature.

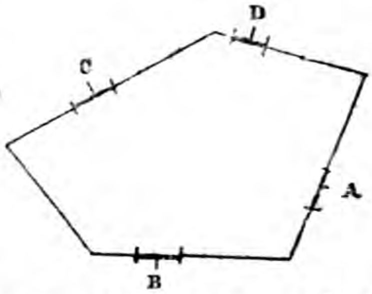
67. *Compressibility.*—The experiments on the compressibility of water have considerable historical interest. The academicians of Florence conceived that they had succeeded in establishing the incompressibility of water in the following manner. A sphere of gold was filled with water, and accurately closed; the sphere was then put into a press, and subjected to pressure, when some of the water appeared on the outside, in small drops, like dew, having been forced through the pores of the gold. This escape of the fluid was supposed to prove its incompressibility, but it can only prove that water may be pressed through the pores of gold more easily than it can be compressed. And had the experiment been attended with a different result; had the water appeared to yield to the pressure, and not been forced through the gold, this fact would not have proved the compressibility of the water, unless the philosophers

could have been sure that there was no extension of the gold, so that the apparent diminution in the bulk of the water was owing to the yielding of the metal.

But there are some well-known facts indicating at once the compressibility of water. It is well known that if a bottle be filled with pure water, corked, and sunk to a sufficient depth in the sea, the water will acquire a saltish taste; from this it was inferred that the cork had been pressed in; and to ascertain this with accuracy Mr. Perkins employed a copper flask, with a stopper, so contrived that he could at once determine whether the stopper had been pressed in, and how far. On sinking this in deep water, it appeared, that the stopper had been pressed in, and consequently that the water had been made to occupy a less space, or had been compressed. This is a most decisive experiment, and can admit of no other explanation; the flask cannot yield in any manner; for the compressing forces being, as we shall see presently, the pressure of the superincumbent fluid, the pressures are equal, both on the inside and the outside of the flask, according to the characteristic law of fluids (Art. 68); hence there can be no yielding or distortion of the flask in this or any similar experiments. It is found that at the depth of 1000 fathoms water is compressed by about $\frac{1}{20}$th of its bulk.

This experiment proves also the elasticity of water; for the stopper, after having been pressed in, always reascends to its original position, as the flask is drawn up; that is, the water having been compressed, resumes its original bulk by virtue of its elasticity (Art. 11), so soon as the forces to which it is subject cease to act. We shall see other proofs of the elasticity of water, in speaking of sound; for this medium will transmit sound, which cannot be transmitted except by vibrations, whose existence imply elasticity. These remarks apply equally to other liquids, as oil, mercury, but their degrees of compressibility and elasticity are very different. The gases, as has been already observed (Art. 11), possess these qualities in an eminent degree; so that there is no known fluid exempt from this law.

68. *Equal Transmission of Pressure.*—The characteristic distinction between fluids and solids is the equal transmission of pressure, which is the property of the former. Solids transmit a pressure only in one direction, namely, in the direction in which it is impressed; but fluids transmit a pressure in every direction throughout their entire mass. If we press a solid with the hand, we know that it will yield principally in the direction in which we press it, but if we grasp in our hands any flexible vessel full of fluid, as a bladder containing air or water, we know that the parts under our fingers are not more pressed than every other part of the fluid. The pressure which takes place at any one part is transmitted to every other part. And this is the peculiar character of a fluid; all fluids have weight, but the equal transmission of pressure is a property unconnected with the force of gravity; we can, in imagination, conceive a mass of fluid deprived of its weight, but retaining its fluid character, that is, not subject to the action of gravity, but only to the laws of its own molecular forces; if any portion of such a mass be subjected to pressure, then every other portion will be subjected to an equal pressure. This may be shewn experimentally in the following manner.



Let the accompanying figure represent a vessel full of fluid, having any number of equal portions of its surfaces removed and replaced by pistons; then if any one of these pistons, as A, be pressed *in* with a given force, all the others will start out, unless an equal force be applied to all of them. The pistons, B, C, D, may be situated any where; hence it is evident that the pressure is equal on all equal portions of the surfaces wherever situated.

The pressure which is exerted on the fluid will evidently be proportional to the size of the piston, that is, to its base; but the important fact to be borne in mind is, that a pressure exerted on any portion of the surface will cause an equal pressure on every equal portion throughout the whole surface. Any one of the pistons may be conceived as balancing all the rest. Suppose now that the whole of one side of the vessel is replaced by pistons; then, if the pressure which one piston exerts on the fluid be one pound, the whole pressure on this side will be as many pounds as the side contains areas equal to the area of the piston. Hence we may understand the hydro-mechanical press of Bramah; a small piston exerts a pressure on a portion of the surface of water, which communicates with the surface of a large piston. If the large piston have 1000 times more area than the small piston, one pound placed on the small piston will sustain 1000 pounds placed on the large one.* Thus, a fluid may be regarded as a machine for the transmission of pressure; other machines transmit force in particular directions, and with particular modifications, but a fluid transmits it in all directions equally.

69. *Illustrations.*—The practical applications which depend on the preceding principle of the equal transmission of pressure in all directions are exceedingly numerous. Every one has heard of a safety valve; now the whole dependence and faith which we put in these is derived from our conviction of the truth of this principle. Were a fluid not equally pressed on all equal portions of its containing vessel, a pressure might exist in one part of a vessel sufficient to burst it; so that unless the safety valve were placed at this particular part we should never be in security. But acquainted with this principle, we place the safety valve according to convenience at any part of the containing vessel which is in free communication with the parts subject to pressure, and know, that whenever the pressure becomes too great at any part of the fluid, the

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* Webster's *Principles of Hydrostatics*, ch. ix.

valve will be opened, and the pressure will be relieved by the escape of some of the fluid. Thus, in steam engine boilers the safety valve may be at any part of the containing vessels with which the steam is in constant contact, and it is generally placed at the end of a short pipe, just above the boiler. Suppose now a steam boiler is constructed to bear a pressure of 20 lbs. on every circular inch, that is, on every small circular portion of an inch in diameter, without the least danger of bursting, and that from any cause, as from the sudden increase of the fire, or the stoppage of the engine, there is more steam than usual in the boiler, and that the pressure becomes increased to 21 lbs. on the circular inch, the safety valve will open, and the steam will continue to issue out until its elastic force is diminished by 1 lb. on the circular inch, when the valve will immediately close.

Bellows for blowing furnaces may be made of any shape, and the orifice through which the blast is to issue may be made in any part of the bellows; and a common pair of bellows might be fitted with a snout at any part without producing any effect on the magnitude of the blast.

70. *Remarks.*—The preceding are perfect illustrations of the equal transmission of pressure, or of the equality of pressure, as it is sometimes termed, and many others will readily present themselves. The point especially to be attended to is, that the pressures here spoken of are essentially distinct from what is usually meant by the pressure of a fluid under ordinary circumstances. The pressures just spoken of are impressed from some extraneous cause on a fluid contained in a vessel, and completely filling that vessel. The use of the vessel is to keep the particles of the fluid together, so that the fluid may be acted on as a machine by any pressure which may be made upon it. In all the preceding cases the fluid may be supposed to be without weight. But in ordinary cases, when we speak of the pressure of a fluid, we mean the pressure which

arises from the weight of the fluid, when the fluid is not contained in a closed vessel. The former pressures, or those which we have spoken of as arising from some extraneous or impressed forces, are the same at every part of the vessel; the latter pressures, or those which arise from the weight of the fluid, are greatest at the lowest parts, and their magnitude depends altogether on the position of the part.

71. *Form of Surface.*—The preceding articles have treated of the properties of fluids not considered subject to gravity, and contained in a closed vessel, so that the form which any portions of their surfaces assume will depend on the shape of the containing vessel; but we shall now consider fluids as subject to gravity, and free; that is, their surfaces being at liberty to assume their natural forms. Under these circumstances, let the surfaces of a fluid contained in any number of vessels which communicate and stand near each other be observed; it will be seen that all the surfaces are in the same horizontal line: for if a line touch any two of the surfaces, that line produced will touch all of them, and will appear parallel to the horizon, so that all the surfaces will be in the same horizontal plane. If the surface of a fluid contained in a large tub be observed, every part of it will appear to be in the same horizontal plane.

This, which is thus derived from observation, may be shewn to be the necessary consequence of the action of gravity on the particles of a fluid mass. We know, from experience, that gravity produces the same effects on every particle of matter, situated at the same distance from the centre of the earth. Now all points near each other on the earth's surface, and at the same distance from the earth's centre, may be considered as situated in the same horizontal plane. Hence, when the surface is horizontal, every particle will be equally acted on by gravity, and there will be equilibrium; but if the surface be not horizontal, some particles will be more acted on than others;

unequal pressures will consequently be transmitted in every direction, and the fluid will not be at rest.

A small extent therefore of the surface of still water is horizontal; and the same is true for all other fluids subject to gravity, so that a small portion of the surface of the atmosphere which envelopes us is also horizontal; since this also is subject to the action of gravity.

The preceding reasoning may be considered as sufficient when gravity is the only force to which the fluid is subject. But we may have many other forces acting on a fluid; the form of its free surface will depend upon these forces, and be subject to the following invariable condition; 'That the surface must at every point be perpendicular to the resultant of the forces which act at that point.' This theoretical condition is evidently verified by the preceding remarks, for gravity being the only force, and its direction being parallel for all near points, any small extent of surface must be a plane.

72. *Surfaces perpendicular to resultant of forces.*—The application of the principle, that the surface of a still fluid is perpendicular to the direction of the force which acts upon it, shews that a large extent of water must be nearly spherical, while at the same time a small portion is apparently plane. The same principle must be applied in many other remarkable phenomena. When the particles are acted on by any other force than gravity, the surface will not then be perpendicular to gravity only, but to the resultant of the forces which act upon it. Thus, the centrifugal force arising from the rotation of the earth, when combined with gravity, is compounded into a third force, and it is the resultant of these to which gravity is perpendicular. Hence it is that the surface of the sea, and also of the earth, is more curved at the equator than at the poles. Near great mountains, whose attraction is sufficient to cause a deviation in the plumb-line (Art. 63), the surface of still water will not have its regular form, but it will adapt itself so as to be perpendicular to the resultant

of the forces which act upon it; and similarly, when the moon passes over any place, its attractive force compounded with gravity gives a resultant whose direction is different from the direction of gravity; and it is this attempt of the surface constantly to adapt itself to the proper form which gives rise to the periodic motions of the tides.

But there are many other phenomena referable to the same principle; it is known perfectly well that water in any vessel is elevated at the edges where it is in contact with the vessel, and that mercury is depressed; and when the fluid is contained in small tubes, the effect is so great that the whole surface becomes curved—being concave in water, and convex in mercury. Now gravity is not the only force which acts here; there are two other forces, the mutual attractions of cohesion which subsist between the particles of the fluid, and of adhesion betwixt them and the containing vessel. It is to the resultant of these three forces that the fluid surface is to be perpendicular; and the degree of curvature depends on the ratio of the intensity of the two molecular forces.

73. *Level Surface.*—In many cases the term level is the same as horizontal, and this may be taken as its true meaning, when only a small extent of surface is referred to; but it has a very different meaning when we speak of a great extent of surface, as the sea, a large lake, or extended plain. The horizontal plane or surface is in these cases a tangent plane to the level surface. We may define a level as that surface into which water forms itself when subject to the laws of gravity; and we must see what sort of surface observation and theory will decide this to be.

The earth's figure may be considered as spherical; for the slight deviation from this form may be disregarded in the present inquiry. Now, the inequalities which exist on the surface of the earth do not exist at all on the surface of a calm sea; but this surface, if continued uninterruptedly, would present a surface uniformly curved, and very nearly spherical. Such, then, is the form, according to observation. If, now, we consider the action of gravity, it will be evident that a surface of no other form can be at rest. If the surface have not all its points at the same distance from the earth's centre, the particles will be unequally acted on, and there can only be equilibrium when they have all settled down into a spherical form. This surface, then, of equilibrium, or spherical surface, as we may at present consider it, is a level surface, and if the whole globe were fluid, as once was probably the case, or entirely covered with water, there would be but one level. But as the world now exists, there are many surfaces, and consequently many levels; these are situated at different distances from the earth's centre, and one level is said to be above or below another, according as it is at a greater or a less distance from the centre of the earth.

The vast ocean of water which surrounds our globe, furnishes a level to which all other levels are referred. The level of the sea is the standard by which we compare the elevations of the mountains and continents of different parts of the earth. Thus, some large tracts of land, as one in the interior of Africa, are below the level of the sea, and the question of the permanency of the level of the ocean, that is, whether any change is taking place in the distance of this surface from the centre of the earth, is one of the most interesting questions of physical geology.

The level of different seas has been made the subject of the researches of several philosophers. It appears that the water of the ocean is constantly flowing into the Mediterranean through the straits of Gibraltar; whether or not this is compensated for by a constant under current is not known. If this under current exists, it is caused by the different densities of the upper and lower strata; the water of the Mediterranean being more dense than that of the ocean, flows out underneath it. If this under current does not exist, we must suppose that the Mediterranean loses by evaporation more water than it receives from the Nile, the Rhone, the Danube, and the numerous smaller streams which are emptied into it; and that the water of the ocean flowing in to compensate this loss, keeps the level at the height requisite for equilibrium. With respect to other seas, we may remark, that it seems clearly made out, that the level of the Red Sea is considerably above the level of the Mediterranean.* The level of the Caspian Sea is said to be several hundred feet below the North Sea;† as this, however, does not communicate directly with the ocean, there is no level to be preserved. The interesting question is, how came this depression of level? There is distinct evidence, from the nature of the soil, its chemical constitution, and the presence of salt water shells, that salt water once existed at a vast distance from its present shores.

74. *Fluids rise to their Level.*—All the points on the same level being at the same distance from the earth's centre, and consequently subject to the same action of gravity, it will follow from the principles already laid down, that a fluid cannot be at rest unless every part of its surface is on the same level. This is illustrated by the well-known fact, that a fluid will always sink or rise to the same level; when this is attained, the fluid is at rest.

The supply of towns with water furnishes a grand illustration of this law. The ancient method of supplying towns by means of aqueducts is now almost entirely superseded by long pipes, laid under ground and above ground, and turned in any direction. A reservoir is selected in some situation more elevated than the places to which the water is to be supplied. Pipes are conveyed from it in every direction, and the water may be 'laid on,' that is,

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* The French engineers state the average difference of level to be about 30 feet.

† The difference in level is stated to be 100 metres, about 326 feet.

supplied at the tops of houses at any distance, provided the tops of the houses are not on a higher level than the surface of the water in the reservoir. Thus does man, by taking advantage of the invariable laws of nature, add most materially to the happiness of his species; there are, perhaps, few things more wonderful to reflect on, than the thousands of miles of pipes by which the houses of London are supplied with this precious element, solely in obedience to the simple law which we have just stated.

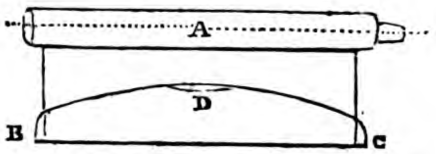
The condition for the equilibrium of fluids in communicating vessels may be at once derived from the preceding principles; if the fluid communicates in any manner, it cannot be at rest unless all the surfaces are on the same level; this is the sole condition, without any reference whatever to the magnitude of the vessels; hence we see that if any number of vessels communicating with each other stand on the same horizontal plane, and water be poured into any one of them, it will immediately stand at the same height above the horizontal plane in all of them; the size and shape of the vessels being any whatever. There is an apparent exception to this law when the tubes are so small in diameter that they are termed capillary; this, however, is no real exception to the preceding principles, but a confirmation of them, for there are other forces besides gravity acting in these cases; and these being properly considered, the one sole condition of equilibrium, that the surface must be perpendicular to the resultant of the forces, is satisfied (Art. 71).

75. *Levelling.*—We have seen that a level surface consists of a series of points at the same distance from the earth's centre, and that water will rise to its level; the question now is, how can we determine what points are on the same level, or to what places water can be supplied; this constitutes the operation of levelling, which depends altogether on the fact, that the surface of a small extent of fluid at rest is horizontal (Art. 71). The instrument em-

ployed for this purpose is termed a *Level,* which, in its simplest form, consists of a tube, with its two ends turned up, and open, and nearly full of water. Upon the surface of the fluid in these two ends are floats, A and B, carrying uprights, with sights C and D, at equal distances above the floats. These sights may be small pieces of wood, or small holes. Now if, when this instrument is placed on any surface, or held in the hand, the sight at C covers the sight at D, on viewing an object, the three points are in the same horizontal line. For the floats at A and B are horizontal, and the line joining C and D is parallel to these, since C A is equal to D B, and therefore C and D are in the same horizontal line. And if these sights cover any third point, the three must be in the same straight line, which is also horizontal. The instrument may be held in any position, since the floats must be horizontal when the fluid is at rest.

The preceding is not, however, a convenient level for practical purposes, and the one in general use is the Spirit Level, so termed because spirits of wine, or alcohol, which does not readily freeze, is the fluid used.

A glass tube, B C, having its lower surface plane, and its upper slightly convex, is nearly filled with the fluid, and hermetically sealed. The small quantity of air which is left in, forms a bubble which always occupies the highest part of the tube: when the lower surface is horizontal, the surface of the fluid will be parallel to it, and the air bubble will occupy what is then the highest part of the level, that is, it will be just under the middle part of the convex surface, as shewn at D: if either end be raised, the bubble will im-



mediately move towards that end. Thus, the position of the air bubble, with reference to the middle of the upper surface of the tube, may determine the actual position of any surface with reference to the horizon. Attached to the level B C is a telescope A, with its axis, as represented by the dotted lines, parallel to the lower surface of the tube; so that when this is horizontal the axis will be horizontal, and all the points seen through the telescope will be in the same horizontal line.

With this instrument we may proceed to the operation of levelling; and suppose that two points are to be determined on opposite sides of a deep valley, which are to be on the same level. An observer takes some position on one side, and setting the level horizontally, looks through the telescope, and notices some object; he is then sure that this object and his eye are on the same horizontal line. Thus, two fixed points on opposite sides are determined, and he can then calculate the places on the opposite sides which are on the same level. The point required on the opposite side will be below the object which he sees; for supposing A to be the place of his eye, the point which he sees will be D on the line A D, which is a tangent to the earth's surface at A. But A B being the surface of the earth, the point B is the point on the same level as A. Hence the true point will be below the apparent point by the distance D B; this quantity is termed the *depression*, and is always known when the distance A B is known; but into the mathematics of this question we cannot enter.*

In the great works of engineering, the levelling is one of the first employments. In conducting a railroad, the level of every point must be ascertained, in order that as much as possible the road may be all on the same level; and to

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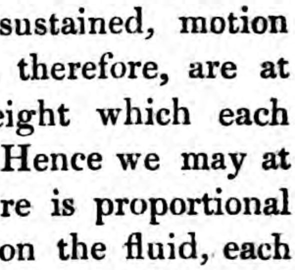
* The value of the depression in feet is $\frac{2}{3}\lambda^2$, where λ is the distance in miles. See *Principles of Hydrostatics*, Art. 45.

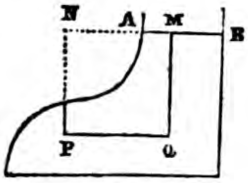
effect this, great cuttings and embankments must sometimes be executed. In conducting a canal across any country the points in the same level must be determined, so that if it be possible there may be no locks, but the water may be at rest, having no tendency to flow either way. In cutting a drain, each successive point must be just below the level of the preceding, and the greater the fall, that is, the greater the difference of the levels of the two ends, the more rapidly will the water run.

76. ***Pressure proportional to the Depth.***—In the preceding articles we have considered the form of the surface of a fluid acted on by gravity and other forces; and we have seen that it must always be perpendicular to the resultant of the forces. Now gravity acts on every particle of a fluid, and we must consider the pressure at any point which arises from this action. When a fluid contained in any vessel is at rest, each layer of particles, from the top to the bottom, is subject to the action of this force, and that, consequently, unless sustained, motion must ensue. The particles of a fluid, therefore, are at rest, because the pressure or the weight which each exerts is balanced and counteracted. Hence we may at once arrive at the law, 'that the pressure is proportional to the depth.' For, since gravity acts on the fluid, each particle presses on that which is next below it, and this pressure is transmitted in every direction (Art. 68).



Let, now, P be any point immediately below the surface A B of any fluid, as water, contained in any vessel. Now, since the whole fluid is at rest, any portion of it, as the line of particles in P N, drawn perpendicular to the surface, will be at rest also; they may, therefore, be conceived as isolated from the surrounding particles, just as if all the surrounding particles were to become solid, and P N were the only fluid matter left. Then the pressure at P would evidently result simply from the particles in P N, and since the weight of each particle would be transmitted along the line N P to P, the pressure at P will be the aggregate of these transmitted pressures, that is, of the weights of the particles. The greater, then, the number of particles, or the greater the depth of P below the surface, the greater will be the weight, or the pressure at any point will be proportional to the depth.

The point P is, in the preceding case, immediately below the surface of the fluid; but suppose it under some part of the containing vessel, as at P in this figure. Draw P Q parallel, and Q M perpendicular, to the surface of the fluid. Then, the fluid in these lines being considered as detached from the surrounding fluid, as in the preceding case, the pressure at Q will be the weight of the line Q M of particles, and the pressure at P will be the transmitted pressure from Q; for each of the particles in P Q will, since it is parallel to the surface, be similarly situated with respect to gravity, and have the same weight: so that the pressure at P will be the same as that at Q, that is, proportional to P N, or to the depth of the point below the surface of the fluid. Now, the point P may be situated any where, as at any part of the containing vessel; hence the pressure at any point is entirely independent of the shape of the vessel, and depends only on the depth of the point below the surface of the fluid.



77. *Pressure on any Surface.*—The preceding articles shew that the pressure at any point is the weight of the superincumbent column of fluid; and since the directions of all these pressures are parallel, we may find the whole effect which they produce on any surface immersed in a fluid, or on any portion of the surface of the containing vessel. We cannot here state the mathematical reasoning* by which this is effected, but the result may be stated in

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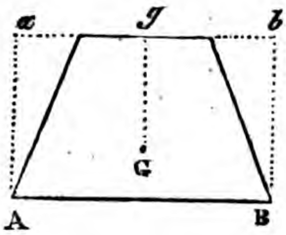
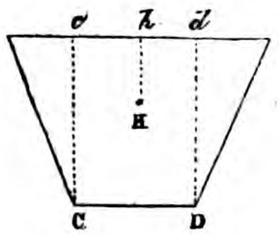
* See *Principles of Hydrostatics*, Art. 33.

the following simple terms :—'The pressure of a fluid on any surface is the weight of a column of the fluid, whose base is equal to the area of the surface pressed, and whose height is equal to the depth of the centre of gravity of the surface below the surface of the fluid.' This we shall proceed to apply.

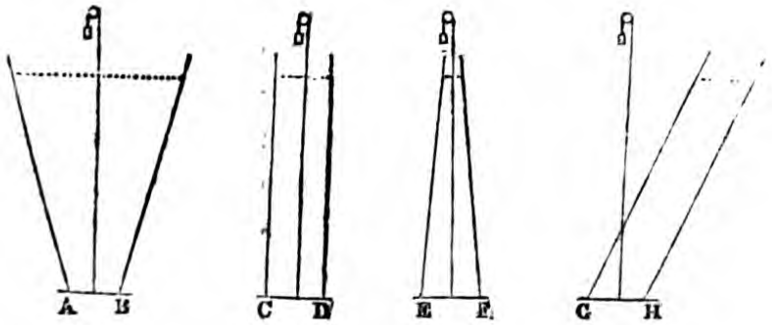
Let the pressures on the bases and sides of two exactly equal portions of a truncated cone, one having the largest and the other the smallest end for its base, be required.





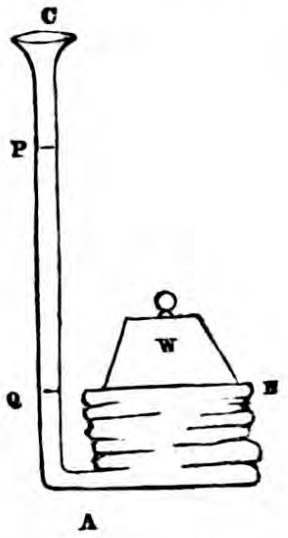
The column of fluid whose base is equal to the surface pressed, and whose height is equal to the depth of the centre of gravity below the surface of the fluid, is that represented by *a* A B *b*, in one case, and by *c* C D *d* in the other; for the centres of gravity of the two surfaces pressed are at the same depth in both cases below the surface of the fluid. But the centres of gravity of their sides are at very different depths: it will be near the base, as at G, in the first figure; and near the top, as at H, in the second figure; so that it is in one case at much a greater depth than the other; hence the column of fluid, whose weight equals the pressure, is much higher when the frustum stands on the larger end, than when it stands on its smaller end. If, then, the sides of a vessel converge, as in the figure A B, the pressure on the base is greater than the weight of the contained fluid, and if they diverge, as in the figure C D, it is less. It may be shewn, experimentally, that if water be poured into a hollow cone, with its base downwards, the water will raise the cone, unless the cone be very heavy.

The preceding conclusions may be arrived at, experimentally, in the following manner; let four vessels, whose bases A B, C D, E F, G H, are all exactly equal, be made so that



their bottoms will open downwards and permit the water to escape, when a pressure on their upward surfaces is sufficiently great. The vessels may be kept closed by a spring, or by a small weight acting over a pulley, and drawing a string attached to their bottoms. This spring or weight will serve for an accurate measure of the pressure on the bases, and let it be exactly the same for all. If now water be poured in so as to stand at the same height in all, the bottoms will all descend at exactly the same instant, or when the weight of the water becomes equal to the weight across the pulley; and in all the cases it will be exactly equal to the weight of the column whose base is the base of the vessel, and height that of the fluid, as will evidently be the case in the second figure. The result would have been precisely the same whatever shapes are assigned to the vessels. The law then of fluid pressure is such as we have enunciated, and is sometimes stated in the paradoxical form, that the pressure on the base of a vessel does not depend upon the quantity of the fluid; that is, the pressures on the bases A B or E F are the same, though one vessel holds many times the contents of the other.

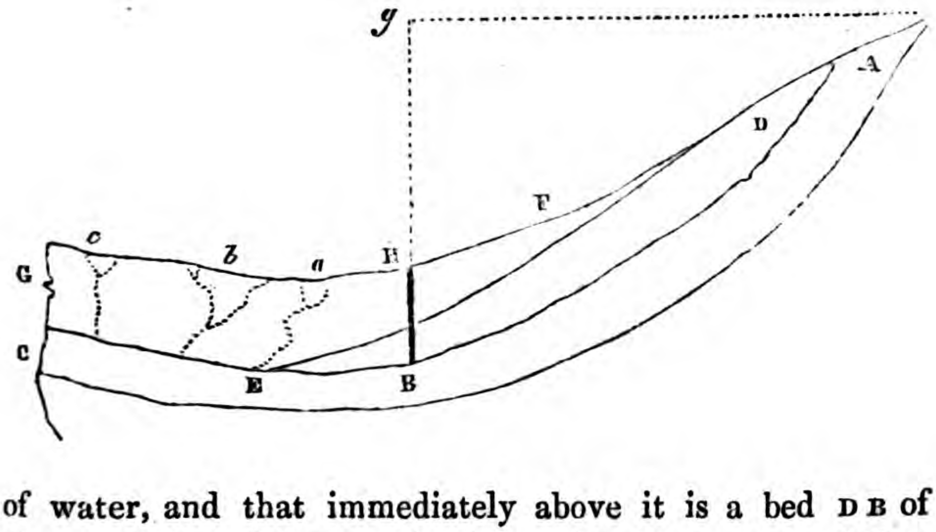
78. *Hydrostatic Bellows.*—This instrument will furnish an illustration of the foregoing principles. It consists of



two pieces of board united together by some flexible waterproof substance, and of a small tube communicating with the interior of the bellows so formed. If now water be poured down the tube at C, it will run into the bellows at A, and raise the upper board. There will be some point at which the upper board will cease to rise, and there will be an equilibrium betwixt the upward pressure of the water on the under side of the board B, and the downward pressure of the board and of the sustained weight W. Let P be the height of the water in the tall tube at some instant when there is equilibrium; then if Q be on the same level (Art. 74) as the water in the bellows, P Q is the column of water which supports the whole weight raised. The way in which this acts will be readily understood from the principle of the transmission of pressure. The column P Q exerts by its weight a certain pressure on the water at Q; this is transmitted throughout the whole mass, and impressed on every equal portion of the fluid and bellows. Now, suppose that the board at B is one thousand times larger than the section of the tall tube; this would not be an improbable proportion; then one pound pressure at Q would sustain one thousand pounds at B. And the effects may be increased, theoretically, without limit, in the three following ways; by increasing the area of the upper board, by diminishing the diameter, and increasing the altitude of the tube. Thus, it appears that a quantity of water, however small, may be so employed as to sustain a weight however great; and simply by taking advantage of the law of the transmission of fluid pressure.

If a heavier fluid, as mercury, be used, the effects will be much greater, that is, a much smaller column will produce the same effects. A similar application may be made of elastic fluids; and a man standing on the upper board may blow into the tube with his mouth, and cause an upward pressure sufficient to raise himself.

79. *Natural Fountains and Springs.*—The preceding laws of fluids may be illustrated by many natural phenomena, which at first sight appear somewhat startling. Whence is it that the springs rise out of the bowels of the earth; and how comes it to pass, that in boring for water, a sudden fountain will spring up, and continue to throw its waters to a great height above the surface of the earth? These will be seen at once to be the necessary consequence of the preceding laws and of the known structure of the earth. The globe consists of strata of various materials, which once lay in regular levels, but have since been broken up, elevated in some places and depressed in others. Suppose now that the present position of the strata is such as in the accompanying figure; that A B C is a sand containing plenty of water, and that immediately above it is a bed D B of clay, or some substance quite impervious to water, and that above the clay is the natural soil, consisting of different substances, more or less pervious to water. Let the clay terminate at B, so that some portion of the sand is overlaid by the natural earth. Then the water at A will rise to its level; consequently at *a*, *b*, *c*, there may be springs whose



actual courses, as indicated by the dotted lines, from the stratum A B C will depend on the nature of the upper layer. Suppose that a person at H wishes for a well; he begins to dig and then to bore, till the clay, as represented by the shaft H B, is penetrated. The water will instantly rise to the same level as that at which it stands in A, to *g* for instance; thus it will spout out to a considerable height above the surface of the soil. When the stratum A B lies up the side of a mountain, the height to which the water will spout on being let out may shew us, that the pressure on the under surface of the impervious matter must be very great, and such as may be sufficient to elevate the whole mass. Should a small water channel leading from the top of a high mountain to a cavern in its interior be full of water, and the cavern and channel be both water tight, the pressure which this column of several hundred feet vertical height will cause on the cavern sides must be such as scarce any of the ordinary materials of the surface-crust of the earth can resist.

80. *Centre of Pressure.*—In the preceding articles the method of estimating the amount of fluid pressure which any surface sustains has been shewn. This whole pressure is the sum of all the elementary pressures, and such may be represented by a single pressure; or, in other words, these pressures have a resultant, and the point at which this single resultant pressure is to be applied, so as to produce the same effect, or to counterbalance these pressures, is called the *centre of pressure* of the surface. The position of this point may be determined by the aid of mathematics from the preceding principles, and we shall here state the result which theory gives for some of the more simple figures.*

The centre of pressure of the bottom of any vessel, if the bottom be horizontal, is the same as the centre of gravity, for the forces being in both cases parallel forces, the position of this resultant will be the same; but the

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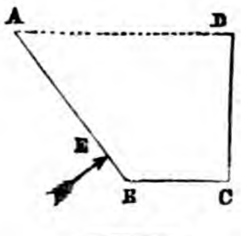
* *Theory of Fluids*, Arts. 48—53.

centre of pressure of the side of any vessel containing the fluid will always be below the centre of gravity, because the pressure, being proportional to the depth (Art. 76), is greater at the lower than at the upper parts; the two centres would coincide if the pressures did not increase for the lower parts: thus in a vessel containing a portion of highly elastic fluid of no sensible weight, the centres of pressure of the sides coincide very nearly with their centres of gravity.

If the side of a vessel be a parallelogram, the centre of pressure is one-third of the height from the bottom, that is, two-thirds of the depth of the fluid below the surface. In an isosceles, or equilateral triangle, its base coinciding with the surface of the fluid, it is in the middle of the line joining the vertex and the bisection of the base; if the base be downwards and the vertex in the surface, it is at one-fourth from the base, or three-fourths from the vertex. If a parabola be placed with its vertex downwards, it will be at a distance of four-sevenths from the surface of the fluid, or three-sevenths from the vertex.

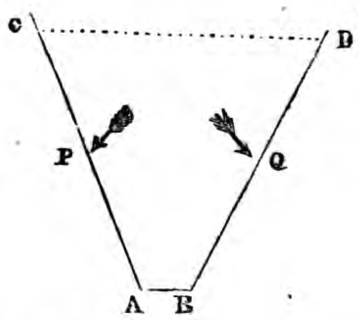
Let the side A B of any vessel containing water be loose; let it be in form a parallelogram; then if a point E be taken, such that $AE = \frac{2}{3} AB$, a single force, as represented by the arrow, will keep the side from moving.



Similarly, we may have a barrel with only a single hoop. For each of the staves may be kept at rest by a single force applied at a point one-third from its bottom; hence, if a hoop, A B, pass round the cask at this distance from the bottom, the staves will all be kept in their places.

A knowledge of the position of the centre of pressure in different figures is of the greatest practical importance. In drainage, in canal navigation, in harbours, and many other cases, large gates have to be erected which will be ubject to the pressure of water. Now, it is desirable to know at what points the greatest strength is required, so that a given quantity of materials may be most effective. The hinges of such gates should evidently be placed with reference to their centres of pressure, or there will be more strength than is necessary at some points, and not enough at others.

81. *Lateral Pressure.* — When water is contained in any vessel, the lateral or horizontal pressures destroy, that is, are in equilibrium with each other. This may be shewn at once from mathematical considerations, but it is proved experimentally by the fact, that a vessel full of fluid has never the least tendency to move laterally; but if a portion of one side be removed the vessel may tilt over towards the other, or be overturned. Before the surface was removed, the pressure was the same on both sides of the vessel, but when the surface is removed on one side there is pressure only on one side, which consequently may overturn the vessel.



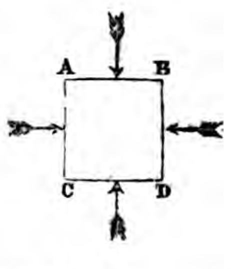
Let A B C D be a tall vessel containing fluid; the lateral pressures at P and Q balance each other; but let a portion of the surface be removed at Q, the force at P only is left, and the vessel, consequently, tumbles over.

The application of this principle in Barker's mill is very well known, and the celebrated Bernouilli proposed to move vessels through water by the reaction of water flowing out from behind. The preceding principle will enable us to understand the impelling force on a sky rocket. A great pressure is produced on every point of the chamber which contains the combustible materials. The reaction of the sides of the chamber counteract each other; but there being nothing to counteract the reaction on the end of the chamber, the rocket is impelled forward, whilst the action which would be exerted on the other end, if closed, is dissipated into the surrounding air.

SECTION II.

FLOATING BODIES—CONDITIONS OF EQUILIBRIUM—SPECIFIC GRAVITY—ASCENT OF BODIES IN FLUIDS.

82. In bodies surrounded by a fluid we constantly see apparent exceptions to the law of gravity, for heavy bodies move in a direction opposite to it; thus cork, wood, and many other substances, rise up when plunged in water; iron ascends in the same manner on being immersed in mercury; the smoke also rises in the air; the clouds appear to float suspended above our heads, just as any light body at the surface of water. Thus fluids have some peculiar property of rejecting those light bodies which are entirely surrounded by them, and of sustaining those which rest at their surfaces; all these and many other phenomena may be derived at once from the laws established in the preceding chapters, and are the immediate consequence of that principle which is immortalized by the name of Archimedes. This principle may be stated in the following terms: 'A body immersed in a fluid loses as much of its own weight as is equal to the weight of the fluid displaced.' The law is equally true whether the fluid be a liquid or a gas.



Let a cube be immersed in a fluid, and let its upper and lower face be horizontal, that is, parallel to the surface. Then, since every point will be pressed by the fluid, we may represent the pressures which its faces sustain by the arrows in the figure (Art. 80). Then it is evident, 1°. That the lateral pressures, which are equal and contrary, will destroy each other. 2°. That the upper face A B sustains a force, pressing downwards, which is equal to the weight of the superincumbent column. 3°. That the lower face C D sustains a force pressing from below upwards, which is equal to the weight of the column which would rest on it if the cube were fluid (Art. 77). Thus the body is acted on by two opposite forces, its own weight tending to make it descend, and the difference between the pressures of the fluid on its two faces, which is a force tending to make it ascend. If these forces are equal, the body remains at rest; if unequal, it descends or ascends, according as its weight is greater or less than the opposite force. This proposition, which may be established rigorously on the principles of statical equilibrium,* may also be treated in the following manner.

83. *Loss of Weight.*—A body immersed in a fluid, since it appears to lose some of its weight, is supported in some way or other by the fluid. Now before the body was immersed, there was a certain quantity of fluid which occupied exactly the same space; this fluid may be conceived to be detached from the rest and to become solid; it will then be supported exactly as before by some pressure acting upwards, which must be exactly equal to the weight of the solidified fluid. The immersed body therefore must in the same manner be supported by a pressure acting upwards, which is exactly equal to the weight of the fluid displaced. When then the weight of the body equals the weight of the fluid displaced it will be at rest, or appear to lose all its weight; when it is greater than it, it will appear diminished, by exactly that weight; and when less than it, it will be pushed upwards, and float at the surface, displacing only as much fluid as exactly counterbalances its weight.

The cause of this loss of weight was a great difficulty in the early era of science, and gave rise to many curious doctrines respecting the gravitation of fluids. It was asserted that gravity was the effort of a body when out of its place to get into it; hence, when a body was not out

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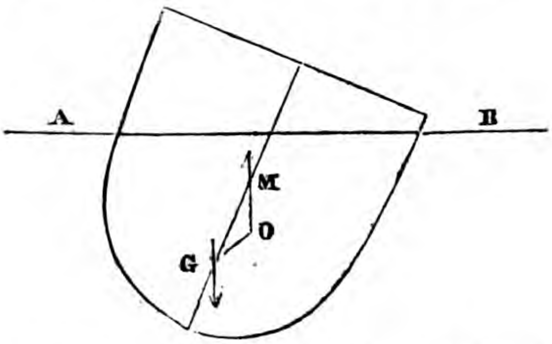
* *Theory of Fluids*, Arts. 54—57.

of its place there was no reason for gravity to exert itself, and consequently, when a bucket full of water is immersed in water it does not gravitate, because the water is surrounded by its own element, or is in its place; but as soon as the bucket is raised a little out, the fluid which is thus raised out of its place begins to gravitate.

84. *Conditions of Equilibrium.*—If solid bodies were homogeneous, that is, of the same density, or, uniform constitution in all their parts, the condition, 'that the weight of the body should be equal to the weight of the fluid displaced,' would be the only one necessary for equilibrium. But since no substances are perfectly homogeneous, we must always make use of the imaginary point, which is termed the centre of gravity (Art. 46), and consider the forces as applied at that point. There are then two centres of gravity to be considered, the one of the floating body, the other of the fluid displaced; the weight of the body may be conceived to be a force applied to the centre of the gravity of the body, and acting downwards; and the weight of the fluid displaced may be conceived as a force applied at its centre of gravity, and acting upwards. Now the directions of these two equal forces are parallel but opposite; hence, unless they are applied on the same line the body cannot rest; for it is known that two equal opposite parallel forces cannot preserve equilibrium (Art. 22).



Let G be the centre of gravity of any body immersed in a fluid, and O the centre of gravity of the fluid displaced. The weight of the body is then a downward force through G;

and the weight of the fluid displaced is an upward force through O, as shewn by the arrows. These will evidently twist the body, and there cannot be equilibrium unless the directions of the two arrows coincide with the line G O, which will be the case when this line becomes vertical, that is, when the lines G O and G M coincide. The other condition then at which we arrive is, 'that the line joining the centres of gravity of the body and of the fluid displaced must be vertical.'

Besides these two conditions which are sufficient for an equilibrium, there is a most important question as to what is the nature of this equilibrium;—is it stable, unstable, or indifferent? The complete answer to this question cannot be given in the present treatise, since recourse must be had to difficult mathematical reasoning;* but from what we have already said on the question of stability (Art. 50), it will be evident that for stable equilibrium the centre of gravity of the floating mass must be as low as possible. Hence, the heavier parts of a cargo must always be stowed at the bottom of the vessel, and heavy iron, or stone ballast, is frequently necessary at the lowest parts of a ship; thus the centre of gravity is brought below that of the fluid displaced. If a person were to attempt to walk or stand on water supported by bladders or cork, his success might be considered as almost miraculous; for his centre of gravity being far above that of the fluid displaced, his position would consequently be one of unstable equilibrium, and the least disturbance would infallibly bring his head below, and his heels above, the water. Every one must have observed the ease with which a small boat can be upset, if persons stand up in it; the elevation of the centre of gravity of the system places the boat in a most dangerous condition, as is at once shewn by the facility with which it rocks or oscillates, like an inverted pendulum, from side to side.

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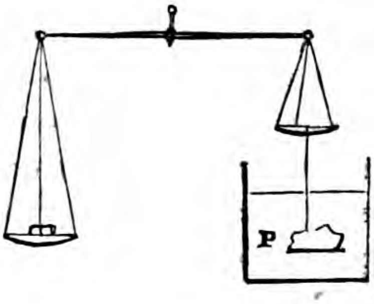
* See *Theory of Fluids*, Arts. 67—73.

85. *Specific Gravities.*—The preceding law of the loss of weight on the immersion of a solid has a very useful application in the determination of the specific gravities of different substances. One substance is specifically heavier than another when, being equal in bulk, the weight of one exceeds, or falls short, of the weight of the other. Thus, iron and mercury are specifically heavier than water, for the weight of a cubic inch of either is greater than of a cubic inch of water, and the weight of a pint of mercury is greater than of a pint of water. Similarly, cork and most woods are specifically lighter than water. Now, insuperable difficulties present themselves in ascertaining the bulks of different substances so as to ascertain and compare the weights of equal bulks. But they may all be readily compared with water, and so with each other. And this process depends on a proposition, immediately deducible from the preceding law of floating bodies, which states, 'That when a solid is immersed in a fluid, the weight lost is to the whole weight of the body, as the specific gravity of the fluid is to that of the solid.'* Thus, by weighing different substances in the same fluid, and observing the weight lost, their specific gravities are given by a simple proportion; and may be immediately compared with each other. This proposition is of great practical importance in determining the specific gravities and consequent strengths of spirituous liquors, by weighing the same substance in them; but on this we cannot dwell here.†



The same principle is also illustrated by the method of determining the specific gravity of a solid by the Hydrostatic balance. This instrument in its simplest form is a common pair of scales, with a fine wire attached to the un-

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* *Principles of Hydrostatics*, Art. 48.

† *Ibid*, Art. 60.

der surface of one of the scale pans. The solid whose specific gravity is required, is weighed in air, and then, being attached to the wire, is immersed in water, and again weighed. The weight lost, which is the weight of the fluid displaced, being thus ascertained, the specific gravity will be found by dividing the actual weight of the body by the weight of an equal bulk of the water. Thus, suppose a piece of metal weighs 35 grains in air, and that when immersed in water it weighs only 31 grains, there is then a loss of weight equal to 4 grains, that is, the fluid displaced weighs 4 grains; the specific gravity of the copper will then, by the above rule, be $\frac{35}{4}$ or 8·75, nearly.

86. *Ascent and Descent of a Body.*—When the preceding condition of equilibrium is not satisfied, the immersed body will ascend or descend, according as its weight is less or greater than the weight of the fluid displaced. And the moving force by which it will ascend or descend is the difference of the weights of the solid and fluid displaced. Hence we may understand what is meant by the *buoyancy* of light vessels full of air, as wooden chests, tin, or thin iron vessels, bladders, &c.; any vessel of this kind sunk in deep water, and attached to a heavy sunken body, will draw it up. Thus, vessels may be raised by large chests, sunk full of water on each side of it, and made fast to the keel by straps underneath; when the water is pumped out of these chests, their buoyancy will raise the vessel. These principles are illustrated by the facility with which fishes rise to the surface, or descend to the bottom of water. There is in their bodies a small air vessel, by the expansion or contraction of which the size of their bodies, and consequently the bulk of the water displaced, is altered. When the weight of the water displaced becomes greater than the weight of their bodies, they are forced upwards, or ascend to the surface, and when it becomes less, they descend.

The human body naturally displaces a bulk of water, whose weight is greater than its own weight, and this quantity may be slightly varied by the expansion and contraction of the chest. This is shewn to be the case by the fact, that the body will float at the surface of the water if the individual has the presence of mind to throw his head back, and to keep his arms under water. But if the arms be raised out of the water, the quantity of fluid displaced weighs less than the body, and the head sinks below the surface.

When the body is sunk so far, that the pressure of the water diminishes sensibly the bulk of the body, it becomes at once heavier than the fluid displaced, and cannot rise again to the surface. This sometimes occurs when an individual pitches from a great height, as from the yard-arm of a ship, into deep water; the velocity acquired by the descent through the air carries him to such a depth in the water, that his body by compression becomes greater in weight than the bulk of the fluid displaced; in such cases the individual is seen no more, until the swelling, which always takes place at a short period after death, displaces a quantity of fluid greater than was previously displaced, and the lifeless body rises again to the surface.

The ascent of *balloons* will be at once understood, by considering the preceding principles. Any body immersed in a fluid loses a part of its weight, that is, appears to weigh less than it really does; and this apparent loss of weight is, as we have seen, equal to the weight of the fluid displaced. Now, the air is a fluid, and must cause a consequent diminution in the apparent weight. The air is so light, that this diminution cannot in general be detected but by the most delicate experiments. If, however, we have any doubt as to such being the actual fact, we need only appeal to the rise of balloons, which ascend in the air by virtue of this very action, and carry up the weight of several human beings. The first balloons were filled with heated air, of which a given volume weighs much less than the same volume of cold air; the weight, consequently, of the cold air which it displaced being greater than the weight of the materials of the balloon and the same bulk of hot air, the balloon is forced upwards. The balloons are now generally filled with gas, which being four or five times lighter than common air, enables a heavy weight to ascend with great rapidity, and to considerable heights.

The ascent of small air bubbles in water takes place according to the preceding laws; a bubble of this kind is observed to dilate as it ascends, and consequently the bulk of water which it displaces is increased as it approaches near the surface. This is the immediate consequence of the law, that the pressure is proportional to the depth (Art. 76), and of another which we shall mention presently, that the elastic force of air is inversely proportional to the space which it occupies (Art. 89).

87. *Ascent of hot air in chimneys.*—The rapidity with which a column of smoke issues out of a tall chimney, is explicable at once on the preceding principles. Hot air is specifically lighter than cold air; and, consequently, since a given portion of air expands on being heated, it displaces a greater quantity of air than before, that is, a quantity of air whose weight is greater; it is, therefore, forced upwards by the difference of these weights. This ascent of warm air is always going on from our mouths, and from other parts of our bodies. This is not generally perceptible, except in the case of smoke, which is visible in consequence of a number of small black particles light enough to be carried up by the rising current of heated air. All these visible parts of smoke fall again in the form of soot. The use of tall chimneys is, that they give a long column of hot air; a long piece of wood rises much more rapidly when immersed in deep water than a short piece; and for the same reason a column of hot air of 150 feet in length will rise much more rapidly than one of only 50 feet. Every one must have observed the rate at which smoke pours out from the enormous chimneys of our steam engines and manu-

factories; the smoke is, as it were, projected upwards to a very great height above the top of the chimneys; whereas, from the common chimneys of our houses, it sometimes seems to have scarcely the power of escape, and when perplexed by violent gusts of air, we know full well that it frequently cannot issue forth. The rapidity with which a tall column of hot air rises, causes the *draught* of the chimney; this is necessary for the supply of air to the fire, a constant uniform current of air is thus carried through the fire, and supersedes the necessity of blowing the fire by means of bellows, which would require troublesome machinery, and not answer the purpose nearly so well. There are other considerations connected with the velocity of ascent, as, for instance, the degree of heat, the decreasing density of the air, the form of the chimney, but on these subjects we cannot here enter; it is merely the general principle which we wished to illustrate.

In further illustration of the preceding, we may mention that a single tall chimney suffices not only for all the fires of one establishment, but frequently for all the fires of the immediate neighbourhood. Flues are conveyed from the different fire-places to the great chimney, which, by its draught, keeps all burning in brisk activity. Should all the fires go out, which is rarely the case in large establishments, the fires cannot be lighted till the column of air has been warmed, so as to re-establish the draught, which is readily effected by throwing lighted straw or shavings into some part of it. At the copper smelting works near Swansea, one or two very tall chimneys may be seen, which communicate with a vast number of smelting furnaces; here, beside the draught, there is another most important end to be answered by these tall chimneys, namely, the distributing the noxious particles which are carried up, over a very widely extended district. These particles are utterly destructive of all vegetation when congregated in great numbers; from short chimneys they would all fall in the immediate neighbourhood, but being carried up into the higher strata of the atmosphere, where the currents are generally very rapid, they become dissipated over many miles, and thus their very destructive effects are in a great measure prevented.

SECTION III.

LAWS OF ELASTIC FLUIDS—PRESSURE INVERSELY AS THE SPACE—DALTON'S LAWS.

88. The laws of fluids which have been discussed in the preceding chapters apply equally to all gases as well as liquids, since gravity acts on all. But the elastic fluids have some properties which are entirely unconnected with gravity, and which are the necessary consequences of the repulsive force which exists between the particles, and by virtue of which they exist in the gaseous state. The action of the molecular forces is entirely different here from the cases which we have already considered. In the solids we have seen that these forces retain the particles in their places, and press them against each other; in the liquids they retain the particles in their places, suffering them to move with great freedom amongst each other; but in gases these forces compel the particles to separate from each other, and recede, until opposed by some obstacle, as the sides of the containing vessel. Thus, any gas or common air contained in a vessel, exerts by virtue of its nature a constant pressure on the sides. These considerations shew us that when any portion of air is at rest, every particle must be subject to some pressure from without inwards, and if there be not an exact equilibrium between these forces, the air will not be at rest. This pressure, which every portion of confined air exerts, is called its *elastic force*, and must be carefully distinguished

from any pressure which may arise at any point from the action of gravity. In considering this pressure, we may suppose the fluid as absolutely without weight, just as when we spoke of the transmission of pressure, which is a property of all fluids (Art. 68). When air is contained in any vessel, it exerts a pressure on the sides; now, suppose an orifice made, so that there is no longer any surface to counteract the elastic force, will motion ensue, will the external air rush in, or will the internal air rush out, or will both remain in equilibrium? If the air which was enclosed in the vessel is of the same state of density and temperature as the external air, there will be perfect rest; the external air will counterbalance the expansive force of the internal air which was exerted on the sides of the vessel. But if there be any difference in the states of the internal and of the external air, the forces will not counteract each other, and motion will ensue in the direction of the greater.

89. *Elastic Force.*—There is a remarkable law connecting the elastic force of a gas with the space which it occupies, or which comes to the same thing with its density, which may be expressed in the following terms: 'The elastic force of air at the same temperature varies inversely as the space it occupies.' This was first established by Boyle,* and afterwards by Marriotte, and may be proved by the simplest experiments.

Suppose a tall cylindrical vessel to be inverted over water, and gradually pressed down, so that the air is continually forced to occupy a less space, it will be found that the force requisite to keep the vessel down, or to balance the elastic force of the compressed air, must be increased precisely in proportion as the space diminishes; that is, the elastic force of the air varies inversely as the space it occupies. Should the temperature be augmented by any cause during the operation, the elastic force will be increased,

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* In 1662.

and the preceding law will not be accurately true. The same result may be obtained by compressing any gas by a piston fitting accurately into a cylinder, or in many other ways.

The method which is generally adopted, and admits of the greatest accuracy, is to compress the air or gas in the upper part of the tube B C, by pouring mercury into the tube A B. Suppose the air which occupied the whole space B C to be compressed into the space C Q, then if an additional quantity of mercury be poured in, the air will be still further compressed. The weight of the elevated column in the tube A B will measure the elastic force of the air compressed into the top of the tube B C. The weights of these columns corresponding to the spaces occupied by the air, being compared, the law just stated is clearly established.

The density of any gas varies inversely as the space it occupies; for the density of any substance is said to be greater in proportion as there is more matter in the same space, or the same matter occupies a less space, and less according as there is less matter in the same space, or the same matter occupies a greater space. But the elastic force is found to vary inversely as the space; it therefore varies as the density.

90. *Illustrations.*—The action of the *Air Pump*, the practical applications of which are so well known, will serve to illustrate the preceding remarks. A portion of the air being removed from the receiver by the ascent of the piston, that which is left immediately dilates or expands, and fills its place. But since after every stroke there is less air in the receiver, that is, it becomes rarer and rarer, or diminishes in density, its elastic force will at last become very feeble; and when it is so far diminished as to be unable to raise the valves, no more air can be removed, or the rarefaction cannot be carried any further.

The application of the *Condenser* is exactly the reverse of the preceding; this instrument is employed to compress a great quantity of air into a given space, and by this we may verify the law stated in the preceding article, that the elastic force of the air is proportional to its density. If the force requisite to squeeze in air increase in exact proportion to the quantity of air already squeezed in, the preceding law will be satisfied. The instrument is not much used, except for supplying the reservoir of an air-gun. The elastic force of the air so compressed into the chamber of the gun is exerted again in exact conformity with the law, that the elastic force is proportional to the density. When the air is very dense, its elastic force will throw bullets with a force not much inferior to that of gunpowder; and the force, with which the pellet is driven from the school-boy's pop-gun by the elasticity of the condensed air, is exerted in conformity with the preceding law.

But the very important applications of the *Air Vessel* furnish us with too important an illustration of the elastic force of the air to be wholly omitted. The action of all pumps is intermittent, that is, there is some part of the stroke, or some instant, at which no water flows; now this is in many cases extremely inconvenient, and is entirely obviated by forcing the water into an air-tight vessel, instead of raising it at once by the pump. The water so forced in compresses the air, and the elastic force resulting from this compression is sufficient to raise the water through a smaller pipe, and in a continuous stream, to the same height as the pump could have raised it directly. There are other advantages resulting from the use of the air vessel; as, for instance, the prevention of jar in machinery; hence, it has been termed the *Air Spring*, and a most appropriate name it is, since its effects are precisely similar to those attendant on the steel spring in carriages: it prevents that sudden and instantaneous destruction of velocity which is so fatal to the durability of the surfaces which are brought into contact. The application of the air vessel on a small scale may be seen in the common fire engine; but its grandest applications are in water works, where, with its assistance, a steam engine, occupying but one small building, may entirely supersede the necessity of raising water into elevated reservoirs for the supplying extensive districts with water. It is quite astonishing to reflect on the results which are brought about by the simplest applications of the laws of nature; the water works of London are among the most wonderful monuments of human genius and ingenuity.

Another striking illustration of the preceding laws of elastic fluids, is that of the application of *high pressure steam* as a moving power. It is well known that water at the temperature of 212° passes into an invisible vapour, under the ordinary pressure of the atmosphere (Art. 96); but when the temperature is much higher than this, the steam has an elastic force which the strongest vessels cannot resist. For all temperatures higher than 212° it is called high pressure steam, that is, its elastic force is greater than the elastic force of the atmosphere in its natural state, and when this invisible highly elastic fluid is applied after the manner which modern science has devised, it leads to results which it would take volumes to detail, and which will occupy the energies of generations to come to bring to perfection.

91. *Dalton's Laws.*—There are some facts connected with elastic fluids so remarkable and curious that they deserve the attentive consideration of every one; hitherto, however, they have not been generally laid before the student of physics. They relate to the mixture of gases with each other, and their diffusion, in defiance of the laws of gravity. The phenomena are briefly as follows; let any two vessels be taken, the one containing hydrogen, and the other carbonic acid gas, and let the hydrogen, which is an extremely light gas, be set above the other, which is an extremely heavy one, and a communication opened between them. Then on the gases being examined after a short

interval, carbonic acid gas will be found in the upper, and hydrogen in the lower vessel, and there will be a complete mixture, or, diffusion through each other. Again, if three or more vessels be set one above the other, each containing a different gas, the same diffusion will take place; there will be a perfect mixture in all the vessels; the gases, whatever be their number, will be equally diffused through each other, so that any portion of any one vessel will contain a portion of all the gases. Again, if a gas be contained in a cracked or porous vessel, the gas will gradually diffuse itself into the air, and the air into the gas, each passing through the cracks or pores at the same time, but in opposite directions.

The consideration of these and many similar phenomena, led Dalton to infer that the particles of one gas, though highly repulsive to each other, exert no repulsive action on the particles of another gas. Thus, one gas is as a vacuum to every other, the particles of one permeate freely the particles of another, without any obstruction except the mechanical action which they may experience from impinging on each other. Thus one gas travels through the interstices of the other, just as a stream of water permeates a sand bed, or air permeates a porous substance, without any active opposition; and though, during the diffusion, the inertia of the particles of another gas may sometimes cause some retardation of the motion, yet when the mixture is complete, or the gases are in a state of rest, the particles act only on those of their own kind.

The evidence for the truth of this theory is of the presumptive kind, and derives its strength from the beautiful explanation which it furnishes of the known phenomena. Any other hypothesis, affording as good an explanation, would be equally entitled to be received as true. But in default of this, if the simplicity of an hypothesis which furnishes a complete explanation of many phenomena, otherwise inexplicable, be evidence of the truth of a physical theory, then has this of Dalton strong claims, if not on our belief, at least on our attentive consideration. The difficulty of all other explanations arises from the fact, that the phenomena take place in defiance of the known laws of gravity. Carbonic acid gas, which is twenty-two times heavier than hydrogen, remains in equilibrium with this and all other gases, in a state of perfect admixture. But there is one phenomenon which affords direct evidence of the non-action of the particles of one elastic fluid on the particles of the other. If a mixture of alcohol and water be placed under a partially exhausted receiver, the evaporation both of the alcohol and water will proceed rapidly, and only be suspended when the space above becomes charged with vapour, the elastic force of which puts a stop to the formation of any fresh vapour. If now a small quantity of lime be put under the receiver in a cup, the vapour of water combining with this will leave a space for the formation of fresh vapour; in this way may all the water be drawn off, and what is left will be pure alcohol. Thus it appears that the action of the watery vapour alone checks the evaporation of water, the action of the alcohol vapour alone checks the evaporation of the alcohol; withdraw either, and the evaporation proceeds. Thus the action of the particles of the two fluids appears to be entirely independent; each vapour acts only on its own fluid, without any connexion with the particles of the other. This simple experiment alone gives a strong presumption in favour of Dalton's Law.*

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* See *Principles of Hydrostatics*, Arts. 74—77, and *Memoirs of Manchester Society*, Vol. v.

SECTION IV.

ON THE ATMOSPHERE—ITS WEIGHT—EFFECTS—THEORY OF WINDS—LIMITS—CONSTITUTION OF ATMOSPHERE.

92. It would be quite superfluous to attempt any proof of the existence of the invisible medium in which we live and breathe ; though it does not ordinarily affect our senses as immediately as the solid and liquid matter by which we are surrounded, yet its agency and existence are indicated every where. There are clouds in all climates and tempests in all seas ; hence the whole surface of the globe is encompassed by this airy envelope. It forms every where a layer of vast thickness ; for in all countries, on the tops of the highest mountains, as well as on the plains, we see the clouds carried along by the wind, and above these clouds we behold the deep colour of the vault of heaven, shewing the height of the atmosphere, just as the colour of the ocean shews the depth of the water. Were it not for the air the heaven would be dark and colourless ; it would appear like a black vault, in which the stars would shine with the same brilliancy by day as they do by night. This mighty mass of fluid, which is expanded over the whole globe, and of which the successive layers extend far higher than the highest mountains, is summed up in the term atmosphere. Its constitution is chemically the same at all altitudes, places, and periods, and consists of oxygen and nitrogen, with small quantities of other gases, respecting which however we shall add more hereafter. Besides the molecular force to which it owes its gaseous character, it is subject to gravity ; hence it is brought at once under the laws of fluid equilibrium.

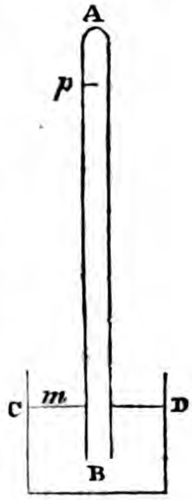
93. *Pressure of the Atmosphere.*—The atmosphere being a fluid acted on by gravity, we must have the same propo-

sitions respecting its pressure and weight as for a liquid. Hence the pressure is proportional to the depth; but it must be remembered, that we at the surface of the earth are at the bottom of the fluid in question; hence the pressure or weight of the superincumbent column will be greater at the surface of the earth than at any higher levels, and will diminish regularly as we ascend. The weight of the atmosphere, which follows so immediately from known laws, was not established till the year 1640, by Galileo; this discovery being followed out by his pupil Torricelli, was applied to account for the ascent of water in the common suction pump; and in the hands of Pascal, was traced out in all its consequences. The instrument by which the weight of the atmospheric column is measured is termed a Barometer. From this, with the assistance of the air-pump, the most distinct and complete proof of the weight of this invisible medium may be derived. The barometer, in its simplest form, consists of a small glass tube, of about 32 inches in length, hermetically closed at one end; the tube being filled with mercury, and a finger placed over the open end to prevent the escape of the mercury, it is inverted over a vessel of mercury, termed the cistern or basin; the finger then being removed, there is free communication betwixt the mercury in the tube and the mercury in the basin, and the former will sink down a little, and stand at a height varying from 28 to 31 inches above the mercury in the basin. The inner diameter of the tube must not be less than one-eighth of an inch, and the mercury must be dry and pure. When a barometer tube has been well filled, the space at the top is the most perfect vacuum with which we are acquainted.

The column of mercury in the tube being thus sustained at a considerable height above the mercury in the basin, contrary to the established law of all fluids in equilibrium standing at the same level, gave rise to the invention of most curious hypotheses for its explanation. When the tube is less than about 29 inches no vacant space is left at the top, the whole tube remains full. This was referred to the ancient physical dogma of nature's horror of a vacuum; but when it appeared from these longer tubes that there was a vacant space, and that this was largest in the taller tubes, it was decided that nature's horror had certain limits, and could be overcome by about 29 inches of mercury, and that then she lets down the column by a sort of invisible chain, one end whereof is attached to the upper part of the tube, and the other to the mercury. These hypotheses, however, are now but matters of very interesting and instructive history.

To shew that the column of the atmosphere pressing on the surface of the mercury in the basin is the real cause of this suspension, let the barometer be placed under the receiver of an air-pump. It will be seen that the column of mercury sinks at every stroke of the pump, and if the air could be entirely exhausted, so that there should be no pressure exerted on the surface of the mercury in the basin, the surfaces of the mercury in the tube and in the basin would coincide. When the air is admitted again into the receiver the column rises to its original height.

The true cause then being discovered of this sustained column, we may make use of this column to determine the weight of the atmosphere.



Let A B be the tube inverted over mercury whose surface is C D, as we have just explained; and let *p* be the upper surface of the mercury: then *p m* is the sustained column. Now this column will transmit to every portion of the surface C D a pressure equal to its weight. Suppose the diameter of this column to be one-eighth of an inch, then every equal portion of the surface C D will sustain an upward pressure equal to that which the column exerts at *m*, and this must be counterbalanced by the downward pressure of the atmosphere; that is, by the weight of a column of the atmosphere, which is one-eighth of an inch in diameter. Thus there exists an equality between the weights of a column of mercury and of the atmosphere; hence, knowing one we know the other; we know the weight of the column of mercury, and therefore we know the pressure which the atmosphere exerts on any given portion of the surface, which is equal to the section of this column.

94. *Levelling by the Barometer.*—We have already seen several instances of levelling by means of the common, and spirit level (Art. 75), that is, methods of determining a series of points on the same level; but the preceding principles furnish us with direct means of ascertaining the elevation of levels; that is, the relative distance of places above or below some grand level, as the level of the sea (Art. 73), to which all places are referred. This is effected by means of a barometer, and though we cannot here exhibit the theoretical formula by which the question must be solved, the principle of the method may be explained in a few words. The pressure of the atmosphere at any point is the weight of the superincumbent column; this must therefore be less at higher points than at lower. Suppose now that the barometer at the level of the sea stands at 30 inches; at the top of a mountain it will stand at a less height, since the column of the superincumbent atmosphere is less; at the bottom of a mine it will stand a little higher, since the superincumbent column is greater. There exists then an accurate law between a change of level and the change in the height of the barometer, and the latter being observed, the former can be calculated by the assistance of theory.*

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* For the accurate equations and the various corrections requisite in this most beautiful problem, I must refer the mathematical reader to my *Theory of Fluids*, Arts. 82—84.

95. *Height of homogeneous Atmosphere.*—The pressure at any point being proportional to the depth (Art. 76), and the air being an elastic fluid in which the density varies as the pressure, it follows that the air must diminish in density, as we ascend. Were the atmosphere of uniform density its height as well as its weight could be accurately determined; but this not being the case, its height can only be calculated on some hypothetical law of its density; as for instance, we may proceed to determine what would be its height supposing that the density throughout were the same as the density at the surface of the earth. The method of effecting this is as follows; we know the height of the column of mercury which is in equilibrium with the atmospheric column; we know also the density of the mercury and of the air; the fourth quantity, which is the height of the column of air, may be at once calculated from the other three; the result gives about five miles. So we may consider that the effects due to the pressure alone of the atmosphere, are the same as if the atmosphere were of the same density as at the earth's surface, and about five miles high.

96. *Weight and Effects of Atmosphere.*—Not only does the density of the atmosphere diminish continuously as we ascend, according to a known and constant law, but it is also subject to incessant variations from other causes; hence the pressure of the atmosphere on a given portion of surface is subject to corresponding variations. These are, however, but small, and will not prevent us from obtaining a mean value which may be considered as the true one. The process by which this is effected is most simple. We have seen that the weight of a column of the atmosphere, one-eighth of an inch in diameter, may be determined from the weight of a similar column of mercury. The same reasoning would apply to columns of any size; suppose that the columns are square, and an inch each way, that is, that the section of each is a square inch. This then will give the pressure on a square inch of surface. Now the mean

height of the barometer in this country is about 30 inches; the atmospheric column then which is in equilibrium with this will press on a square inch of surface with a weight equal to that of a quantity of mercury 30 inches high, and one inch square, that is, equal to 30 cubic inches of mercury. A cubic inch of mercury weighs 7·85 ounces, therefore 30 cubic inches weigh 7·85 × 30, or 235·5 ounces, which is 14·9 pounds. The pressure of the atmosphere may therefore be taken at 15 lbs. on the square inch.

Thus, when we consider the number of square inches which the surface of the human body presents, we may readily believe the assertion that at every instant we are pressed with a weight little short of 30,000 pounds. How is it then that we are not sensible of this enormous force? evidently because of the equilibrium which subsists on every side. And this equilibrium may be referred to two laws of physics, the one of the equal transmission of fluid pressure (Art. 68), the other that the elastic force of air increases with the density, or as the space which contains it is diminished (Art. 89). So long as there is perfect equilibrium in the external air its pressure acts so equally on all sides that we are not sensible of its existence, but we move all our limbs as freely as in an absolute vacuum; and this enormous pressure from without inwards, is balanced by the elastic force of the air within us, pressing from within outwards. Thus the human body may be considered as a vessel which has its closed parts equally pressed both on the inside and the outside, and in which, at the open parts, there is equilibrium between the internal and external air; and we may consider the human frame as a collection of open and close vessels, all of which are 'packed in fluids.'* But let us consider what takes place when this external pressure is increased or diminished in any degree. Suppose it to be increased, then the apparent bulk of the body will be slightly diminished, all the air in

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* Paley's *Natural Theology*.

the interior will consequently be compelled to occupy a less space, its elastic force will therefore be increased: thus will there be perfect equilibrium between the external and internal pressures, so that we are insensible of the changes and adaptations which have been going on. Nor are these changes trifling or inconsiderable; they will frequently be very great, as when the body is immersed to any depth below water; if a person descend 16 feet, the pressure on the surface is increased one-half, and yet no diver was ever sensible of this, and in the cases where they descend to many fathoms the pressure may be multiplied many times; every 32 feet of descent is equivalent to compressing the body by another atmosphere, and yet not one of the many millions of delicate nerves which envelope the body was ever injured by it. All which surprising phenomena are at once resolved by the consideration, that in virtue of the laws of fluids, the external and internal pressures will neutralize each other, whatever be the weight of the superincumbent mass.

A diminution of pressure will be attended with a corresponding adaptation on which it is unnecessary to dwell. But it will be interesting to consider for an instant the effects produced by preventing the possibility of this adaptation of internal forces, as by removing a portion of the external air. The operation of *cupping* presents an admirable illustration of the effects that would be produced. Here, when the warm air in the interior of the cupping glass has cooled to the natural temperature of the external air, it is of much less elastic force than the external air, and consequently it cannot balance the internal pressure which was before in equilibrium with the external air; the internal pressures not being counterbalanced, cause the vessels of the body to be distended and swell out.

The pressure of the atmosphere determines the boiling point of water, as we shall see hereafter; when the air is removed, water presents the usual phenomena of boiling at very low temperatures. The ordinary pressure of the atmosphere and the ordinary boiling point are then subject to like variations, but these being small, no errors of any importance result from them.

97. *Inverted Vessels.*—The suspension of water in an inverted vessel is owing to the pressure of the atmosphere. If a tube closed at one end, and of small diameter, be filled with water and inverted, the fluid will remain suspended; and if means be taken to insure the stability of the surface, that is, to prevent the particles from being shaken out of their places, a vessel of any diameter may be inverted. Thus, for instance, if a tumbler be filled with water, and a piece of paper be laid on the surface of the water, the vessel may be inverted, and the atmospheric pressure on the under surface of the paper will prevent the water from running out. The paper is merely a means by which steadiness may be given to the particles at the surface of the fluid. A tumbler so inverted may be set down on a table, and the piece of paper drawn away; the tumbler cannot be raised up, without spilling all the water.

The *siphon* is an instrument in very general use, and whose action may be at once explained by the preceding principles. The water which is sustained in the two legs has a tendency to separate at the upper part, one column running out by each orifice. But this cannot take place without a partial vacuum being formed at the top, and this will be prevented by the atmospheric pressure, unless the columns be more than 32 feet, which is never the case in the siphon: one of these pressures acts directly at the orifice of the longer leg, and the other is transmitted through the surface of the fluid. Now one column is longer than the other, both legs being full, and the longer column being the heavier will draw the other in its direction. This motion will go on continuously, and the siphon will be kept full by the pressure of the air on the surface of the water in the vessel from which it is drawn off. Were the tube not to be kept constantly full there would be a separation at some point which the atmospheric pressure is sufficient to prevent. Thus the motion of a fluid through the siphon is precisely similar to the motion of a smooth chain hanging over a point. If the two parts of the chain are equal the chain remains at rest, but if one portion be longer than the other it moves in the direction of the longer portion. Fresh links, so to speak, are added continuously to this fluid chain by the atmospheric pressure on the surface of the fluid, so that the chain being continuous, the motion is continuous also, and does not cease till one portion of the chain becomes equal to the other; thus the water continues to run through the siphon until the level of the water in the basin coincides with the level of the orifice through which the fluid is discharged.

98. *Atmospheric Strata.*—The mathematical conditions of equilibrium of a fluid mass, such as the atmosphere is known to be, suggest some important considerations respecting the strata of the atmosphere. The density at any point is proportional to the pressure by the known laws of elastic fluids; hence the density of the atmosphere diminishes gradually from the surface of the earth upwards. The atmosphere, as we shall see presently, must have a limit, and consequently, a bounding surface, and the form of this surface will be nearly spherical; that is, it will be parallel to the surface of the ocean; both the atmosphere and the ocean are seas of fluid matter, and subject to the same forces of gravity and rotation. The bounding surface will therefore be a level surface, and every surface similar to this, or every other level, must, if the atmosphere is in equilibrium, be subject to the following condition: 'That the pressure, the density, and the temperature, is the same throughout;'* that is, whatever two or more points of the same level we choose, the pressures on any equal portions must be the same, and consequently, the

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* *Theory of Fluids*, Arts. 17—20.

densities the same; also they must be of the same temperature. This being the case, the atmosphere will be at rest, and will be composed of concentric level strata, whose densities differ from each other by insensible gradations. These considerations of homogeneous level strata will be found of very great importance in the subject of the refraction of light.

99. *Theory of Winds.*—Simple as the preceding condition is, it evidently cannot be fulfilled in the ocean of the atmosphere; an universal calm is inconceivable in a fluid possessing such mobility and elasticity, since a disturbance at a single point will set the whole in motion. But the alternate presence and absence of the sun is the cause to which the disturbances of the atmosphere are to be attributed; this may probably ultimately be considered as the sole cause; it is certainly a very principal one. The condition of equilibrium expresses that the temperature must be uniform in the same level, or, in other words, it must be every where the same at the same height above the earth's surface. There are many causes which conspire to prevent this uniformity of temperature. The quantity of heat derived from the sun is very various during the twenty-four hours. But besides this, the variations in temperature, arising from local causes, are amply sufficient to disturb the uniformity which is requisite for absolute rest.

The disturbances, however, which must principally be considered, are those due to the temperature for different latitudes. The climates of different parts of the earth's surface are, unquestionably, owing in a great measure to their position with respect to the sun. At the equator, the sun is during all seasons nearly vertical, and any given portion of the surface receives at all times a much greater quantity of heat than an equal portion near the poles; for the passage of the rays of light and heat in a vertical direction is much less interrupted than in an oblique direction. It is owing to the heat lost in consequence of the oblique incidence of the sun's rays that the inhabitants of our latitudes receive so much less heat in winter than in summer, although the earth is much nearer the sun at the former than at the latter period. There is a continuous diminution in the mean temperature as we advance from the equator towards either pole; this may be interrupted at particular places, owing to local causes, but the general law is such as we have stated. The mean temperature of the equator is about 84° F. The temperature of our latitude is exceedingly variable; the mean in January being 36° F., in July and August 61° F., and in December 39° F.; the mean temperature for the whole year is about 50° F. in London. From the observations of Scoresby, in high northern latitudes, it appears that the mean temperature for latitude 76° 45′, is about 18° F., and for latitude 78° about 16° F.: from these and other data the mean temperature of the North pole is supposed to be about 4° F. From these statements it will be at once seen that there must exist about the equatorial regions a belt of air of much higher temperature than exists in other latitudes. The effect of this increased temperature is a dilatation or increase in bulk; the mass so heated and dilated becomes specifically lighter than the surrounding air, rises up, and its place is supplied by colder air, which, becoming heated, is, in its turn, replaced by a fresh quantity. The ascent of the heated air causes a constant upward current, and the motion of the air, which replaces this, causes a constant current flowing in on each side from the poles towards the equator. The heated air having ascended, flows towards each pole. Thus we have two systems of currents, an upper and a lower current; whereof the upper current consists of the hot air, which having ascended from the equatorial regions, is travelling towards the poles, and the lower current is the cold air of higher latitudes, which is travelling towards the equator.

We may now endeavour to give some account of the *constant winds,* such as the trade winds, the monsoons, and other local or periodic winds, which follow some regular law. The upper current would, were there no other causes in operation, travel due north and south; that is, it would be a south wind in the northern, or our hemisphere, and a north wind in the southern hemisphere; but the lower current, on the contrary, would be a north wind in our hemisphere, and a south wind in the southern hemisphere. The directions of these currents are, however, modified by the motion of the rotation of the earth. The atmosphere revolves round with the earth, but since the particles of the air in the lower current are, as they move towards the equator, travelling successively over points of the earth which have a greater and greater linear velocity; the air does not acquire all at once the linear velocity which is due to the latitude to which it has descended, and the particles of the air appear consequently to oppose the motion of the earth, which is from west to east; thus, a north-east wind is created in our hemisphere, and a south-east in the southern hemisphere. These north-east winds are the regular trade winds, which are of such vast importance to mariners, since they furnish a constant wind within 30° on each side of the equator. At some points near the equator the winds will lose their regular easterly character, and will be as irregular as in our own latitude. The air having acquired the velocity of the earth in its approach to the equator will appear to be at rest, or to be simply a north and south wind. The regular trade winds, then, result from the fact that air, being rapidly transferred from higher to lower latitudes, does not acquire all at once the velocity which is due to the distance at which it is from the earth's centre.

The motion of the upper current will furnish us with an explanation of some other constant winds, which are known to exist. In the extra-tropical regions there frequently exists a south-westerly wind in the northern hemisphere, and a north-westerly wind in the southern hemisphere. These winds may be seen at once to arise from the combined motion of the earth and of the upper current. The upper current having the velocity in a westerly direction, which is due to the equatorial regions of the earth, moves faster than the air in those higher latitudes, towards which it is moving. As it descends to the earth, on parting with its heat, it does not lose all this velocity, but moves faster than the other air; and as this excess, or the relative velocity increases as the air approaches the surface of the earth, the current, by the time that it reaches the earth, having a decidedly westerly motion, appears as a strong south-west wind. In the southern hemisphere the wind arising from the combination of this excess of motion in the westerly direction with the northerly motion creates the north-west winds which are known to prevail in the extra-tropical regions of that hemisphere. The motion of this upper current is known from actual observation to be such as here stated. The top of the Peak of Teneriffe is swept by a wind whose direction is contrary to the trade wind which blows at its base. Heavy metallic dust, such as is projected from a volcano, is frequently carried many miles in a direction quite contrary to the wind which prevails at the top of the mountain. The island of St. Vincent is many miles to the west of Barbadoes, and both lie within the regular action of the trade winds. But during one eruption of a volcano in St. Vincent, the dust was carried in a dense cloud in a direction opposite to the trade-wind, and overhung and fell upon the island, and many miles out to sea to the eastern side of the island. In this case the dust was projected up through the lower current which moves in a north-easterly direction, into the upper current which moves in a south-westerly direction, and was carried along by it. This fact shews the immense rapidity of the westerly current, whence the fearful hurricanes, which so frequently devastate these tropical regions, may arise.

These south-westerly and north-westerly currents have been called *compensation* currents, from the way in which they assist in restoring and maintaining the rotatory motion of the earth. The continuous action of the trade-winds, opposed as they are to the direction of the earth's rotation, must to a certain, though only an infinitesimal extent, retard that motion, and this retardation might be expected to be sensible after a long lapse of years. But no such retardation has been detected, and yet the continuous action of these winds in a direction opposed to that of the earth's rotation is a certain fact; their action must then be compensated; and this is effected by the upper current, which has, on being diverted downwards, an excess of motion *in* the direction of the earth's rotation. The continuous action then of these winds would accelerate the motion of the earth, just as much as the continuous action of the trade-winds would retard that motion: but since both are in action they compensate each other's effects, and the rotation of the earth continues invariable. The preceding remarks furnish a striking illustration of what was previously stated (Arts. 25 and 33), that power is not created, but only converted, and that the amount of motion which exists in the world can neither be increased nor diminished.

There are periodical winds which blow, during particular seasons, in a constant direction, and which illustrate the preceding principles. The *monsoons*, which prevail between Madagascar and New Holland, blow as a north-wind during our summer, and a south-wind during our winter. The land and sea breezes are very well known; during the day a breeze frequently sets in from sea to land, and during the night from land to sea; the land being hotter than the sea during the day, and colder during the night. The effects of the hot sandy plains of Africa in changing the direction of the wind, and in causing the trades to lose their easterly character, is very well known; but we cannot dwell any longer upon these most interesting phenomena; they may in general be readily explained by the principles which have here been laid down.

100. *Limits of the Atmosphere.*—The atmosphere being supposed to be unlimited, would pervade all space, and accumulating about the sun, moon, and planets, would form around each an atmosphere analagous in its laws to our terrestrial atmosphere. But optical and astronomical observations render it certain that our atmosphere is confined to the earth. There is then a point beyond which no particle of the air we breathe exists; the bounding surface, or last stratum of the atmosphere, is the utmost limit at which the ponderable matter of our earth exists; at this point the void, in the sense just explained, commences.

Such being the case, we must explain the causes which fix this limit. The air diminishes in density as we ascend; the elastic force, that is, the repulsive power of the particles, diminishes. This repulsion, which compels the particles to separate from each other, and become diffused, causes them to recede from the centre of the earth, or in the direction opposed to gravity. There will then be some point at which the elasticity becomes so much diminished that the repulsive force is exactly equal to the force of gravity; at this point no further diffusion can take place, or a limit will be fixed to the atmosphere. One cause which will contribute much to a rapid diminution in the elastic force of the air is the extreme cold of the upper regions; so that this, combined with the diminished density, will bring about the limit which we are sure must exist at no great elevation.*

101. *Constitution of the Atmosphere.*—The actual composition of the atmosphere is generally regarded as belonging to Chemistry rather than to Physics. This, however,

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* The actual height of the atmosphere is not fully agreed upon; it may be stated however as less than 50 miles: about 45 is Wollaston's calculation.

arises from the view which is sometimes taken of the union of the different gases composing it. The old opinion of a chemical union is untenable, since it is not sufficient to account for all the phenomena, and recourse must be had to the theory of Dalton, which supposes a mere mechanical admixture according to the laws of the mixture of elastic fluids, which we have already explained (Art. 91). Pure atmospheric air consists of 20 or 21 parts of oxygen, and 80 or 79 of nitrogen, out of every 100 measures. These proportions are invariably preserved at all times, places, and heights, above the earth's surface. Several other substances are always present, as carbonic acid gas, aqueous vapour, &c., but they are small in amount. The question is, as to the state of combination in which these quantities exist so as to constitute our atmosphere. It is certain that the atmosphere possesses all the characteristics of a mechanical mixture, such as results from Dalton's law; hence, in the absence of all other sufficient explanations, we are bound at present to receive this, and reason upon it as, at least, if not a true, a possible and a probable theory. It appears that our atmosphere is a compound of several simple atmospheres; there is the oxygen atmosphere, the azote or nitrogen atmosphere, the carbonic acid gas atmosphere, the aqueous atmosphere, and, perhaps, several others. Each is in equilibrium with itself, and each can be withdrawn without disturbing the others. It is impossible, within our present limits, to insist on the applications of this theory, but enough has been said to shew what may, perhaps, be the true law of the constitution of the atmosphere.

SECTION V.

FLUIDS IN MOTION—VELOCITY OF EFFLUX—VENA CONTRACTA—ADJUTAGES—RESISTANCE OF FLUIDS—APPLICATIONS OF FLUID MOTION—MOTION OF RIVERS—WAVES—TIDES.

102. A portion of any fluid, left entirely to itself, would fall to the earth precisely according to the same laws as those which regulate the descent of a solid. Of this we have sufficient evidence in the fall of rain, or of any vessel containing fluid; and if any mass of air were suddenly deprived of all the surrounding air, it would fall to the earth, as if it were a mass of solid stone. Any liquid also will oscillate precisely according to the same laws as a solid: of this we have already had an instance in the bobs of pendulums which are generally mercurial, that is, small vessels filled with mercury; and if any liquid, as water, be contained in a bent tube, it will oscillate precisely according to the same laws as a solid, the duration of the oscillations in different tubes being as the square roots of the lengths of the tubes. These considerations are, however, of no great importance, except on account of the evidence which they afford of the universality of the action of gravity; it is still the same force acting every where, whose laws may be detected equally in the fall of a stone, and of a cataract; or in the more useful motions of the stream, or of the fluid issuing from the orifice of a vessel.

103. *Velocity of Efflux.*—When any liquid flows freely into the air, and has its surface retained at a constant height, the following proposition is very nearly true: 'The particles, as they pass the orifice, have the velocity which they would acquire by falling in vacuo, through a height equal to the height from which they have descended.'

Some important conclusions may be drawn from this, and compared with experiment.

1°. The velocity of efflux depending simply on the depth of the orifice, and not at all on the nature of the liquid, must be the same for all fluids; for all substances falling from the same height, in vacuo, acquire the same velocity. Thus, water and mercury will flow through orifices which are at the same depth below the surface of the fluid with the same velocity. The mercury, however, is acted on by a much greater pressure at the orifice than the water; for if the depth of the orifice be 32 feet below the surface, the water will be pressed only with the pressure of one atmosphere, but the mercury will be acted on by a pressure of more than thirteen atmospheres.

2°. 'In the same liquid the velocity of efflux will be as the square roots of the height from which it has descended.' For the velocity of all heavy bodies, falling freely, are as the square roots of the heights from which they have fallen. Thus, in a vessel 100 feet high, if two orifices be pierced, the one at the depth of one foot, and the other at the depth of 100 feet, the velocity of the liquid flowing out of the latter will be ten times greater than the velocity of the liquid from the former. If orifices be made at intermediate points, as at 4, 9, 16, &c., feet from the surface, there will issue 2, 3, 4, &c., times the quantity which issues from the depth of one foot. In all these cases there is a loss both in the quantity and velocity of the issuing fluid due to friction, which makes the determination of the exact amount of the issuing fluid both with reference to quantity and velocity a difficult question; but the preceding statements are independent of this retarding cause; we have merely stated that the amount and velocity will be double in one case what it is in another; the absolute amount is a quantity only to be decided by most careful experiments; this having been determined for one case, all other cases will be known by theory.

In considering the discharge from a given orifice, we must remember that the quantity of the fluid, and the velocity with which it issues forth, are doubled at the same time. When the velocity of a fluid is doubled, twice the quantity passes through the same orifice in one second; and when twice the quantity passes through the same orifice in one second, the velocity of the issuing fluid is doubled; this of course applies only to a fluid like water, which may be considered incompressible. Hence the preceding law is perfectly consistent with itself, since the real effects are exactly those which the change in the pressure at the orifice would lead us to expect. Should the upper surface of the fluid be subject to any pressure besides the ordinary atmospheric pressure, that is, should there be any appreciable difference between the pressure at the surface of the fluid, and of the air from without inwards, at the orifice, it will be equivalent to an increased height of fluid column, and may be allowed for accordingly. When water issues from a vessel into the air, the pressure of the atmosphere on its surface transmits a pressure through the fluid to the issuing portion at the orifice, which may be considered as exactly equal to the pressure which the atmosphere exerts directly at the orifice, to oppose the issuing fluid; hence, under ordinary circumstances, the laws of water issuing into the atmosphere will be the same as if the whole operation took place under an exhausted receiver, in a perfect vacuum. If now any pressure besides this be exerted on the surface, as if the vessel have a piston fitted to it, which is pressed down by a given weight, the additional pressure thus caused at the orifice produces the same effect in increasing the discharge as would be produced by an additional column of water of the same weight. Again, if the pressure on the surface be diminished in any manner, that is, be less than the pressure at the orifice, as, for instance, when free communication is cut off with the external air, the discharge will soon cease altogether. Hence, we may at once see the necessity of a cask being furnished with a vent peg, if any liquid is to be drawn from it; there must be a supply of air above the liquid in the cask, whose elastic force, together with the weight of a column of the liquid, must more than equal the external pressure of the atmosphere, or there can be no discharge; and this must generally be supplied by giving vent or admission to the external air at the top of the cask.

104. *Vena Contracta.*—When fluid issues from an orifice there is a remarkable contraction of the vein or stream, to which the Latin phrase, *vena contracta*, or contracted vein, has been applied. Suppose, for example, that water descends in a vertical stream from an orifice pierced in the bottom of a vessel, or in a parabolic jet from an orifice at the side; let this orifice be a circle of an inch diameter; then close by the vessel the issuing stream will be nearly an inch in diameter, but it will gradually contract, and at a small distance it will be considerably less, not more than $\frac{5}{8}$ths of an inch.* Thus the particles of the fluid converge to a section at a certain distance, from which it goes on in a constant permanent form. This convergence results from the different velocities at different parts of the issuing stream.† If all the particles passed the orifice with the same velocities, and in directions parallel to the axis of the issuing stream, there would be no contraction, because there would be nothing to make them deviate from the direct line of their motion. But the fluid descends in all directions towards the orifice, so that within a short distance of the orifice the particles form a sort of funnel, which extends through the orifice up to the commencement of the vena contracta; these converging particles in the interior of a fluid constitute what is termed the *gorge;* which is formed equally, whether the orifice be at the bottom, or at the side. Every one must have observed that a stream from any orifice is less at some distance than close to the vessel; but the particular shape of the issuing

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* See Rennie's *Report*, Brit. Assoc., 1834.

† *Theory of Fluids*, Art. 118.

stream, and of the vena contracta, will depend on the form of the orifice, and the distance at which the sections are taken. When the orifice is a circle, the section of the stream is always a circle; but when the orifice is a square, the sections at different distances have very various shapes. At a small distance from the orifice the angles disappear altogether, or are cut off and replaced by straight lines, so that the section is an octagon of four small equal sides, and four large equal sides; a little farther the section becomes nearly a regular octagon with the sides slightly curved; still farther it is a curvilinear four-sided figure, being concave towards the exterior. There are several other remarkable varieties in the form of the stream issuing from other orifices, but we cannot now dwell upon them; they all evidently arise from the particular converging directions which the fluid particles take just before entering the orifices.

In all theoretical estimates of the quantity of water discharged from a given orifice, the section of the vena contracta, or about $\frac{5}{8}$ths of the actual orifice, must be considered as the *effective* orifice, or that through which the discharge really takes place.

106. *Effects of Adjutages.*—The quantity of fluid discharged through a given orifice may be augmented very much by the application of a short pipe, termed an adjutage. These may be of very various shapes; suppose for instance a cylindrical one, and of the same diameter as the orifice, and placed vertically; then if this be once full of the fluid, the discharge through it will be much greater than through the simple orifice; but if this adjutage be not filled with the fluid before the discharge commences, the stream contracts as before, and passes through it without ever touching the sides; in this case then there is no effect produced on the discharge. But the adjutage which produces the greatest effect on the discharge is a conical one, consisting of a portion of two cones, united by their narrowest ends at the commencement

of the vena contracta. The one attached to the orifice is exactly the size of the issuing stream, as far as the commencement of the vena contracta, and the other diverges, but less rapidly than the preceding, so that it is longer, having the extreme section equal to the orifice. An adjutage of this kind is said to increase the discharge from 100 to 150. The effectiveness of these adjutages arises from the lengthening the descending column; the lower parts descending with a greater velocity than the upper, have a tendency to separate from them, and so leave a vacuum. This, however, is prevented, partly by the fluid being forced in more rapidly, and partly by the pressure from without inwards at the orifice.

106. *Resistance of Fluids.*—A body moved rapidly through a fluid experiences a resistance whose magnitude depends on the density of the fluid, and on the velocity of the motion. When a body moves at the ordinary rates through a thin fluid, like air, the resistance which it experiences is scarcely sensible; but when the velocity is great, as that of a cannon ball, the resistance causes considerable retardation. Again, when a body moves very slowly through water the resistance is very small, but when the rate of motion increases, as when a boat is drawn at two, three, or four miles an hour, the resistance becomes very great. The general law of the resistance of water is, that it increases as the square of the velocity, that is, the resistance on a boat, moving at the rate of two miles an hour, will be four times as great as on one moving at the rate of one mile; at three miles an hour it will be nine times as great, and so on. Some surfaces sustain less resistance than others, and the particular form of the surface of least resistance is a difficult and much disputed question. But, supposing this solved, there are other elements of equal, if not greater importance, namely, the shape of the stern and its distance from the prow, that is, the length of the vessel, and the shape of the intermediate parts. Our mathematical knowledge is not at present

competent to settle these questions, and practical men entertain very various and opposite opinions on many of them.

In treating of resistances to bodies moving in fluids, care must be taken to distinguish the cases of the resistance on a body wholly immersed, and on one, as a boat, only partially immersed. Again, a distinction must be made betwixt vessels moving on a wide expanse of water, as the sea, or a river, and on a canal, or any narrow confined channel. It is very well known that the usual law of resistances holds on canals up to a certain velocity, as four or five miles an hour, but that when boats are moved on *narrow* canals at rates of nine, twelve, or fourteen miles an hour, the law of the resistance seems entirely changed, and indeed almost suspended. The fact is certain, that two horses drag with ease, on the Paisley Canal, a passage boat with her complement of seventy-five or ninety passengers, at the rate of ten miles an hour, whereas it would kill them, or even double the number of horses, to drag the same boat along the same canal at the rate of six miles an hour. It would be much easier to draw the boat along the canal at the rate of fifteen miles than at the lower velocity of six miles an hour. The same facts have been proved and exhibited on other canals, but not so decidedly as on the Paisley Canal, because this is narrower than most others. The explanation of this phenomenon is not at first sight obvious; it is, however, connected with the motion of the wave which the boats generate. It appears from experiment, and theory also predicts the same result, that the boat rises during the motion; it appears also that the size of the canal and of the boat must have a particular proportion to each other.*

The resistance of the air to an extended surface is

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* For farther information on this most interesting subject we must refer the reader to Mr. Macneill's paper in the first volume of the *Transactions of the Institution of Civil Engineers.*

illustrated by the descent from great heights in a parachute. This, which is nothing more than a large umbrella, is so resisted by the air, that the weight of the attached individual is not sufficient to produce any acceleration of motion after the first few instants; the whole mass descends with a uniform steady motion. It is to the same resistance that birds owe their flight; the muscular effort of the wings produces an action by which they are sustained and impelled, and the tail, acting as a rudder, guides their motions.

107. *Applications of Fluid motion.*—The effect which a fluid in motion produces on a solid at rest is similar to that which would be produced by the impact of any solid body; motion ensues, or the solid body receives a shock whose force depends on the momentum of the fluid. A heavy wave, dashing against the side of a vessel, may force her from her moorings, and carry every obstacle before it. A wind, moving at the rate of six miles an hour is just perceptible; but at the rate of 80 or 100 miles it is a frightful hurricane, tearing up trees and houses. The violence of the hurricanes in tropical climates is sometimes such, that every dwelling and tree is levelled with the ground, and swept along the surface like stubble; yet all this is owing to the momentum of the invisible agent of whose existence, in a state of rest, we are scarcely sensible. We cannot here dwell upon the advantage which is taken of a stream in motion to turn a water-wheel; of the oblique action of the wind on the sails of a ship, or of a windmill, and of the numerous other ways in which man converts the powers already existing in nature to his own purposes (Art. 25).

The effects produced when the momentum of a solid body is suddenly destroyed, have been already (Art. 37) described; the sudden destruction of the velocity of a fluid is attended with precisely the same results. The action produced is inversely as the time during which the motion is being stopped. But the different circumstances under which solids and fluids are, with reference to the transmission of an action or pressure exerted at any point, gives rise to some important considerations. The action which is exerted on the sudden destruction of momentum in a fluid will be transmitted throughout the whole fluid (Art. 68). Suppose now that several pipes lead from a reservoir of water, and that one of these being open, the water flows through it with a certain velocity; let this water be suddenly stopped; the action produced by the sudden destruction of this momentum will be impressed throughout all the pipes and reservoir, on every portion of surface, which is equal to the section of the stream which was stopped; if then there is any weak place in any part of the system, the pipe will burst first at that point. Thus, the sudden stoppage of a main in the street may burst all the pipes for miles round.

This principle has been applied most beautifully to the raising of water to great heights, and the contrivance by which it is effected is termed the Hydraulic Ram. The mechanical parts of this contrivance are such as to allow a small descending stream of water to acquire a certain velocity; its motion is suddenly stopped; the action thus produced is made available for the raising of water to a great height. The motion of the stream having been stopped must commence again, and the contrivances by which this motion may be stopped, rendered available, and restored, are exceedingly simple and ingenious.*

108. ***Motion of Water in Channels.***—Nothing is more variable than the velocity with which water passes over the beds of streams and rivers. Every change in the inclination of the bed, every bend in the course of the channel, friction, and numerous other causes, interfere with the regular motion, diminish the velocity, and produce

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* *Principles of Hydrostatics*, Chap. x.

currents and eddies, of which no account can be given, without a most accurate acquaintance with all the local circumstances. Artificial water-courses which have a regular inclination, a straight direction, and uniform dimensions, may be treated with considerable accuracy, and the laws are very general and simple. On these, however, we cannot dwell. The velocity of a stream is more rapid at the surface, and decreases as we descend, so that the water must be considered as consisting of different strata, moving with different velocities. Again, the water at the sides cannot have the same velocity as the water in the middle, for the friction against the banks, and the mechanical obstacles which the inequalities and bendings oppose to the motion of the stream, must frequently almost entirely destroy the motion near the sides. Hence we see the reason of the rapidity of the middle of the stream, and of the apparent tranquillity of the water at the sides. The same causes operate in water pipes, the motion is retarded at every instant by the friction, and by every bend and inequality in the pipe; the surfaces are here, however, so regular, that the retardation due to these causes may be calculated, and engineers can determine with great accuracy the quantity of water which will be supplied in a given time by a particular series of pipes. When a river bends in a considerable degree, the velocity is generally observed to be greater at its concave than at its convex side; this is probably owing to the accumulation of water at that point from the centrifugal force of the particles.

Not only have the strata of the water near the surface different velocities from those near the bottom; they may have also different directions; the water at the surface may be moving in one direction, and at the bottom in exactly the opposite. Of this we have some remarkable examples in rivers which communicate with the sea, and whose water is salt or fresh, at some points, according to the state of the tide. In these cases there appears, when the tide is running in from the sea, to be for many miles an undercurrent of salt water running upwards, while the upper current of fresh water is running downwards. This has been observed and carefully examined at the mouth of the Dee in Scotland, and in the Thames between London and Woolwich. The saltness of the lower strata is said to be generally sensible near Woolwich; thus, from Woolwich downwards, the Thames, instead of flowing over its own muddy bottom, is flowing over a stream of salt water. There will be an intermediate strata in which the fresh and salt water are intermixed, which may be absolutely at rest; and the depth of this, as well as the degree of mixture, will evidently depend on local circumstances. This singular phenomenon is the consequence of the different specific gravities of the fluids; the fresh water floats on the salt water like oil upon water, or warm water upon cold. There is another consequence worth remarking which follows from these statements, namely, that the fresh water must be elevated in a mass by the under stream of salt water at every rise of the tide. We may here remark the provision which is thus supplied for a thorough interchange of water; the unwholesome water of a city thus continues to flow away long after the under current has begun to ascend. Were this otherwise much unwholesome water would be returned by the ascending stream, which is now carried off at once to the ocean. An illustration of the preceding remarks is afforded by the freshness of the salt water at the surface of the ocean for many miles in the region of the mouths of large rivers. The fresh water spreads itself as a thin film over an immense extent of surface, and is finally mixed with the salt water, or raised by evaporation, to be again dissipated over the earth.

109. *Waves.*—Closely connected with the subject of the preceding articles is that of the generation and motion of waves, or of the propagation of an undulation through a mass of fluid; and the motion of the water which is the

consequence of this, as exhibited in the tides at different places. We shall endeavour briefly to point out the laws which appear to obtain in these phenomena.

A wave, as it is generally observed, is an elevated portion of water travelling successively along the general surface. Thus, if but a single wave is propagated through the fluid, the whole surface is successively, in order of time, in a similar state of elevation or depression; and when, as is generally the case, there are an infinite number of waves, the whole surface is undulated, that is, covered with elevations and depressions.

A very common misconception prevails respecting the motion of waves. The wave is seen to advance towards the shore, and the water appears to be moving in the same direction. This is not however the case; the only necessary motion of the water is in the vertical direction; the water may be perfectly at rest, excepting this vertical ascent or descent, or it may be moving in any direction coincident with, or opposed to, the direction in which the wave is moving, without at all affecting the motion of the wave. That this is really the case; and that there is generally no sensible motion of the water in the horizontal direction, or that in which the wave is advancing, will be at once apparent from the following considerations. A ship rides over thousands of waves in a single day, and may remain in the same place, or float gently onward with the wind or current; a chip of wood, or any light substance will lie for hours at a short distance from shore while the waves are rolling in incessantly. Thus the motion of the wave has no tendency to impress any motion of translation on a body floating at the surface of the water; and consequently the water itself has no motion in the direction in which the wave is going. The water has only a vertical motion; it rises and sinks alternately. The wave is an advancing form; and the surface of the water taking these forms in succession, appears to the eye to move in a particular direction. A proper conception of what is meant by the motion and velocity of a wave is of the greatest importance, and we shall endeavour to illustrate it by a simple case of the waves which every one must have repeatedly observed. If a stone, or any small body, be dropped into still water of sufficient depth, the surface will be disturbed, and there is an elevated ridge or wave, then a second, and a third, and so on; and a wave travels successively throughout the whole surface of the fluid. If two or more bodies be dropped in at the same instant each becomes the centre of undulations, which are equally concentric, and which will meet and cross each other without any change of direction, or without interfering with each other's progress. The waves are propagated onwards, the elevation of each being less than of the preceding one, until, if the surface be of sufficient extent, they finally cease to be visible. As any portion of a wave meets an obstacle, opposing its farther advance, the point of contact becomes a fresh centre, whence semicircular waves, or a new series of undulations, are propagated as before. These reflected waves cross the waves moving in the opposite direction just as the waves which occur on dropping two or more stones near each other into the water. The rate at which these elevated concentric ridges, or disturbances, pass across the surface of the water is called the velocity of the wave. Thus, if the edge of the water be ten feet from the point at which the stone is dropped in, and a wave strikes this edge, two seconds after the stone was dropped in, the velocity of that wave is five feet per second.

The action of the wind upon the surface of the water is the principal cause of the waves which exist, and the height of the wave depends in a great measure on the depth of the water in which it is produced. In a sheet of water of two or three hundred feet across, and only three or four feet deep, the waves will rarely have a greater height than two or three inches; whereas, if the same water had a depth of twenty or thirty feet, the waves might be raised one or two feet. The waves of the Mediterranean are much less both in height and breadth than the waves of the ocean. This will be partially owing to the small extent of the former, as compared with the latter, but it is principally owing to the difference of depth. The waves of the ocean frequently acquire a magnitude sufficient to hide from each other's view two vessels of the largest size when only at a small distance apart. When the theory of this subject is brought to a greater degree of perfection than it at present possesses we shall probably be able to sound the depths of the Atlantic by means of the observed height of its waves.

The velocity of the wave, or the rate at which this advancing form travels, is a most interesting inquiry, and one on which we must make a few observations. Both theory and observation seem to shew that the velocity of the wave depends both on its elevation and on its form. So that the same wave will travel at different rates at different parts of its course. It is this change of form, as connected with the consequent variation in the velocity of propagation, which introduces some of the greatest difficulties into this subject. The important practical question is respecting the rate at which the *tide*-wave travels. The tides in our seas are derivate tides; that is, tides derived from the great elevation and depression which takes place twice every day in the equatorial regions of the vast Atlantic. This elevation causes our tides. Now, from the researches of Mr. Whewell,* it appears probable that the tide-wave travels at the rate of 700 miles an hour in the Atlantic Ocean. The wave travels from the south point of Ireland to the north point of Scotland, at the rate of about 180 miles an hour. The rate on the eastern coast of England is much less; from Buchanness to Sunderland at about 60 miles an

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* *Philosophical Transactions*, 1833.

hour, from Scarborough to Cromer at about 35 miles an hour; from the North Foreland to London at about 30 miles, and from London to Richmond at about 13 miles. The effect of a constrained channel and a diminished depth is shewn very remarkably by the observations in the Thames.

The results recorded in the memoir just quoted shew most clearly that the velocity of the wave diminishes as we ascend the river. The importance of the subject of the tides to us, as a naval power and a commercial nation, ought to have procured for it a much greater share of attention than they have met with. Within the last few years Messrs. Whewell and Lubbock have succeeded in drawing the attention of the world to this inquiry, and as many individuals may have the opportunity and inclination to assist in this department, we shall close this subject with the directions which are given by Mr. Whewell for the investigation of the laws of these most interesting and important phenomena.

110. *Tide Observations.*—These observations may be either continued observations at the same place, or comparative observations at different places.

I. The use of continued observations of Tides at the same place is to determine the dependence of the time, height, and other circumstances, of high and low water upon the places and distances of the sun and moon. Particular tides are affected by considerable anomalies and uncertainties, but in the *averages* of a long series of observations, general rules, consistent with theory, prevail with great constancy. The object of observation should be to verify these rules and to determine the constant quantities which enter into them. For this purpose we have to attend to

1°. The establishment of the place. The interval at which high water follows the moon's meridian passage or transit at a given place varies from day to day (being affected by the Semimenstrual Inequality). The vulgar establishment is the duration of this interval on the day of new or full moon. The *corrected* establishment is the *mean* duration of this interval.

2°. The law of semimenstrual inequality. In the mean state of the parallaxes and declinations of the sun and moon, the interval at which high water follows the moon's meridian passage or transit is affected by an inequality depending on the Moon's distance from the sun, and going through all its changes in half a lunation; this is the *semimenstrual inequality*. This inequality is, theoretically, the same at all places; and therefore in simple tides, at every place, the law and amount of the inequality of the interval of tide and moon's transit during a half lunation is the same. It is desirable to verify this rule; and if exceptions occur, to examine the circumstances of them.

3°. The age of the tide. The *circumstances* of each tide do not correspond to the places of the sun and moon at the time of that tide, but at a time one, two, or three days earlier; this distance of time is called the *age of the tide*. Two such circumstances may be especially noted: the spring tide, or *highest* high water, is not on the half-day of new or full moon, but at a certain tide on some later half-day: also, the interval of tide and moon's transit has not its *mean* value on the half-day of new or full moon, but for a certain tide at some later half-day. The distance of time from the new or full moon to the time when the interval of tide and moon's transit has its mean value, is the *age of the tide*.

4°. The diurnal difference of the tides. It appears from theory, that in simple tides there should be a difference in the height of the two high waters on the same day: in such cases, during one part of the year the morning tide, during another part the evening tide is the higher. It is desirable to verify this *diurnal difference*, and to determine its amount at particular places.

5°. The peculiarities of tides at particular places. At many places the tides are compounded of two simple tides which arrive by different paths; this composition may give rise to new circumstances. For instance, the diurnal difference may be obliterated; or it may be accumulated so as to produce only one tide in twenty-four hours.

6°. The effect of the changes of parallax and declination of the sun and moon. These changes may affect both the height and the time of high water. Their effect can only be detected by a considerable series of good observations, carefully discussed.

Continued observations at the same place should give the time (in hours and minutes, by a well-regulated watch) of high water, and the height of high and low water every day, or, if it may be, every tide. The height of the water ought to be observed with regard to fixed marks, and measured on a vertical scale, in a place as free from waves as is possible. The uncertainty occasioned by waves may be avoided by fixing in the water an upright tube (of wood or tin, for instance), the bottom or sides of the tube being perforated, so that a float carrying an upright measuring rod, may rise and fall in the tube with the rise and fall of the tide. By means of an index fixed to the tube, it may be seen when the measuring rod is at the highest and lowest, and the heights may be measured. In this way the time and height of high and low water may be observed. The measuring rod may be so constructed that it shall leave a moveable index at the highest and lowest points. It may also be so constructed that it shall record the height of the water at any time upon the surface (and along the length) of a cylinder, which is made to turn uniformly on its axis by clock-work: and by such an apparatus we may learn the height of the tide at any time, and at what time the tide has been highest.*

The time of high water (according to *mean time*, reckoned

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* Machines of this kind are particularly described in the *Philosophical Transactions*, 1831, and in the *Nautical Magazine*, for October, 1832.

by a good watch regulated for the place) is to be compared with the time of the preceding transit of the moon, whether above or below the horizon. The time of the moon's south or upper transit for Greenwich is given in the Nautical and other Almanacks; the time of the north or lower transit may be found by taking the mean of the preceding and succeeding southing. The time of the transit at other places may be obtained with sufficient accuracy by adding 2^m to the time of transit for every one hour of west longitude, or by deducting this for east longitude. The intervals of the time between high water and the next preceding transit of the moon are the establishment of the place, affected by the semimenstrual inequality.

II. The use of comparative observations of tides at different places is to determine the form and progress of the *tide-wave,* or elevation of the waters, which, by its arrival at each place, brings high water to that place. If a line be drawn at any time through all the points of the ocean at which it is high water at that time, this is called *a cotidal line.* And if, on the day of new or full moon, we draw such lines corresponding to each hour, we make a *map of cotidal lines.* Such a map exhibits the progress of the *tide-wave,* and in order to draw cotidal lines, it is necessary to know the absolute or comparative establishments of the places through which the lines are to be drawn. The establishment of any place may be determined from observations of the absolute time of high water, according to the preceding rules. A few observations will give a determination, which will be of greater accuracy according to the number of observations. If the observations be not made on the day of new or full moon, they must be corrected for the difference of the semimenstrual inequality on the day of new or full moon and on the day of observation. But the arrangement of the cotidal lines may often be better discovered by comparative observations of neighbouring places than by independent determinations of the establishments at the separate places. If the tide in the same half day be observed at several such places, and the observations compared, it will be seen by how much each succeeding place has its tide later than preceding places; and the motion of the tide-wave will be thus known. And these differences of times will be much less affected by accidental causes and by errors of observation than the absolute times. In surveying any coast it would be desirable to station a tide-observer at some convenient place, in order to obtain the corrected establishment, the law of the semimenstrual inequality, the age of the tide, the diurnal inequality of height, and any other peculiar circumstances. And it would be desirable also to make numerous observations of the tides at other points of the coast, and to compare each of these with the *corresponding tide* as recorded by the stationary observer. A small number of sets of observations so made would give us much more exact knowledge concerning the motion of the tide-wave than we at present possess. They would also enable us to determine whether the motion of the tide-wave is different at different periods of a lunation; and, if so, how it differs.

The motion of the tide-wave must be carefully distinguished from the *tide-currents* or *stream of tide*. The velocity and direction of the tide-wave have no necessary connexion with the velocity and direction of the *stream* of flood. The transfer of the tide-wave (and of any wave) is the transfer of the *form* which bounds the fluid from one position to another, and may take place by a number of different modes of flowing of the *fluid itself*. It does not imply that the fluid moves in the direction in which the wave moves. Perhaps the reader may be assisted in his conception of this by observing that when a long pendant is flying at a mast-head, we see curves like waves running along from the fast to the loose end of the pendant, though there can be no motion of the cloth itself in that direction. In many situations the rising and falling of the tide is accompanied by a stream running *alternately* in opposite directions. In these cases it will not happen in general that the stream will run in one direction while the water is rising, and in the opposite direction while the water is falling. The time of high water will not generally coincide with the *time of slack water*. In bays, and near the shore, the time of high water will generally coincide with the time of slack water. But in a channel open at both ends the time of slack water is generally after the time of high water. The stream of flood continues running for one, two, or three hours after high water, and then turns; and the stream of ebb runs for one, two, or three hours after low water.

In other cases, for instance where different channels branch off from each other, or meet together, the changes of the direction of the stream which accompany the rising and falling of the tide are not alternate; but we have *revolving tide-streams*. The stream, in the course of twelve hours, shifts round to various points of the compass: the change of its direction in some places going round E. S. W. N., and in others E. N. W. S. It changes also its velocity along with its directions. It is desirable in all cases to observe the changes of stream which accompany the rise and fall of the tide. In tide observations it will therefore be proper to note, whether there is an alternate current (a stream of flood and of ebb): and if so, at what hour (with respect to the time of high and low water) the slack water, after the stream of flood and after the stream of ebb, respectively occur. In cases of a revolving stream of tide, the times and directions of the changes may be observed and recorded either by stating them in the usual manner, or by some appropriate notation. Such changes are now marked in the English and in the Dutch charts.

In giving an account of Tide Observations the observer ought to state the manner in which the height was measured, and the line from which it was measured; so that this line may be found again at a future time: the manner in which the moment of high water was fixed upon: the time employed, whether apparent, or mean solar time, and in what manner obtained: and any other peculiarities in the mode of observing.

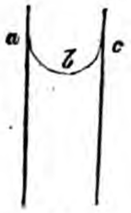
CHAP. VII.

ON CAPILLARY PHENOMENA.

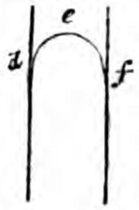
111. In all that has hitherto been said respecting the general equilibrium of liquids, the only force which has been considered is gravity. But the attraction which the particles of the solid exerts on those of the fluid, and which the fluid exerts on its own particles, all of which may be included under the term molecular forces, introduce modifications, which must now be briefly considered. It will be impossible to trace here the profound analysis by which Laplace has submitted the whole subject to rigorous calculation, but we shall endeavour to indicate the most important phenomena, and the principles of the theory which explains them.

If the lower end of a glass tube of small diameter be dipped into any liquid, the surface of the liquid which enters the tube will not coincide with the exterior level of the liquid. In some liquids, as in water, the column is elevated, or stands above the exterior fluid; in others, as is generally the case with mercury, the column is depressed, or sinks below the exterior surface. These phenomena were first observed in tubes whose internal diameters were so small, that they might be compared with the diameter of a hair; they occur, however, more or less, in every tube; and similar phenomena present themselves whenever water is in contact with a solid; and the combined actions from which these phenomena of capillary spaces arise are expressed by the term *capillarity.*

112. *Form of Surface.*—Whenever there is an elevation or a depression of a liquid in a straight tube, the surface of the liquid column assumes and preserves a determinate form. When the column is elevated, the surface is nearly a hollow hemisphere, whose diameter is the same as the diameter of the tube. This which is represented by *a b c* is called a *concave meniscus.*



Again, when the column is depressed, its surface is always a full hemisphere, so that any section, as *d e f,* is a *convex meniscus.*



These particular forms of the surface are essential conditions of the elevation or depression. For if the interior surface of the tube be smeared with any unctuous substance, the water will not only not be elevated, but it will be depressed, and the surface of the depressed column will be a convex meniscus, just as a column of mercury in an ordinary tube. It will follow from this, that the difference of height depends on the form of the meniscus, and consequently whatever prevents the latter from taking the form which it ought to have, will prevent the liquid from standing at its proper height.

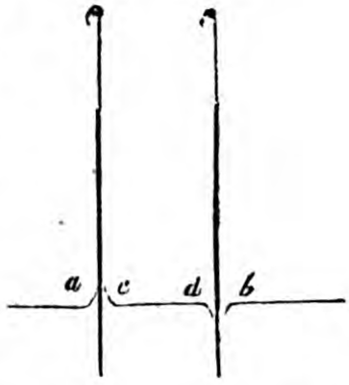
113. *Heights of the Columns.*—A very simple law, made out by experiments with capillary tubes, is, that the heights of the columns, raised or depressed, are in the inverse ratio of the diameter of the tubes. This will be seen at once by immersing any number of tubes of different diameters in the same liquid. The column elevated will be longest, and the depression of the column will be greatest, in the tube of smallest diameter.

It appears also that the effects are entirely independent of the thickness of the tube; that the internal diameter being unchanged, any increase or diminution in their external diameters will not produce any effect on the position of the top of the column. These important fundamental facts were clearly established by the experiments of Boyle and Hawksbee. The nature of the materials of the tube also appears to have no further influence, than so far as it determines whether the liquid can or cannot *wet* the tube; thus a tube of iron or the stalk of a vegetable, provided their inner surfaces are wetted with equal facility, will represent the same phenomena.

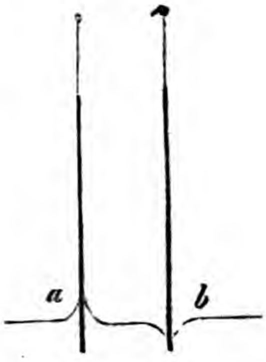
All experiments seem to shew that the height of the sustained column is inversely proportional to the diameter of the tube: and the curved form which water takes between two glass plates, placed together by their edges, appears, on varying the inclination of the plates, to follow the same law of the distance.

The preceding phenomena shew distinctly that solids and liquids cannot touch each other without the surface of the liquid experiencing near the point of contact some change of form; and the change of form, or the curvature which takes place, depends on the nature of the substances, as will be seen in the following articles.

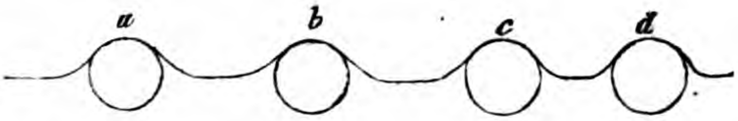
114. *Attractions and Repulsions.*—A single thin strip of metal suspended in a liquid does not experience any motion of translation, whether it be wetted, as at *a*, or whether it be not wetted, as at *b*, for in these cases the forces are equal on both sides of the metal. Two similar pieces of metal immersed near each other do not experience any motion provided they are so far from each other that the curvatures of the elevated or depressed liquid are separated by a rectilinear space *c d*; but if the bodies are so near that the curvatures cross each other, there is a sensible attraction, and the bodies



approach each other. This attraction takes place equally, whether the bodies are wetted, or whether they are not, as when two pieces of glass are suspended in water and in mercury. But if one body is wetted and the other is not, the action is repulsive, and they recede from each other. Thus, if a strip of ivory which is readily wetted by water, and a strip of talc which cannot be wetted, be suspended sufficiently near each other in water, the curvatures of the surface caused by the two substances *a* and *b* will cross each other, so that the surface will take a form as represented in the figure; and in this case the two substances will recede from each other, or appear to be repelled.



Similarly, two balls of cork or wood, floating on water, or two balls of pewter floating in mercury, approach each other, when they are at a capillary distance, that is, at a distance so near that the curvatures can interfere. Thus,



at the distances *a b*, or *b c*, they are without any action, but at the distance *c d* they attract each other. Two balls which do not wet with the liquid, as two balls of wax or smoked cork, floating on water, or two balls of iron in mercury, exert an attraction under the same circumstances. In general, all floating bodies experience from the same cause motions more or less rapid, when they approach each other, or when they approach the sides of the vessel at which the liquid is curved, whether by elevation or depression. In a vessel of water, for example, which is not full, all small bodies which are wetted approach the sides, and those which are not wetted recede from them. The exact contrary takes place in a vessel which is quite full. The motion which takes place under these circumstances cannot be referred to the direct attraction of matter, but evidently depends on the curvatures of the surface; for the same substances which approach and recede from each other when floating on water, present no similar phenomena when wholly immersed in the fluid.

It is very well known that insects can walk on the surface of water. Their covering cannot be wetted; hence, a depression takes place in conformity with the preceding principles. Thus the quantity of water displaced becoming equal to the weight of their bodies, they are sustained in conformity with the well-known principles of Hydrostatics.

The experiment of making a needle, which is of iron or steel, float on the surface of a lighter medium, as water, is to be referred to the same principles. The surface of the metal, owing to its polish, or greasiness, cannot be wetted; hence, more fluid being displaced than is equal to the weight of the needle, it swims. Having once been wetted, however, it cannot rest on the surface.

115. *Forces of Capillarity.*—A solid plate placed in contact with a liquid cannot be raised up as if it were in free air, but will require a greater force than that required merely to sustain the plate. This may be readily measured by balancing a plate of metal on a scale beam, and observing the weights which must be added to raise it up from the surface of a liquid with which it is in contact. From these experiments it appears that every substance, provided the diameter of the plate be the same and it can be wetted by the liquid, requires exactly the same weight to raise it. The adhesion, then, as well as the capillarity, is independent of the nature of the solid, and depends solely on the nature of the liquid. It is easy to see the reason of this, for the plate always brings away with it a

layer of the liquid. The effort of the additional weight is employed, not in separating the particles of the plate from those of the liquid, but in separating the particles of the liquid from each other; it is the cohesion of the liquid which is overcome. These experiments give a measure of the cohesion of a liquid, or of the attraction which it exerts on itself, and this attraction is very different for different liquids. When the surface of the solid is not wetted by a liquid, as when a plate of glass is in contact with mercury, the weight which must be added to draw up the glass expresses no longer the cohesion of the liquid, but the adhesion between the liquid and the glass. Thus, there always exists between the molecules of a solid and liquid an attraction more or less strong. The cohesion of a liquid is always greater than its adhesion to a solid.

The preceding experiments lead to the two following principles. 1°. That there exists in each liquid a force of cohesion, that is, a molecular attraction betwixt the adjacent particles. 2°. That there exists between solids and liquids a force of adhesion, that is, a molecular attraction betwixt the molecules of the solid and the liquid. These two species of attractive forces can only be distinctly laid down by their relative intensity at the same distance, and by the law, according to which their intensity decreases as the distance increases. These, however, not being at present known, some hypothesis must be adopted, and there can be no difficulty in adopting that of Laplace. He supposes that the attractive forces which produce these phenomena decrease with such rapidity that they are nothing at sensible distances; and that when a liquid is raised in a tube, an infinitely thin layer first attaches itself to the sides of the tube, and so forms an interior fluid tube which, acting solely by its attraction, sustains the column at a height depending on the cohesive power and density of the liquid. From these principles he explains all the preceding phenomena, and reproduces the observed facts with an exactitude which can leave no doubt of the truth of the theory.* We shall endeavour to give an idea of the way in which the equilibrium is preserved.

116. *Equilibrium of the Column.*—The small liquid column which occupies the axis of the capillary tube cannot be sustained above its level by any attraction of the sides; for this tube, though capillary, has still a sensible magnitude, and the attraction of its particles cannot extend so far as the axis of the tube. This is confirmed by the fact, that the height of the sustained column is entirely independent of the thickness of the tube. We must conclude, therefore, that the column is elevated by the action of the water upon itself, and examine how this can be effected. When a fluid is at rest the particles at its surface must be acted upon by some force besides gravity. A particle in the interior is acted on by the attractions of the surrounding particles, but the particles at the surface have no particles above them; hence the action of the liquid must tend to make the particles of the surface enter into the interior of its mass, and it would actually produce this effect, were it not for the equality of the pressure at the end of any canal which can be drawn from one point to any other point of the surface. There is then an action of the interior particles of the liquid on the particles of the surface, and this action must evidently be different for a curved surface from that for a plane surface. The nature of this action must be considered; and it is proved by Laplace that the action from without inwards is less in a concave surface, and greater in a convex surface, than when the surface is plane. Thus, when the natures of the solid and the liquid are such that the solid is wetted by the liquid, the surface is concave, and

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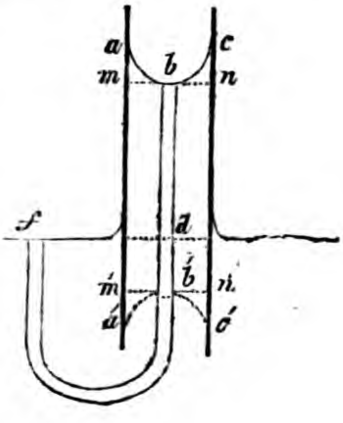
* M. Poisson has recently published his *New Theory of Capillary Attraction*, which is sometimes spoken of as being opposed to that of Laplace. But the fact seems to be that Laplace's results must be considered as approximations, which are very nearly accurate. Laplace supposes water and mercury as incompressible; now though this is not accurately the case, the deviations from this law do not affect capillary phenomena as to kind, nor are they certainly known to affect them in degree.—See Professor Challis on *Capillary Attraction*, in Reports of the British Association, 1834.

the diminution of pressure from without inwards which results from the surface being concave instead of plane, must be made up by an additional column of the fluid; in this case there is an elevation. But when the solid cannot be wetted by the fluid, and the surface is convex, the increase of pressure from without inwards which results from the surface being convex instead of plane, must be corrected by a diminution in the column; in this case, then, there is a depression.

We may, perhaps, form a more distinct idea of the way in which the equilibrium is effected, by the following considerations. The column terminated by the concave surface may be conceived to consist of a column terminated by a plane surface *plus* a meniscus with its concavity turned upwards; and the convex column to consist of a column terminated by a plane surface *minus* a meniscus with its concavity downwards. Now, the attraction of this additional meniscus is in both cases the same in amount; and the fact of its presence or absence causes too great or too small an upward action; thus there is an unequal action at the two extremities of the canal, and this inequality is compensated by an elevation of the fluid in one case, and by a depression in the other. The deviations, then, from the law of fluid levels are the consequence of the forces to which the different points of the surface are subject; and the law that when a fluid is in equilibrium the pressure must be the same at all points of the surface (Art. 98), holds here.



Let *a b c* represent the capillary surface of water raised above the external level; and let *b d b' f* be any imaginary canal leading from one surface to the other; since the whole liquid is in equilibrium, this canal will be also in equilibrium. If, now, the capillary surface were plane, that is, horizontal, or parallel to the surface of the external fluid, the downward action of the liquid on a particle at *b* and *f*, tending to make it enter into the liquid, would be the same; but the surface *a b c* being concave, it is greater; hence the equilibrium is preserved by the weight of the column *b d* compensating for the difference of these actions. But suppose *a′ b′ c′* to be the capillary surface; then the downward action of the liquid being greater in a convex than in a plane surface, this greater action is compensated for by the defect *b′ d* of the column.

Again, draw *m n*, *m′ n′* touching the columns at *b* and *b′*, then the elevated column may be conceived to consist of the column terminated by *m n* *plus* the meniscus *a m n c*; and the depressed column of a column terminated by *m′ n′* *minus* the meniscus *a′ m′ b′ n′ c′*. Now, the meniscus *a m b n c* draws up and sustains the elevated column; the meniscus *a′ m′ b′ n′ c′* *would*, if it existed, draw up the liquid, but by its absence the downward pressure is greater, and the surface is consequently depressed.

117. *General Observations.* — In the preceding theory Laplace starts from the form of the surface; when nothing interferes with the natural action of the fluid its surface is plane; but if there be any foreign or extraneous action, the surface takes a different form, and we must see whether, from this form, the action of the liquid on itself is increased or diminished. When the surface is concave the action is less, because all the liquid which is above the tangent plane at any point acts upwards, and therefore weakens the natural action of gravity, which is downwards; so that if we conceive that the liquid curves itself in order to mount up to the level of the external fluid, there cannot be equilibrium unless there be an excess of height sufficient to compensate for the diminution of pressure due to this cause. Just the reverse takes place if the surface formed is convex; this augments the pressure upon itself, and, consequently, the column has a less height, or is below the external level.

The peculiar character of the preceding theory is, that it makes every thing depend upon the form of the surface. The nature of the solid body and that of the fluid determine simply the direction of the first elements where the fluid touches the solid; for it is at this point only that their mutual attraction is sensibly exerted. These directions being given, they become the same always for the same fluid and the same solid, whatever be the figure and mass of the body. But beyond the first elements, and beyond the sphere of the action of the solid, the direction of the elements and the form of the surface are determined simply by the action of the fluid upon itself. All the causes, therefore, which by their action on the surface of the glass can change the direction of the first elements, must change also the curvature of the liquid surface, and, consequently, the elevation of the fluid. This explains the depression of the fluid coated on the interior with an oily substance, the elevation of mercury in dry tubes, and its depression in moist ones. Friction may also produce analogous effects, and Laplace has cited examples of this kind.

Capillary phenomena are not confined to tubes, but take place also in plane spaces. Water rises and mercury sinks between two glass plates placed at a small distance from each other. The law of these phenomena is the same as in the case of tubes. The elevations and depressions are reciprocally proportional to the distances of the plates. But there is this singular difference, remarked by Newton, that the absolute effect is exactly half of what it is in tubes; that is, between plates at the distance of $\frac{1}{30}$th of an inch, the water rises to precisely the same height as in a tube of $\frac{1}{15}$th of an inch in diameter. This singular relation is an immediate consequence of the preceding theory when traced out by mathematical reasoning.[*] The preceding theory of capillary attraction would furnish a good example of the establishment of a physical theory; the phenomena are re-

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[*] *Theory of Fluids*, Art. 89.

produced, and predicted by the theory with great exactness; but we cannot here enter on this subject.

118. ***Absorption and Filtration.***—The absorbing action which some substances exert on those liquids which can wet them, is evidently due to capillarity; all their small interstices are analogous to tubes more or less fine; their sides are first lined with a thin layer of the liquid, and this layer attracts the contiguous particles according to its density, and retains them according to its cohesive power. The rate of the absorption depends on the form and magnitude of the pores of the absorbing body; on the attraction which it exerts on the air with which the pores are impregnated; on the attraction which subsists between it and the liquid; and lastly, on the attraction which the liquid exerts on itself. All bodies are porous; hence it would seem that all ought to be absorbents; but we must distinguish between the pores which depend on the nature of the substance, and the pores which depend on the structure and arrangement of its parts; the former, being only the *necessary* intervals which separate the particles, will not in general admit of foreign substances, whilst *accidental* pores are almost always, from their dimensions, fitted to receive the liquids which wet them. Thus the regular crystalline masses seldom possess any absorbing power, whereas masses irregularly aggregated, as those which consist of a mass of dust or small fragments, are always absorbents. Inorganic nature does not present a single exception to this law, nor does any appear to exist in organic nature; for all solid organized bodies consist of fibres, tissues, and generally of formations destined to receive nourishment, and, consequently, the fluids which convey it.

The filtration of water through filtering stones, or through sand, of spirits through unsized paper, of several liquids through wool or cotton, are so many examples of absorption by different solids. For a filter does not act as a sieve by stopping all those particles which are too coarse to pass; but it becomes wetted by its capillarity, it transmits liquids independently of the pressure to which they are subjected, and all the drops which pass have been during their passage constantly subject to a pressure more or less powerful.

The ascent of the sap, and its spread through the whole of a plant, from the lowest root to the extremity of the highest and most distant leaves, are phenomena closely allied to capillarity; and the passage of water into vegetables furnishes a most striking instance of absorption. But the theory in its present state seems inadequate fully to explain these phenomena.

CHAP. VIII.

ACOUSTICS, OR THE LAWS OF SOUND.

Section I.

PRODUCTION AND TRANSMISSION OF SOUND—WAVES OF SOUND—DECAY AND VELOCITY OF SOUND—RAYS OF SOUND—REFLECTED SOUND—SPEAKING TRUMPETS—THUNDER—THE EAR.

119. The object of that part of science which is termed Acoustics, is the determination of the laws according to which sound is produced and transmitted to our organs. This subject belongs peculiarly to the province of physics, because all bodies, whilst they are producing noise or sound, experience remarkable modifications, entirely dependent on the physical laws of their constitution. For we shall see that no body can emit a sound without being shaken throughout its whole mass, and that all the particles which compose it perform oscillations or motions of vibration, with a rapidity, such that direct observation cannot count their number. The extent and duration of these movements, the direction in which they are propagated, and the harmony which must exist among them, so that they may be sustained and transmitted without being destroyed, are among the most striking phenomena in which philosophers may contemplate the molecular arrangement of the particles of bodies, their elasticity, and all the circumstances of their internal structure.

Some idea may be formed of the number and variety of the phenomena which acoustics embraces when we consider, that to all the sounds we hear, to all the gradations and tones which our organ can detect, there most certainly corresponds a different physical modification in the air which conveys to us these impressions, and in the sounding body from which the air has received them.

It is the series of these distinct motions communicated one after the other from the sounding body to us which it is required fully to explain. Thus the science of acoustics takes the sound at its birth, so to speak; it proves unquestionably that it is the motion of all the particles of the body which produces it; that this motion is communicated to and traverses the air, coming at last to our organ; there science has reached its limit; from the instant the nerve of the ear is beaten there is no perceptible trace of any material modification, or consequently of physical phenomena. These general remarks shew distinctly in what the science of acoustics differs from that of music—the former treating of sound as it exists without us, and without any reference to the particular sensations which it produces; the latter treating of the laws of those sounds which are calculated to excite or allay peculiar emotions and passions.

120. *Sound produced by a motion of vibration.*—Sound considered with respect to the sounding body, consists of a motion of vibration impressed on the parts of the body. In general, that a body may be capable of producing sound, it must possess some elasticity. Soft bodies, as wool, cotton, and down, cannot produce any sound; those which are absolutely hard, or which approach to an absolute hardness, as stones and rocks, are not generally ranked among sounding bodies; and they are in fact more capable of producing a dull noise than a sound properly so called. Liquids, also, whose elasticity is small, appear incapable of producing sound. Sometimes we hear water resound as it falls into a vessel; it also produces sound when it is put on the fire in a deep vessel and approaches the point of ebullition. This effect, however, must be attributed to the

vessel which contains it, or to the air which it carries with it during the fall, or disengages during the approach to the boiling point. It is not, however, contended that water is absolutely incapable of producing sound; for we shall see that any sound produced in water can be heard, and any substance which has the property of transmitting sound can produce it also; but only that the power which water or other liquids have of producing sound is exceedingly small, and scarce worth any consideration.

The production of sound then being peculiarly the property of elastic bodies, those are the most sonorous whose elasticity is the most perfect. Thus glass, some metals hardened by mixture or by tempering, strings of musical instruments, wood reduced to thin layers, the air itself enclosed or free, are the substances most proper to produce sound, because they are also the most elastic. We know from the consideration of the constitution of bodies that the essential condition of elasticity is a fixed arrangement of the elementary particles, and this cannot be changed in ever so small a degree, without the bodies making some effort to return to their former state. Left to themselves they return to it at last, after several oscillations more or less numerous. But it is when the elasticity of bodies has been thus called into play, and during the continuance of their oscillations, that they produce sound. The sound is more or less feeble according as their elastic power has been more or less stretched by the compression or the impulse. Any person may be convinced of this by holding a bell glass in the hand, and striking it gently at the lower part a sound will be produced, which, lasting some instants, will gradually die away. We have only to consider what took place on striking the glass. The particles which were struck recede from the blow, and then, immediately recovering themselves, move back towards their original position; they pass, however, beyond this position, and go on moving backwards and forwards until rest is restored. During all this time the bell will have sounded, and it is only when the motion has ceased that the sound will cease also. This may be shewn to the eye by holding a bar near the glass; it will be alternately struck, as the glass deviates from its original circular form, passing alternately into an elongated or flattened form. It is to this rapid succession of small shocks, rendered sensible by the change of form, that the name of oscillations is given, and which we here consider as the cause of the sound. We are never sensible of sound unless there exist these vibrations of a body. Every body then in the act of sounding makes vibrations more or less rapid; and the air itself, when it produces sound, as by the stroke of a whip, or the rapid revolution of a cut cord, takes a similar motion, produced by the alternations of the motion of the aerial particles, so as to produce condensations and rarefactions. But the strongest proof that sound, considered with reference to the sounding body, is nothing but the rapid motion of oscillation, is that the sound ceases at the instant when this motion is arrested by any cause whatever. If the sounding glass be set down on a cloth its sound instantly ceases, that is, the vibrations are extinguished.

121. *Transmission of Sound.*—Knowing what passes in a body which produces sound, we can easily determine what takes place in the air which surrounds the sounding body. The glass struck by the hand has all its zones set in vibration, that is to say, they are alternately flattened and lengthened, thus oscillating or balancing, so to speak, for some time about their true form. The air in contact with the bell necessarily participates in these oscillatory motions; its particles at the first instance approach each other, or a condensation takes place, which is communicated successively throughout the fluid; but the returning motion of the particles of the bell permits the air to dilate itself previous to being compressed again; thus there is established in the surrounding air a rapid alternation of compression and dilation, corresponding to the alternating motion which exists in the sounding body. By virtue of

its being an elastic fluid the air returns vibration for vibration, and thus the shock given by the glass is transmitted to our organs. The air is then the vehicle of sound; without it we should not be sensible of the vibrations which were taking place in the sounding body. This will be rendered at once evident by placing a bell under the receiver of an air pump, with a contrivance that it should ring itself. As the air is exhausted the sound dies away, and is at last absolutely extinguished, although the vibrations of the bell are going on. The sound revives again as the air is let in. If air be forced in by a condenser the sound becomes louder. The preceding experiment explains the diminution of sound at high elevations; on the top of Mount Blanc, according to Saussure, the report of a pistol is only a slight pop. Hence no sound can reach us from very great heights.

But atmospheric air is not the only medium capable of transmitting sound; all other fluids, similar to air, as gases and vapours, will transmit it. Liquids also possess this property. If a small watch, covered with a glass, be let down in water, its beats will be heard by an ear at the surface; and the sound of the stones at the bottom is transmitted to our ears as the murmur of the stream. A person immersed in water hears a sound from without; a slight sound however is not audible to our organs, but fishes, whose preservation depends on it, can hear the slightest sound from without, and the fish of a pond will come to the surface at the known sound of music. In the descent with the diving bell the signals are given by striking on the side of the bell. It has been asserted that water transmits sound simply by virtue of the air which it contains; this however is not the case, since it equally possesses that property when the air is entirely removed. Water then can of itself propagate sound, and this fact is a proof of its elasticity. The motions which sound produces in water may be seen by taking a tumbler nearly full of water and running a wet finger round the edge so as to produce a musical note. The vibrations of the glass will cause an oscillation in the water and a motion so violent, that the water may be thrown out of the glass by dashing over the edge.

Solids possess the same property of transmitting sound; if the ear be placed at one extremity of a long piece of wood and a watch at the other, the ticking of the watch will be heard most distinctly; bars of iron, and all other solid substances, can transmit sound according to their own laws; thus an ear placed near the ground will distinguish an approaching footstep long before it would have been audible if conveyed simply by the air. Since, however, the air is the great vehicle of sound, we must examine particularly into the manner in which this propagation takes place in this and other similar elastic media.

122. *Waves of Sound.*—Suppose now that a bell suspended in air is struck by a hammer; the sound produced travels to a great distance and fills a circular space which would be accurately spherical if the sounding body were but a point, and had an equal quantity of air on all sides of it. But the sound does not instantly travel over all the space through which it can be heard; its propagation is *successive,* and takes place in the following manner. The parts of the bell which are in vibration strike the particles of the air, and displace them successively to a certain distance; thus a compression or condensation takes place. The effect of this first impulse is necessarily limited; for in proportion as it recedes from the origin of the motion the number of particles disturbed increases, and consequently the effect becomes weakened by propagation. Let us suppose that at the first instant there is in contact with the sounding body an envelope of condensed air of greater or less thickness, according to circumstances. This condensed air will, by virtue of its elasticity, return to its former state of rest. Similarly we may conceive the sounding body to be surrounded by an envelope of rarefied air, which will almost immediately be restored to the state of elasticity

and density in which it existed previous to its being disturbed. The state of condensation and rarefaction which we have supposed to exist in each of these envelopes, is transmitted throughout the whole mass of air. The air is condensed successively throughout its whole extent, and rarefied successively. These effects, however, diminish as we recede from the point of the original disturbance, and finally become insensible. Such is the manner in which, reasoning on the known properties of the air, we are led to believe that sound is propagated through the atmosphere; and the preceding shews us that sound must pass by degrees, and successively, across the space throughout which it can be heard.

A sounding body then may be considered as enveloped with layers of air nearly concentric, which are brought into their particular state one after the other, and the particles in which execute their particular vibrations, which are of less extent as the particles are more removed from the origin of the sound. These layers of air have been called waves of sound; they may be compared to the waves which are excited in still water when a small body is dropped into it (Art. 109). It is of importance to remark that the waves produced in this manner in still water have all the same breadth; the same is the case with sound; that is to say, for a given cause producing sound the waves are every where of the same thickness. This oscillating movement, or undulation, evidently proceeds from the suddenness of the impulses of the sounding body. The impact is so sudden that the air at the first instant cannot yield except to a certain distance, and it is by the action of this air, causing a successive displacement in the contiguous particles, that sound is transmitted.

123. *Decay of Sound.*—The air then is agitated by the sounding body, but not sensibly displaced. The loudest noise and the most startling sounds, produce not the least agitation in the flame of a candle. Moreover it is certain, that the air of a concert room is agitated on all sides;

that it experiences an infinity of sudden condensations and rarefactions. All this however produces in the air not the least current or motion of translation; each particle of air remains sensibly in its place, and makes small oscillations forwards and backwards, which succeed with more or less rapidity, which are of the *same* duration for the same sound, at every distance from its origin, and which diminish in extent only, as they recede from the original disturbance; it is from this cause that the sound diminishes with the distance. It is evident that the number of particles which exist on a spherical surface increase as the square of the diameter of the sphere; hence the intensity of sound must decrease in the same ratio; this is expressed by saying that the force or intensity of sound decreases as the inverse square of the distance. This conclusion cannot be doubted when sound spreads spherically, or all round the body which produces it; but when sound is transmitted down a cylindrical column there is no similar reason for its decay; and we find that the slightest whisper may be heard to a very great distance in a long tube. The distance at which sound can be heard depends as much on the sensibility of the organ as on the intensity of the sound. The timid deer will start at a sound which many other animals would not detect.

124. *Velocity of Sound.*—The propagation of sound being successive its transmission requires time, hence the actual velocity of sound is a most interesting question. On this subject theory and experiment are well agreed, and it appears that the temperature being the same, the velocity of all sound is about 1115 feet per second.* The fact that all sounds in the same air travel with the same velocity is clearly proved by the performance of a rapid piece of music by a band at a distance. Did the slightest difference exist in the velocity of the sounds of different notes, there would be utter destruction to all harmony, the

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* *Theory of Fluids*, Art. 142.

essential condition of which is, that the sounds should reach our ears in a precise order, and at exact intervals. The causes which influence the velocity of sound are such as produce any change in the state or elastic force of the air. If the air be foggy, or if snow be falling, the free vibration of the particles is disturbed; if the temperature change in any manner, the elastic force of the air undergoes a corresponding change. The history of the theoretical determination of the velocity of sound is curious, and furnishes a remarkable instance of the effect which must be attributed to the development of heat. The velocity of sound, as calculated by Newton, was about one-sixth less than the observed velocity; this great difference between the theoretical and practical results embarrassed philosophers, until Laplace suggested, whether the change in the elasticity, consequent on the development of heat when air is condensed, and the absorption of heat when air is rarefied, might not account for the perplexing difference; this being included in the calculation, the results of theory and observation agree as nearly as can be expected.*

The velocity of sound is also affected by the direction of the wind; if the whole body of air in which the sound is propagated be moving in any direction, the velocity with which sound appears to travel in that direction will be diminished by the velocity of the wind; but if the wind blows from the sounding body direct to the ear, the velocity of the wind must be added to that of sound in still air. But the wind will not influence the velocity of sound in the direction perpendicular to that in which it is going.

The knowledge of the velocity of sound will frequently enable us to determine distances with considerable accuracy. Every one must have observed that the flash of a gun precedes the sound, and that the interval depends on the distance at which we are from the sounding body. Now

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* *Encyc. Metrop.* Art. *Sound*, 67—70.

for all distances on the earth's surface the passage of light may be considered as instantaneous; its motion is so rapid that the flash of the gun may be considered as seen at the instant at which it takes place; if then the report be not heard for some seconds, we may, knowing the rate at which the sound travels, and observing the time during which it has been travelling, determine the distance over which it has travelled, or our distance from its origin. This is illustrated on a grand scale in the phenomenon of thunder; we see the lightning, but the thunder is frequently not heard for several seconds; hence the interval after which the report follows the flash may inform us of the distance of the electric cloud.

125. *Rays of Sound.*—A sounding body excites in the air which surrounds it a general disturbance, which extends spherically about it, and forms successive waves, whereof it occupies the centre. There is not in the whole space which the sound fills, a single point at which the ear being placed would not receive the sensation; but the undulatory motion does not prevent the propagation of sound also in straight lines. If there be no obstacle, or peculiar circumstance connected with our ear being affected so as to produce in us the sensation of sound, we judge very well of the position of the body with reference to us which produces the sound; and, if necessary, we can go directly to it. The aerial particles, which are situated on the straight line from us to the sounding body, constitute a ray of sound. But in the space filled with the sound we can draw from the centre to the surface an infinity of rays, and consequently a very great number of organs can have a perception of the same sound, and all will judge that it comes from the place from which it really comes. This propagation of sound in a straight line is not at all contrary to the doctrine of propagation by waves; each molecule of air is supposed to be in contact with many others, to which it necessarily communicates the motion of vibration which itself possesses. Then at the same instant that

this motion is transmitted forward it is also propagated laterally on all sides; and hence we hear, although the sound is not directed to our ear.

126. *Reflection of Sound.*—Sound has then a progressive course, and extends to great distances when nothing opposes it. But if it meets any obstacle, if the wave of sound is arrested in its progress by a hard or elastic body, then the sound cannot advance farther; the motion is not however extinguished; the aerial particles striking against this obstacle continue their vibrations, and communicate them to those which are before them. The sound will, so to speak, return on itself, making the angle of reflection equal to that of incidence. The obstacle will be the origin of a new vibratory motion in the air; it will be the centre of new waves which can cross without disturbing the former; just as we know the waves of still water can cross each other, when waves are formed at two points near each other (Art. 109). The sound thus reflected has received the name of *echo.* The body which produces the echo may be conceived as it were the image of the sounding body, and this image, just as in the reflection of light, often leads us into an error by making us believe that the sounding body is where it is not. Every person must have remarked that bells are often heard as if in a situation different from their real one; on the right for instance, when they are really on the left; this arises from the direct sound being intercepted by some obstacle, so that the ear can only hear the sound reflected from some other body.

Any body, hard or elastic, can reflect sound; a rock, the wall of a house, of a cavern, or of a vault, reflect it exceedingly well. We know with what force the voice returns to itself in wells, or in a cistern arched with stones well fitted together; and with what difficulty a speaker can be heard in some vaulted rooms of moderate extent; the sound reflected from near points interferes with the direct sound, and disturbs the clearness. The Romans, in order to heighten the voices of their actors, placed in the corners of their great theatres surfaces, which, reflecting the sound, enabled it to reach all the spectators; to make use however of these contrivances, a slow and studied articulation is necessary. But the air itself, when enclosed in any space, and constrained in its motions, is the best obstacle for the reflection of sound. Thus, when a forest makes an echo, it is not so much the leaves of the trees, or the branches, or the trunks, which reflect the sound; but the air, which, contained in the forest, constrained and entangled by the foliage, repels the rays of sound as a solid body would repel it; and with much greater advantage, since it is possessed of the same elasticity, and returns the vibrations, without any sensible loss of motion. Hence it is that the echo of a forest is so much more perfect than the echo produced under most other circumstances. It is evident that soft bodies cannot make an echo—they are more calculated to extinguish sound; thus the carpets and tapestry of our apartments render the voice dull, and prevent the resounding of the words which may be perceived in an unfurnished room.

The preceding principles have been recently applied in the construction of a parabolic *sounding board*, by which the voice may be conveyed straight forward to the most distant parts of a building. It is a property of the parabola, that all lines from the focus to the surface make the same angle with the perpendicular to the surface at any point as a line parallel to the axis of the parabola. Hence, since the angles of incidence and reflection are equal, every ray of sound proceeding from this point on the axis is reflected in one and the same direction, namely, parallel to the axis of the parabola. If therefore the mouth of the speaker be in the focus, the sound which diverges in spherical waves above his head will be caught by the board and reflected in one and the same direction. Those who are within the ordinary range of the speaker's voice will hear by direct rays of sound, and those beyond by reflected rays. Some individuals may hear in both ways, and no confusion will be occasioned, since the two rays will sensibly come at precisely the same instant. The same instrument will also collect the slightest whisper, so that an ear in the focus may hear at the distance of one hundred feet sounds which, conveyed naturally through the air, would be scarcely audible at the distance of ten feet. It is stated that the unpleasant sensation to the speaker from the number of small sounds which are thus rendered audible, is a great practical inconvenience in the use of these sounding boards.

127. *Echo.*—The successive propagation of sound and its reflection at elastic surfaces, suitably situated, give rise to the phenomena of echos. We know that if two or three syllables are pronounced in front of some obstacle, sufficiently distant, they will frequently be heard repeated the instant afterwards, as if some one afar off was mimicking the speaker. This imitation of the human voice by inanimate objects might well be regarded with astonishment when the cause was not understood; now, however, it can only serve as a beautiful illustration of a physical law. The waves of sound proceeding from the mouth to the obstacle undergo reflection, and the direct rays returning to the place from which they started, the syllables pronounced are heard again by the speaker. Thus the waves of sound start in one direction and return in the opposite, without in any way disturbing each other. The syllables pronounced may be heard many times if there are several obstacles distributed at unequal and suitable distances, and in proper relative situations. In one second sound travels over about 1100 feet: suppose now the obstacle which causes the echo to be at one-half this distance from the speaker; the sound will take half a second to reach the obstacle, and half a second to return. The echo will be heard therefore after about one second; but in a second the mouth can pronounce distinctly five or six syllables; these then will be heard repeated one after the other, and in the same order. An obstacle placed at double the distance in a different direction would return the sound in two

seconds; the echo would, however, be much more feeble, since the distance over which the sound travels before reflection is doubled. But the reflected sound meeting with another obstacle may be again reflected, and then the echo may be repeated several times in succession, becoming, however, fainter and fainter until it dies away entirely; sometimes it will revive suddenly, so that these variations in the sound, depending entirely on the distance and position of the reflecting surfaces, may constitute a series of notes. Of this there is a remarkable instance under the Menai Bridge. The sound of a blow on the principal pier is returned in succession from each of the cross beams which support the roadway, and from the opposite pier at a distance of near six hundred feet; besides which the sound is many times repeated between the water and the roadway. The series of sounds thus produced by a single blow is very remarkable, and furnishes several beautiful illustrations of the laws of sound.*

Vaults are sometimes so constructed that two persons placed at two distant points may hear each other most distinctly, although speaking in so low a voice, that a person near either of them cannot hear a syllable. Such a phenomenon may be produced by an ellipse. For it is a property of this figure that all straight lines drawn from two fixed points, termed the foci, on its axis, make equal angles with the curve, that is, with the tangent at any point of the curve. If then a sounding body be placed at one focus of an ellipse, all the rays which start from this point will, on striking the concavity, be reflected so as to reach the other focus; where, by their concourse, they will produce a sensible disturbance. An ear then placed at this focus will receive, besides the direct rays, a great number of reflected rays, so that the sound will be strengthened and made sensible; whereas an ear situated at any other

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* See *Encyc. Metrop.* Art. *Sound*, 35.

point will receive only the direct rays which are not sufficiently intense to produce the sensation of sound. Thus the sound, though too feeble to be heard directly, may be strengthened by the reflected rays, and become perfectly audible.

128. *Speaking Trumpets.*—The preceding principles will enable us to understand the common speaking trumpet, which is an instrument frequently used at sea for conveying the human voice to a very great distance. It commonly consists of a hollow tube of metal, narrower at one end than at the other; it is terminated by a part opened out, which is called the pavilion. The mouth being applied to the narrow end of the instrument, there are some rays conveyed directly down the tube without experiencing any reflection from the sides; but besides these are others, which, dispersed on all sides, are reflected at the sides of the tube towards the axis, and combine with the others. Thus the vibration of the air about the axis is increased by the two sets of rays, and the sound is propagated very distinctly in the direction of the axis. By means of this instrument sound may be conveyed to very great distances; care, however, must be taken to pronounce the words slowly and distinctly, or the sounds will be confused. For the better direction of the rays of sound along the axis, the interior of the tube, close to the mouth, has a parabolic form, the mouth being in the focus; the rays then which start from the focus and fall on this concave parabola will be reflected straight down the tube. The open form of the more distant part reflects also in the same direction the rays which come directly.

There are many other instruments and contrivances for increasing the sound by the union of the vibrations of direct and reflected waves, and for conveying sounds to places, whence they may issue as by some magic; but they are all illustrations of the preceding laws. The construction of the *ear trumpet*, by which sounds are to be collected, so that a deaf person may be sensible of an ordinary sound, or a good ear may be enabled to catch a low whisper, is at once intelligible on the preceding principles.

129. *Thunder.*—The rolling of thunder, and its sudden and capricious bursts, may be explained on the preceding principles. It appears that under a perfectly clear sky the explosion of a cannon is always heard single and sharp; but that when the sky is overcast there will frequently be a long continued roll, and sometimes a double sound from each shot. Thus, the rolling of thunder may be considered as a continuous series of echos from different parts of the dense clouds which accompany a thunder storm. There is also another cause. The transmission of electricity, like that of light, is, for all distances with which we have to deal, instantaneous. The sound then will be generated at the same instant, through many miles of cloud, but the sound will not in general reach our ears at one instant; it will arrive successively from successive points; hence there will be a continuous peal or roll of thunder. When the sound arrives from any number of points at the same instant, there is a fearful clap, or single burst; but in ordinary cases the sound is continuous, augmented at different intervals by echos, so as to cause all those variations of sound which add so much to the grandeur of the scene.

130. *The Ear.*—Sound, considered in the organ which receives it, is a motion of vibration communicated to the different ramifications of a nerve, which enters into the ear, and which is called the auditory nerve: this communication is made by means which merit our attention. The Creator has composed the organ of the ear of a great number of pieces of admirable delicacy, and of which the uses are not yet understood. The ear is distinguished into the *external* and *internal ear*. The first is a species of natural hearing trumpet, containing in its sinuosities a mass of air proper for receiving, preserving, and propagating, the vibratory motions of the waves of sound. The

in some detail, since the whole doctrine of harmonics, and our knowledge of the vibration of bodies, is founded upon it.

132. *Tones.*—The rapidity with which the impulses are repeated, or the duration of the vibrations, being compared in different cases, we have an exact comparison of sounds, or a means of estimating what is meant by *tones*. Tones are distinguished into grave and acute; the former supposing slow, the latter rapid vibrations of the sounding body. This distinction is, to a certain extent, arbitrary, since sounds are low and high only by comparison; but their essential characteristics depend entirely on the rapidity of the vibrations; as may be easily shewn. Suppose a musical string, as a metallic wire, stretched between two points, to be lightly pressed or struck, and then left to itself; it will make oscillations more or less quick, and give some sound which will be heard at a greater or less distance. If now the string be struck with greater force, so that it is moved farther from its original position, it will make oscillations of much greater extent than the preceding, but of precisely the same duration; it will also give a louder sound, or one which will be heard to a greater distance, but it will have the same tone as the preceding; so that the sound emitted by a musical string is strong or feeble, according to the extent of the vibrations; but the tone remains the same, provided the time of the vibrations is unchanged. A string once struck, continues to sound for some seconds, and during the whole of this time it gives the same note; now this is the consequence of the isochronism of the vibrations; the extent of the excursions is constantly changing, but the time of each excursion remains unchanged.

Suppose now that the string is stretched with a greater force, so that its vibrations are more rapid. If then it be struck as before, the sound will not have the same tone; it will be higher, or more shrill. Thus, the same sounding body will, under different circumstances, give two tones, whereof one is high or low, compared with the other. There are many different ways of illustrating the preceding principles, by the production of a regular series of impulses, in which the vibrations have different times; and the experiments of M. Savart are among the most remarkable. He made a wheel of about nine inches in diameter, having three hundred and sixty teeth set at equal distances apart on its rim, revolve rapidly; each of these teeth striking in succession on a piece of card. The tone was unchanged so long as the velocity of rotation remained the same, but increased in pitch with the rapidity of the rotation. From experiments of this kind it appears that there are limits to the human ear; the impulses may be too few or too numerous; when they are less than about sixteen a second the continuity of the sound is lost, and when their frequency exceeds a certain limit all sense of *pitch* is lost: many individuals, not the least deaf in all other respects, are altogether insensible to sounds which are painfully acute to others. The explanation of this phenomenon is derived from the consideration that the impulses lose in intensity more than they gain in number, and thus the sound grows more and more feeble, till our organs can no longer detect it; or it may be, that the parts of the ear put in vibration by the aerial vibrations, can respond only to a limited number of impulses in a given time, and that this limit may be different for organs of different construction. We may imagine that animals, whose powers appear to commence nearly where ours terminate, may have the faculty of hearing still sharper sounds, which we do not even know to exist; thus there may be distinct sounds and but one medium of sound, for different parts of creation; so that there may be whole classes of animals having no sound in common; the shrimp and the whale, for instance, may have no sound in common.

133. *Laws of vibratory Strings.*—When a musical string is made to sound, the vibrations which it performs

are far too rapid to be counted or ascertained by any direct means; there is also a constant relation subsisting between the number of vibrations, the time of each, the length of the string, and the nature of the sound. These phenomena, which may be readily exhibited by experiment, can only be reduced to laws by the assistance of mathematical reasoning; we shall therefore briefly state the results of theory, and shew how the laws may be verified.

1°. 'The number of vibrations in a given time varies inversely as the length of the string.' Thus, suppose a string of a given length vibrate *ten* times in a second, then a string of double the length will vibrate only *five* times, and one of half the length will vibrate *twenty* times. If the string of a violin, guitar, or any other instrument, make a number of vibrations, which we will call unity, in a given time; it will make 2, 3, 4, &c. in the same time when, without changing the tension of the string, we make a portion $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, &c. of it vibrate. It will make a number of vibrations which will be represented by $\frac{3}{2}$, $\frac{4}{3}$, $\frac{5}{4}$, &c., if we make a portion $\frac{2}{3}$, $\frac{3}{4}$, $\frac{4}{5}$, &c. of its length vibrate. The vibrating portion may be made of any length by placing a piece of wood, as a bridge, under the string at the required distance, and pressing the string down upon it with the finger.

2°. 'The number of vibrations are proportional to the square roots of the weights by which the strings are stretched.' Thus, if *unity* represent the number of vibrations of a string which is stretched by a force equal to a weight of *one* pound, the number of vibrations will become 2, 3, 4, when, without changing the length of the string, it is stretched by forces equal to the weights 4, 9, 16, pounds.

3°. 'The times of vibration of different strings are as their lengths directly, and the square roots of the tending forces inversely.' Thus, if a string of a given length vibrate in *one* second, one of double the length will take *two* seconds, the force by which it is stretched being the same; but if the force with which it is stretched be quadrupled, the time of vibration will be *one-half* a second.

The number of vibrations will also depend on the thickness and density of the strings, being much less in thick and heavy strings than in thin and light ones. These laws are at once illustrated in the violin. The bass string is thick and very heavy, being covered with metallic wire, and the others gradually diminish up to the treble. The strings are also of different lengths, and are tuned by an increase or diminution of tension. The vibratory lengths of the strings and their tensions may also be altered by the action of the fingers pressing them at different points against the board. In every stringed instrument the tones depend on the preceding laws, and may be modified in some similar manner, so as to counteract the various changes to which the strings are subject from variations in temperature, and in the state of the atmosphere as to dryness or moisture.

134. *Unison.*—We have already seen that the number of the vibrations performed in a given time determines that most essential character of a musical sound, which is termed the pitch. When the vibrations of two, or of any number of strings are performed in exactly the same time, whatever difference may exist in the quality or intensity of their sounds, the strings are said to be in unison. Our minds are so constituted that one set of vibrations occurring as frequently as another, irresistibly impresses us with the conviction of their similarity or identity, and the strings are consequently said to sound the same *note*. From this fact we may learn that the rapidity of the impulse stamps the character of the sound; that when two impulses occur with equal frequency the mind cannot distinguish them, but they are blended together and form a compound impulse, differing in intensity and quality from its constituents, but not in the frequency of its recurrence; and that, consequently, the ear will pronounce it of the same

pitch, though differing in some other respects from any of the single notes.

135. *Concords and Discords.*—When two strings are vibrating together in different times, or not in unison, the ear can distinctly perceive the note of both; but besides these two separate notes, there will be an impression from the two jointly, very different from that which it receives from either of them separately, and which leads to some curious considerations. This impression is sometimes most agreeable, at others harsh and grating, and according to these sensations the sounds are said to be in concordance or discordance. But the remarkable fact is, that this impression of concord will be experienced whenever the number of vibrations of the individual notes are in some near relation to each other, as 1 to 2, 1 to 3, 2 to 3, &c., that is, where one string makes two, three, or four vibrations, while the other makes one, or accomplishes three while the other accomplishes two or four; and the concord is the more perfect and pleasing the lower the terms of these ratios are. But if on the contrary the times of vibration, or number of vibrations in a given time, have not a low numerical ratio to each other, but one in which the terms are considerable, as 8 to 15, that is, one string executing fifteen vibrations while the other executes only eight, then there is a discord, the impression on the ear is harsh and disagreeable.

The whole of harmony consists in following out these laws; any combinations of sounds which violate them cannot be agreeable. The pleasure of these harmonious sounds depends, according to Dr. Young, on a love of order and a predilection for a regular recurrence of sensations, primitively implanted in the human mind. Hence, when two sounds occur together, those proportions are most satisfactory to the ear which exhibit a recurrence of a more or less perfect coincidence at the shortest intervals. This same constitution of the human mind which fits it for the perception of harmony, appears also to be the cause of the love of rhythm, or of a regular succession of any impressions whatever, at equal intervals of time. And a great part of the pleasure of dancing is derived from the recurrence of sensations and actions at regular periods of time.*

136. *Musical Scale.*—The unison, that is, the note from strings whose vibrations have the ratio 1 to 1, is the most simple concord; next to this is the concord in which the vibrations are as 2 to 1; or when one string performs two vibrations for each single one of the other; which will, as we have seen, be the case when one string is half the length of the other. This concord is termed an octave. The highness or lowness of a note depends on the rapidity of the vibrations: having fixed on some one tone we may have an octave higher, that is, a note in which the vibrations are twice as fast, or an octave lower, that is, a note in which the vibrations are half as fast. Thus the musical scale may be extended each way by a repetition of similar octaves, in each of which the vibrations are twice as many as in the octave below, and half as many as in the octave above.

The human voice in attempting to rise from one octave to the next, proceeds naturally by a regular series of steps, as it were, or succession of sounds. This natural series of sounds constitutes the scale of music, which has been adopted by all nations in all ages. The series of sounds, from the lowest to the highest, which we are capable of detecting, consists of an infinite number of sounds; but the natural feelings of the voice and the ear being consulted, we have the whole series formed into periods of seven sounds, such that, starting from the lowest, if the 1st and the 8th be sounded together, they will be so confounded that an ordinary ear will distinguish but one sound. The same will be the case with the 2nd and 9th; the 3rd and

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* See *Nat. Phil.* Lecture xxxiii.

10th, and so on. Each of these periods being an octave, we may, in conformity with the preceding principles, assign to each note of this scale the length of the strings and the number of vibrations which correspond to it.

Suppose then that we have a musical string stretched in the usual manner, and made to vibrate. Let its sound be called the lowest or fundamental note, and let the number of its vibrations be unity, and its length be unity. Then the octave higher being sounded, the number of vibrations will be expressed by 2, and the length of the string consequently by $\frac{1}{2}$. The intermediate notes being sounded we may measure the length of the string, and the number of vibrations being inversely as the length, will consequently be known. The following table shews at once the respective designations of the notes of an octave, the lengths of the strings, and the number of vibrations.

English characters....	C	D	E	F	G	A	B	C
Continental sounds....	*ut*	*ré*	*mi*	*fa*	*sol*	*la*	*si*	*ut*
Length of strings.....	1	$\frac{8}{9}$	$\frac{4}{5}$	$\frac{3}{4}$	$\frac{2}{3}$	$\frac{3}{5}$	$\frac{8}{15}$	$\frac{1}{2}$
Number of vibrations..	1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$	2

137. ***Beats.***—The phenomena of beats in music furnish us with most direct proofs of the interference of sound. The transmission of sound being by undulations, we may conceive two undulations to exist exactly similar, and to produce simultaneous impulses in the same direction, so that the effect on the ear will be double what either would have produced separately. Here one sound wave is augmented by the addition of another. But we may also readily conceive cases in which one sound wave may interfere with, that is, diminish the effect of another, so that the resulting effect on the ear is less than either would have produced had it alone existed. For suppose two disturbances propagated in air to travel in the same direction along the same line; it may so happen that the

series of particles situated along the line are solicited in opposite directions at the same instant, by one wave in one direction, and by the other in the contrary direction; the wave then which the combined motion would transmit will undergo considerable modification from this action. And it may even happen that the motions of the particles are absolutely destroyed, and consequently, that no wave will be propagated, or no sound come to the ear. Of this several remarkable instances occur in the vibration of musical strings, and in other cases.

Suppose two strings to be so nearly in unison that one performs 100 vibrations while the other performs 101. Their first few vibrations will conspire and produce a sound wave, such that the effect on the ear will be double. But at the 50th vibration one string will be half a vibration in advance of the other, that is, the motions of the strings will be at this instant in exactly opposite directions, and consequently the motion of the aerial particles in the two waves, one of which is produced by each string, will not be in the same, but in opposite directions; and the two waves being supposed exactly equal, they will interfere and exactly destroy each other. At this instant then the ear can receive no sound. The same will be partially the case for many vibrations on each side of the 50th; there will then be a general decay of sound up to this point, and it will gradually increase up to the 100th, when one string having gained *one* vibration on the other, the motions of the particles will be exactly in the same direction, and the sound wave will consequently be double.

The general effect on the ear then resulting from two such strings will be an intermitting sound, alternately loud and faint. These alternate subsidences and augmentations of sound are termed by musicians *beats*. The nearer the strings are in unison the longer will be the interval between the beats; and perfect harmony consists in the complete destruction of beats by tuning the strings to unison. If the notes differ much from each other, or the unison be very defective, these alternations cause a disagreeable rattle, which is only removed by preventing the interference of opposite waves.

138. *Musical Instruments.*—The laws which have just been so fully stated with respect to musical sounds and strings will be at once recognised in all musical sounds in whatever manner produced. In the bell, for instance, or whenever the sound originates from a similar cause, the vibration of a metallic mass, the tone depends on the rapidity with which the vibrations are executed, and on its mass. The large church bell gives us a very deep low sound, because of the slowness of the vibrations. The mass of metal which is here set in motion may be considered as composed of circular rings of different diameters, which, when separate, would perform their vibrations in different times, but which, owing to their connexion, take a mean undulation or motion of vibration; the size of the rings enables them to make extended excursions, which being executed with a certain slowness, give deepness to the resulting tone. But in a small bell the circular zones are incomparably less; their vibrations being then much less extended are performed in less time. For a very deep tone there must be a mass of metal and a consequent slowness of vibration; and the tone will be higher as the metal is less, and the rapidity of vibration greater. Bells may be combined so as to have the natural musical relations, and thus produce harmonious sounds.

In wind instruments the sound is produced by the vibrations of a column of air contained in a straight or crooked pipe, and having openings by which the sound waves can diverge. The simplest method of producing a musical note from a column of air is by blowing across the end of a reed or pipe; the edge will catch some of the current, and diverting it downwards will produce a series of alternate condensations and rarefactions, which being reflected at the closed end will produce a musical note. The tone emitted by a pipe depends on the dimensions of the contained column, as well as on the magnitude and form of the orifice, by which the communication is effected. The tone is deeper or more grave when the column of air is large and long, and becomes higher in proportion as it is shortened. Thus in an organ there are pipes of very different lengths. In a flute the column is lengthened or shortened, by closing or opening the holes, and it appears both from theory and experiment that a tube open at both ends gives the same note as one of half the length whose end is closed. The lowest or fundamental note being sounded by blowing steadily across a pipe, if the blast be increased the note will start up an octave higher; and there are here, as well as in vibrating strings, limits to the powers of the ear; or vibrations which, so far as we are concerned, are as if they did not exist.

Nearly all solid bodies have a note peculiar to themselves; particular panes in the window will rattle to particular notes of an organ; the glasses in a room may be set in vibration, and sometimes broken, by singing into them; each portion of inanimate matter appears to have some note to which it responds. It is from a principle analogous to this that the sounding boards and cases of instruments are so essential; the vibrations transmitted directly or through the air to these substances strengthen the sound of the instrument, since they cause larger sound waves than could be generated by the single strings. The co-existence of vibrations, their isochronism and sympathy, and all the phenomena of nodal sections, are questions into which we cannot possibly enter; but enough we hope has been said to place the principal phenomena of sound in a distinct point of view, and to establish the general laws of its propagation.

CHAPTER IX.

ON HEAT.

SECTION I.

PRELIMINARY REMARKS—TEMPERATURE—THERMOMETERS—EXPANSION OF SOLIDS—COMPENSATION PENDULUM—ILLUSTRATIONS.

139. THE phenomena and laws of gravity having been considered, those of heat are unquestionably the most universal. Its agency is to be recognised every where, and has been already alluded to as the probable cause of the three different states, as solid, liquid, or gaseous, in which matter may exist. Of this important agent we propose to treat in the present chapter; and that the student may not be embarrassed by any unnecessary difficulties, we shall defer for the present all hypothesis respecting the nature of heat, and commence with the phenomena which present themselves naturally for every one's consideration.

Every substance in nature is capable of exciting or producing in us those peculiar sensations to which the terms heat and cold have been applied. These sensations may be produced either by what we consider immediate contact, or at great distances, and their peculiar character forbids our considering the particles of mere matter as the cause. We readily admit that it is not the material particles of the coals composing the fire which reach and warm us, or the constituent matter of the sun, which by its action on our bodies produces the sensation of heat, and on our eyes the sensations referred to light. There is then an *agent*, distinct from the peculiar substance of the body, residing in their masses, transmitting itself to great distances, and establishing betwixt us and it a continual communication; which agent is the *cause* of the sensations we experience. This unknown agent has received different names; it is sometimes called *heat*, thereby confounding cause and effect. This, however, in general, leads to no confusion; but the term *caloric* may be used specifically for the agent, while the term heat is confined to designate the science which treats of the properties, the effects, and the laws, of caloric. It is not necessary rigidly to observe these distinctions; and in the following pages we shall, in conformity to the more established usage, continue to employ the word heat, both with reference to the cause and the effect; the preceding explanation will preclude any misapprehension which might arise in the mind of the student from this apparent confusion in terms.

Of the effect and influence of heat on our own organized bodies we are perfectly sensible; but it likewise acts on all inorganic substances. Ice melts, water boils, iron becomes red hot and passes into a fluid state; these and many other phenomena have necessarily a cause, and our senses inform us that this cause is caloric. There exists such a correspondence, such a simultaneous action, between the modifications of these substances and the changes in our sensations, that we feel no hesitation in forming this opinion. These considerations enable us at once to class the phenomena, and they may be referred to the following heads: the physical effects of heat, as shewn in the dilatation and change of state of substances; the propagation of heat; the quantity of heat which substances contain; and the production of heat and cold.

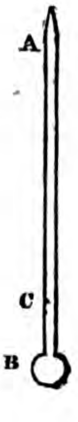
140. *Temperature.*—All bodies can produce in us the sensation of heat or cold, and the degree of heat or of cold produced is to a certain extent an indication of the state of

the body with respect to heat. This state of the body is expressed by the word *temperature*. Let us suppose that all the bodies in the room produce the same sensation of heat or cold on touching them; let the circumstances be changed, as by the introduction of a hot body; the substances will now all give the sensation of greater heat or less cold, that is, their state with reference to heat or their temperature is changed, being raised in this instance. Thus, whenever from any change of circumstances there is a gain or a loss of heat, the temperature is said to be higher or lower. In the preceding we have referred to our sensations as the test; for it is from these that all our knowledge originally comes; but, from causes to be hereafter mentioned, though they are admirable indicators of the existence of certain changes, yet they indicate most inaccurately the sensible amount of those changes; they enable us to say at two successive instants that this body is gaining or losing heat, but they will lead us into the greatest errors if we attempt by comparing two sensations separated by any interval, to deduce from them any information respecting the intensity of the cause which is in action. Recourse must therefore be had to some of the uniform changes which heat produces, and among these none are so easily observed, or so accurately measured, as the change in volume. All bodies dilate when heat is added to them, that is, when the temperature increases; and contract when heat is taken from them, that is, when their temperature diminishes; and return to the same volume under the same degrees of heat. Various instruments have been contrived for this purpose, and called thermometers; an explanation of some of which will fully illustrate the preceding remarks.

141. *Thermometers.*—Certain substances are preferable to others for the purpose of measuring degrees of heat; and the circumstances to which they are to be applied will at once point out which can best be used. Solids, for instance, dilate very little, so that small changes in tem-

perature would not make any sensible difference in their volume; hence they are only used when great degrees of heat are to be measured. Gases, on the contrary, undergo very great changes of volume for small degrees of heat; hence, they are peculiarly adapted for measuring those small changes which a solid would never indicate. But liquids occupy an intermediate rank, they dilate more than solids, and less than gases, and can be enclosed in vessels of the shape best adapted for observing variations in their volume; these are consequently most used for measuring ordinary variations of temperature. Any liquid will do for this purpose, but some are much preferable to others; uniformity of expansion is the great point to be gained, and mercury possesses this in a remarkable degree. For all ordinary temperatures, that is, from the boiling to the freezing point, its expansion is remarkably regular and uniform; and even beyond these points its indications may be relied on. But when intense cold is to be observed, spirits of wine, or pure alcohol, must be used, since it retains its fluidity under all circumstances, whereas mercury sometimes freezes. But alcohol cannot be used to measure heat since it boils very readily. Thus we see that mercury is the liquid best adapted for ordinary purposes; we shall therefore briefly shew how it can be best applied for this purpose.

142. *Common Mercurial Thermometer.*—The accompanying figure represents the common thermometer, in which the mercury fills the bulb B and part of the stem A B to a point C. The stem is a tube of exceedingly small bore, and the height at which the mercury stands in this stem will depend on the temperature. For if the bulb B be warmed, the mercury in its interior will expand and rise up the tube; and when the bulb is cooled it will contract; the bulb, consequently, will be able to hold some of that in the tube, and the mercury will consequently descend. Thus, variations in tempera-



ture produce corresponding variations in the volume of the liquid, which are, by this contrivance, immediately observable. The diameter of the tube is very small compared with the diameter of the bulb; hence the slightest variation in the volume of the mercury in the bulb produces a great and sensible variation in the height of the column. Whenever a thermometer stands at the same point, that is, when the mercury is at the same state of volume, the temperature is the same. If another thermometer be observed, the two will rise and fall together, but the amount of this rise and fall may be very different. If the bulbs are exactly the same size, and the stems of exactly the same diameter, then will the rise and fall be exactly equal in the two; but if there be the slightest difference, and it is impossible to conceive two exactly alike, the amount of rise and fall will be very different. Thus, suppose the bulb of one to contain twice as much mercury as the bulb of the other, the diameters of their stems being equal; then if the mercury in each bulb is increased by the same fraction of its volume, the one will be twice as much increased as the other; hence the one will rise twice as much in the tube as the other. But all this difficulty, apparently so insuperable, is removed by the graduation, which enables us to express the changes by numbers, and thus to compare different temperatures under different circumstances, and so ascertain some of the laws of heat.

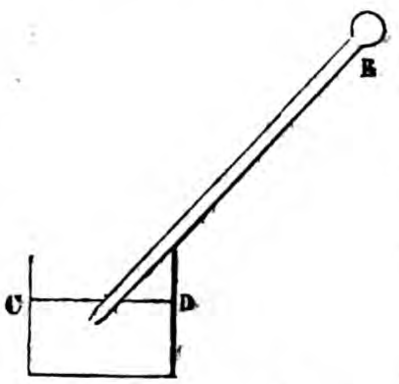
143. *Graduation.*—The principle of the graduation of thermometers depends on the fact, that there are certain phenomena which invariably present themselves at the same temperature. Thus, if the bulb of a thermometer be held in the palm of the hand, it will be seen to rise, more or less, according to the temperature of the hand. But if it be held for some time, the hand being tightly closed about it, the mercury will rise very slowly to a certain point, continue at this point, and never pass it. At all seasons, in all climates, and in the hands of all individuals, it will stop at the same point, or very nearly. Thus the tem-

perature of the human body is a constant temperature, it affords a *fixed point* which may be taken as the point of starting for the numerical estimate of temperature. There are, however, other phenomena which are more accurately constant, and to which therefore it is better to have recourse. Thus in melting ice a thermometer returns always exactly to the same point, whether the ice be formed artificially or naturally, at the top of mountains, in the sea, or in rivers; provided the ice be pure, its point of fusion is a point perfectly fixed. The same holds for other substances, as iron, lead, wax, &c., in their passage from the solid to the fluid state; each has its fixed point of fusion, so that their temperature is then always the same.

Boiling water presents an analagous phenomenon; the water having once arrived at the point when ebullition commences, however much the fire be urged the ebullition will proceed more rapidly, but the water will not become warmer; the thermometer rests perfectly invariable at the same point. Under the *same barometric pressure* (Art. 93), in all parts of the world, water in ebullition will give the same fixed point. The same holds for all liquids at their passage from a state of liquid to a state of vapour; each has its own fixed point, which is invariable for the same barometric pressure.

Conceive now that two fixed points have been chosen, viz. that of melting ice and that of boiling water. The distance between these two points may be divided in any manner; thus we shall have an arbitrary scale whereby to compare degrees of temperature between these two known points. It will be seen that the actual size of the thermometer is of no importance, the two fixed points are determined on each, and the intermediate space is divided into the same number of equal divisions. The temperature then is indicated by the number of divisions from a given point without any reference whatever to the absolute magnitude of these divisions.

144. *Construction of the Thermometer.*—The filling a tube so that it may be used as a thermometer, requires several simple operations easy of execution, and illustrative of the preceding principles, which may with advantage be briefly detailed. The tube must be prepared, filled with mercury, closed, and graduated. The tube must have a uniform bore, otherwise equal lengths will not contain equal quantities of mercury. This is readily ascertained by observing whether a small quantity of the liquid always occupies the same length. One end then being blown out into a bulb, the tube is complete. To introduce the mercury, the bulb and stem being warmed so as to dilate the air, the open end is suddenly plunged into a basin of mercury, as represented in the figure. The bulb and tube being allowed to cool, the elasticity of the internal air is diminished, and the atmosphere pressing on the surface, C D, of the mercury in the basin, forces it up the tube into the bulb. A few drops of mercury being thus introduced into the bulb B, the whole is again heated, so that the mercury expanding expels the air, and occupies the whole tube. The open end is then again plunged in a basin of mercury, and as the tube cools more mercury is forced in and entirely fills the tube. The proper quantity having been thus introduced, the tube is again warmed so as to expel all the air; and when the mercury first rises to the top of the stem, the orifice is closed by darting the fine pointed flame from a blow pipe across the end; the glass is fused, and the end completely stopped. To graduate the stem, we have to determine the two fixed points of melting ice and boiling water. The thermometer is placed as represented in the figure in a vessel of pounded ice



or snow. The surrounding temperature being above freezing, the ice or snow begins to thaw, and the mercury takes a fixed position, from which it does not stir till *all* the ice or snow is melted. This then is the freezing point. For the boiling point, the thermometer is placed with its bulb in distilled or pure water; the water then being made to boil, the steam or vapour rising up envelopes the stem and passes rapidly off. Soon the column arrives at a fixed point; and does not stir so long as the boiling is continued. The height of the barometer must be observed during this operation, since the atmospheric pressure influences the temperature at which water presents the appearance of boiling, that is, the position of the boiling point. These two points then having been fixed, the intermediate space is to be divided, and different philosophers have chosen different divisions and methods of numbering. The space in Fahrenheit's thermometer is divided into 180 equal parts, called degrees; the freezing point is called 32, so that the boiling point is marked 212. In the centrigrade thermometer the distance is divided into 100, and in Reaumur into 80; in both these the freezing point is zero, or nothing, so that the boiling point is 100, in the one, and 80 in the other. The magnitude of each division having been determined in this manner, the gradation is extended both ways, that is, above and below the boiling and freezing points, so that the scale being once established, higher and lower temperatures may be measured. The scale of Fahrenheit is generally used in this country, and that of Reaumur on the continent; hence it is desirable to be able to change the numbers of one scale into the other so as to compare the temperature.

The requisite rules may be deduced at once by a simple proportion according to the division which has been adopted in each of the preceding cases; they are the following.

To convert Fahrenheit into Reaumur, 'Subtract 32° from the proposed number, and multiply the remainder by $\frac{4}{9}$;' the result will be the corresponding number, of degrees according to Reaumur's division. Thus, suppose that the temperature as shewn according to Fahrenheit's division is 77°, that is, 77° F., as we shall generally write it; then subtracting 32, the remainder is 45, and this being multiplied by $\frac{4}{9}$ becomes 20; the same temperature therefore would, according to Reaumur's division, be 20° R.

To convert Reaumur into Fahrenheit, 'Multiply the proposed number by $\frac{9}{4}$, that is $2\frac{1}{4}$, and to the result add 32;' the sum is the number of degrees according to the Fahrenheit division; thus, suppose that the proposed temperature is 24° R.; then multiplying 24 by $\frac{9}{4}$ the result is 54; and adding 32, their sum is 86; the same temperature would therefore be 86° F. according to Fahrenheit's division.[*] Similar rules may be given for the other four cases, but it is not necessary to dwell upon them.

The effects of the increase of heat in expanding, and of its diminution in contracting liquids, will be sufficiently apparent from the preceding remarks, so that the construction of a thermometer with any other liquid, as alcohol, may readily be conceived. The mercurial thermometer answers extremely well for all ordinary temperatures; as we approach however the boiling and freezing points of mercury, or 660° above, and 39° below the zero of Fahrenheit, the laws of expansion and contraction no longer preserve their uniformity. For intense cold an alcohol thermometer is used. The effect of heat and the methods to be adopted for its measurement will be sufficiently illustrated in the following articles.

145. *Dilatation of Solids.*—The laws which the con-

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[*] All the six rules are comprised in the following formula:

$$\tfrac{1}{9}\,(\text{F}^{\circ}. - 32) = \tfrac{1}{4}\,\text{R}^{\circ}. = \tfrac{1}{5}\,\text{C}^{\circ}.$$

for the proof of which see *Principles of Hydrostatics*, Art. 139.

traction and expansion of solids follow has been accurately ascertained, and made subservient to many useful purposes. This fact will be rendered apparent by the simplest experiments; a piece of metal which accurately fits a hole, or goes into an interstice, will not be able to enter when heated; and again, a ring which fits very well when hot will be much too small when it has become cold. Great use is made of this property in the hooping of casks, and in the tiring of wheels. The hoop or tire being driven on when warm, contracts as it cools, and embraces the woodwork very forcibly. There is a notable instance of the application of this principle for the preservation of a large building. The walls of the Conservatoire des Arts et Metiers at Paris were observed to bulge, being pushed out by the roof. Iron bars were placed across the building, and the walls were effectually prevented from bulging any farther by broad plates on the outside, which were screwed up on the ends of these bars. Every alternate bar was then heated by several lamps in the middle, the consequence of which being an increase in its length, the plates were no longer in close contact with the exterior walls; the plates were then screwed up close to the wall, and the bars being allowed to cool drew the walls gradually together. The others were then heated, and the same effect being produced, the walls were brought nearly into their vertical position, and in which they still remain. The variation of metals for every variation in temperature is an inconceivable perplexity in all very accurate operations. Thus, in astronomical instruments, where very small variations can be detected, the presence of a candle will, by unequal warming, sometimes cause a distortion, which may sensibly affect the accuracy of the observations.

146. *Compensation Pendulums.*—The object which the compensation pendulum is designed to effect having been already briefly pointed out (Art. 56), we shall now endeavour to make intelligible the way in which this is effected,

since it furnishes a good practical example of the laws of the expansion and contraction of solid bodies from changes of temperature. In the accompanying figure the point of suspension is supposed to be at A, and the bob B is sustained directly by the rod *a b*, which can move through a hole in C D, and connected with the point A of suspension by the frame-work, as will be seen at once from the figure. The outer bars E C, F D, are of iron; when these expand they lower the piece C D, and consequently the bob. The inner bars at *c* and *d* are of brass; when these expand they elevate the piece *c d*, and consequently the point *a* and the bob; the suspension bar *a b* sliding freely through a hole at *b*. Now since brass expands more than iron, the depression of B consequent on the expansion of the longer iron bars may be exactly counteracted by the elevation of B consequent on the expansion of the shorter brass bars. Thus the centre of oscillation of the whole pendulum, which will lie within the bob, may be kept at exactly the same distance from the point of suspension, notwithstanding the incessant variations of temperature to which the pendulum is subject.

Another application of the same principle to produce the same effect deserves to be noticed. Two small bars, or strips of brass and iron, as nearly equal as can be procured, are soldered together, or fastened to each other by small screws. The temperatures being raised, the brass expands more than the iron, and throws the compound plate into the curved form which is represented in the upper figure. The temperature being lowered, the brass contracts more than the iron, and the plate takes the form shewn in the lower

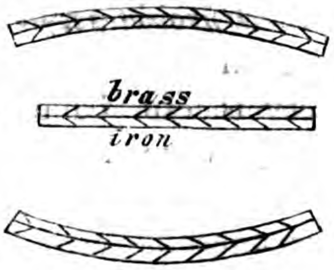
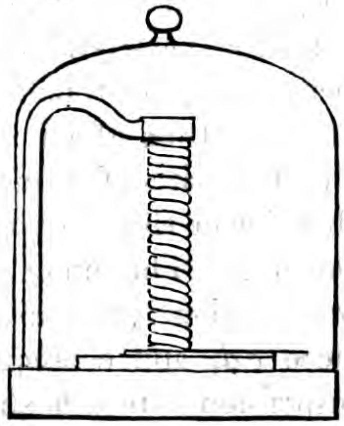


figure. If now the pendulum be suspended to the centre of this mass, the variations in the position of the centre of oscillation may be prevented; the lengthening or shortening of the pendulum rod may be compensated by the upward or downward flexure of the plates.

147. *Breguet's Thermometer.*— This most delicate thermometer consists of a ribbon of metal wound into a spiral form, as in the figure. The spiral is attached at one extremity to a metal support, and carries at the other a very light needle, which points to a graduated circle. The whole is covered by a bell glass to guard it against currents of air which would agitate it. The spiral ribbon is composed of three metals, silver, gold, and platinum. A thin bar of silver and platinum is soldered on each side of one of gold; the whole is then rolled out into an inconceivable thinness, so that it takes at once the temperature of the surrounding air. From the unequal dilation of the silver and platinum the spiral twists or untwists according as the temperature rises or falls, and the needle obeying these motions points out the degrees of change. The instrument is graduated by comparing the motion of the needle with the changes of a delicate mercurial thermometer.



148. *Pyrometers.*—Those instruments which can be used to measure high temperatures are called pyrometers; and by the term high temperatures we generally understand all those which are near to, or above, the boiling point of mercury, that is, above 660° F. The substances which must be used for this purpose are either solid or gaseous; the former have hitherto been employed exclusively, though the great uniformity with which the latter expand renders them on this account preferable. The action of most pyrometers depends on the elongation of a metallic

bar by heat, and the objections to which they are liable arise from the difficulty of finding a metal of uniform expansibility, and not readily fusible, and of measuring with accuracy the amount of the expansion. The pyrometer of Daniell is the one which appears best adapted for general purposes; it consists of a bar of platinum inserted in a piece of black lead earthenware; this substance expands less rapidly than the metal, and there is an index by which the difference of the elongation of the platinum bar and of the black lead case which contains it can be measured. The bar does not expand quite uniformly, but the different degrees of elongation furnish a good practical test of the relative intensity of different fires. All argillaceous substances apparently contract at first on being exposed to heat; hence the earthenware case will be unfit for use until it has been well baked up to the highest temperature at which it is generally used. The expansions of the case will then be exceedingly small for the increase of temperature.

The pyrometer of Wedgewood acts on a very different principle, namely, the property which has been already alluded to of the contraction of an argillaceous substance, as the water becomes gradually dissipated on exposure to high temperatures. The contraction continues even after every trace of water has been removed, in consequence of the partial vitrifaction which takes place, and tends to bring the particles into greater proximity. This contraction will furnish us with some measure of the intensity of the heat. There must, however, be a different piece of clay for every observation; hence no accurate comparison of temperatures can be established, and recourse is at present had to the changes produced on a metallic bar, by which comparative changes are very accurately measured; the pyrometer of Daniell being, as we have just seen, very well adapted for this purpose.

149. *Illustrations.*—Every one must have observed the breakage of glass and porcelain vessels from any sudden

change of temperature; this is entirely due to unequal expansion and contraction, as may be readily shewn. Glass conducts heat so slowly that one side of a vessel may become much heated, and consequently expanded, while the other remains much colder; and if the vessel cannot readily accommodate its form to this change of proportions, it will most certainly crack; the colder part divides in consequence of its being too much stretched by the adjoining hot parts. Hence, the thinner the glass, the more readily does it acquire the temperature, and the less liable is it to crack from any sudden expansion; and if it be very thick it must crack, for no flexure which it can assume can be sufficient for the equilibrium of the external parts without being too great for that of the parts near the middle.

When glass in fusion is suddenly cooled, its external parts become solid first, and determine the magnitude of the whole piece. The internal part as it cools is disposed to contract still farther, but its contraction is prevented by the resistance of the external parts, which form an arch or vault round it, so that the whole is left in a state of constraint, and as soon as the equilibrium is destroyed in any one part the whole mass breaks up. Hence it becomes necessary to anneal all glass by placing it in an oven where it is allowed to cool slowly; for without this precaution a very slight cause would destroy it. The small glass drops called Prince Rupert's drops, which are formed by suffering a portion of green glass in fusion to fall into water, remain in equilibrium while they are entire; but when the small projecting part is broken off the whole rushes together with great force, and the particles rebounding by their elasticity, an explosion appears to have taken place.

The tempering of metals bears considerable analogy to the annealing of glass; when they are made red hot and suddenly cooled they acquire a degree of hardness which renders them useful for some purposes, but, owing to the accompanying brittleness, extremely inconvenient for others.

By heating them again to a more moderate temperature, and suffering them to cool more gradually, they are rendered softer and more flexible. The colours which appear at the surface of polished iron or steel serve as a test of the degree of heat which is applied to it; the yellowish colour indicates the first stage of tempering, the violet the second, and the blue the last: and if the heat be raised until the surface becomes grey, the steel will be rendered perfectly soft. All these phenomena appear to result from the unequal distributions of the mutual actions of the particles; but it would be useless to hazard conjecture on these subjects.

The expansion or dilatation of all bodies for an increased temperature, and their contraction when the temperature is diminished, are general laws of all matter, and any apparent exceptions arise from some peculiar circumstances which may readily be pointed out. For instance, some vegetable and animal substances contract when we might expect that they would expand; there is here a loss of some fluid from the effects of this heat. Similarly moist earths are often seen to contract; but this results from the fact that the water which they contain passes off very rapidly in the invisible form of vapour, so that the contraction from drying is greater than, or overbalances, the expansion due to the increased temperature. The remarkable exception to this law in water has been already noticed. For about eight or ten degrees from the freezing point water gradually contracts as its temperature is raised; but at about 40° F. this contraction ceases, and it expands for every additional degree of temperature; if the water is cooled from a temperature above 40° F. the phenomena are exactly the converse; it contracts to about this point, when, on lowering the temperature farther, it begins to expand. These phenomena may be very readily observed in any thermometer tube, having a small bore and large bulb containing water. The least change in the temperature will occasion a most sensible variation in the position of the water in the tube. The presence of any foreign substance, as a salt in any liquid, modifies the preceding phenomena; this is evidently to be referred to the change in the respective positions of the particles which always accompanies a change of state.

One most important consequence resulting from these laws of fluids is, the circulation which takes place in consequence of the change in the specific gravity of any substance which expands or contracts. The volume or space which any number of particles occupy being changed, they rise or fall according as the mass has become lighter or heavier than the bulk of the fluid displaced. Hence in every mass of fluid there are constant currents from the changes which are taking place in the temperature of certain portions; in the great ocean of the atmosphere masses of air will always be ascending and descending, according as their bulk is being increased or diminished from the constant changes of temperature to which different portions are subject, as we have already seen in speaking of the equilibrium of the atmosphere.

One of the most important illustrations of the preceding principles is that furnished by the warming and ventilating of our dwelling-houses, conservatories, and public buildings. We have already seen how the draught of a large chimney is caused by the dilatation occasioned by heat in the long column of air which it contains; this and other causes give rise to all the circulation which is necessary that a room may be properly warmed and ventilated. The fire cannot burn without a constant supply of fresh air, and all this takes place in obedience to the simple law that a light fluid will rise in a heavier; the atmosphere of a room becomes unwholesome unless the air can be constantly changed, and this is effected by affording facilities for the operation of the preceding law. The unwholesome air rises to the top of the room and should be allowed to escape through an opening in the ceiling. The art of ventilation consists in properly apportioning the requisite supplies of fresh air; if too much is admitted the room becomes cooled unnecessarily, which will lead to a wasteful expenditure of fuel; if too little, the room feels close, and the air becomes unfit for healthy respiration. On the details of this great question we cannot enter; we have alluded to it only with the view of impressing on the student's attention the constant applications which exist of the laws of nature here referred to.

SECTION II.

CHANGE OF STATE—LATENT HEAT—FREEZING MIXTURES—EBULLITION AND EVAPORATION—STEAM ENGINE—LAWS OF VAPOUR—MAXIMUM FUSION—LIQUEFACTION OF GASES—COLD PRODUCED BY EVAPORATION.

IT will readily be admitted that *fusion*, or the passage from the solid to the fluid state, is a phenomenon produced entirely by heat, and that no other cause in nature can bring about this change of state; ice may be broken and reduced to a powder, it may be subjected to all the mechanical powers and natural agents, but it will still be a solid unless heat exerts its action upon it to convert it into water. It is the same with wax, and when melting in the rays of the sun we are certain that it is the heat and not the light which produces this change; and if lead becomes liquid by being hammered on an anvil, it is because of the heat developed by the compression consequent on percussion. Thus the state of solidity or of fluidity of a body is a relative state, and depends entirely on the temperature to which the body is subject. At a different distance from the sun our earth would be of a very different consistency and aspect. Were it nearer, most of the metals would be in an habitual state of fusion, and the bottom of the sea, instead of being filled with water, might as well be filled with liquefied metallic substances; were it on the contrary farther off, the sea would be a solid mass; there would not be any running water, or sufficient liquid for the purposes of life and vegetation.

Since heat penetrates and dilates all substances, it is an interesting question, whether it can convert them all into a liquid state. In examining under this point of view solid bodies, we meet with remarkable differences; some are very fusible, and cannot sustain even very low temperatures without passing into the liquid form; such are ice, phosphorus, sulphur, wax, all fat and resinous substances; there are others which require temperatures more elevated to melt them, such are pewter, lead, and various alloys; others, as gold, iron, platinum, cannot be brought into a state of fusion except by the very highest temperatures, continued for a very long time. Those bodies which resist the greatest degrees of heat are called infusible; but as our means of producing heat increase, their number diminishes. Carbon or charcoal appears to be the most refractory, though some experimentalists appear to have detected slight traces of fusion in the diamond. We are bound, however, to conclude from analogy that there are no bodies absolutely infusible. Organic substances being in general composed of carbon and gaseous elements, more or less volatile, are frequently readily decomposed by the action of the fire, though not liquefied. Thus wood burnt in a furnace is carbonised, but not melted; the same is the case with fruits, flowers, and vegetables, and with the muscles and fibres of animal existence. All organic substances are decomposed by heat; their volatile essences fly off, and there remains nought but carbon and other fixed elements or bases. Many inorganic bodies also are decomposed before being melted, and their fusibility has been shewn by the ingenious experiments of Hall. He heated bodies, keeping them under great pressure, thereby preventing their volatile essences from separating and flying off. In this manner Hall succeeded in melting marble without converting it into chalk, and in the same manner he has shewn the fusibility of several volcanic substances. These results are of the greatest importance in considering the origin and formation of the different strata of the earth.

151. *Fluidity the consequence of Heat.*—From the preceding statements it appears that whenever a solid body is converted into a liquid a much greater quantity of heat enters into it than can be detected by the thermometer; heat, which before entering into the substance was sensible, has on entering into it become insensible. When a liquid assumes the gaseous form there is no difference between the apparent temperature of the liquid and of the invisible vapour which rises from it; yet it is certain that the vapour contains great quantities of heat; for the heat is given out again when the vapour returns to the liquid form. These facts led Black to the hypothesis that the presence of this great quantity of heat is the principal and immediate cause of the fluidity induced; or, in other words, that the fluidity of a body is entirely produced by the infusion of a certain quantity of heat, which causes no change in the temperature, but only in the state of the substance. Thus the infusion of a certain dose of heat will cause ice of the temperature of 32° F. to become water of 32° F.; and similarly a certain quantity of heat causes water of 212° F. to become steam of the same temperature.

152. *Conditions of Fusion. Latent Heat.*—In the passage of a substance from a solid to a liquid, or from a liquid to a gaseous state, two remarkable phenomena occur; first, the substance remains solid or liquid until it has arrived at a certain fixed temperature, which is always the same for the same substance, and then only is it that the fusion can commence; secondly, it retains the same temperature during fusion whatever quantity of heat is supplied. The heat so absorbed, while the substance is

passing into a liquid or gaseous state, seems, as it were, to become concealed among the particles. Thus a *fixed point of temperature* and the *absorption of heat* are the two essential conditions of fusion; all fusion is accompanied by these two phenomena. The heat which then disappears is termed *latent heat;* for it evidently exists in a very different state from that which is sensible to the hand, or to the thermometer. Thus, as we have already seen, a mass of ice or snow retains invariably the same temperature, till the whole is melted. Before these conditions were distinctly understood, it was reasonably enough expected, that ice would melt at different temperatures, according to the latitude or the place in which it is formed. The quantity of latent heat which a body absorbs in fusion, evidently depends on the mass of the body melted, but we shall see hereafter that different bodies, though equal in mass, require very different quantities of latent heat; and that each substance has as distinct a character with reference to heat as that which it derives from its density, or from any other of the primitive qualities of matter.

The same phenomena occur also in the passage of a liquid into vapour. The temperature, as we have seen, comes to a stand, and the vapour is of the same temperature as the water from which it is formed, but equal weights of the two contain very different quantities of heat. The vapour absorbs very great quantities of heat, as is most distinctly proved by its being given out again in condensation, that is, when the vapour returns to its liquid form.

These absorptions of heat in such different proportions during fusion and the formation of vapour, and its reproduction on solidification and condensation, furnish strong evidence in favour of the proposition, 'that the phenomena of latent heat are the essential conditions of every change of state.'

133. *Solidification.*—When liquids pass into the solid state there are two conditions corresponding to the preceding two of fusion; first, it takes place at a fixed temperature,

which is the same as the temperature of fusion; secondly, all the latent heat which had been absorbed during fusion is reproduced and disengaged during solidification. The first of these phenomena may be observed at once by any thermometer or pyrometer; the temperature will be at a stand and will not change during the change of state, that is, till after the solidification is complete. The second condition is shewn at once by some experiments of Fahrenheit, in which it appears that water may be cooled to 10° or 12° below the freezing point, but then on being shaken it will instantly become solid. The thermometer which indicates this low temperature will rise at the instant of this change of state to the proper temperature of that state. The rapidity of the solidification and the ascent of the thermometer are readily explicable. The latent heat of those parts which freeze first is distributed among the parts which are still liquid; their temperature is raised, not however sufficiently to prevent their change of state. Thus arises the double effect of the change of state and temperature.

In the formation of ice, when solidification takes place slowly, as at the ordinary temperature, there is no sensible disengagement of heat. When water freezes, the congelation generally commences at several points at once; at all these points the first particles which become frozen give their latent heat to the neighbouring particles, which are thus maintained in the liquid state. Thus freezing is necessarily a work of time. Hence there first appear thin layers of ice, or very fine needles or filaments which cross each other in all directions at the surface of the liquid mass. At a certain distance from the first filaments others are formed, and so on, until all the latent heat is dissipated, and cold has taken successively all the particles and united them into a solid mass. Were it not for the latent heat the solidification of bodies would be instantaneous; thus the rate of freezing must depend on the quantity of heat disengaged, and on the facility with which it can be dissipated. The same substance, during solidification, will take very different forms, according as the operation goes on naturally, or is interfered with. When the process goes on slowly and without any disturbance, crystallization generally takes place, that is, the particles arrange themselves according to some definite order, and the substance has the greatest density of which it is susceptible; but when the liquid is disturbed in any manner, the particles have not time to group and arrange themselves, but they form a solid, of which the interior is in a state of greater or less constraint. But whatever be the rate at which the solidification takes place, most bodies suffer a sudden diminution in volume at the instant of their passing into this state; water, however, is a remarkable exception to this law, and similar phenomena of expansion at the instant of solidification have been observed in one or two other substances.

104. *Freezing Mixtures.*—The theory of those mixtures by which the temperature of bodies may be reduced furnishes the best illustration of the connexion which subsists between latent heat and a change of state. The substances to be mixed are either all solid, or one of them at least is solid, and they begin to liquefy on being mixed. In the passage of any of the substances from a solid to a fluid state sensible heat becomes insensible or latent; and we shall find that whenever from any combination of particles there is a change of state or a change of volume, there is always a corresponding change in the temperature. Suppose a cup containing a mixture of salt and snow be brought into a warm room, the snow will gradually melt, but the liquefaction of the salt will cause such a reduction of temperature that the snow water will be converted into ice as fast as it is thawed. If a quantity of nitre be thrown into water its solution will reduce the temperature of the water considerably. This is the common mode of cooling wine in India; the bottle is surrounded with water containing nitre; the nitre being completely liquefied no farther reduction of temperature takes place, and the water

of the solution being evaporated, by the next day the nitre is ready for use as before.

The best freezing mixtures are made with some ice or snow; but as these cannot always be had we may produce a reduction of temperature amounting to 40° F., or even 50° F., by *five* parts of sulphate of soda, that is, glauber salts, and *four* of diluted sulphuric acid. There are numerous other mixtures for this purpose of which the student may find the elements in works on chemistry.

135. *Formation of Vapour.*—The change of state which water undergoes in the formation of vapour being due simply to the influence of heat, we must examine into what takes place during this change, and into the laws of the fluid so produced. When a liquid is heated to the fixed point of temperature (Art. 132) at which ebullition commences, we may observe a rapid formation of bubbles in all parts of the interior of the fluid, which increase in volume as they approach the surface, where they burst or pass off in invisible vapour. Their gradual increase in size, and sudden disappearance on reaching the surface, deserve particularly to be remarked. The vapour, or invisible elastic fluid, which is formed at the bottom by the immediate action of the fire, is pressed on all sides by the fluid; this pressure being proportionate to the depth diminishes as the bubble ascends; on arriving at the surface, where it comes in contact with a different medium, namely the air, the pressure is not sufficient to keep the bubble in the same definite form, as when it was entirely covered by the water. In fact, the instant the phenomenon of ebullition commences, we are certain that the elastic force of the vapour formed is exactly equal to the elastic force of the atmosphere at the surface of the water. This has already been alluded to in speaking of the effects of the atmospheric pressure.

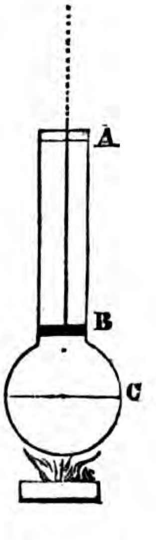
Another fact to be remarked, and one which may readily be observed if water be made to boil in any glass vessel, as in a soda water bottle, is, that the bubbles are formed entirely at the surface of the glass, where it is heated by the fire. It is to this that the disturbance consequent on ebullition is owing; the vessel being much hotter than the rest of the fluid, the water in immediate contact with the surface of the vessel is suddenly transformed into vapour, the rising up of which causes the disturbed motion of which we have spoken. Vapour is also formed at the surface of the water as well as at its lower parts, but imperceptibly, because of the uniform temperature which exists, there being no hot metallic surface to cause the rapid formation which takes place at the lower parts. This insensible or imperceptible formation of vapour, is called evaporation, and it must carefully be borne in mind that there is no real distinction in the two operations which have received these different names. The formation of vapour or evaporation is going on at all temperatures; when however the extraneous circumstances are such as to cause the rapid and violent formation of vapour, which exhibits itself in the tumultuous motion of the water, the operation is termed ebullition. The vapour formed under these circumstances, or at higher temperatures, is from the important applications which are made of it generally called steam.

156. ***Elastic, or High Pressure Steam.***—When water passes into the invisible form of vapour at a temperature of 212° F. we have stated that the vapour is generally called steam. It is convenient to distinguish the vapour formed up to this point, and that formed beyond this point, by separate names; simply because that the latter, owing to its elastic force being equal to that of the ordinary atmospheric air, may be used as a moving power, being the source of all the wonderful phenomena which are exhibited in the ordinary steam engine. Though this is a convenient distinction, and one which the circumstances of the case fully warrant, it must, nevertheless, ever be borne in mind that so far as the formation of the invisible elastic fluid is

concerned, the cases are identical: each fluid being water combined with a certain dose of caloric.

Steam cannot be generated in an open vessel of a higher temperature than 212° F.; for at this point the vapour is of the same elastic force as the atmosphere; and vapour being invariably of the same temperature as the fluid from which it is formed, and this being the fixed point of temperature for the production of steam under the ordinary atmospheric pressure, any attempt to raise the temperature of the steam is attended with no other result than an increase in the rate at which the steam is generated. If however the vessel be closed, the steam, not being able to escape as before, may acquire any temperature which we please; but inasmuch as its elastic force increases more rapidly than the temperature, the pressure of the steam against the sides of the vessel will soon become too great for the strength of the vessel. Steam produced at this higher temperature is called elastic, or high pressure steam. The term elastic being applied to it because steam at the temperature of 212° F. appears to have no elasticity; its elastic force is counterbalanced, or is in equilibrium, being exactly equal to that of the atmosphere. Similarly, the words high pressure imply that its pressure, or elastic force, as we have already explained the term (Art. 88), is greater than that of the atmosphere. The temperature then at which steam can be generated, or to which water in a close vessel can be raised, depends only on the strength of the vessel. Steam may thus be produced of an elastic force sufficient to overcome the cohesive force of the materials of the vessel in which it is generated; hence we see the cause of those dreadful explosions which sometimes occur. If from neglect, or from the safety valve having too great a load upon it (Art. 69), the temperature of the water and steam collected above it becomes too great, the vessel is rent asunder, as if burst by the expansive force of gunpowder.

157. *Steam Engine.*—It would not be consistent with the object of this work to enter upon the construction of steam engines, or the interesting history of their advancement to the present state of perfection. Either of these subjects would alone furnish materials for a very bulky volume. All that we can here attempt will be to point out distinctly and briefly the principle of the application of steam as a moving power. The application of steam as a moving power depends on the following facts. 1°. That steam from water of 212° F. exerts on the sides of any containing vessel a pressure equal to the pressure of the atmosphere. 2°. That steam from water of a higher temperature than 212° F. exerts a pressure against the sides of the containing vessel greater than the pressure of the atmosphere. 3°. That this pressure, or the elastic force of the steam, may be entirely destroyed by diminishing the temperature, when the steam will instantly return to water.



The principle of the application of steam as a moving power, founded on these facts, is well illustrated by a little instrument suggested by the celebrated Wollaston. This, as is represented in the accompanying figure, consists of a cylindrical glass tube A B, blown at the bottom into a bulb. A piston is fitted to this tube so as to move up and down with ease, but air-tight. Some water is put into the bulb, as represented at C, and suppose the piston to be at the bottom of the cylindrical tube, as at B. Suppose now that the bulb is held over a spirit lamp, or made to boil in any other way; the piston B will be driven up by the elastic force of the steam, from the water in the bulb pressing upwards on the under side of the piston with a greater force than the atmosphere presses downwards on the upper side of the piston. Suppose now that the piston has reached the top of the tube. Let the bulb be dipped in cold water; the temperature of the water will instantly fall, the steam will be condensed, and there will be a vacuum between the under side of the piston and the surface of the water. There will then be no upward pressure to counterbalance the atmospheric pressure; the latter will consequently produce its full effect, and the piston will be driven down suddenly and with a great force. The vacuum below the piston will not be quite perfect, nor will the descent of the piston be delayed until all the steam is condensed, but will commence the instant the temperature is the least lowered, so that there becomes the least appreciable difference between the upward and downward pressures. The piston having descended to the bottom, the operation may be again repeated. This alternating motion is the source of the power of the steam engine; this motion once obtained is the power which may be converted, transferred, and modified, by the intervention of machinery in any way which the circumstances of the case may require.

The illustration just given may lead us to consider the application of heat to water and the consequent production of steam as the means whereby we may avail ourselves of the weight of the atmosphere. The weight or pressure of the atmosphere may be considered as equal to 15 lbs. on every square inch; but suppose now, in consequence of the pressure on the under side not being entirely destroyed, that we have an effective pressure on the upper side of the piston amounting to 10 lbs. and that the distance through which it moves is 6 inches; then since the product of these numbers is 60, we have an available effective power equal to this quantity; then making a small deduction for friction, one-sixth suppose, we should, by means of the intervention of machinery, be able to apply the power thus obtained so as to raise *one* pound 50 inches high, or 50 lbs. *one* inch high.

The preceding statement, simple as it may appear, is the principle of the application of steam as a moving power in the steam engine, and the calculation of the power obtained. Practical considerations as to economy in fuel consumed and convenience, have led engineers to adopt modifications of this principle, on which we cannot dwell here. The application of steam of high pressure will be understood at once from the preceding illustration. Suppose that the small piston does not move easily, the elastic force of the steam which is now confined will soon become sufficient to move the piston or to burst the vessel; on this therefore we need not dwell, as it will be readily understood from what we have already stated. The principle of the steam engine may be summed up in a few words. The combustion of fuel calls into action the elastic force of steam, which is applied to produce the to and fro, or alternating motion of the piston, which has just been described. This motion through a given space constitutes power, which is by the intervention of machinery to be converted and applied in the way which will best suit the wants of man.

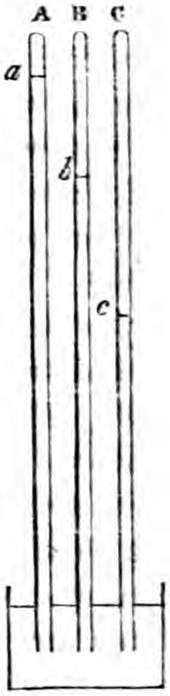
158. ***Evaporation always taking place.***—Evaporation is the slow and imperceptible formation of vapour at the surface of the water, whilst ebullition is, as we have seen, the rapid formation of vapour in the interior of the mass. This operation is going on at the surface of all water, and of all substances wherever any moisture is present. The simplest observations will shew the truth of the preceding statement. Now since the absorption of heat is the essential condition of a change of state (Art. 152), we may reasonably expect that the state of the body with reference to heat, or the rapidity with which heat can be supplied, will determine the rate of evaporation. If water in a shallow vessel be placed in a warm situation, it will diminish very rapidly by this insensible formation of vapour. The same is the case with other liquids, as may be seen by suspending particular substances above their surfaces; these substances will be acted upon and changed by the vapour. But evaporation goes on also from ice, as may be readily

proved by observing how much weight a lump of ice or a mass of snow loses in a given time, the circumstances being such that the ice or snow cannot thaw.

Evaporation is also constantly going on at the surface of many other substances besides water, or where moisture exists; as, for instance, at the surface of mercury. If small pieces of gold leaf be suspended above the surface of mercury, there will be a vapour from the mercury collected on the leaf. This natural sublimation, so to speak, of different substances, is a curious phenomenon, and must be referred entirely to the agency of heat.

The most favourable circumstances for evaporation are when the temperature of the liquid is considerably higher than the temperature of the surrounding air, and when there is but little vapour collected above, or pressing on the liquid. We shall see hereafter that there is reason for believing the evaporation to be checked simply by the vapour which is already formed. Consequently, if the vapour is removed as soon as formed, the evaporation will go on with great rapidity, as we know to be the case after a warm day when there is a brisk wind to carry off the vapour as soon as formed.

159. *The Air impedes Evaporation.*—When a liquid, as water, is exposed to the air, it generally undergoes a gradual diminution, till at last all has disappeared. Thus, the rain which falls on the earth is either absorbed by the soil, or rapidly disappears from the action of the sun and of the wind. This disappearance of a fluid, or its evaporation, was for a long time attributed to the solvent power of the atmosphere. The air was supposed to hold the water in solution just as water holds salt. It will be seen, however, that not only is the air unnecessary for the evaporation, but its presence actually impedes the process; so that the existence of vapour must be due to some other cause, and entirely independent of the air. In fact, the vapour has an independent existence, as the following experiment will shew.



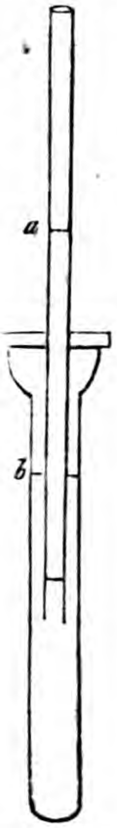
Let the figure represent three barometers, A, B, C, which give exactly the pressure of atmosphere, and all stand at the same height. Let a drop of water be forced by a bent tube into the lower part of B; it will rise to the top, and in its natural state it would occupy, on reaching the top, a very small space, as the $\frac{1}{100}$th part of an inch; but the mercurial column will instantly descend several inches, and instead of standing at the height of *a* in A, it will stand at *b*. This depression is not owing to the weight of the water, which is not sufficient to produce any sensible influence, or to any air which the water may contain, for it may be supposed free from air. It is the water itself which has formed an elastic fluid by passing into vapour, and it is the ***elastic force*** or ***tension*** of this vapour which acts on the surface of the mercury, and causes it to descend. The amount of depression is the measure of the elastic force of the vapour. If the third barometer have some ether introduced in the same way, the barometric column will probably be depressed by one-half, and stand as at *c*; whence it follows, that the elastic force of the vapour of ether is equal to about half the atmospheric pressure.

The preceding experiment establishes two important points: first, that all liquids furnish vapours of different degrees of elasticity; and, secondly, that the ***vapour is formed instantly*** in vacuo. Now we know that vapours are formed in the air; but this being a comparatively slow process, we must conclude that the presence of the air is an impediment to evaporation. There is no difficulty in seeing how the air impedes the formation of vapour; it is by presenting its particles as it were mechanical obstacles to the speedy removal of the particles of vapour as they are formed; just as the particles of sand prevent the free motion of the particles of water which trickles through it. That this is the case will be seen at once by observing the evaporation of ether in vacuo, and in an equal space full of air. In vacuo, as we have seen, the vapour is formed instantly, but it is a slow progress in air, and the time required depends on the density of the air; but the quantity of ether evaporated, or of vapour formed, is precisely the same in both cases. These beautiful and extraordinary phenomena, for the discovery and explanation of which we are indebted to Dr. Dalton, will require to be examined in more detail.

160. *The Temperature determines the quantity of Vapour.*—If the temperature of a vessel containing water be 40°, the quantity of vapour which exists above the water will be small; if the temperature be increased to 60°, the quantity of vapour will be increased, and so on; an increase of temperature always occasioning an increase of vapour. If now the temperature be reduced to 50°, some vapour will return again to water; and if to 40°, there will be precisely the same relative quantities of vapour and water as at the commencement of the experiment. And the presence of air in the space above the water makes no difference in the quantity of vapour formed; in this case time must be allowed for the completion of those changes which take place almost instantaneously if there is no air. The elastic force of the vapour in vacuo is always the same at the same temperature; it increases very rapidly with the temperature, as will be seen if the upper part of the barometer tube in the preceding experiment be warmed; the column will be more and more depressed. Thus, by observing the amounts of depression, tables of the elastic force of vapour at all temperatures have been made out, for the use of those who have to employ steam and other elastic fluids in the arts or as a moving power.

161. *Maximum Tension.*—The elastic force of elastic fluids may in general be increased by compression, and diminished by rarefaction; vapour, however, presents under certain circumstances a most remarkable exception to this

law, since its elastic force cannot be altered by any of these or similar means; it being always supposed that the temperature remains constant. If the space which a given quantity of vapour occupies be diminished, so that the vapour is compressed, some of it resumes the liquid form; again, if the space be enlarged, so that the vapour being less pressed would be rarefied, some of the liquid becomes vapour; thus the elastic force is unchangeable. This is expressed by saying, that the elastic force or tension is a maximum; that is, any change in the elastic force will be resisted by a change taking place in the state either of some of the vapour or of the liquid. This curious fact will be fully understood from the following experiment.



Let a barometer be inverted over a deep vessel of mercury, and let a very small quantity of ether be introduced as before above the mercury; its vapour will cause a considerable depression, so that the surface will stand at *a*. Let the height *a b* of the column be accurately measured. Now let the tube be pressed down in the basin, so as to reduce considerably the space occupied by the vapour of ether; then the two following remarkable phenomena will be observed; first, the height of the sustained column will be exactly the same as before, which shews that the elastic force of the vapour in the top of the tube is unaltered: secondly, the layer of ether at *a* will be seen to increase in thickness as the tube is pressed down; which shews that the vapour is condensed into liquid and that it cannot be compressed into a less space. Again, if the tube be raised instead of being depressed, the column will still preserve exactly its same height: thus affording an evident proof, that fresh vapour is formed as fast as the space augments, and that it always preserves the same elastic force or tension. If the tube be raised sufficiently to admit of all the liquid passing into vapour, the column from this instant will begin to rise, so that the depression will become less. From this point the vapour is subject to the law of Boyle (Art. 89), which it follows accurately when not compressed to the point of condensation. The vapours of all other liquids follow the same laws, but their elastic forces are very different.

162. *The pressure of Vapour stops Evaporation.*—From the preceding experiment we see that the formation of fresh vapour is prevented by the pressure of that which already exists on the surface of the liquid; the liquid is always ready to furnish fresh vapour, if any that already exists be removed, or the space in which it exists be increased so that the pressure on its surface be for the instant relieved. The air, we have seen (Art. 160), produces no effect on the quantity of vapour which can exist; hence the conclusions of the preceding article will apply to the vapour formed in a space containing air as well as in vacuo. This which we have shewn in a limited space is constantly taking place in the air; evaporation is always going on, impeded, but not absolutely stopped, by the presence of the air: if the evaporation is ever stopped, it is because of the pressure of the vapour which already exists. Hence we see why a smart breeze is so very favourable to evaporation. The vapour which is formed being instantly carried away by the motion of the air, cannot press on the surface of the liquid; the evaporation goes on therefore with no impediment but that which is always presented by the atmosphere. Hence, also, when the air is dry and warm the evaporation must go on most rapidly, and this is in strict conformity with our daily experience.

The air is often said to be saturated with vapour, but great caution must be used in the application and interpretation of this term. When properly applied it means that there is as much vapour in the atmosphere, or in a given space, as the temperature of the liquid can furnish; when then the air is saturated, the vapour which exists in it stops all farther evaporation. As this, however, is probably never the case in the atmosphere, the term is used simply to express the fact that a great quantity of vapour exists, and the air is said to be more saturated with vapour at one time than at another. It must always be remembered that the vapour has an existence independent of the air, that it is as an aqueous atmosphere, and governed by its own laws. When the vapour which exists in any space has the maximum tension, then only can the space be properly said to be saturated, or to be quite full.

163. *Condensation of Vapour and Liquefaction of Gases.*—All vapours are condensed, that is, brought back to their liquid form, by compression and cooling. When the space which the vapour occupies is saturated, we have simply to increase the pressure to which it is subject, when some of it will instantly be liquefied. In other cases it may be compressed as a gas, and cooled within certain limits, and still preserve its gaseous form. The perfect identity which exists between some properties of the permanent gases and vapours, has led to the belief that the former are but vapours, more or less removed from their point of maximum tension; and many experiments have been tried, but till lately without success. It now appears, from the experiments of Davy and Faraday, that several gases may be liquefied, and that the production of cold is the great means by which this is to be accomplished. So long as the gas preserves its heat the elastic force is indomitable; but once deprived of this it immediately assumes the inelastic form of a liquid.

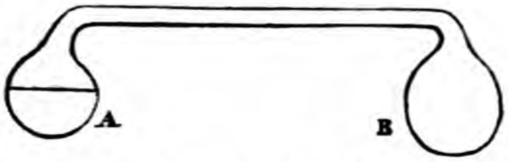
The simplest case of condensation is that we have already explained in the application of steam as a moving power. The water having passed into a gaseous form by receiving a certain quantity of heat, reassumes its liquid form on the removal of this quantity. The combination of the heat and water is apparently in this case very simple and different from the combination which exists in a permanently elastic fluid.

164. *Cold produced by Evaporation.*—From what has been said it is evident, that whenever a liquid passes into a vapour it absorbs great quantities of heat, which must be supplied from the surrounding bodies; consequently, there must be cold produced in all these bodies. If a small quantity of ether or alcohol be poured into the palm of the hand, it will speedily evaporate, and the sensation of cold produced is very intense. Or if the bulb of a thermometer be covered with cotton moistened with ether, the evaporation will be accompanied with a sinking of the mercury to many degrees below the freezing point. The cooling effect of bathing the surface of the skin with mixtures whose base is alcohol is due to the rapidity with which this substance evaporates, thus producing the sensation of cold by the rapid absorption of heat which is necessary for this change of state. The cooling effects of warm bathing are also to be explained on the principles just stated.

If the surface of any body be kept constantly moist, the evaporation which goes on will reduce its temperature; it is on this principle that we must explain the action of coolers. These are formed of a porous substance which readily absorbs water; the evaporation which takes place at the outer surface reduces the temperature of the interior very rapidly. The temperature of the liquid contained in any vessel, as, for instance, the temperature of a bottle of wine, may be lowered very much by promoting evaporation from its external surface. If the bottle be wrapt in a cloth previously dipped in warm water, and be set in a current of air, as at an open window, the heat abstracted by the formation of vapour will lower the temperature of the bottle several degrees.

But the most ingenious illustration of the preceding law is that furnished by Leslie's method of making ice under the partial vacuum of an air-pump. A small shallow pan of water and a vessel of sulphuric acid are placed under the receiver of an air-pump, and a partial vacuum is formed by exhausting the air. Ebullition, as is well known, takes place, and vapour is formed rapidly, but it is withdrawn so soon as formed by combining with the sulphuric acid. Thus a rapid evaporation is kept up, and after a few minutes small flakes of ice will be seen on the surface of the water in the pan, and soon the whole water will become a solid mass. The pan of water must be isolated as much as possible, that it may not receive heat readily from the substance on which it rests; it must also be very thin, that it may participate as quickly as possible in the cold produced by the evaporation. A degree of cold may be produced by the evaporation of ether sufficient to freeze mercury; the degree of cold depending in all cases on the rate at which the vapour is formed.

The *cryophorus* of Wollaston is too ingenious an instrument to be omitted here. It consists of two glass bulbs,



A and B, perfectly free from air, and formed as here represented. One bulb A contains distilled water, and the other parts of the instrument which appear empty are filled with aqueous vapour, whose elastic force checks the evaporation of the water by the pressure which it exerts on the surface. If now some means be taken to draw off this vapour as soon as it is formed, as if the other bulb B be plunged into a freezing mixture, which will immediately condense all the vapour, the evaporation will proceed rapidly, and the water will be frozen in the bulb A in a few minutes by the cold produced by the evaporation.

The abundant perspiration which takes place at the surface of living bodies produces a great degree of cold. The blood of all animals, as we shall see presently, has a fixed and invariable temperature, which cannot be changed without producing great inconvenience, or even death. For the human frame this is about 96° F., whatever be the climate which man inhabits. Thus, the inhabitant of the torrid zone, where the temperature of the air is frequently 120° F., has a proper temperature, which does not differ sensibly from that of the inhabitant of our more temperate latitude. The activity of perspiration is most probably proportioned to the intensity of the heat; so that the Indian and the Laplander have their blood at nearly the same temperature.

SECTION III.

TRANSFER OF HEAT — COMMUNICATION — RADIATION — REFLECTION — ABSORPTION — EQUILIBRIUM OF TEMPERATURE — THEORY OF DEW — LAWS OF COOLING.

165. The effects of heat on different substances have been stated in the preceding articles; it now remains to trace the laws according to which the heat is transferred from one substance to another. No substance is absolutely devoid of heat; however cold it may be, some of this imponderable agent still exists in it, and can be transferred from it into another substance. There are two distinct ways by which heat can be transferred, namely, communication and radiation. When one substance is warmed by contact with another, the heat is said to be transferred by *communication,* as when the hand is laid on a warm stone, or the poker is heated in the fire; but when there is no contact, as when wax is melted before a fire, the heat is said to be transferred by *radiation.* It is in the latter way that the sun warms the earth, the heat is radiated in every direction, and when the progress of the rays is not intercepted by dense clouds or artificial means, the heat received is very intense.

The different ways in which heat is transferred from a hot body, according as the body in contact with it is solid or fluid, is so different, that distinct terms have been adopted. When a bar of metal is placed with one extremity in contact with some hot substance, all the sections at different distances from the heating body have different temperatures; the heat is transferred by *conduction* from one particle of the mass to another, and the rapidity with which this transfer takes place, or with which the body becomes heated throughout its length, depends entirely on the nature of the substance. Hence bodies are called good and bad conductors. All the metals are good conductors; gold, silver, platinum, and copper, are much the best, and lead the worst. Marble, porcelain, clays, glass, and wood, are exceedingly bad conductors, and charcoal is worst of all. These statements may be verified at once by holding small pieces of the substances in the hand and touching a hot body; if the substance be a good conductor, the heat felt will very soon be nearly as great as that which would be experienced directly by contact with the hot body. To hold a vessel containing hot water by a metallic handle is extremely inconvenient, but no difficulty whatever is experienced if the handle be of wood. The simplest methods of trying the conducting power of different substances, is to place small cylinders of them, covered with wax, in contact with a vessel of copper, full of hot water or oil. The heat penetrating the cylinders melts the wax to a great or small distance, according to the excellence of their conducting power. The power of conduction depends very much on the intimate contact of the particles; hence all substances reduced to a state of powder, wool, silk, feathers, and saw-dust, are very bad conductors.

It appears from many very accurate experiments, that fluids either do not conduct at all, or conduct so slightly that the quantity of heat transferred by this means is almost insensible. For instance, if a delicate thermometer be immersed horizontally just below the surface of water on which a thin layer of alcohol is burning, the position of the mercury will scarcely change; and the slight change which it does experience, arises almost entirely from heat derived indirectly from the sides of the vessel. But if heat is applied to the lower parts of a fluid, the transfer is very rapid; this, which is owing to the currents which are excited, is termed *convection*;* the fluid immediately in contact with the hot surface becoming heated expands, and rising up is succeeded by colder fluid; thus the heat is conveyed away with the current which is created. In gases any change of temperature produces currents more numerous and rapid than in liquids, and we at present consider their power of conduction as absolutely insensible. The warmth of air-tight clothes is owing to the non-conducting power of the air; communication with the external air being prevented, there is very slight internal motion in the thin layer of air; the convection then of heat is almost entirely prevented, and there being no conduction, the only transfer which can take place is by radiation.

166. *Radiation.*—Radiant heat may be defined as the heat which passes through certain substances, as light passes through transparent media. The heat of the sun in coming to the earth traverses the whole atmosphere; and if the air becomes warm, every one knows that the surrounding bodies are warmed also, and that their temperature is in general greater than the temperature of the air. A part therefore of the solar heat traverses, like light, the atmosphere without being absorbed. In the same manner the fire warms us at a distance, though the air betwixt us and it experiences no change in its temperature; the air may remain cool, or may be removed and renewed successively, without our experiencing any change in the heat. A red-hot ball suspended in the middle of the room produces an elevation of temperature in the surrounding bodies, and a sensation of heat in us, without the

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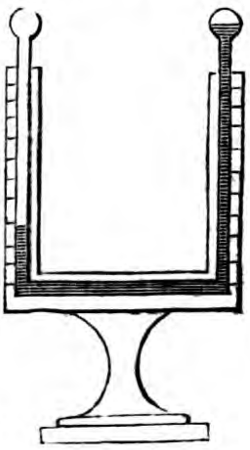
* See Prout's *Bridgewater Treatise*, p. 65.

intermediate air undergoing any sensible change. Bodies, then, which are heated to redness, have the same property of *emitting* heat all around them, as of emitting light. Thus, from analogy, we speak of rays of heat and radiant heat, just as of rays of light and radiant light. But rays of heat are emitted from the body when it has lost the property of emitting light; it still radiates heat, and the remarkable fact is, that this heat still follows precisely the same laws as the preceding. There is no difference, except in intensity, between the heat from a red-hot body and from the same body cooled to blackness. The rays are less powerful than when the body emitted light as well as heat, but they traverse the air in both cases in the same manner, and warm all the surrounding bodies. The same kind of phenomena are produced by all bodies, whatever their nature and temperature; a tin case filled with warm water exhibits the laws of radiant heat, as well as a red-hot bullet; the human body radiates in the same way; ice and bodies colder than ice possess the same quality. Thus, every body may be considered in respect of heat, what a lighted candle is in respect of light; all points of the flame emit rays in every direction; similarly, all points of all bodies emit rays of heat which traverse the air, and are propagated freely until they meet some body which arrests their progress. It is of the utmost importance to consider well the preceding phenomena of radiant heat; these, together with some circumstances hereafter to be related, seem to warrant the hypothesis, 'that every body, whatever its nature and temperature, is at every instant radiating heat in every direction.'



167. *Differential Thermometer.*—This instrument, admirably adapted for observing the laws of radiant heat, is represented in the accompanying figure. The two bulbs are full of air, and the liquid is sulphuric acid

coloured red; if now one bulb be heated the air will expand, and drive the sulphuric out of its tube towards the other; when the temperature is the same in both, the liquid will stand at the same height in both tubes; but when there is any difference of temperature, the liquid will stand highest in the cooler tube. It is the difference of temperature of the two bulbs which is measured by this thermometer; hence its name.

168. *Absorbing Power.*—All bodies have the power of absorbing more or less of the heat to which they are exposed; and these powers are very different in different bodies. All bodies are warmed by the sun, but very unequally in equal times, and the same may be shewn at once by the differential thermometer. Also the absorbing power depends principally on the nature of the surface; for if the bulbs of the differential thermometer be exposed to the sun or to any warm body, one being in its natural state, and the other blackened or covered with some very thin substance, the difference in temperature will be greater or less, according to the nature of the covering. A bright metallic covering, as one of gold or silver, almost destroys the absorbing power, whereas a thin piece of black paper increases it many fold.

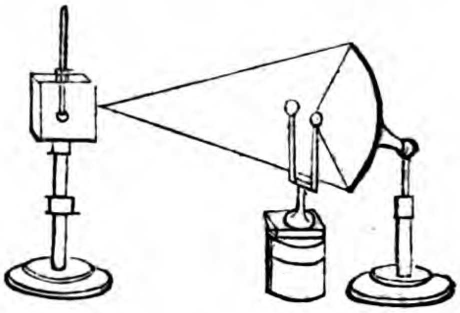
169. *Safety Lamp.*—The safety lamp, which has been of such invaluable service to miners when working in an atmosphere which may explode, depends for its safety entirely on the rapidity with which metallic wire absorbs and conducts heat. Flame is gaseous matter heated so intensely as to become luminous; the temperature at which this luminous appearance is produced has been shewn by Davy to be far higher than the temperature corresponding to the white heat of solid bodies. Now flame in contact with wire gauze cannot pass through it; the heat is absorbed and conducted away so rapidly by the metal that the temperature of the luminous gaseous matter, which was passing out, is reduced below that at which it can continue luminous. The gaseous matter, therefore, which

passes freely through the interstices of the wire, though still very hot, is no longer incandescent. The temperature of the gas, provided it be below incandescence, may be any whatever, for it was ascertained by Davy, that the strongest explosive mixture may come into contact with iron heated to redness, or even to whiteness, without an explosion taking place, provided the bodies are not in a state of actual combustion. But the smallest point of flame, owing to its higher temperature, instantly causes an explosion.

170. *Reflecting Power.*—By the reflexion of heat we mean to express the faculty which all surfaces have in a greater or less degree, of conveying the heat in a particular direction in preference to all other directions. This direction is such that the angle of reflexion is equal to the angle of incidence. Light, as we shall see hereafter, obeys in this respect precisely the same laws; and it is found, that if any warm body be placed in the focus of a parabolic mirror, the rays will be reflected parallel to the axis; that if another mirror be placed so as to receive these rays, they will be collected in its focus, and the concentration of heat at this point may be proved by the fact of the ignition of a piece of tinder. The reflecting power, as well as the absorbing power, depends on the nature of the body, and on the state of the surface. If the mirrors are not well polished, or if they are the least dull, they will not bring the heat to a focus in sufficient intensity to produce ignition. These two powers have a manifest connexion; the rays which are not reflected must be absorbed; hence it is generally said, that reflecting power varies inversely as the absorbing power, or that one is the complement of the other; but whatever be the exact law, it is certain that those surfaces which reflect best absorb worst, and conversely; the circumstances with respect to heat being the same.

171. *Radiating Power.*—The radiating or emissive power is the faculty which all bodies have of radiating or emitting heat in all directions (Art. 166), just as luminous bodies

emit light. The existence of this faculty is shewn by the existence of radiant heat, and we must examine upon what circumstances it depends. The radiating power depends entirely on the state of the surface; it is less in proportion as the surface is bright and polished, and greater as the surface is striated and rough. This may be shewn at once by the following experiment. Let a square box of metal, having its surfaces of very different degrees of polish, be placed before a spherical mirror, in whose focus is placed a bulb of the differential thermometer. Let the box be filled with warm water; then every face will have the same temperature, and on presenting different faces the different effects will be seen. The least polished surface will produce twice or three times as great an elevation as the most polished surfaces, and the other faces will produce intermediate effects. From this it appears that the same substance will have at the same temperature very different radiating powers, according to the state of its surface, and will, consequently, lose by radiation very different quantities of heat in the same time. The radiating powers of different substances can be readily ascertained by attaching thin layers of the substances to the sides of a cube of very thin metal, as in the preceding experiment. If the surface be smoked or blackened, the radiating power is the greatest known; thus the radiating power of soot being taken as the standard, that of other substances may be compared with it by observing the effects on the thermometer. Care must be taken that the layers are very thin, so as readily to acquire the temperature of the water. When a polished metal surface is wetted with any liquid, as water, oil, &c., its emissive power is increased instantly in a very great degree; any layer of varnish produces a similar effect; and,



what is remarkable, a second and third layer are attended with similar results up to a certain thickness. From this it appears, that the rays of heat start not only from the surface, but from a sensible depth below the surface. This being the case with the radiated heat, the absorbed heat must be subject to similar laws, and a varnished mirror must reflect less than a naked polished mirror. Such is found to be the case, and it reflects less the thicker the varnish. Hence it follows, that reflection must take place at a certain depth below the mathematical surface of the last layer of varnish; for if it took place at this surface, it must be the same, whatever the thickness of the layer. From the preceding we may conclude that the best radiators are the worst reflectors, and conversely; and also that the absorbing and radiating powers of any surface are equal.

172. *Equilibrium of Temperature.*—The radiation of heat has already been enunciated in the form of a general law (Art. 166); from this we may easily pass to the beautiful theory of Prevost, 'that the temperature of a body falls when it radiates more than it absorbs, and rises when it absorbs more than it radiates.' Thus the temperature is always tending to equilibrium. The analogies between heat and light furnish a presumption in favour of this theory; but the beautiful explanation which may be derived from it of numerous phenomena, apparently very contradictory, gives to it a consistency and evidence possessed by none other. The equilibrium is established when the thermometer becomes stationary; for then the interchange of radiation which takes place is exactly equal, the thermometer appropriates by absorption just as much as it loses by emission; hence it follows, that in a state of equilibrium the absorbing power is always equal to the radiating power, as we have already seen. There is then in every case an exchange or compensation, more or less complete; and that body which is gaining by this exchange rises, and that which is losing falls, in temperature. This theory renders all hypotheses respecting frigorific rays per-

fectly unnecessary. The sensation of cold arises entirely from the fact that our bodies are radiating more than they are absorbing; their temperature consequently falls, or the sensation of cold is produced.

But the remarks which have just been made are not to be restricted to radiant heat. The heat which is transferred by conduction or immediate contact, is subject to the same law, so that it is impossible for bodies which are near each other to be of different temperatures, unless the hotter body is constantly receiving from some source a fresh supply of heat. The tendency to an equilibrium of temperature is one of the general laws to which all matter is subject.

173. *Apparent Reflection or Radiation of Cold.*—If the hot body which was referred to in a preceding experiment (Art. 171.) be replaced by a piece of ice, the thermometer, whose bulb is in the focus of the mirror, will sink as rapidly as it previously rose. This, or the preceding effect, may be shewn more decidedly by placing the body in the focus of another mirror, as represented in the accompanying figure.

Suppose that A B, A′ B′, represent two spherical mirrors; that the bulb of a thermometer is in the focus F of A B, and a small lump of ice in the focus F′ of A′ B′. The thermometer will sink very rapidly, if it is of a higher temperature than 32° F. The thermometer is here the hot body, and being, in the interchange of heat, the loser, that is, radiating more than it can absorb, its temperature falls, and the more rapidly in proportion to the excess of its temperature above the temperature of the ice. It was by this experiment that the supposed existence of frigorific rays was principally supported; but we have seen in the preceding article that there is no necessity for any such an hypothesis; the rapid fall of temperature which any body must experience when it radiates more than it absorbs, furnishing a complete explanation of this and all other similar phenomena.

The sensation of chill which we experience in standing before a large mass of ice in warm weather, is evidently owing to the cooling which is the necessary consequence of the excess of radiation, which is going on from our bodies. Hence our temperature falls, and the sensation of cold is produced. The radiated heat passes through any substance which may be interposed, but with different degrees of rapidity. A screen of glass placed between the fire and the thermometer does not much affect the ready transmission of heat by radiation; and the glass itself experiences but a small rise in temperature; the same is the case with a thin sheet of mica. Since, however, some light is absorbed by the most transparent bodies, we may conclude from analogy, and verify it also by experiment, that some radiant heat is absorbed, whatever be the medium which it traverses. The experiments of De Laroche have led to some remarkable results. It appears that the radiant heat from bodies at high temperatures passes more readily through transparent media, and is less absorbed, than from bodies of a low temperature; for instance, a glass screen stopped $\frac{17}{18}^{\mathrm{ths}}$ of the rays of heat emitted from a body of 180°, but only $\frac{6}{7}^{\mathrm{ths}}$ of the heat from a body at 400°, and only one-half the heat from the flame of a lamp. Also, the radiant heat is absorbed in less proportion in traversing a second or third layer of glass than in traversing the first. It appears probable that this singular property extends to all transparent media. Thus, the rays of heat which traverse a mass of air of certain thickness experience a less and less absorption at each successive stratum, and that, consequently, radiant heat may be propagated to very great distances, without being completely extinguished.

174. *Cold of Clear Nights.*—The preceding principles will enable us to explain certain phenomena with which every one is acquainted, and respecting which great misconception prevails; thus the cold of clear nights, especially when the moon shines bright, has been referred to various hypothetical causes, and especially to the existence of frigorific rays; but it may be viewed as the immediate consequence of the preceding laws of radiant heat. The earth, our bodies, and every substance about us, is radiating heat into the immensity of surrounding space; this heat passes most readily through the air, and if it meets with no absorbing medium, as a dense watery cloud, it for the time passes away entirely from our earth. Thus, when the sky is clear there is no interchange of radiation; our earth and the bodies upon it are rapidly giving out heat into the space above us, but receive none from it; hence the temperature of all these radiating masses, and especially of our bodies, which have a temperature of many degrees above the surrounding masses, falls very rapidly, and an acute sensation of cold is produced. But if the sky above us is covered with thick clouds, there is a constant interchange of radiation, the earth radiates heat to them, and they radiate heat to us, so that the change of temperature takes place much more gradually. When the moon and stars shine with great brightness the atmosphere is very clear, and then only can this rapid diminution of temperature take place; hence the shining of the moon and stars, whose frigorific rays are sometimes supposed to be the cause of our chilly sensations, is the consequence of that state of the sky above us which admits of the diminution of temperature by exclusive radiation from us upwards, thus producing the sensation of cold. In cloudy nights the moon and stars are not visible; the clouds radiate back heat to us. Thus, the existence of clouds, which prevents our seeing the

heavenly bodies, prevents also our experiencing the sensations of cold produced by a rapid diminution of temperature.

There are many other illustrations of the preceding principles which must suggest themselves to the mind of every observer of nature. Whence can arise the protection furnished by a thin layer of straw over a bed, or a thin mat over the glass of a conservatory, or placed before delicate plants and flowers? There is no warmth in them, but they, by the interchange of radiation which is going on between every neighbouring body, prevent that rapid diminution of temperature which would be destructive to their existence. The slightest substance produces most sensible effects; if a thermometer be brought into the air on a clear night it will fall very rapidly, but the rate of its fall will be most sensibly diminished by extending a thin handkerchief as an awning above it.

175. *Deposition of Dew.*—The deposition of dew on the surfaces of some bodies under certain states of the atmosphere, and its non-deposition on other bodies and under other circumstances, furnishes a most beautiful illustration of the preceding principles. Dew is vapour condensed on the surface of the body; it does not fall like rain and rest there, but its existence depends entirely on the power which the surface has of becoming sufficiently reduced in temperature to effect this condensation. Every one has observed the deposition of dew on glasses which are brought into a warm room, or when cold water is poured into them; this is an instantaneous effect, which taking place suddenly soon passes away. The explanation is very simple. Vapour is always present in the atmosphere, but sometimes, and in some places, it is much more abundant than in others, and it is more abundant the higher the temperature of the air or of the water from which it is formed. Suppose now that a cold surface, as of a glass tumbler, is brought into a room of higher temperature, and in which there is, consequently, an abundance

of aqueous vapour; the air and the vapour which is diffused through it, coming in contact with the cold glass, is chilled, the vapour is condensed upon the surface, and dew is formed. But the glass will soon acquire the temperature of the surrounding bodies, and then this vapour, which was condensed on its surface, will assume its invisible form, and the glass will be again clear. The same effect is produced on pouring cold water or cold wine into any vessel; the external surface is suddenly chilled, and the vapour in immediate contact with it is suddenly condensed; the equilibrium of temperature is however rapidly restored, and the vapour reassumes its invisible form.

This, which may take place at any instant in every room, provided a sufficiently cold surface be brought into it, frequently takes place on a large scale in the wide field of nature, and gives rise to the beautiful phenomena of dew, which stands in pearly globules on every blade of glass, and to the crystals of hoar-frost, which shine with such splendour in the morning sun. Dew is only deposited on those surfaces which radiate freely; glass, the thread of the gossamer, wool, and all leaves are covered with dew; these are all good radiators; but a polished metal plate will have scarcely any deposited upon it. The temperatures of the surfaces fall in proportion to the amount of their radiation; hence the condensation of the vapour which comes in contact with them, or the deposition of dew upon them, is in the same proportion. The large pearly drops on the leaves of a cabbage must arrest the attention of every observer, and in their existence he sees at once evidence of the excessive radiation of the leaf, and of the molecular attraction by which the particles of the body cohere together so as to assume their particular forms.

It is specially to be observed, that dew is never deposited on cloudy nights; the presence of the clouds prevents the requisite diminution of the temperature. Any similar circumstance prevents the deposition of dew; the neighbouring trees interfere most materially with it; hence it is much less abundant in a garden than in an open field where no surrounding bodies interfere with the diminution of temperature by their interchange of radiation. One remarkable case is mentioned by Wells, to whom we are entirely indebted for the preceding theory; the temperature of a grass-plot at half-past nine was 32° F.; at twenty minutes later, the sky having become overcast, the thermometer rose to 39° F., and when the clouds disappeared it sunk again to 32° F. The clouds were evidently the sole cause of this effect, they restored heat to the grass-plot; and the thinnest cambric handkerchief stretched above the thermometer near the ground will produce a similar effect. Again, the night must be tolerably calm for a good deposition of dew; a slight breeze, from the assistance which it gives to evaporation, does not interfere with the deposition; in some cases it may be favourable; but on a windy night little dew is deposited. The wind restores the equilibrium of temperature by the heat which is transferred by convection, and when there are any clouds to assist still farther in restoring the heat, no dew whatever can be deposited.

The vapour having been condensed on those surfaces whose temperature has fallen sufficiently, is collected into small drops by the molecular forces. The state of the liquid on the condensing surface as to the shape and size of its particles, will depend on the relative intensity of the forces of cohesion and adhesion (Art. 6). When the force of cohesion, that is, the attraction which subsists between the particles of the fluid and the body, is small, the drops will be very nearly accurate spheres; in other cases the liquid will be collected in the small interstices of the leaves. It will always participate in the changes of temperature to which the surface is subject; hence, if the temperature be raised by the passage of a cloud, the dew will return to the state of invisible vapour, and by the morning it may have entirely disappeared; if the sky continues clear, the surface may be reduced to as low a temperature as 32° F., and the dew will then be congealed, or present the well-known appearance of hoar-frost.

It appears then that dew, under whatever circumstances produced, is the aqueous vapour of the atmosphere condensed on surfaces whose temperature is sufficiently low for the condensation of the vapour.

176. *Laws of Cooling.*—If a body whose temperature is considerably above that of the surrounding bodies be situated in vacuo, the only way in which it can lose its heat is by radiation; but when it is surrounded by air it also loses by communication, that is, by convection, and in a very slight degree by conduction. The surrounding air being warmed rises up and is replaced by colder air. Thus, the cooling of a body, which is the combined effect of the radiation and communication, depends on several circumstances, as the radiating power of the body, the excess of temperature, the state of the air; and the law is consequently very complicated. It will, however, be perfectly understood from the preceding principles why two bodies equally warm may lose unequal quantities of heat in the same time. When the radiating hot body is surrounded by bodies whose temperature is much lower than itself, the heat which it receives from the interchange of radiation is exceedingly small, and, consequently, its temperature falls very rapidly. The rate at which the temperature diminishes must evidently depend on the excess of the temperature of the body above the temperature of the surrounding bodies; and the law according to which this takes place may be expressed at once by a simple mathematical formula. This part of the cooling of a body, or that which is due to radiation, depends in a great measure on the nature of the surface of the radiating body, as has been already explained (Art. 171). The cooling which arises from conduction and convection will depend on several causes, which may be briefly pointed out. If the hot body

is placed on a stand so as to be in contact with any substance which is a good conductor, the heat transferred away by this cause will be considerable. But when the body is in a close vessel surrounded by air, the cooling due to this cause will be exceedingly slow, since air at rest is a very bad conductor. When, however, fresh air can come in contact with a body, the heated air rising up causes a constant circulation, and the heat transferred by convection is far more considerable than that transferred in any other manner. The state of the air, its elastic force, and many other causes, have an influence on the cooling of a body suspended in it. The complete law of cooling, that is, an expression which shall include all those various elements, and give the rate at which, under any circumstances, the temperature of a body will fall, is a very difficult problem; some progress has, however, of late years been made towards determining it by the researches of Leslie, Fourier, and others.

SECTION IV.

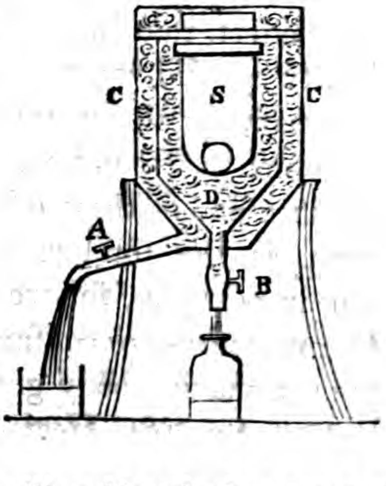
SPECIFIC HEAT—CALORIMETER—METHOD OF MIXTURES—SPECIFIC HEAT OF GASES—CONSEQUENCES.

177. The researches into the quantity of heat which a body contains, and the measure of it, are founded on the self-evident principle, or axiom, that to produce the same effect the same quantity of heat will always be necessary. Thus, if a pound of iron passes by any means from a temperature of 60° to 70°, we are sure that it is because of the same quantity of heat having passed into it, whether that heat comes from the sun, or from the contact or radiation of any body whatever. Similarly, a pound of ice always requires

the same quantity of heat to fuse it, under whatever circumstances the fusion takes place, and a pound of water at 212° F. requires the same quantity of heat to evaporate it, whether the evaporation be slow or rapid. That the effect may be the same, it is not always sufficient that the masses should be equal, and the material the same; but the matter being identical in its nature, must be identical also in the arrangement of its particles. Thus, two equal masses of iron differently worked, that is, one of which has been more forged than the other, will require different quantities of heat to raise their temperature from 60° to 70°. Two equal masses of ice will require different quantities of heat, if one is solid or compact, and the other snow or pounded ice. Also, the same quantity of water will require different quantities of heat to evaporate it, according as the evaporation takes place at 32° F. or at 212° F. All these differences are due to the different arrangement which exists among the particles. On this fundamental principle we may compare the actual quantities of heat whenever it can be applied in succession to produce the same effect, that is, to elevate the temperature of a body, to liquify a solid, or to evaporate a liquid. But since it is necessary for this purpose that the heat go out of the body in which it is, and pass into the body in which it is to produce one of these effects, it follows, that we can never compare the total or absolute quantities of heat which a body possesses, for we can never deprive it of all its heat. Our measures are confined to those quantities of heat which we can make a body give out.

178. *Specific Heat.*—One substance is said to have greater or less *capacity* for heat than another, according as it requires more or less heat to produce a given change in its temperature; and this quality in respect of heat is called the specific heat of the substance. The capacity is constant when an equal weight of a substance requires an equal quantity of heat to raise it 1° in all parts of the thermometric scale, that is, when it requires the same quantity to make

it pass from 1° to 2°, from 2° to 3°, from 100° to 101°, and so on. Thus, iron for example has not a constant capacity, but a capacity which is variable and increasing; for a pound of iron requires one quantity of heat to raise its temperature from 40° to 41°, and a greater quantity to raise it from 100° to 101°. Hence the specific heat of iron is greater at high than at low temperatures. The ratio of the capacities of any substance at two points of the scale is the ratio of the quantities of heat which it requires at each of these points for equal changes of temperature. The ratio of these capacities is the same as the ratio of the specific heats. The capacities of all substances are referred to water as the unity. Thus, when the capacity of a substance is said to be 2, 3, 4, &c., it means that its capacity is 2, 3, 4, &c., times that of water. In the same manner and in the same sense we should say that the specific heat of a substance is 2, 3, 4, &c. The preceding terms will be fully understood after the methods which are employed to determine the quantities in question have been explained.



179. *Calorimeter.*—This instrument consists of three vessels of sheet iron or tin placed within each other; the space between the two exterior vessels is filled with pounded ice. The water from the ice in the first interval can be drawn off by a stop-cock A, and that from the second by a stop-cock B, small gratings being placed to prevent the ice from stopping the passages. The external heat will evidently be arrested by the first layer of ice, and never reach the second layer; the internal heat, or that arising from the vessel D, that is, from whatever substance is placed in it, can never reach the external layer C, but will be wholly absorbed by D. The external heat will be wholly employed in melting the

ice in C, and the internal in melting the ice in D; the water produced will be drawn off and measured at A and B. The method then of using this instrument will be at once apparent. Suppose we wish to know whether the capacity of iron is constant; an iron ball is heated to 100°, put into the interior vessels, and the covers are adjusted as quickly as possible. The water which is melted during the cooling of the ball to 32° is measured. The ball being heated to 200° or 300°, the experiment is repeated. The quantity of heat given out is as the quantity of ice melted, that is, as the quantity of water obtained. It will be found that the water melted is not as the numbers 1, 2, 3, &c., but in a greater ratio; hence it follows, that the capacity of iron increases with the temperature.

The capacities of different substances are determined by heating them to the same temperature, and measuring the water which they furnish in falling to the temperature 32° F. If they are all of the same weight, their capacities are as the quantities of water which come away; if not, the ratio of their weights must be ascertained.

180. *Method of Mixtures.*—In this method two different substances are always employed; a warm body which cools and a cold body which becomes warm, so that the heat which goes out of one is employed in raising the temperature of the other. Suppose, for example, that a pound of mercury at 100° and a pound of water at 60° are mixed together, the mercury will be cooled and the water warmed, so that the mixture will have a temperature different from that either of the mercury or the water. If equal quantities of the same substance are mixed together, one will be as much cooled as the other is warmed; thus, if equal quantities of water at 100° and at 50° be mixed together, the temperature of the mixture will be 75°, and so for any other substance. But the result is very different if different substances be mixed together, as the following experiment most distinctly shews. Let a pound of mercury at 160° and a pound of water at 40° be mixed together; the

temperature of the mixture will be 45°; thus, although the mercury loses 115°, the water gains only 5°; the capacity therefore of water for heat as compared with that of mercury is 115 to 5, or 23 to 1. Again, let a pound of water at 160° be mixed with a pound of mercury at 40°, the temperature of the mixture will be 155°; thus the water loses 5° but the mercury gains 115°; or the relative capacities of water and mercury for heat are expressed by the numbers 115 and 5, that is, by 23 and 1. In order, therefore, to increase the temperatures of equal weights of water to the same extent, the water will require 23 times more heat than the mercury. Water being taken as the standard, its specific heat is called unity, hence the specific heat of mercury will be represented by $\frac{1}{23}$, for it only requires $\frac{1}{23}$rd the same quantity of heat to raise the same quantity of mercury by one degree, as it requires for water. This method may be adopted for any other substances which can be mixed together.

181. *Specific Heat of Gases.*—The determination of the specific heat of gases is a very difficult question, and the results hitherto obtained have not all the certainty which we could desire; some, however, are of too great importance to be omitted. It appears that the specific heat of equal weights of the same gas varies as the density and the elasticity. Thus, when 100 measures of air are expanded by diminished pressure to 200 measures, its specific heat is increased, and when the same quantity is compressed into 50 measures, its specific heat is diminished. Again, any change in specific heat is always accompanied by a change in the temperature. Increase in the former is attended by diminution of the latter, and decrease in the former by increase in the latter. Thus in the preceding instance the specific heat of the 100 measures of gas is increased on their being expanded into 200 measures, but there would be a considerable diminution of temperature. This may be shewn on a small scale by an air-pump; a thermometer placed under the receiver of an air-pump in a flaccid

bladder, that is, in a bladder containing a small quantity of air, will indicate cold produced at every stroke of the pump. The air within the bladder dilates at every stroke, its specific heat is increased, and its temperature diminished. This diminished temperature will be only instantaneous, for the equilibrium will be restored by the radiation of the surrounding bodies, so that the thermometer will return almost immediately to its former state. On the contrary, when air is compressed, the corresponding diminution in its specific heat gives rise to an increase in temperature. Of these facts we shall have occasion to speak hereafter, but their explanation must be obviously derived from the doctrine of latent heat; when the air is dilated, heat becomes insensible which was previously sensible; when air is compressed, heat becomes sensible which was previously insensible; this latter fact is often stated by saying, that heat is, as it were, squeezed out by the compression.

182. *Consequences.*—The laws of the specific heat of gases, which are stated in the preceding article, will furnish us with an explanation of several phenomena which are otherwise somewhat inexplicable. Among these the rapid diminution in temperature as we ascend a mountain, and the excessive cold of the upper regions of the atmosphere, are facts requiring some explanation. There is a constant transfer of heated air from the surface of the earth upwards, but this cannot warm the upper strata, for the volume of any given portion increases as it ascends; hence its specific heat increases, and its temperature diminishes. The density of the air decreases regularly as we ascend, but the specific heat increases with the diminution f density, and increase in specific heat is always accompanied by a diminution of temperature; hence the temperature falls as we ascend, and, according to the best observations, the thermometer sinks 1° F. for about every 350 feet of ascent. These laws cannot of course be verified for very great heights, but supposing it near the truth, we see

sufficient reason for the excessive cold which must prevail in the upper regions of the atmosphere. This cold must have very great influence in bringing about the limits of the atmosphere, of which we have spoken (Art. 100), since the elastic force of the air depends both on its temperature and its density.

Hence we see that at a certain height above the level of the sea, in every region of the earth, even the torrid zone, there is a region of perpetual snow, or a level of congelation. The summits of the Andes, some of which are elevated 20,000 feet above the level of the sea, are covered with perpetual snow, even under the equator. As we advance from the equator towards the poles the line of perpetual snow gradually approaches nearer to the earth; in our latitudes the level of congelation is about 8000 feet above the level of the sea; in latitude 20°, it is not more than 3000 feet. There are very great anomalies in the height of the level for different places; it depends partly on the general diminution of temperature as we travel from the equator to the poles, but in a very great measure also on local circumstances. Wherever an extensive table land occurs its effect is manifest upon the atmosphere in the elevation which it produces in the level of congelation. Thus the table land of Mexico is elevated about 8000 feet above the level of the sea, and the level of perpetual snow at this place is not more than 400 feet lower than under the equator; this level is also high in the Himalaya mountains from the same cause. Extensive glaciers produce their effect in lowering the level; thus the level is much lower in Iceland than in Norway than can be attributed to the small difference in the latitudes of the two countries.

There are some other remarkable phenomena connected with the different sensations produced by a current of air which require notice. Suppose that a wind is blowing along the plain, up one side of a mountain and down the other. In the plain it may be a hot blast, towards the top of the mountain it will be chilling cold; and increasing in temperature as it descends the other side, it will be again a hot blast on reaching the plain. This change in the apparent temperature arises entirely from the change in volume which it experiences; a cubic yard of air at the bottom of the mountain may be considerably expanded before it passes the summit, and is then condensed again as it descends the other side. The varying sensations produced by different winds may probably be considered as principally due to the change in the specific heat, consequent on a sudden increase or diminution in the volume of the air.

Another remarkable illustration of the preceding laws is furnished by the fact, that high pressure steam does not scald. Ordinary steam, such as is raised from boiling water open to the atmosphere, at the temperature of 212° F., scalds dreadfully; but the hand may be held with impunity in the vapour which issues from water in a close vessel heated to much higher temperatures. The elastic force of such vapour, or high pressure steam, as it is called, is much greater than the elastic force of common air; hence, when on rushing out from any vessel it expands into many times its previous volume, the diminution in temperature consequent on this sudden change renders such steam perfectly harmless.

Section V.

SOURCES OF HEAT—THE SUN—CENTRAL HEAT OF THE EARTH—ANIMAL HEAT—HEAT DEVELOPED BY MECHANICAL MEANS AND CHEMICAL COMBINATIONS—THEORIES OF HEAT.

183. In speaking of the sources of heat our thoughts will at once be directed towards the sun as the great natural source of heat. Every ray of light is accompanied by a ray of heat; and the first beams of the morning sun raise in some degree the temperature of the bodies which receive them. The intensely heating power of the solar rays may be shewn at all seasons by concentrating several of them into one point by means of a convex glass, or lens; a fire may instantly be kindled by such concentration; but there is no necessity to have recourse to contrivances to convince us of the intensely heating effects of the sun; the mid-day sun, even of our temperate summers, scorches every thing, and drives all animated nature to seek shelter from its rays. The most striking illustration of its effect is afforded by the different condition of the inhabitants at different parts of the globe at the same hour of the day, according as the sun's heat is received directly or indirectly. In the East or West Indies, at mid-day, the heat is so intense that the European cannot exist under its direct influence, whereas in Greenland and higher latitudes, where its influence is indirect, he can only sustain life by the heat supplied from other sources. Again, the change of temperature from day to night, the change of the seasons, and, in fact, all the phenomena of nature, point to the sun as the great source of heat as well as of light.

184. *Central Heat of the Earth.*—The earth may very

properly be considered as a source of heat. From numerous observations made in mines, and at different depths below the earth's surface, it is certain that the temperature increases as we descend. Thus we are compelled to admit that some part of the earth, whether the centre or any other part we need not now inquire, is much hotter than near the surface, and that as this heat is gradually escaping our temperature must be affected by it. The hot springs which issue forth from the interior of the earth, the irruptions of heated and liquid matter from the volcanoes in different parts of the world, all indicate that there is a great degree of heat either existing naturally, or produced by some cause, in the interior. Many objections have been urged to the evidence which is furnished of the gradual increasing temperature as we descend in mines, from the sources of inaccuracy which may attend the observations. But the evidence furnished by the temperature of the water from wells of various depths, especially from those wells which have been called Artesian, cannot admit of any other explanation than that the water is heated by acquiring the temperature of the strata through which it passes. The water from the Artesian wells is prevented by the sides of the tube from being carried away or influenced by the strata through which it passes; and since it must have originally descended from the surface of the earth, and have then had the temperature of water at its surface, it must have acquired its increased temperature by its passage through hot strata; in every instance the temperature depends on the depth of the well, and the law of increase as furnished by some very favourable observations, was 1° F. for about every 52 feet of descent: and this result agrees very nearly with some results recently obtained by Mr. Hopkins from observations in mines in Derbyshire. If this result be received as somewhere near the truth, and the hypothesis of a central nucleus of fluid matter be admissible, we should, at two miles below the surface, reach the ordinary boiling point of water, and at a depth of twenty-five miles, the melting point of iron. We see then that on this hypothesis there is a comparatively thin crust of solid matter resting on an enormous mass of hot liquid. The researches of Fourier shew that the influence which this liquid nucleus can produce on the temperature of the surface is very small, owing to the slow conducting power of the solid crust; but we must leave this most interesting question to the geologist.

185. *Animal Heat.*—Organized bodies seem to be exempt from the ordinary laws of heat, for they are scarcely ever of the same temperature as the medium in which they exist. The human body is never of the temperature of the surrounding air; the animals of the polar regions are much warmer than the ice on which they dwell, while those of the equatorial regions are colder than the air which they breathe; birds have not the temperature of the atmosphere, nor fishes that of the water, in which they live. There is then in all organized beings a proper and peculiar heat, or rather some means of producing, as may be required, the proper degrees of heat and cold; for the ponderable matter of which their bodies consist must necessarily be subject to the general laws of the equilibrium of temperature. The amount of this temperature for different animals, and the means of maintaining it, are among the most interesting questions of physical science.

The internal temperature of the human body appears to be the same for all the different organs, and experiences no sensible variation with age, disease, sex, or climate. The sailors who, at the north pole, breathe air in which mercury freezes,* and the inhabitants of India, with the thermometer standing at 110° F. in the shade, have nearly the same natural temperature, which is about 98° F. It appears that an European experiences a slight increase of temperature on going to warm climates, but it never amounts to 2° F. Sudden and intense cold may destroy

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* Parry's *Voyages*.

the faculties of the system, and bring on sleep, which is fatal both in animals and men. The celebrated bulletin of Napoleon, in which it was stated that 30,000 horses perished in one night, the thermometer being 43° F. below freezing, told not the myriads of human beings which must have perished from the same cause. The maintenance of the temperature of the system is an evident condition of existence, when this faculty is impaired death must ensue as inevitably as from any other cause. The temperature of man is lower than that of most land animals. Birds occupy the highest rank in the scale of temperature, then come the mammifers and the amphibious animals, as fishes and insects. The mollusca and crustacea, as oysters and crabs, have the temperature of the medium in which they live.

186. *Development of Heat by mechanical means.*—The sudden compression of any gas, or mixture of gases, as common air, is attended with a great development of heat; if a piece of tinder be attached to the piston by which the air is compressed, the heat evolved will be sufficient to ignite the tinder. This development of heat is entirely due to the change of volume, the particles being brought nearer to each other there is less space than the heat can occupy, it is squeezed out, so to speak, and an elevation of temperature is occasioned, a quantity of heat having become sensible which was before insensible. This increase of temperature is, however, only instantaneous. The equilibrium is immediately established by radiation, and by the conduction of the surrounding bodies. If air be forced into a glass receiver, in which is placed a delicate thermometer, there will be an instantaneous elevation of temperature on every stroke of the piston. The sudden expansion or dilatation of air is attended, as may reasonably be expected, with an exactly contrary effect. A thermometer placed in the receiver of an air-pump sinks at every stroke of the pump; the equilibrium of temperature is however immediately restored from the surrounding bodies. The gain and loss

of heat is exactly the same for the same degrees of condensation and rarefaction, and may be at once referred to the general principle, that the existence of the gaseous form depends on the presence of heat; and these effects take place conformably to the laws of specific heat already stated (Art. 178).

Closely allied to the production of heat by the compression of an elastic fluid is the intense heat which may be produced by smartly hammering a piece of iron or any other metal. It is very remarkable that a permanent change of form is the necessary condition of the production of heat by this means; it appears also that metals disengage less heat each successive stroke of the hammer, and where they have been so much beaten that their molecules cannot be brought into closer contact, the most violent strokes produce no farther elevation of temperature. At this point of condensation they are analagous to liquids; they may be compressed still farther, but since no permanent alteration of form takes place, the heat disengaged by the instantaneous compression is too small to be sensible, or is absorbed by the instantaneous expansion which succeeds.

Metals, wood, and all solid bodies, disengage heat by friction; the action which takes place between a wheel and its axle is sufficient to produce ignition; two pieces of wood may be ignited by rapidly rubbing them together, as is constantly practised by savages; the rope carried rapidly over the side of the boat when the whale has been harpooned, is constantly wetted to prevent ignition; and two pieces of ice quickly rubbed together, will melt at the surfaces which are in contact. From these phenomena it is difficult to decide whether the heat produced by friction results from a permanent alteration in bulk, that is, a compression of the bodies which are rubbed together, or from the vibrations of the particles themselves being a cause of heat. It is certain, however, that every change of state, or of volume, is accompanied by some change in the temperature; hence it follows, that the absorption and development of heat are essential conditions of any change in the state of substances.

Closely connected also with the preceding is the development of heat arising from molecular action. Whenever a solid body is wetted by a liquid, heat is disengaged. The molecular action which here takes place between the liquid and the solid must be referred to as the cause of the elevation of temperature which invariably occurs under these circumstances.

187. *Chemical Combinations.*—The heat produced by chemical combinations is very abundant. There is a change of temperature associated with every change of state. The intense heat produced during the slaking of lime is a well-known illustration of this law. The water is by some chemical action passing from a liquid to a solid state, and the heat given out is very great. Again, the whole action of freezing mixtures depends on the chemical combinations which are going on; one or more substances are passing from a solid to a liquid, and the diminution of temperature is proportional to the intensity of this change. When a pint of sulphuric acid and a pint of water are mixed together at the ordinary temperature of 60° F., the temperature of the mixture will suddenly rise to 212° F., or to that of boiling water; here, however, the mixture will be considerably less than a quart; there is a considerable diminution in volume; a consequent diminution in the specific heat, and a rise in temperature (Art. 178).

The intense heat produced by combustion is but another instance of chemical combination; whenever two substances are combining together with intense energy, they may become heated even to incandescence. If a piece of iron wire be heated at one end and plunged into a jar of oxygen, it will burn with a brilliant flame, and form small drops or scales of iron. Now during this operation, the oxygen may be all consumed, and if the scales be collected and weighed with the iron wire which is left unconsumed, the weight will be found increased exactly by the weight of the oxygen which is expended. The iron and oxygen may be separated again, and both exhibited without loss. Thus, every instance of combustion being but an instance of chemical union, there is no loss in nature. The great combining substance is oxygen; this being present wherever man can live, is always ready to unite itself with any matter exposed to it at the necessary temperature. Those substances are usually called combustibles which combine at low temperatures with oxygen, and of whose visible existence we are conscious; thus pit-coal, oil, &c., have received the names of combustibles, because these substances readily present the phenomena of heat and light; the oxygen is, on the contrary, generally termed the supporter of combustion. The general opinion of modern chemists on the theory of combustion is, that it results from the rapid or sudden union of bodies with each other; and Davy has pointed to electricity as the cause.

188. *Theories of Heat.*—In the preceding section of this chapter we have detailed the various phenomena which may be referred to heat as their cause: with respect to the nature of this agent no hypothesis has yet been mentioned. On this point there are two principal theories, whereof one admits the materiality of heat; the other, denying that it is a substance, conceives it to be a property of matter which produces its effects by an actual vibration amongst the molecules of the bodies. Whatever view we take of its nature it must certainly be considered as a force, somehow or other, opposed to the molecular attraction which is known to subsist. The hypothesis of the material nature of heat is supported very naturally by urging, that the expansion which heat causes in bodies is owing to the actual insertion of a material substance between their molecules: also the transfer of given quantities of heat, which may be accurately measured, so as to effect a particular purpose, as fusion or evaporation, is strongly consistent with the hypothesis of its materiality. But on the contrary, the vibratory hypothesis, or non-materiality of heat, is sup-

ported by the facts, that the most careful experiments could never prove it ponderable; this, however, is not conclusive evidence, since its weight may be altogether inappreciable by our experiments. The inexhaustible supply of heat which friction furnishes is strong evidence in support of this hypothesis; so that when these facts are viewed in connexion with the known laws of the reflexion of heat, and the striking analogy which subsists between the principal phenomena of heat, light, and sound, there is strong presumption in favour of the hypothesis, that heat consists in the vibrations of an elastic medium. The parallel betwixt heat and light is exceedingly close; the interference of the rays of heat, the polarization* of heat, are now distinctly established; so that though much remains to be done before the identity of the cause of heat and light can be said to be clearly established, yet there is strong evidence for at least entertaining the hypothesis. If darkness results from the interference of two rays of light, if cold results from the interference of two rays of heat, it is a mechanical impossibility that this should result from any emission of material particles; it is inconceivable how any hypothesis not strongly analagous to that of undulations can explain the phenomena.

We will close this chapter by the following remarks of Davy on this most interesting subject. 'The immediate cause of the phenomena of heat then is motion; and the laws of its communication are precisely the same as the laws of the communication of motion. Since all matter may be made to fill a smaller volume by cooling, it is evident that the particles of matter must have space between them; and since every body can communicate the power of expansion to a body of a lower temperature, that is, can give an expansive motion to its particles, it is a probable inference that its own particles are possessed of motion; but as there is no change in the position of its

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[*] This term will be explained in the chapter on *Light*.

parts as long as its temperature is uniform, the motion, if it exist, must be a vibratory or undulatory motion, or a motion of particles round their axes, or a motion of particles round each other.' Again, 'it seems possible to account for all the phenomena of heat, if it be supposed that in solids the particles are in a state of vibratory motion, the particles of the hottest moving with the greatest velocity, and through the greatest space. That in liquids and elastic fluids, besides the vibratory motion, which must be conceived greatest in the last, the particles have a motion round their own axes, with different velocities, the particles of elastic fluids moving with the greatest quickness; and that in ethereal substances the particles move round their own axes with different velocities, and separate from each other, penetrating in right lines through space. Temperature may be conceived to depend upon the velocities of the vibrations; increase of capacity on the motion being performed in greater space; and the diminution of temperature during the conversion of solids into fluids or gases, may be explained on the idea of the loss of vibratory motion in consequence of the revolution of particles round their axes, at the moment when the body becomes liquid or uniform; or from the loss of rapidity of vibration in consequence of the motion of the particles through greater space.'

CHAPTER X.

SECTION I.

GENERAL PROPERTIES OF LIGHT—PROPAGATION—INTENSITY—SHADOWS—VELOCITY.

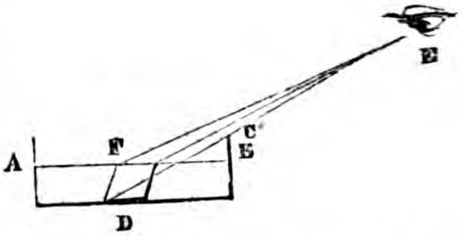
189. The agent whose action on the eye originates the sensation of seeing, by which we are made conscious of the presence of external bodies, is at once admitted to differ most essentially from the ponderable matter of the globe. The cause or agent producing the effects which we refer to heat, was considered independent of ponderable matter, because the characteristic property of matter, or its weight, is never affected by it. Similarly, all the phenomena of seeing are referred to an imponderable agent, which is called light. Respecting the nature of this agent we shall at present venture no hypothesis, but proceed at once to the laws of the phenomena.

Light, whatever be its nature, is propagated in every direction; the simplest considerations will satisfy us of the truth of this law. The flame of a candle is visible from all parts of a room; the electric spark, or any phosphorescent, can be seen in all directions. This, which our experiments can only shew on the small scale, is exhibited in all its grandeur in the expanse of the heavens; for the sun disperses in all directions through all space the same brilliancy, lighting up the earth, the planets, and the comets, and shining on all bodies, whatever be their position in the infinity of space.

All luminous bodies are composed of ponderable matter; we see that without ponderable matter there can be no light; it may be propagated or transmitted without ponderable matter, but it cannot be originated. Hence luminous bodies may be divided into ponderable fragments, more or less minute, and the smallest ultimate particles which we can conceive are called luminous points. Thus, as a body is a collection of molecules or atoms, a luminous body is a collection or combination of luminous atoms or points. Each luminous point propagates its light in all directions, as we have already seen; but from a luminous body, as from a red-hot ball, we only receive the light from the surface; the light from the internal particles is absorbed or stifled in some way by the matter of which the body is composed; the same is the case with the light which is propagated towards the interior from the points at the surface. Thus does light expand itself in every direction; but as we shall see hereafter it is not propagated under all circumstances with equal facility in every direction. Those bodies which are not in themselves luminous shine with borrowed or reflected light, the laws of which we shall presently consider.

190. *Direction of Propagation.*—In a homogeneous medium, that is, in one which is absolutely or sensibly of the same density throughout, light is propagated in straight lines. The simplest experiments will shew the truth of this law. If any number of plates or flat pieces of any substance have a small hole pierced in them, a candle or any luminous point will be seen through them if their centres are all in the same straight line. If the centre of any hole be the least out of the line the luminous body will be obscured. Whenever light meets any surface, polished or unpolished, its direction is changed abruptly, as we shall see in speaking of reflexion and refraction, but after this abrupt change its new direction is rectilinear, provided the medium be homogeneous.

If the medium be not homogeneous, but heterogeneous, that is, if it be of different densities at different points, the propagation will no longer take place in straight lines, its direction will be curvilinear. Thus the light of the sun or a star does not come to us in a straight line; the atmosphere, as we have seen (Art. 98), is a heterogeneous medium composed of successive strata, each differing in density from the preceding; hence it follows, that a heavenly body is never exactly in the place in which it appears to be. Our observations on all bodies at great distances are attended with the same illusions. When the distances are small, the deviation of the direction of propagation from a straight line is, on account of the smallness of the curvature, insensible; just as the deviation of the surface of still water from a plane is not sensible. But since the atmosphere is composed of layers of different densities, light must suffer this deviation in passing through. The change which takes place will be readily understood by considering the change which takes place when light passes from air to water, or from water to air; here it traverses two media of very different densities, and the deviation is very striking.



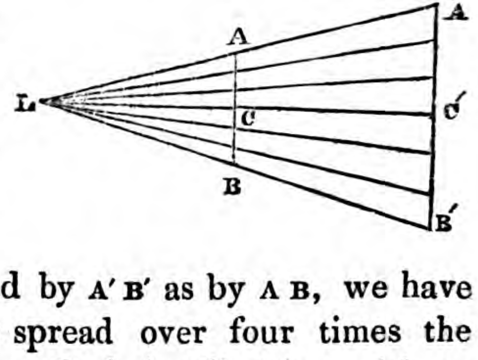
Let any object, as a shilling, be placed in any vessel, and let the farthest point of the object be visible by an eye at E just over the edge of the vessel in the direction E C D. Then if water be poured into the vessel the whole shilling will come into view, though it is still really concealed by the vessel. Here the light is propagated in a straight line in the water, and in a straight line in the air, for each medium may be considered as homogeneous through this small extent, and it will be seen immediately that the light follows a broken line, as D F E. The same may be rendered at once apparent by placing a stick in a vessel of water, and looking down it; the stick will appear broken at the surface of the water, and the portion immersed will only be visible by placing the eye below the outer end of the stick. The light which comes from the heavenly bodies does not experience any abrupt breaks, as when the density of the media changes abruptly, but being constantly bent by insensible degrees has a curvilinear instead of a rectilinear path.

191. *Ray and Pencil of Light.*—Any line drawn from the luminous body along which light is propagated may be considered as a *ray* of light, and several such lines, or a collection of rays, constitute a pencil. When light is allowed to pass through a very small hole it appears as a single ray. It is, however, in reality a small pencil, since a single ray of light, like a mathematical line, has no actual existence; but, being by definition invested with certain properties, serves as the basis of our reasonings. If from any luminous point straight lines be conceived, drawn in all directions, these will represent the rays for all small distances. When light is propagated in a homogeneous medium round any point, and received on any surface, we say that any small portion of this surface is illuminated by a pencil of rays. This portion of the surface is considered as the base of a cone, whose summit is the luminous point, and the pencil of light is the light comprised in this cone; but when the medium is very heterogeneous, this cone can no longer be considered as having any existence. A pencil of light is naturally *divergent*, that is, its section increases as we recede from the luminous point; when, however, the luminous point is at a great distance, the pencil may be considered as parallel, since all the sections are sensibly equal, or all the rays sensibly parallel. Thus, for example, the light from the sun constitutes parallel pencils, since whatever portion of surface we consider, lines drawn from it to the centre of the sun will be parallel. Pencils of light may also be *convergent*, that is, the rays may be so directed that they will meet in a point. This point of concourse for all

the rays is called a *focus*. But it must be specially remembered that the rays, after being thus brought to a focus, continue their course, so that beyond the focus the pencil is divergent, just as a natural pencil.

192. ***Intensity varies as inverse square.***—From the remarks which were made (Art. 123) on the decay of sound emanating from a point at different distances, we may readily understand the diminution in the intensity of light, or the decay of brightness in receding from the luminous point. The law can be established with much greater experimental accuracy in this case than in the one just referred to; for sound and all sensations are very transient, and we have no exact means of doubling a sound, or any exact measure of a sound so increased; but we can double a light, we can observe the illumination of two candles instead of one, and so on. Now it appears, from a variety of experiments which it would be unnecessary to detail, that four candles at a distance of two feet give the same illumination as *one* candle at the distance of *one* foot; thus, supposing all the candles to be equal, each one at the distance of *two* feet gives *one-fourth* the light which it gives at *one* foot. Thus the intensity of the light decreases as the square of the distance increases.

Again, suppose that light is emanating from the luminous point L; then the light included between L A and L B constitutes a divergent pencil; and suppose that A B, A′ B′ are the sections of the pencil at the distances L C, L C′, whereof one is double the other; then, since L C′ is double L C, the area of the section A′ B′ will be quadruple that of A B, and since the same rays are intercepted by A′ B′ as by A B, we have the same quantity of light spread over four times the space; each portion therefore of A′ B′ will shine with an

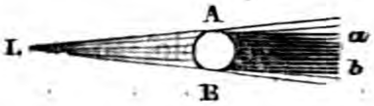


intensity which is four times less than the corresponding portion of A B, or the intensity of the light decreases as the square of the distance increases.

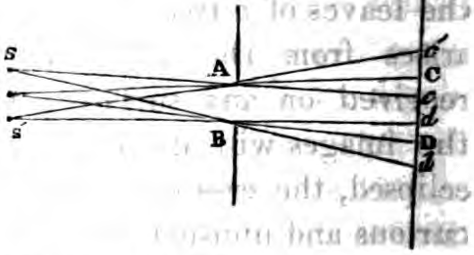
193. *Opaque Bodies.*—Bodies which are not naturally luminous may be divided into opaque, as wood, stones, and metals; transparent, as air, water, glass; and semi-transparent, as silver paper, ground glass. Opaque substances do not transmit any light through their mass. But the opacity arises more from the thickness than from the nature of the substances, since all substances when reduced to sufficiently thin plates or sheets permit some portion of the light which falls upon them to pass; thus, the light of a candle, or of the sun, falling on a sheet of a gold-leaf laid on glass, is transmitted as a faint green glimmer. Transparent substances transmit light, and admit of objects being distinctly seen through them. Most gases, liquids, and crystallized bodies, have perfect transparency when they are not too thick; for they are in general absolutely colourless, and shew not only the forms of objects, but also their colours. But the most transparent bodies become coloured when of sufficient thickness, which proves that they absorb some of the light which falls upon them. Thus a drop of water is perfectly clear, but a large mass of water is blue or green, and it has been calculated that a person sunk to the depth of thirty fathoms in the sea would not receive a stronger light from the sun than we do from the moon. There are other substances, commonly called semi-transparent, which differ from the preceding, in that while they transmit a portion of the light which they receive, they do not admit of any colour, distance, or form, being seen through them.

194. *Shadows.*—When an opaque body is illumined by a luminous point, the form of the *umbra,* or of the shadow, can be easily discovered; for we have only to conceive a straight line passing through the point to trace out the contour of the body. This line produced beyond the body

will trace out a species of conical surface, the contour of which is that of the shadow. Thus, if the light from a luminous point L be intercepted by an opaque body A B, the shadow or umbra will be a cone of indefinite length behind the body, as represented by the shaded part. But a luminous body consists of several points; hence the shadow will not be exactly as here represented; but the light coming from a point just above L will illumine the part of the shadow which is above some line, as A *a*, and the light from a point below L will illumine the part below some line, as B *b*; hence the only part which is really in shade will be that included between these lines. This partially illumined portion is called the ***penumbra***. Every one is familiar with this term as applied to that part of the earth's shadow into which the moon enters first when she is about to be eclipsed. When light passes through a hole, and enters into a dark room, we have a corresponding phenomenon, which we shall endeavour to illustrate.



Suppose that light enters a dark chamber through a small aperture A B, and that S is a point at the centre of the luminous body; then, drawing the lines S A C, S B D, which being produced meet a screen in C and D, all the parts above and below C D will be in the umbra, and the cone whose vertex is S, and base C D, is the only luminous part. But the body has other points, as S and S′, and these will give rise to similar luminous cones, so that there will be portions *d* B D and *d′* A C, which are in the umbra, but which have some light; these constitute the penumbra. The portion *c d* on the screen will be most bright, because it receives light from



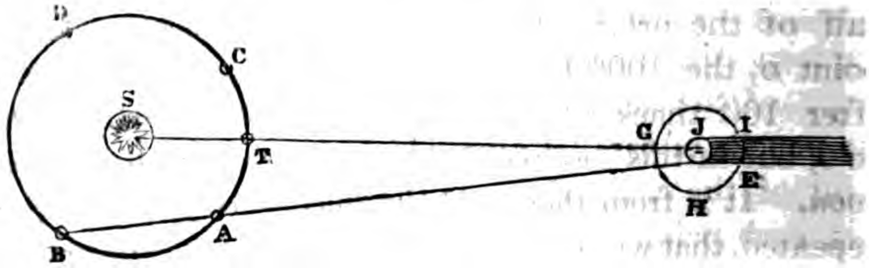
every point in the luminous body; the portion C D will also be bright; but the extreme parts C d', D d', will not have much light.

This is what will take place when the luminous body is near to the hole, so that the rays from each point have sensible divergence; but when the light is received directly from the sun, the rays may be always considered parallel, or every point in the sun gives a pencil of parallel rays. Hence the image or luminous part C D on the screen will not in general be much larger than the hole when the light comes at once from the sun.

195. *Image of Sun always round.*—When the sun shines through a small hole so as to make an image of itself on a screen, this image is always circular, whatever be the shape of the hole. This is the necessary consequence of the pencils of parallel rays which are conveyed from each point of the sun. Suppose the hole to be a small square, then each point in the sun will make a square image opposite the hole, and the infinity of these little squares will make up a little round. Every one must have observed the small elliptical images with which the ground is bespangled, when the sun shines through the interstices of the leaves of a tree. The elliptical form of these images arises from the obliquity of the ground; if they are received on any surface perpendicular to their direction the images will all be round. When the sun is partially eclipsed, the crescent shapes of the images present a very curious and unusual appearance.

In experiments with light it is usual to darken the room, or the general light would be too great for a distinct exhibition of the phenomena; into the room so darkened light is admitted through a small hole in one of the shutters. The relative position of the sun and of the shutter will rarely be such to admit of the sun shining directly through the hole; hence the light must be diverted from its usual course by the interposition of a plane mirror, which may be so adjusted as to reflect the light horizontally; thus the sun's light will enter just as if it were exactly opposite the hole, and whatever be the shape of the hole there will be formed a round bright spot on the opposite wall, or an image of the sun.

196. *Velocity of Light.*—The transmission of light is so rapid that in all ordinary cases it may be considered as instantaneous; but when very great distances are to be passed over, we find that light requires time to travel; this, one of the most important discoveries in science, was made by Reaumur[*] from his observations on Jupiter's first satellite, as we shall attempt to explain. In the accompanying figure let S represent the sun, T A B C D the earth's orbit, J the position of Jupiter, supposed to be in the plane of the ecliptic, and immoveable, during one revolution of the earth, and suppose that the first satellite describes a circle, E H G. The shaded part represents the umbra which Jupiter casts behind him; this umbra, and the orbit also of the satellite, are considerably magnified. During one half of the year, as while the earth is in the portion T A B of its orbit, we can observe the *emersions* of the satellite, that is, the instant at which it leaves the umbra; and during the other half, we can observe the *immersions*, that is, the instant at which it enters the umbra. The interval between two successive immersions or emersions, is the period of the satellite's revolution. Whatever be the point of the orbit from which we make these observations, its duration is always 42^h 28′ 35″, that is, very near



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[*] In 1675 and 1676.

42 and ½ hours. Consequently, if at the point A, for example, we observe an immersion at any given instant, we can predict that the 100th following immersion will take place precisely after 100 times 42h 28′ 35″, and that it will be seen from some point, B, at which the earth has arrived in this time by its motion in its orbit. But it is found by experience that the eclipse happens *too late*, that is, after the calculated time, and we must conclude that this difference is the time which the light takes to travel over the space A B. Hence we have the velocity of transmission by dividing the distance by the time. This conclusion may be verified by observations made in the other half of the orbit. If we observe an immersion from the point D, the 100th following immersion ought to take place after 100 times 42h 28′ 35″, or when the earth has come to C, but in this case we find that the eclipse commences *too soon*. It is from these and similar observations, frequently repeated, that we conclude that light takes 16′ 26″ to traverse the diameter of the earth's orbit, and that, consequently, it comes to us from the sun in 8′ 13″. Thus it is estimated that the propagation of light takes place at the rate of about 192,000 miles in a second.

197. *Aberration.*—One of the most important consequences of light requiring time for transmission is the displacement which the motion of the earth in its orbit causes in the apparent place of the fixed stars. The earth is moving through space with a velocity of about nineteen miles a second; if the transmission of light were instantaneous, a star would be seen in the exact place at which it really was when the light started from it. But during the period of the light's passage the earth has changed its place, and, consequently, the ray which we receive will not be in the same direction as the line drawn from the star to us at the instant of the light's starting. The motion of the earth and of the light will be combined, so that the light will appear to come in a different

direction from that in which it really does come, and the change which is thus occasioned in the place of a star is termed aberration. The effect of aberration may be illustrated by what every one must have observed in moving rapidly forward during a shower of rain. Suppose rain to fall vertically in a dead calm, if a person stands perfectly still a very small covering over his head will receive all the rain, and effectually shelter him, but if he runs forward the rain will beat against his front. The effect is precisely the same as if the rain were drifted by wind against his front as he stands still. A person walking briskly in a shower, although the rain may be falling quite vertically, holds the umbrella forward to prevent the rain wetting him, that is, he inclines the stick or axis of the umbrella, directing it to some point in the heavens before the point immediately above him. The astronomer does precisely the same with his telescope; light may be considered as a shower of luminous particles, through which we are rapidly moving; that these rays, as they descend, may not impinge on the sides of the tube as it is carried forward, the telescope must have the end at which the light enters inclined forward, that is, in the direction in which the earth is moving. The effect thus produced on the place of a star will be seen from the accompanying figure.

Let S A, S′ A′, be the parallel rays of light from any star S to the earth, and while the light is coming from S to A let the earth move from A to A′. If a telescope then be held in the direction S′ A the light from S will travel directly down it; hence the star will be seen at S′ instead of at S. The angle S′ A S is called the angle of aberration.

198. *Consequences.*—If now light is propagated according to the law stated in the preceding article, it will be

curious to consider the different times which it takes to reach the planets of the solar system; and the results are exhibited in the following table:

Names of Planets.	Time of light's passage from the Sun.		
	h	′	″
Mercury	0	3	10
Venus	0	5	56
Earth	0	8	13
Mars	0	12	31
Vesta	0	19	25
Juno	0	21	57
Ceres	0	22	44
Pallas	0	22	46
Jupiter	0	42	45
Saturn	1	18	23
Uranus	4	9	48

The time which the light takes to come from any planet, Uranus for example, to the earth, is sometimes greater sometimes less than $4^h\ 9'\ 48''$, according to the position of the two planets; but we may say without any risk of error, that the astronomer who views the globe of Uranus does not see it where it *is*, but where it *was* four hours before, and that if this planet were annihilated at any instant we should not be aware of it till four hours after it had ceased to be.

We know not at what distance from the earth the stars are scattered, but we can be assured that they are not less than 200,000 times the distance of the sun from the earth; hence their light does not reach us in less than 200,000 times $8'\ 13''$, that is, 1141 days, or 3 years and 45 days; and beyond a doubt it is no exaggeration to suppose that we see stars which are some hundreds of millions times farther distant, and consequently, that their light takes millions of ages to reach us. 'Every thing which exists in the heavens beyond our system may have been broken up and annihilated, and we, the peaceable inhabitants of this earth, shall pass unnumbered years in contemplating as at present a superb spectacle of order and magnificence, which is but a deceitful illusion, an image without any reality.'*

Ponderable matter does not appear to be susceptible of a motion so rapid as that of light. The greatest velocities which we are acquainted with at the surface of the earth are those which result from the explosion of fulminating powders ; and the velocity with which a bullet is expelled from a gun is such, that if it continued its motion for a year it would pass over the space which light traverses in *one second*. If now we ascend to the heavens, the most rapid motion is that of Mercury, whose centre passes over not less than thirty miles in a second. Thus, ponderable matter, so far as we are acquainted with it, never receives a velocity greater than one six-thousandth part the velocity of light. Hence we are led almost at once to the conclusion, that if light be a movement, it is of a substance essentially different from that of ponderable matter.

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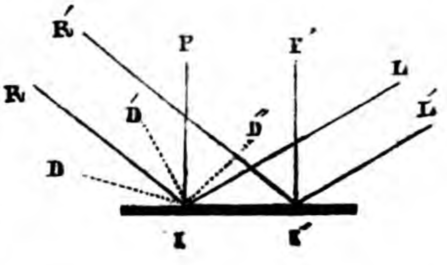
* Pouillet *Elemens de Physique*, Art. 515.

SECTION II.

REFLEXION AT PLANE SURFACE—IMAGES—SPHERICAL MIRRORS.

199. The general law of the transmission of light being that it pursues a rectilinear course, we have to consider the change which its direction experiences on meeting some obstacle, as a polished surface. When light from any source is incident on a polished mirror, the two following remarkable phenomena present themselves. 1°. The rays in one particular direction depict on any object which receives them an exact image of the sun, and their brightness increases with the degree of polish of the mirror. 2°. Rays are conveyed in every other direction; but the brightness of these rays decreases with the degree of polish. The former of these are said to be regularly and the latter irregularly reflected.

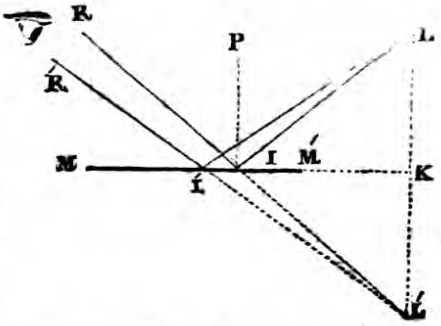


Let L I, L′ I′, be rays from the same source, and let P I, P′ I′, be the perpendicular or normals to the surface. Then the regularly reflected rays are those reflected in the directions R I, R′ I′, such that the angle R I P of reflexion is equal to the angle L I P of incidence. The irregularly reflected rays are represented by I D, I D′, I D″, &c.; these convey some portion of the light in every direction. We have to deal at present only with the light which is regularly reflected, and we shall proceed to state and illustrate its laws.

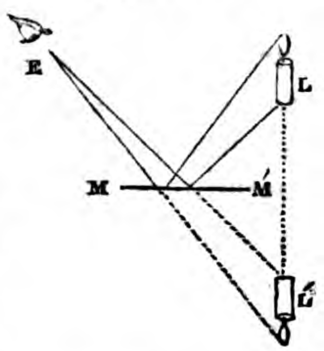
200. *Laws of Reflexion.*—When light is incident on a medium into which it cannot enter, the change in its direc-

tion is expressed by saying, that 'the angle of reflexion is equal to the angle of incidence, and in the same plane with it.' The following method, which is constantly practised in astronomical observations, will serve to establish the preceding laws. A telescope with which any heavenly body is to be observed is fixed to a large circle, moveable about an axis passing through its centre. The star is first observed directly and then by reflexion at the surface of mercury, or at some other reflector. The circle being graduated, the position of the telescope may be accurately ascertained. Thus the angles of incidence and reflexion may be measured with great precision, and the agreement of the results is such as warrants us in assuming these as the true laws. The results deduced on these laws, assumed to be true, are under every variety of circumstance consistent with each other. The laws are equally true for natural or for artificial light, and for reflexion at all surfaces, whether of metals, precious stones, solids, or fluids. All substances reflect light in some measure; it is only by the reflexion of light, incident from some luminary, that we see non-luminous substances; but polished surfaces alone reflect light according to the laws with which we are at present concerned.

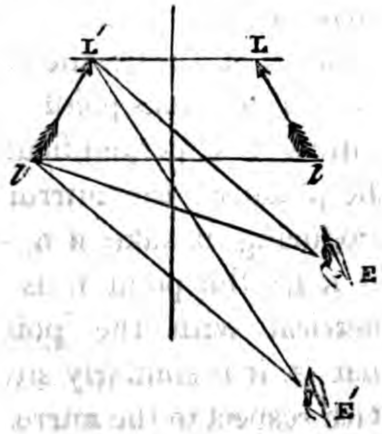
201. *Formation of Images.*—From the preceding principles we may readily explain the formation of images, and their symmetrical position with respect to the reflecting surface.



Let M M′ be a plane mirror, and L a luminous point. From L draw L K perpendicular to the plane of the mirror, and producing it take K L′ equal to K L: the point L′ is symmetrical with the point L, that is, it is similarly situated with respect to the mirror. Then if any line L′ I R be drawn, and L I be joined, the angles L′ I K and L I K being equal, the angles L I P and R I P will be equal also. Hence, any ray in the direction L I will be reflected in the direction of L′ I produced. That which is true for one ray will be true for all others, as L I′, &c., so that all the rays of the reflected pencil R I R′ I′ are reflected at the surface, and proceed just as if they had come originally from the point L′, which is symmetrical with the point L. Suppose now that an eye is placed at a point of the reflected pencil. The small pencil of light which falls on the pupil is directed exactly as if it came from L′; thus, by this pencil the eye sees the luminous point at L′, without ever supposing that the light comes from L, having been bent by reflexion at I I′ on the surface of the mirror. The same reasoning will apply to every point of a luminous body, so that the flame of a candle situated at L, the eye being at E, would be seen in a mirror M M′ as at L′: for the top of the flame would be seen lowest, or the object would be inverted.



Bodies which are not luminous, but only visible by borrowed light, present the same phenomena, since the light which is irregularly reflected from each point of their surface, and by which alone they are visible, is propagated, as if it were actually produced by those points. The two ends L and *l* of an arrow, for instance, will be seen by the eye, as if at L′ and *l*′, and all the intermediate points will give an image on the line L′ and *l*′. Thus the entire image will be comprised between the extreme rays from L and *l*. The fixed position of the image must also be remarked; wherever the eye is placed, the virtual or



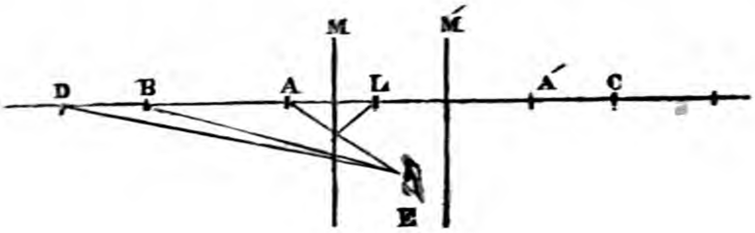
imaginary object is in the same position, and it is the same imaginary object which the eye at E or at E′ views.

Images seen in this manner in a plane mirror are turned from right to left; this every one must have remarked on looking in a plane mirror; and it is at once intelligible from the consideration, that the image of an object seen in a plane mirror is symmetrically situated with respect to the mirror. The construction of this symmetrical image is extremely simple; from every point of the object draw perpendiculars to the plane of the mirror, and producing each to a distance behind the mirror equal to the distance of the point from the front of the mirror, these extremities will form the symmetrical image required.

202. *Consequences.*—If the surfaces of bodies were perfectly polished, the eye could neither distinguish them nor even suspect their existence; and again, if bodies had no polish at all, or rather had no reflecting power, we should be in the same difficulty, so far at least as our eye is concerned. If the moon, for instance, had a polished surface, like a globule of mercury, we should not see it, but only the image of the sun which illumines it; and if the chairs, tables, and objects around us, did not reflect light irregularly, we should never see them.

In the same medium, supposed perfectly homogeneous, light moves on without undergoing any reflexion; but whenever in its passage it meets another medium, it undergoes at the surface, which separates these two, a reflexion more or less abundant. The passage from one medium to another is necessarily attended with reflexion, and since no substance with which we are acquainted is essentially the same medium, or homogeneous, the passage of light is always accompanied by reflexion. Thus a mass of glass presents layers of particles differently arranged, so that light experiences *some* reflexion in passing from one to the other; the same takes place in a much greater degree in a mass of fluid, and a pencil of solar light experiences an infinite number of partial reflexions before it reaches us, since it traverses an infinite number of successive atmospheric strata of different densities.

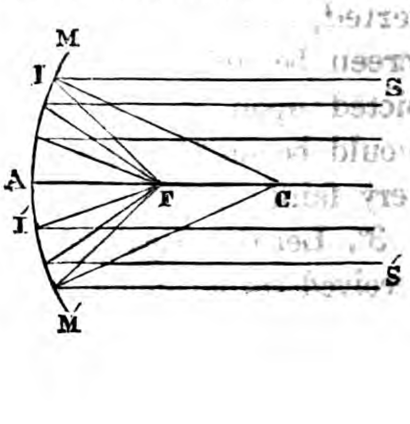
203. *Reflexion at two Plane Mirrors.*—The figure represents an eye E, situated between two plane mirrors,



which receive light from a luminous point or image at L. Here, as in the preceding cases, we only consider the light which is regularly reflected (Art. 200). The eye so situated will perceive a great number of images, whose formation may be readily explained. The rays which fall directly on M form an image at A; those which fall directly on M′ form an image at A′. These latter rays, after reflexion, proceed as if they started from A′, and falling on the mirror M form an image at B, the points B and A′ being symmetrically situated with respect to the mirror M. Behind M′ there is, similarly, an image at C′, the point C and A being symmetrical with respect to the mirror M′. The rays which have undergone a first reflexion at M and a second at M′, return again to M as if they had started from C, and consequently form an image at D, the points D and C being symmetrical with respect to M, and so on. Thus we may easily understand how the successive reflexions give an indefinite number of images more and more faint, and removed from each other, according to a law which may be easily expressed by geometry: to distinguish the images which are formed first at M or M′, we may place a body which is red towards M, and blue towards M′; then on one side the images will be alternately red and blue, and on the other mirror alternately blue and red. The same phenomena present themselves at inclined mirrors, with this difference only, that the number of images depends on the angle of inclination of the mirrors. If two or three small objects be placed at one end of the glasses and the eye at the other, the infinity of images appear depicted in the most beautiful and regular manner that can be conceived: these phenomena every one who has used a kaleidoscope must have gazed on with admiration.

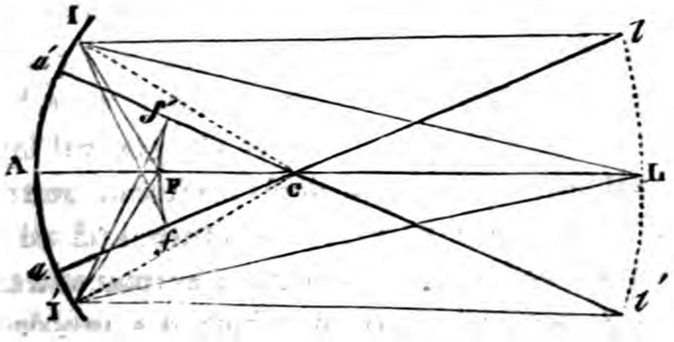
204. *Reflexion of Curved Mirrors.*—The reflexion of light at surfaces which are curved takes place just as it would if the light were incident on a plane mirror, touching the surface at that point. This, which we shall immediately shew to be verified by experiment, may be demonstrated directly by theory. Hence the general laws which we have already enunciated apply, without restriction, to all surfaces, whatever be their curvature, and all questions of reflexion are reduced to finding the normal and tangent at any point of a curved surface, which is a problem in geometry. Thus, if a luminous point be placed at the centre of a hollow sphere polished in the interior, the rays which it emits to every point in the surface will be reflected back on themselves, and return to the centre, for these directions will all be perpendicular to the spherical surface. When the curved surface is a paraboloid or ellipsoid the directions of the reflected rays may be at once ascertained.

205. *Spherical Mirror.*—Since the radii of a spherical surface are all normals, that is, are all perpendicular to the tangent at the point of incidence, the direction of the reflected ray is known at once, as we shall illustrate in the following cases.

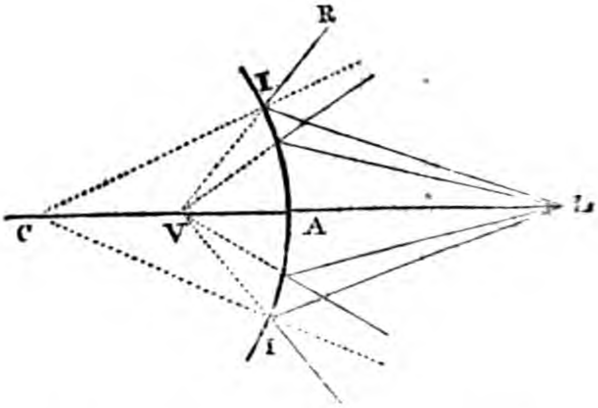


1°. Let M M′ be a portion of a spherical surface, whose centre of curvature is at C. Let rays of light fall upon it parallel to the axis A C; then any ray, as S I, will be reflected at I, so that the angle F I C is equal to the angle S I C. Similarly, any other ray, as S I′, incident at an equal distance A I′, on the other side of A will be reflected to F. And all the intermediate rays will meet in the same point. This point is the focus (Art. 191). Conversely, if the luminous point be at F the rays will be reflected from the surface in directions parallel to I S and I′ S.

2°. Next let the luminous point be on the axis, as at L. Then any rays, as L I, L I′, will be reflected and converge, as before, to a point F, situated between A and C; and the light at this point or focus will be very bright. Suppose that there are any other luminous points, as *l* and *l′*; then drawing *l* C *a*, *l′* C *a′*, through the centre C, the rays from these points will converge to points *f* and *f′* on these axes; these then will be foci, or bright points. Similarly, the light from any points between these, as on the line *l* L *l′*, will be reflected to points on the lines *f* F *f′*; so that there will be formed an image of the object; but it must be observed that this image is inverted, and less than the original object. If a thin paper screen be held at F the object will be seen distinctly depicted upon it. If the object were placed at F there would be an image formed at L; it would, however, be very faint.



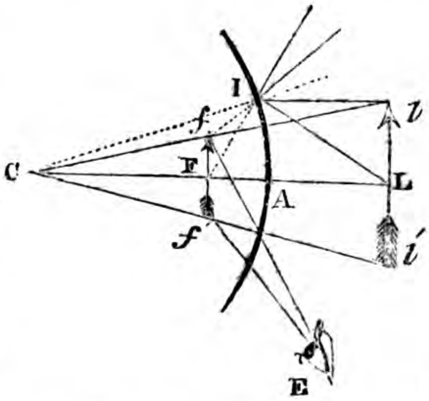
3°. Let the rays proceeding from a point on the axis be received on a convex mirror. Then any rays, as L I, L I′, will be reflected in the directions I R, I′ R′, and proceed as if they started from a point V, which is called the virtual focus.



It appears then that spherical surfaces have the property of turning light from its original direction, and making it either converge to particular points called foci, from which it proceeds as from a fresh origin; or diverge, as if it had proceeded from some imaginary points, called virtual foci. These properties may be shewn at once by receiving light on a spherical mirror; the focus will appear as a bright point, at which all the light and heat incident on the mirror seems to be concentrated.

When the rays incident on a spherical mirror are parallel, they are brought to a focus at the bisection of the radius: conversely, if a luminous point be placed at the bisection of the radius of a spherical mirror, the reflected rays will emerge parallel. Advantage is taken of this property of spherical mirrors in the construction of light-houses. It is necessary to throw a strong light to the distant horizon; this is effected by reflecting the divergent light of a luminous point into one direction by means of a spherical mirror. The lamps are set at the bisection of the radius of the mirrors, and the large silvered reflector which catches its divergent rays reflects them all parallel, so that they are all propagated in the same direction.

206. ***Formation of images by spherical Mirrors.***—Concave or convex mirrors may be used for the production of images, which will differ in magnitude from the size of the original object. We cannot here trace all the consequences of the preceding laws when light is incident at spherical mirrors; this is a simple geometrical problem, which may be readily traced out in any particular case, and the nature of the image both as to magnitude and position accurately determined. We can here only shew how the diminished image of an object by a convex spherical mirror is formed in accordance with the preceding laws.



Let *l* L *l'* be any object placed before a convex spherical mirror; then all the rays from *l* will, after reflection, proceed as if they started originally from *f*, all those from *l'* may be considered as having *f'* for their origin, and the intermediate points will have their virtual foci on the line *f* F *f'*. Thus an image will be formed; and an eye at E will see a diminished image of the object.

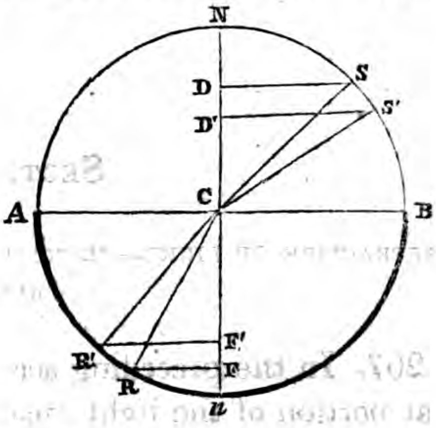
SECTION III.

REFRACTION OF LIGHT—CRITICAL ANGLE—UNUSUAL REFRACTION—MIRAGE.

207. In the preceding section we considered the laws of that portion of the light incident at a given surface, which is thrown back or reflected by that surface; we have now to consider the laws of that portion of the light which enters the medium. The direction of the ray is changed here, and the light is consequently said to be refracted. Thus the refraction of light may be defined to be the change or deviation in direction which light experiences in passing from one medium to another. We have already explained (Art. 190) the nature of the change which takes place when light passes from one medium to another, as from air to water, or from water to air; we have now to state the law which expresses the exact amount of this change in direction.

208. *Law of Refraction.*—When light is incident on a surface at which it enters, so that it passes from one medium to another, the change which takes place in its direction is expressed by saying, that 'the ratio of the sines of the angles of incidence and refraction is invariable for the same medium.' This we shall endeavour to explain.

Let a vessel which is a hemisphere be filled with water, whose surface is A B; let the other hemisphere be represented by the line A S B. Let a solar ray be incident at C in the direction S C, and refracted in the direction C R; then S C N is the angle of incidence, and R C *n* of refraction; also, if S D be drawn perpendicularly to C N, and R F to C *n*, these are respectively the sines of the angles of incidence and refraction. Then if these lines be measured, they will be found to have to each other the ratio of 4 to 3. Again, let S′C be any other incident ray, and CR′ its refracted ray, then drawing the perpendiculars S′D′, R′F′, these lines, which are the sines in this case, will be found to have precisely the same ratio. And whatever angle of incidence be taken, this ratio will be always the same for water. This ratio, which is termed the *index of refraction*, is different for every different substance. Thus, if the water change its temperature, or have any substance dissolved in it, it is really a different medium, and consequently there will be a different value for this ratio. Its value for glass is nearly that of 3 to 2, but it differs slightly for every different kind of glass. A thorough examination of this law, and of the methods by which it is established, would lead us into too great detail; it has recently been verified by Fresnel in a manner and with results which can leave no doubt of its truth. Assuming the truth of the law he calculated the refractions for prisms of very different angles, but of the same material; the calculated and observed results agreed uniformly to six places of decimals.

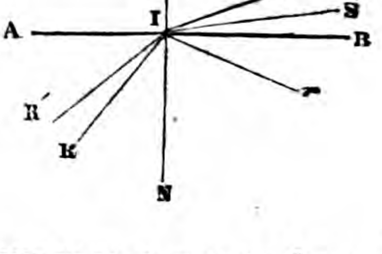


When a ray of light passes from water into air the angle of incidence is that which it makes in the water, and the angle of refraction that which it makes in the air. But their value is still the same, as the simplest experiments will shew, so that a ray of light pursues the same path in whichever direction we suppose it to proceed. Thus, in viewing an object by a ray of light which has been reflected or refracted in any manner, we may consider that the path of the light is precisely the same, whether we trace a ray from the eye to the object, or from the object to the eye. The refraction of light is always accompanied with reflexion as we have already stated; hence there is always some light lost by refraction, that is, the whole of the light is not transmitted.

When light passes into a denser medium, as from air into water or glass, the angle of refraction is less than the angle of incidence, and consequently the refracted ray is drawn nearer to the normal; but when light passes into a rarer medium, as from glass or water into air, the angle of refraction is greater than that of incidence, or the refracted ray is drawn from the normal. This will be at once evident if we consider that the path of a ray is always the same in whichever direction it is supposed to pass.

209. *Critical Angle.*—The least value of the angle of incidence is zero; in this case the ray coincides with the normal, and consequently passes straight in, suffering no refraction. At all other angles there is refraction, and whatever be the angle of incidence, a ray of light can always pass into a denser medium, as glass. But there are certain cases in which a ray of light cannot pass into a rarer medium; as, for instance, a ray of light incident at a particular angle, or at an angle greater than the particular value in a mass of glass, cannot pass out into air. The angle of incidence in glass or water at which it cannot pass out is called the *critical* angle; this will require farther explanation.

A ray, S I, incident at any angle from nothing up to a right angle, will pass into a mass of glass or water, whose surface is A B, and be refracted in some direction, as I R; also a ray, as R I or R′ I, will pass out and be refracted in the direction I S or I S′. But suppose a ray to have a somewhat larger angle of incidence than R′ I, so that the angle of refraction is just a right angle, the emergent ray will then coincide with the surface. If now the angle of

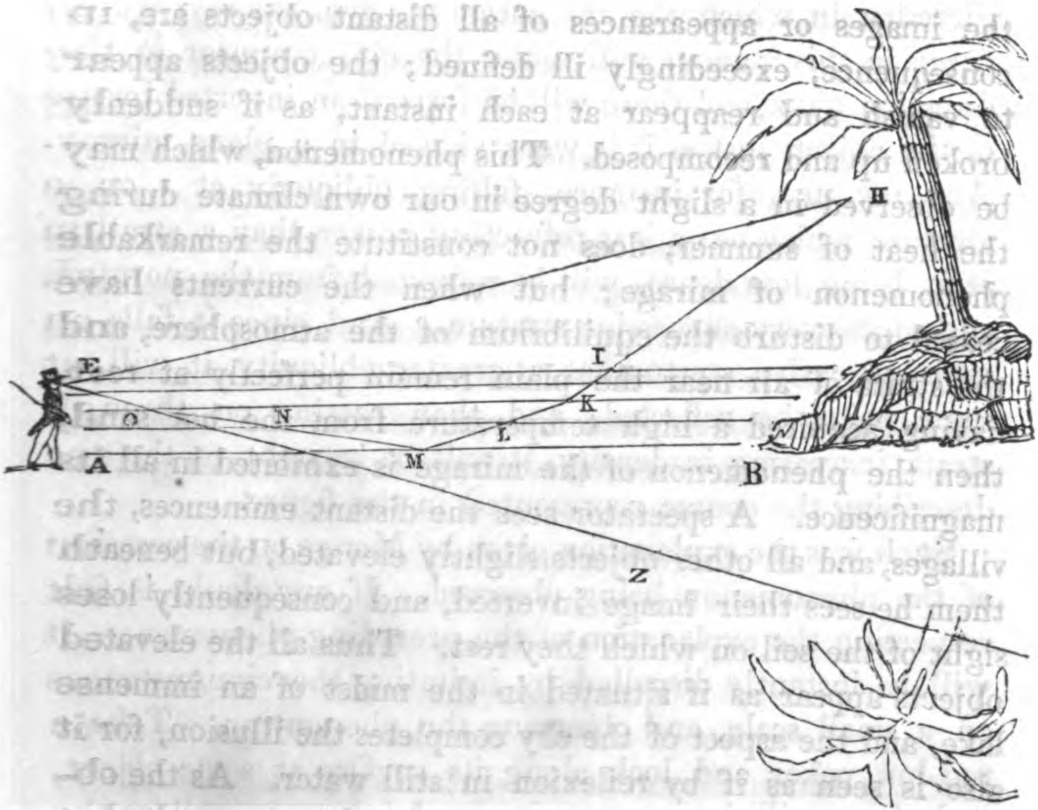


incidence be increased a little more, the ray will not emerge at all, but will be reflected instead of refracted, and lie within the medium, as I *r*. The value of the angle of incidence at which this phenomenon takes place, depends on the nature of the medium; in water it is about 48° 35′, and in glass 41° 35′; when the angle of incidence is greater than this, the light is *totally* reflected; and this is the only case in which light can be reflected without some diminution of intensity. If then a luminous point be under water, there are some positions of the eye in which it cannot be seen. Thus an eye situated under water will see many objects within the water by reflexion at the surface.

210. *Unusual Refraction.*—In viewing distant objects it frequently happens, that under certain circumstances there are seen together with the objects images erect, inverted, and more or less altered in their contour and dimensions. The most notable instances of these phenomena are, the mirage observed by the French expedition in Egypt, the inverted and double images of a ship seen by Scoresby in the Greenland seas, and the apparent elevation, which often occurs. Of these, the mirage is particularly deserving of an attentive consideration.

The soil of Lower Egypt forms an immense plain, over which the waters of the Nile flow at the period of its inundations. On the banks of this river, and at great distances in all directions throughout this desert, are small eminences on which the villages stand. In general the atmosphere is calm and clear; at the rise of the sun the distant eminences and the villages upon them are seen with great distinctness, and the spectator embraces in every direction an extensive field of view, owing to the perfect level of the soil. But as the day advances and the heat increases in intensity, the sand, being much hotter than the atmosphere, heats the strata which are in immediate contact with it. Thus numerous currents are established with greater or less regularity; and there is in the air a species of trembling, which is very sensible to the eye, and the images or appearances of all distant objects are, in consequence, exceedingly ill defined; the objects appear to vanish and reappear at each instant, as if suddenly broken up and recomposed. This phenomenon, which may be observed in a slight degree in our own climate during the heat of summer, does not constitute the remarkable phenomenon of mirage; but when the currents have ceased to disturb the equilibrium of the atmosphere, and the strata of air near the plain remain perfectly at rest, having acquired a high temperature from the hot sand, then the phenomenon of the mirage is exhibited in all its magnificence. A spectator sees the distant eminences, the villages, and all other objects slightly elevated, but beneath them he sees their image inverted, and consequently loses sight of the soil on which they rest. Thus all the elevated objects appear as if situated in the midst of an immense lake, and the aspect of the sky completes the illusion, for it also is seen as if by reflexion in still water. As the observer advances towards the object, he discovers only hot and burning sand at the very spot at which he believed, when at a distance, that he saw the image of the sky, or some other object; but before him, a little farther off, he discovers another object under a similar aspect. This phenomenon, which was often observed during the French expedition in Egypt, was a spectacle equally novel and distressing. The soldiers, when they saw at a distance on the burning plains the reflexion of the sky, the inverted image of the houses, of the palm trees, and of all the objects on the horizon, could not doubt but that they were formed by reflexion at the surface of some beautiful lake. Fatigued by their forced marches under an intense sun, and in an atmosphere full of burning sand, they ran to the imagined water, but it fled before them; it was only the unusual refraction of the heated air which gave this cruel illusion.

Let A B represent the level surface of the soil, which is very much heated by the sun; then since the stratum of air



next the surface is the most heated, the successive strata will increase in density for a certain distance; at some point the density will be constant, and will then decrease, according to the known laws of the constitution of the atmosphere. Under these circumstances let us consider how the rays of light from an elevated object may be modified so as to come to the eye of a spectator. Let the eye be placed at E, and let us consider the rays which start from a point H of the object. It is evident, first, that the eye will see the object directly by the rays in the direction H E; these rays will not come absolutely straight, they will be slightly curved, according to the usual laws which will give a slight elevation to the point H. The distance, however, of the spectator from the object is too small to admit of much deviation. But among all the rays which the point H propagates in every direction there will be some which can come to the eye according to the path H I K L M N O E; now since an object is seen in the direction in which the ray enters the eye, the rays which come in this manner will make the object appear in the direction E O Z, and there will be formed an inverted image of the object, just as if it were viewed in a plane mirror. Any ray, H I for instance, falling obliquely at I on a stratum which has a less refracting power than a stratum at K, being less dense, will be refracted from the normal, and so at every successive stratum. And since it falls on each successive stratum at a greater obliquity, it will at some point be reflected, and then passing on through strata increasing in density, it will be brought to the eye describing the course represented in the figure.

Such was the explanation given by Monge on the occasion of the phenomenon being observed. If any doubt is felt respecting the explanation of the preceding phenomenon, it will be instantly dispelled by imitating the circumstances on a small scale, and observing the phenomena. Take a red-hot poker and look along its surface at some object, and there will be seen an inverted image as well as the object itself. Here the strata of air just about the surface of the poker are affected in the same manner as the air above the hot sand of Egypt.

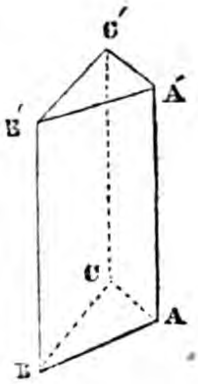
The elevated and inverted images of a ship are to be referred to the same principles of unusual refraction. In 1822, Scoresby recognised his father's ship by its inverted image in the air, although the ship itself was below the horizon, and at a time when, as was afterwards ascertained, it must have been 30 miles distant. In this and all similar cases the direct rays do not come to the eye, or shew the object as it really is; but of the rays which diverge in every direction, some which were propagated upwards meet with strata of proper density, and may be brought to the eye by continued refraction in the manner already described. The density of the air will depend on the temperature; hence from causes which cannot be foreseen the rays may encounter strata of very different densities, so that the eye may receive two rays, having come by different paths from each point of the object, and of these two rays one may give an inverted, and the other an erect, image.

The elevation of coasts, mountains, ships, when seen over the surface of the sea, which is usually termed *looming*, are instances of refraction which may constantly occur. The rays, whose first direction was upwards, meeting with rarer strata, are refracted and brought down again to the eye, which assigns the objects to the direction in which the ray enters it; thus they appear more or less elevated according to the state of the atmosphere.

SECTION IV.

PRISMS—PASSAGE OF LIGHT—DEVIATION—CAMERA LUCIDA—LENSES—IMAGES—MAGIC LANTERN—TELESCOPES.

211. Any transparent medium, having two or more plane surfaces, may be used as a prism in the manner which will be hereafter described. If any number of plane faces be cut on a mass of glass of any conceivable shape, the glass comprised between two of these faces constitutes a prism; and when light enters by one and emerges by the other, it passes through or traverses the prism.



In most experiments, a prism such as is represented in the figure, having three rectangular faces, is employed. These faces are represented by A B′, A C′, and B C′. When the light passes through the faces A B′ and B′ C, the edge B B′ is called the summit of the prism, and the face A C′ is the base; and when it passes through A C′ and B C′, the edge C C′ is the summit, and the face A B′ the base. Such a prism as the one here represented is called a triangular prism, since every section parallel to B C is a triangle; but we may have prisms whose sections are parallelograms or polygons.

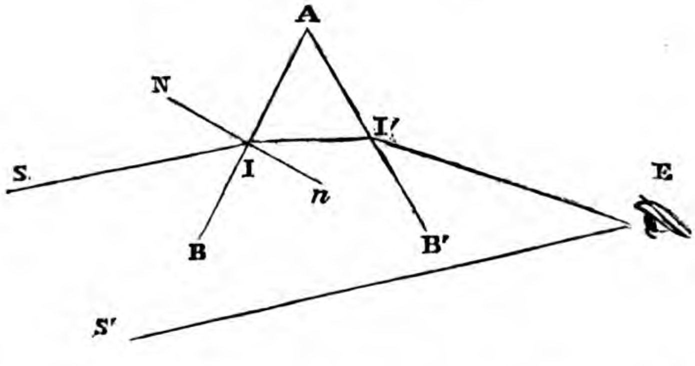
212. *Phenomena of Prisms.*—The prism being placed horizontally with its summit upwards, if the eye be brought near one of the faces so as to receive the light which enters on the opposite face, the following remarkable phenomena will be observed. The light will have undergone considerable deviation, so that all objects will appear elevated towards the summit of the prism; moreover, they will appear coloured at their edges with all the colours of the rainbow. Their horizontal edges only will shew these colours, the vertical ones appearing in their natural colours. The base of the prism must be blackened or covered with paper, so as to prevent irregular reflexions, which would interfere with the distinctness of the appearances. If the summit of the prism be downwards, the phenomena would be inverted, that is, objects would appear extended and displaced downwards. If the prism be placed vertically, that is, standing on one of its triangular ends, the same phenomena will be observed horizontally; the deviation then taking place from right to left or from left to right, according to the position of the summit of the prism. These phenomena are most striking on viewing through a prism the bars of a window, or the flame of a candle in a darkened chamber.

Next, let a pencil of solar light enter a dark chamber

through a small hole A in the direction S A B; it will give a circular and white spot at B. But if a prism be interposed the light will no longer form a white spot opposite the hole, but will be bent from the summit of the prism and form a lengthened line at C, perpendicular to the edges of the prism, and exhibiting the most vivid colours; the phenomenon thus exhibited is called the *solar spectrum*. The same appearances are invariably presented whatever be the position of the prism, the spectrum being always perpendicular to the edges of the prism.

213. *Direction and Emergence of the Rays.*—In the preceding remarks we have supposed the length of the prism to be placed horizontally, so that any vertical section will be a triangle. Now as any ray of light will continue during the whole of its course in the same plane, and as the light will be affected in the same manner in every section, we need only consider the effect produced on a ray in one section of the prism.

Let A B represent the face of a triangular prism at which a ray of light S I is incident, and A B′ the second face at which the ray emerges in the direction I′ E. In passing from air into glass the ray S I is broken at I, and brought nearer to the normal N *n*; on reaching the second surface it is broken again, and passes into the air in a direction removed from the normal. We can conceive then that the direction of the emergent ray I′ E must depend on the index of refraction for air and glass (Art.



208), on the refracting angle of the prism, and on the angle of incidence at the first face. These quantities are connected together by a remarkable formula; but to avoid too complicated a discussion we shall confine ourselves to the examination of some of the most important cases.

We have then to examine the conditions under which the emergence can take place; for we know that light cannot under all circumstances emerge into a less refracting medium, as air; and that there will be some angle of incidence for which the ray will suffer total reflexion at the second surface. Let L be this limiting angle of incidence, or the critical angle (Art. 209), and let A be the refracting angle of the prism. We shall examine in order the three cases.

$$A = 2\,L, \quad A = L, \quad A < L.$$

1°. If the refracting angle of the prism be double the critical angle, none of the rays which enter at the first face can emerge at the second; but the rays on reaching the second surface will all be reflected downwards towards the base of the prism. An orifice then closed with such a prism will not admit the least light; but the interior will be dark as if some perfectly opaque substance were interposed.

2°. When the refracting angle is equal to the critical angle, some rays can emerge, but others cannot. All the rays which are incident, as S I, between the normal N I and the base of the prism can emerge at the second surface, but all that are incident on the side of the normal next the summit or refracting angle cannot emerge; they will be reflected.

3°. When the refracting angle is less than the limiting angle, the preceding case is reversed. All the rays which fall between the normal and the summit can emerge at the second surface, but those which fall on the other side of the normal, between it and the base, as S I, cannot emerge.

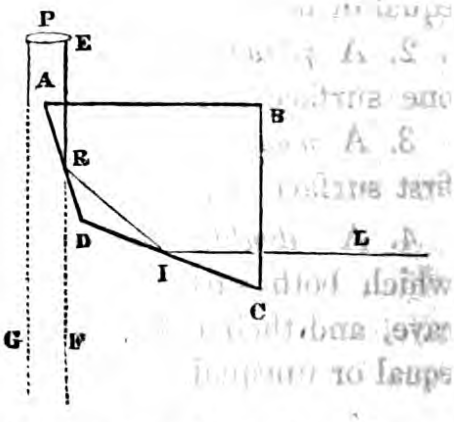
All these laws can be verified in the most distinct manner by experiment, but to trace them out in detail would far exceed our present limits.

214. *Deviation.* — We have seen that a ray of light always suffers a change in direction in its passage through a prism, and the amount of this change can be accurately calculated. The angle of deviation, or the *deviation,* is the angle which the direct image forms with the refracted image, the object being supposed infinitely distant; or it may be defined as the angle through which the incident ray has been bent to bring it into the direction of the emergent ray. Thus S I (Art. 213) being the incident ray, and I′ E the emergent ray, if the eye be placed at E near the prism it may receive at the same time a pencil in the direction I′ E and S′ E; the first will come from the object seen by refraction, the second from the object seen directly, and the angle S′ E I′ which these two images form is the deviation.

If the prism be turned about as an object is viewed, the deviation will change with the apparent change of position of the object. But there is one position of the prism in which the object will appear for a moment stationary, and then if the prism be turned on, the image will move back again; when the image appears for an instant stationary it will be found that the deviation is a *minimum,* that is, less than in any other position of the prism, and it will be found that this minimum obtains when the angles of incidence and emergence are equal. The existence of this minimum deviation can be shewn most distinctly by a pencil of solar light in a dark room. The spectrum will change in position as the prism is turned round. Starting from some extreme position of the spectrum, and turning the prism constantly in the same direction, the motion of the spectrum will at one instant appear to stop; and under these circumstances the deviation is a minimum.

The index of refraction, or the refractive power of different substances, is determined by making a ray of light fall on a prism, so that the deviation may be a minimum.

From mathematical reasoning it appears that the measurements made under these circumstances will be less liable to error than under any other, and also that the deviation is a minimum when the ray is so incident that the angle of emergence shall be equal to the angle of incidence. The refractive power of most substances has been ascertained with great care, and the results are tabulated. The lowest refractive power is that exhibited when light passes into the most perfect vacuum which we can make; next come air and gases of different densities; water, which is the least refractive of liquids, alcohol, oil, glass, and lastly the diamond, which possesses the highest refractive power. There is some relation betwixt the refractive powers and the density or specific gravity of substances. Also those which are inflammable have a higher refractive power than others of the same specific gravity, but which do not possess this property. It was from observing the high refractive power of the diamond in comparison with its actual density that Newton conjectured it to be combustible in its nature.

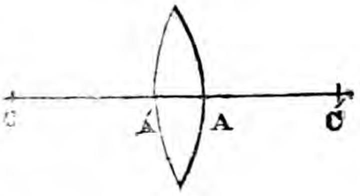


215. *Camera Lucida.*— This beautiful little instrument, invented by Wollaston, furnishes so excellent an illustration of the preceding principles, that we cannot wholly omit it. Its essential part is a quadrilateral prism A B C D, having a right angle at B, and an angle of 135° at A D C. This exact value of the angle is necessary, as the simplest geometry would shew, for the production of the proposed effect. A ray L I from any object enters the prism in a direction perpendicular to the side B C, and is totally reflected at the surface D C; it is again totally reflected at the surface A D, since the angle of incidence at both these surfaces is greater than the

critical angle; then falling perpendicularly on A B it emerges in the direction R E. The eye being placed so that the centre of the pupil P is exactly over the summit A of the prism, will see the image L projected on a piece of paper in the direction E F, and also the paper as at G, on which the image is projected. With a pencil then, since the eye will see both it and the image, an exact copy of the object may be traced.

216. *Lenses.*—A lens is made from some transparent medium, and possesses the property of increasing or diminishing the natural convergence of a pencil of light. The lenses which are used are exclusively spherical, or plane and spherical; other surfaces, as elliptical, parabolic, &c. being exceedingly difficult to execute practically, have not hitherto been employed. The combination of a plane and spherical surface gives six different lenses, to which the following names are assigned.

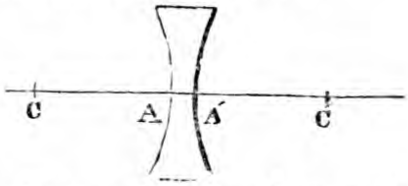
1. A *double convex*, in which both surfaces are convex; whereof the radii C A, C′ A′, may be equal or unequal.



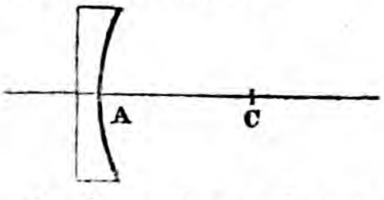
2. A *plano-convex*, in which one surface is plane, and the other convex.

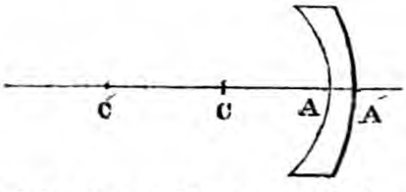
3. A *meniscus-convergent*, in which the radius of the first surface is greater than the radius of the second.

4. A *double concave*, in which both surfaces are concave, and their radii C A, C′A′, equal or unequal.



5. A *plano-concave*, in which one surface is plane and the other concave.





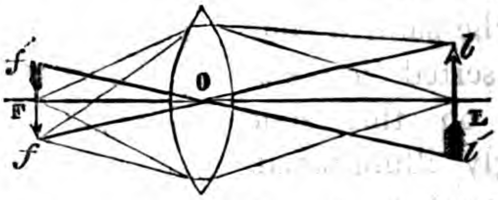
6. A *meniscus-divergent*, in which the radius C A of the

first surface is less than the radius C′ A′ of the second; it is only in this respect of the relative magnitude of the radii that this differs from the 3rd.

The three first of these have sharp edges, or are thinner at the edges than at the middle: they are also convergent, that is, they increase the convergence or diminish the divergence of the pencils of light which pass through them. The three last are thicker at the edges than at the middle; they are divergent lenses, that is, they diminish the convergence, or increase the divergence, of a pencil.

The *axis* of a lens is the mathematical line C C′, which joins the centres of curvature of the two surfaces; in plano-convex and plano-concave lenses the axis is the perpendicular from the centre of curvature on the plane.

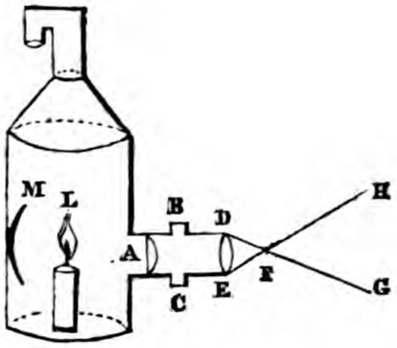
217. *Formation of Images.*—Lenses possess the property of bringing rays to a focus by refraction, as we have already seen done by reflexion at spherical mirrors. Let L be a luminous point on the axis of a double convex lens; then it may be shewn by mathematical calculation that all the rays from L will be brought to a point F, which is termed the focus of the lens. Similarly, the rays from a point l will be brought to a focus f on l O produced; and the rays from l' will similarly be brought to f'. The intermediate points on l L l' will have the foci on f F f'; thus an inverted image of the object will be formed. The points L and F are said to be conjugate to each other, because the object being at either of them its image will be at the other. There are many curious and instructive properties connected with these points in different lenses, on which we cannot here enter. The construction of telescopes, and of



all optical instruments depends on the properties of lenses, and the images which are formed in conformity with the foregoing laws.

In considering the passage of a ray of light through a lens, we may always conceive that it is incident on a plane surface which is a tangent to the curved surface of the lens at the point of incidence. Thus the laws of lenses are reduced to those of prisms; for a tangent being conceived drawn at each point, every ray is affected just as if it were incident on and emergent at the plane surface, which is perpendicular to the radius at each point.

218. *Magic Lantern.*—The construction of this instrument will serve to illustrate most of the laws of reflexion and refraction which have been explained. It consists of a lamp L placed in the focus of a spherical mirror M; the rays reflected at this mirror are received on a lens A, of which the only use is to make them fall in a proper direction on the painted slide which is inserted at B C. The figures on this slide being strongly illuminated, the light proceeds to the lens D E by which it is brought to a focus at F; after this point it diverges in the directions F G, F H; thus a magnified image is formed on a screen placed to receive the rays at some distance from F, and the greater the distance the more will the objects be magnified. The intensity however of the light diminishing as the square of the distance, the image at great distances of the screen is not bright enough for distinct vision.



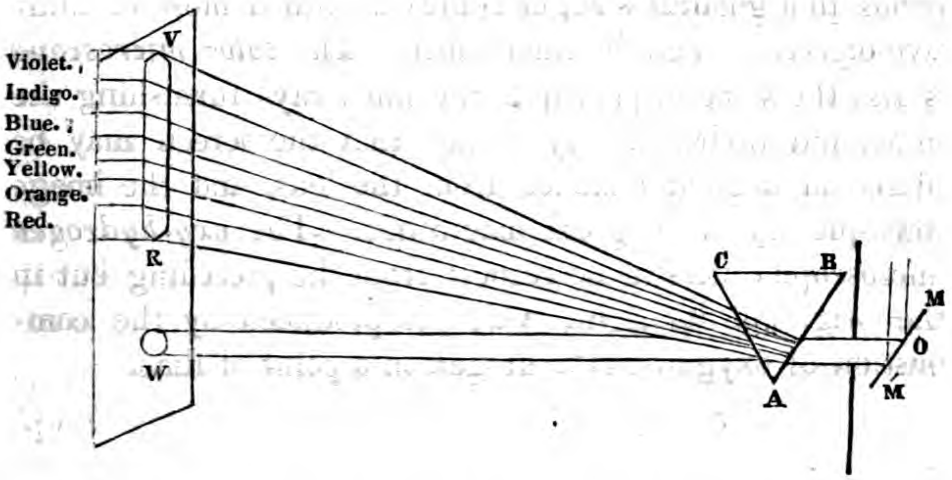
The *phantasmagoria* is nothing but a magic lantern with some contrivance by which the lantern is made to recede or advance, so that the image on the screen expands to a gigantic size, or contracts into a most diminutive object, or mere luminous spot. The ***solar microscope*** is also the same in principle, the sun's rays furnishing the light, and their intensity is such that the screen may be placed at a great distance from the lens, and the image consequently have great magnitude. The ***oxy-hydrogen*** microscope differs in no respect from the preceding but in the origin of its light, which is produced by the combustion of oxygen and hydrogen on a point of lime.

SECTION V.

CONSTITUTION OF LIGHT—ANALYSIS—SPECTRUM—DECOMPOSITION AND RECOMPOSITION OF LIGHT—RAINBOW—LINES IN SPECTRUM—IRRATIONALITY—ACHROMATISM—PROPERTIES OF THE RAYS.

219. We have hitherto spoken of light without any reference to its constitution. We have traced the laws to which the directions of rays are subject when they are received on particular surfaces; it remains now to consider the actual constitution of light itself. The impression which would naturally arise is, that light is a simple element, homogeneous and uncompounded, but it may easily be shewn by experiment that white or solar light is compounded of many different coloured rays.

To effect this let a pencil of solar light be received on a mirror M M′ so situated as to reflect it in a horizontal direction through a hole in a shutter into a dark room. Then if a screen be placed at right angles to the path of the



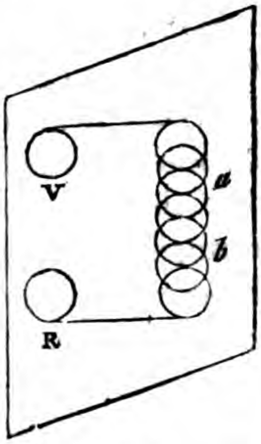
pencil, there will be a round and white image of the sun at W. If now a prism A B C be interposed, the light will no longer form a round white image at W, but an elongated and coloured image R V, which is the solar spectrum. The appearance of the spectrum to a person in front of it is a succession of coloured spaces, as indicated in the figure. The breadth of the spectrum R V is always equal to the diameter of the direct image W; but the length R V of the spectrum depends entirely on the nature of the substance out of which the prism is formed, and on its refracting angle. That the colours may be clearly shewn, the screen on which the light is received must be at such a distance from the prism that the length of the spectrum is double its breadth. When the spectrum is clearly formed the colours succeed each other in the following order: red, orange, yellow, green, blue, indigo, violet. The order of succession is invariable, and the red ray always suffers the least and the violet the greatest deviation: thus the red ray is said to be the least, and the violet the most refrangible; and the other rays possess different degrees of refrangibility. These seven different colours are usually called the seven colours of the prism, or of the rainbow; it will be seen, however, that though our eyes count but seven different colours, the variety of shades of colour which exists is infinite.

220. *Refrangibilities of the rays.*—That the rays have different degrees of refrangibility is evident from the form of the spectrum; for the violet ray which comes to V has a much greater angle of emergence from the prism than the ray which comes to R; and since they both have the same angle of incidence on the first face of the prism, we must conclude that the violet is more refrangible than the red; and from the same reasoning it is evident that the intermediate colours have intermediate refrangibilities. But this law may be shewn in the following simple manner.

Let the spectrum be received on a screen with a small opening, behind which is fixed a second prism. Then by turning the first prism all the colours of the spectrum may be brought successively over the hole and refracted by the second prism, when it will be seen that the violet will be refracted most of all; the indigo a little less than the violet; then the blue, &c.; and last of all the red. Thus the degrees of refrangibility are the same as the order of the colours in the spectrum.

The preceding experiment applies not only to the seven different colours which we have distinguished in the spectrum, but also to different rays of the same colour. For example, the red ray at the extremity of the spectrum, and which is called the extreme red, is less refrangible than a red ray in the middle of the red part of the spectrum, and which is called the mean red, and much less than a ray at the orange end of the red. The same is the case with all the rays throughout the whole length of the spectrum, from the extreme red to the extreme violet. It is this gradually increasing refrangibility which leads us to the opinion that there are in white light an infinity of different colours. In fact, if we observe with care the extreme red and the mean red, we perceive that they do not give the same tint, and as we pass through the whole length of the spectrum there is a continual degradation, or rather change of tint in the successive stripes. Thus, while for the sake of fixing the ideas we name only seven colours, which are more apparent and distinct to the eye, it must be remembered that there exist an infinity of shades in each colour of the spectrum.

221. *Composition of the Spectrum.*—We may now make a more complete analysis of white light, and of the spectrum which it produces. Suppose for an instant that there was in white light but the extreme red and the extreme violet; it is evident then that instead of a spectrum we should have only two images of the sun, round, coloured, and separated; a red one at R and a violet at V. But the red which borders on the extreme red, and which is a little more refrangible, would also give a round image, which would be partly superposed on the preceding on the side towards the violet. The next red would give a similar image, and so on, up to the extreme violet, which would overlay each other as represented at *a b*. Thus in ordinary experiments the spectrum is composed of an infinite number of circular images, encroaching one on the other; and accurately speaking, any portion *a b* being composed of several circles, would consist of several lights, differing in colour and refrangibility; but the circles being of small diameter the colours would be nearly identical, and the refrangibilities nearly equal: this portion then may possibly be considered as composed of one and the same light.



222. ***Each colour of the spectrum a simple colour.***—A colour is said to be simple when it is always essentially the same, and cannot be made to exhibit different colours; we shall see that the colours of the spectrum may be destroyed, but cannot in any manner be modified, the red will always appear red to our eyes, and the green always green. The case is very different with the natural colours of bodies, for all these will, as may readily be shewn, give

elementary tints entirely different from the primitive tints. In vermillion, for example, we shall detect yellow, and green in indigo; and the most vivid colours of nature can all be decomposed in a similar manner. The simplicity and constancy of the colours of the spectrum may be shewn by many experiments, among which the following may be mentioned.

1°. Let any portion of the spectrum be detached from the rest, as, for example, let the violet end pass through a small hole in the screen; this violet pencil may be refracted any number of times, and made to pass through any transparent substance, but the image which it forms will still be violet.

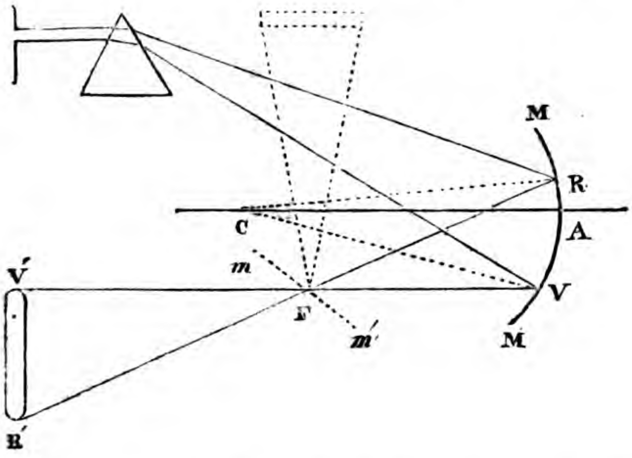
2°. If the violet pencil, isolated as before, fall on any body of a different colour, red, yellow, green, &c., the body will appear violet, without shewing any trace whatever of that colour which seems natural and inherent in it. This experiment may be made on plants, flowers, fruit, &c.; they will all appear violet, as if this was their natural colour. Similarly, with a red ray all bodies will appear red, and the same is true for all the rest.

3°. A violet pencil which is incident on a semi-transparent medium, is either totally absorbed or destroyed; if it passes through, it is violet on its emergence, just as at its entrance. This experiment is most striking with glass coloured red, some red glasses admitting the violet to pass freely, others absorbing it entirely, although if the solar light be viewed by them they all appear equally coloured and equally transparent. That which absorbs the violet generally absorbs all the other rays of the spectrum except the red; thus it is a substance transparent for the red, but more or less opaque for every other colour.

223. *Recomposition of Light.*—When the colours have been separated by a prism they may be brought back into the same direction by a second prism of the same substance and of the same refracting angle as the first, but placed in an inverted position; that is, the summit of the first prism

being upwards in one case is downwards in the other, their bases being always parallel. Then the pencil which is coloured between the two prisms becomes white on leaving the second, and gives on the screen a round image of the sun. If the second prism has a large face it may be placed at some distance from the first, so as to receive a complete spectrum. This experiment shews most distinctly that there does not exist in a prism any peculiar property of decomposing or recomposing white light, but that the separation of its colours, or their reunion, is owing to the unequal refrangibility of the different rays. But it is not necessary for the reproduction of white light that all the colours should be brought back into the same position, but only that they should meet in a point, as the following experiments will shew.

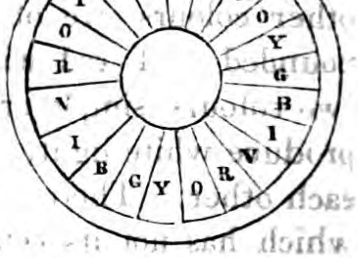
1°. Let the spectrum be received on a mirror *m m′*, so as to be reflected in the direction R R′, and form an inverted spectrum R′ V′; all the colours of the spectrum will meet in the focus F, and at this point the image of the sun received on a small screen, or on a piece of ground glass,



will be a dazzling white, just as if the incident pencil had been a pencil of direct light. The meeting then of all these colours in the same point is sufficient to produce white light. But if instead of receiving the reflected pencil at the focus of the mirror, where the concourse is complete, we receive it a little nearer or a little farther from the mirror, the recomposition is imperfect; and beyond the focus the colours appear in an inverted order.

2°. Let the spectrum be received on a lens instead of a mirror; then at the focus, to which all the rays are made to converge, we obtain white light, as in the focus of the preceding mirror. The round image which it forms is coloured at the edges, because the rays of different refrangibilities cannot come to a focus exactly at the same distance behind the lens. Beyond the focus of the lens the spectrum reappears, but in an inverted position, which is a clear proof that the rays may cross at any point without undergoing any modification, and that each of them acts as if it were a single ray. Also, if in either of the preceding experiments an inclined mirror *m m'* be placed at the focus F, the rays will be reflected and form a spectrum, as represented by the dotted lines, on a screen held above it.

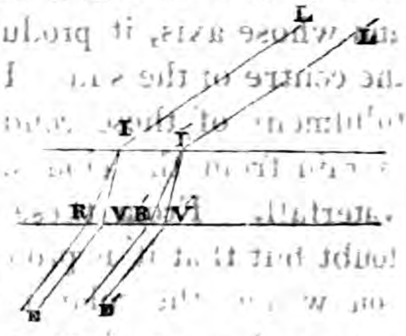
3°. Lastly, there is a mechanical means of recomposing white light, the effect of which is somewhat surprising. Let the figure represent a circle of card board, of about a foot in diameter, having a circle of small diameter at its centre, and a zone at its circumference painted black. In the space between these zones let stripes of coloured paper, R, O, Y, G, B, I, V, be placed next each other, the colours of which imitate as near as may be the colours of the spectrum. Let the whole circular space be filled up with patches of these colours, taking care that the colours are in their proper order, and that each portion has all the colours. The experiment will be more complete if the breadth of the bands have nearly the same proportion as the colours in the spectrum (Art. 227). The card being filled up, and whirled round about its centre, all the coloured bands will disappear, and the space between the



black zones will appear more or less white according as the state of the colours and their proportions have been properly imitated. The explanation of this singular phenomenon is very simple; if there were but one red strip, on a black ground, the eye would perceive during the rotation only a red circle, just as when a lighted stick is turned rapidly round; similarly, if there were but a violet strip, the whole board would appear violet, and the same for any other colour. But if all the bands exist we see, by the rotation, at the same time and in the same place, a red circle, an orange circle, a yellow circle, &c., and consequently a white circle, since the sensation of white is but the simultaneous sensation of all these colours.

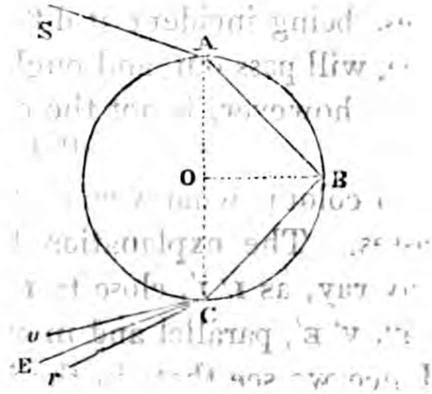
224. *Complementary Colours.* — Since all the simple colours, taken in their natural proportion, that is, in the proportion which they occupy in the spectrum, produce white light, it is evident that, by suppressing one of the colours, or changing the proportion of these colours, we shall alter the whiteness of the light. Thus, by suppressing the red of the spectrum, and compounding all the other colours, we obtain a blue tint; this blue tint compounded with red will produce white light. Whenever two colours, simple or compounded, fulfil this condition, or produce white light, they are said to be complementary to each other. There is no colour, whatever may be the tint, which has not its complementary colour; for if it be not white it wants only the elements of white light, and these elements mixed together form its complementary colour. There are an infinite diversity of shades of the same colour, all of which have the same complementary colour, and an infinite variety of shades of complementary colour for the same colour. The complementary colour of most greens is a reddish violet, and of the yellows a violet indigo. These phenomena are observed by receiving an elongated spectrum on seven different mirrors, which may be placed so as to bring any colour to the same point.

225. *Decomposition and Recomposition of Light on Refraction.*—Whenever a pencil of white light is incident obliquely on a refracting surface, a separation of the colours takes place. This is not, however, always apparent, and in some cases, as when a pencil passes through a piece of glass whose surfaces are parallel, the colours are so reunited that the emergent pencil consists of white light. Thus, let L I, L′ I′, be the extreme rays of a pencil of white light, incident on the upper surface of a piece of glass; then the ray L I is decomposed by refraction into its separate colours, whereof I R is the extreme red, and I V the extreme violet, and these being incident at different angles on the second surface, will pass out, and ought to give a coloured pencil at E. This, however, is not the case, for we know that, provided the surfaces be parallel, the light is invariably free from colour, whatever be the substance through which it passes. The explanation however will be seen at once. Any ray, as L′ I′, close to L I, will give its coloured pencil R′ E′, V′ E′, parallel and in every respect similar to R E, V E. Hence we see that, in the infinity of rays which are incident on a surface, there will be one whose orange will exactly coincide with the red R E, another whose yellow will exactly coincide with it, and so on for all the colours. Thus all the emergent rays are white, the colours having been recomposed on emergence at the second surface. The extreme rays will not be completely recompounded, but the colours will not be visible.



226. *The Rainbow.*—The preceding laws of reflexion, refraction, and decomposition of the solar rays, are illustrated by the beautiful phenomenon of the rainbow. This, as every one must have remarked, is only seen when rain, which is falling in drops in front of the spectator, is strongly

illuminated by the sun, directly behind his back. The coloured arch may then be considered as the portion of the base of a cone whose summit is the eye of the spectator, and whose axis, if produced, would pass directly through the centre of the sun. It is easy to assure ourselves of the fulfilment of these conditions whenever a bow is formed by rain from the clouds, or by the spray of a fountain or waterfall. From these general facts we cannot possibly doubt but that it is produced by some particular modification which the solar rays experience from the drops of rain; and we shall see that the rays come to the eye after having been refracted at the surface of the drop, reflected at its interior, and again refracted on emergence; these drops being supposed perfect spheres.

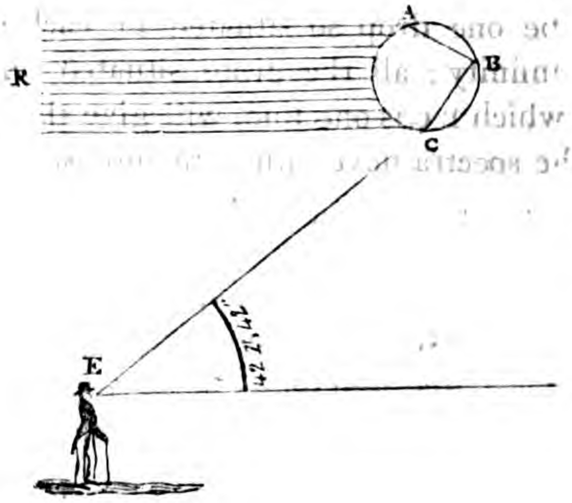


Let a solar ray be incident in a darkened room on a globe of water; then any ray S A will be refracted into the direction A B; the angle of incidence O B A may be such that the ray cannot emerge, but will suffer total reflexion (Art. 209); that is, it will be reflected in the direction B C; at the point C, however, we will suppose that it can emerge; and that it will be refracted in the direction C E. It is evident that such may be the course of a pencil of solar light incident on any sphere, and therefore on a spherical drop of rain. But the light on suffering refraction at the first surface will be decomposed into the seven colours of the spectrum, and these will be incident at B at different angles, since their refrangibilities are different. The red rays will be incident above B and the violet rays below B, supposing the centre of the spectrum to be at B. Each of these colours will be reflected according to the regular laws, and consequently, supposing the centre of the spectrum to be reflected to C, the red rays will lie between C and B, and the violet rays beyond C; these being refracted at C will preserve their relative order, and the red rays will emerge in the direction C *r*, and the violet in the direction C *v*. Thus, if we hold a glass globe full of water above our heads with the sun behind us, we shall see a spectrum in which the red is lowest and the violet uppermost.

Now the rays emergent at C will generally be divergent rays, and consequently there will be no distinct spectrum at any distance from the sphere; in order that distinct perception of the colours may exist at any distance, the emergent pencil must be parallel.

This question being investigated mathematically, it appears that for each separate colour there is a particular angle of incidence, for which the pencil, after having been refracted, reflected, and again refracted, can emerge parallel; from such a pencil the eye can perceive colours at any distance. We will suppose then that a pencil of red light is incident on a drop of rain, and that a spectator is so suitably situated that the light can be brought in a parallel pencil to his eye.

Let the pencil of red light be brought to the eye at E. Let E H be drawn parallel to the incident pencil; then, when the rays emergent at C are parallel, the angle C E H will be 42° 1′ 42″. This is the exact value which calcula-



tion gives from the known refrangibility of red light by water. If then a spectator had his back to a *red* sun, that is, a sun of simple red light, he would see a red spectrum.

Now suppose that the incident pencil is one of pure violet light. The law of refraction for violet light by water is different, and that such a pencil may emerge parallel, calculation says that the angle C E H must be 40° 17′. A spectator with his back to a *violet* sun would, under these circumstances, see a violet spectrum. For all the intermediate colours we should have values of the angle C E H intermediate to these.

But instead of a red or violet sun we have a sun whose light is white and contains them both; let us see then how the preceding principles may be applied to the actual phenomenon. Suppose that the eye of a spectator is at E, and that the sun is behind him. Now when rain is falling there are drops in every position with reference to his eye; consequently, whatever be the position of the sun in the heavens, there must be some drop which has the requisite position that the red rays of a solar pencil, when separated, may emerge parallel; there must be some other drop *below* this from which the violet rays of its separated light may emerge parallel; and there must be drops between these suitably situated for all the intermediate colours. Thus will a series of spectra be produced, which will encroach more or less on each other. But not only will there be one drop so situated for each colour, there will be an infinity; all the drops situated on the conical surface, of which E C is one line, will give the same colour; thus will the spectra have sufficient intensity to be visible at a great distance, and appear to the eye as if depicted on the vault of heaven.

We see then in the preceding explanation the cause for the arched form of the rainbow. The condition that a colour may be produced so as to be visible to the eye at a distance, is simply that, for each colour, the series of drops which produce it must have the same angular position with respect to the sun and the eye. Now all drops on the surface of a cone whose vertical angle is of the proper value, have that position; hence they, and they alone, can affect the eye with the particular colour which corresponds to that position. Thus the rainbow is a series of spectra overlaying each other, and each colour consists of an indefinite number of rays, whose refrangibilities differ from each other, just as they do in the prismatic spectrum. From the preceding we see the reason of the inferiority of the rainbows which are produced by artificial means, or under confined circumstances; as, for instance, when rain falls between a spectator and a wall, or the side of a near mountain. The number of drops is limited, and consequently the intensity of the spectra is proportionally less than when the bow is seen projected on the vault of heaven.

When the sun is strong and the circumstances are favourable, a second or even a third bow may sometimes be seen. The principles here enunciated serve fully to explain the phenomenon, but we cannot dwell upon it on the present occasion. We can only remark, that it is formed by a pencil which, being incident on the under side of the drop, emerges parallel after *two* internal reflexions: the colours also are in an inverted order, that is, in the secondary bow the red is the lowest in the heaven, and the violet highest, whereas in the primary or ordinary bow the red was highest and the violet lowest. The tertiary bow is formed by three internal reflexions, but is rarely visible. A lunar rainbow may sometimes also be seen, but the colours are always exceedingly faint, and will be visible only under extremely favourable circumstances.

227. *Lines in the Spectrum.*—When the spectrum is obtained in great purity* there are certain interruptions

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* The sources of impurity are the breadth of the sun and of the prism; the breadth of the sun is counteracted by reducing the light to a fine line, and taking a point of it and the breadth of the prism by bringing the separated rays to their proper foci by a double convex lens.

or sudden changes of intensity, as dark lines, which were observed about the same time by Wollaston and Fraunhoffer, and which, from the extreme accuracy with which the latter philosopher has laid them down, are called Fraunhoffer's lines. These abrupt changes in some cases, as in the solar light, are intensely black lines, or collections of lines, in others they are bright and coloured.

N. 45	27	40	60	60	48	80
RED	ORANGE	YELLOW	GREEN	BLUE	INDIGO	VIOLET
F. 56	27	27	46	48	47	189

The upper of the accompanying figures represents these lines as they are seen in a pure spectrum of solar light; the lower figure represents the spaces occupied by the different colours. The whole spectrum being supposed divided into 360 equal parts, the upper line of numbers at the end of which N. is placed is the number of these parts which Newton determined the colours of the spectrum of his prism to occupy, and the lower those occupied by the spectrum from a prism of flint glass, as determined by Fraunhoffer.

If we conceive one figure laid upon the other, we shall see the position of the lines with reference to the colours of the spectrum. There is great irregularity both in their appearance and in their position. Some of them are very thin, being separate black lines, and scarcely visible; others are very close together, and resemble a dark shadow more than an assemblage of distinct and separate lines; lastly, others appear extremely well defined, and of a sensible thickness.

To establish some fixed points in the midst of this confused mass, Fraunhoffer has chosen seven lines, marked B, C, D, E, F, G, H, as presenting the double advantage of being easily recognised, and of dividing the spectrum into convenient portions. In the space from B to C he counted 9 fine lines, and well defined; from C to D he counted 30; from D to E about 84 of different thicknesses; from E to F about 76, among which there are three the strongest in the spectrum, and the best defined; from F to G 185, and from G to H, 190; making in all 574 from B to H. Beyond these limits are many others of different degrees of darkness, so that there are more than 600 lines in the whole length of the spectrum.

Fraunhoffer has also determined, that these lines are entirely independent of the refracting angle of the prism, and also of the nature of the refracting substance; that is to say, they remain the same in all cases, both as to number, form, and disposition. On examining other lights, both natural and artificial, in the same manner, it is found that there is an essential difference in their nature, so far as these lines are concerned. The light of Venus and of the Moon gives the same lines as the direct solar light; they are, however, more faint, and exceedingly difficult to distinguish towards the end of the spectrum. The light of Sirius gives black lines; they are, however, altogether different from those of the Sun and Planets; the other stars of first magnitude appear to give very different rays from those of Sirius and of the Sun.

The electric spark gives very bright lines instead of black. Lamp-light gives also very bright lines; the flames of alcohol and hydrogen give nearly the same as those of oil.

From the preceding facts, that the lines are invariably the same for light from the same body, and different for different luminaries, we may conclude that they are essentially a property of the light. Several attempts have been made to produce particular lines, by passing light through different media; and it appears that lamp-light, after passing through a mixture of gases, exhibits lines somewhat similar to those of solar light. The discovery of these lines, or their production in any light, is a matter of the greatest importance, since it furnishes fixed lines for measurement and comparison, as we shall see in the following article.

228. *Refrangibility of different rays.*—The amount of refrangibility, or the index of refraction of any ray, is a question of very great importance in the theory of optics, and in the construction of instruments. The invariability of these lines in the spectrum affords a far more exact measurement than the uncertain shades of the various colours which we were previously compelled to adopt. So that now, instead of determining the index of refraction for the red, orange, &c., we determine the index of refraction for the lines B, C, D. This has been done with the greatest care by Fraunhoffer, and other philosophers, and the different degrees of refraction which these lines, and, consequently, their intermediate colours, undergo, for different substances, as water, crown glass, flint glass, have been accurately determined.

229. *Irrationality of Dispersion.*—When the spectra formed by prisms of different substances are carefully observed, it is seen that the colours, though always ranged in the same order, do not occupy proportionate spaces. Thus, a prism of flint glass, for example, gives proportionally less red, and more violet, than a prism of crown glass; and there are other substances which present this difference in a very striking manner. The general fact is, that in spectra of equal lengths, the same colour is at one time more or less contracted, at another more or less lengthened, as we saw in the different proportions assigned by Newton and Fraunhoffer (Art. 227), for the different colours in the spectrum. This, which is called the irrationality of dispersion of the spectrum, is evidently connected with the indices of refraction corresponding to each colour.

It is this irrationality which presents such insuperable difficulties to the construction of perfect instruments.

230. *Achromatism.*—Refraction at a single medium is always accompanied by dispersion and separation of the colours; hence the formation of colourless or white images by prisms or lenses is extremely difficult. An image in which the colours are separated cannot be of any use, since the object presents a most distorted appearance. We have already seen how the colours may be re-united, so as to form a white image, by bringing the rays back again; but there the whole deviation is destroyed, and the image is consequently useless. But different substances possess equal dispersions with very different refractive powers, that is, with two different lenses or prisms, one of crown glass and the other of flint glass, for example, two spectra of equal length can be produced, in which the mean rays undergo very different amounts of refraction. These being refracted in opposite directions, the dispersion may be counteracted, but a considerable quantity of refraction still remains. Thus, an image nearly colourless can be formed; it is not absolutely free from colour, owing to the irrationality of the spectrum; but its centre part will be sufficiently so for the purposes of observation.

The achromatic object glass is composed of a convex lens of crown glass, and a concave lens of flint glass. The effect of a lens is the same as of a prism touching the surface at the points of incidence and emergence. Thus the colours are re-united, but the pencil is still refracted.

231. *Peculiar properties of the Spectrum.*—The *illuminating power* of the spectrum is found to be different at different points, and the point of maximum. Illumination is determined by Fraunhoffer at a point M, about one-third of the distance between D and E from D, very near the boundary of the orange and yellow; the mean ray is also determined to be near the middle of the blue space.

The *heating* power of the spectrum is found to increase, from the violet to the red end; and a thermometer continues to rise when placed beyond the red extremity of the spectrum, where no ray of light is perceived; hence we may infer, that there are invisible rays in the light of the sun of less refrangibility than the red rays, but which have the power of producing heat.

The rays of the spectrum produce also very different *chemical* effects; thus muriate of silver becomes very soon blackened beyond the violet end of the spectrum. It becomes less blackened in the violet, still less in the blue; the blackening growing less and less towards the red extremity.

The *magnetizing* power of the solar rays which was announced some years ago by Dr. Morichini, has been recently established by the ingenuity of Mrs. Somerville. A sewing needle having one end exposed to the violet rays acquired magnetism in about two hours, the exposed end exhibiting north-polarity. The indigo rays produced nearly the same effect, as also the blue and green, though in a much less degree, but the red, orange, yellow, or heating rays beyond the red, produced no effect.

Mr. Christie has also discovered that when a magnetized needle, or a needle of copper or glass, vibrates by the force of torsion in the white light of the sun, the arc of vibration is more rapidly diminished in the sun's light than in the shade. The effect is greatest on the magnetized needle. Hence he concludes that the compound solar rays posses a sensible magnetic influence.

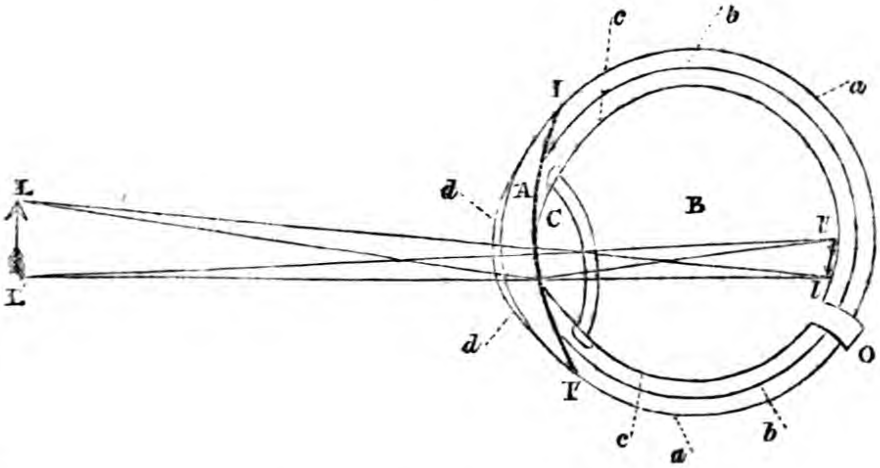
SECTION VI.

LAWS OF VISION—THE EYE—FORMATION OF THE IMAGE—ADAPTATION TO DISTANCES—SINGLE VISION—DEFECTS OF VISION—SPECTACLES—MICROSCOPES.

232. Having in the preceding sections stated the general laws of light, we shall now endeavour to explain their application for the purposes of vision generally. We shall commence this subject by considering how the most exquisite piece of mechanism with which we are acquainted, the eye, is, in conformity with these laws, concerned in contributing to our knowledge of the external world. Here we shall meet with much which is at present but partially explicable; as our knowledge of the laws of light and of the constitution of the eye progresses, we may hope that these difficulties will vanish, and that we shall be able to trace, successively, the modifications which the light experiences from its first entering the eye up to the formation of the image, after which sensation commences, and all physical phenomena are consequently at an end. The simplest conception which we can form of the eye is derived from considering it as a dark chamber into which a small pencil of light is admitted, and forms an image. But it will be necessary to explain in some detail the different parts by which the formation of this image is effected.

233. *Description of the Eye.*—The human eye is very nearly a sphere, with a slight projection in front. The accompanying figure represents a section of it, made so as to pass through all the different parts which compose it.

The external layer *a a* is a strong tough membrane, to which are attached all the muscles which give motion to



the eye-ball; it is termed the *sclerotica*, or *sclerotic* coat. The projection *d d* in front, termed the *cornea*, is a clear tough substance, which fills up, as it were, a circular orifice in the front of the sclerotic coat, fitting in like a watch-glass. The rays of light are first refracted at the surface of the cornea. Lying on the sclerotic coat is a delicate membrane, *b b*, covered on its inner surface with a black pigment, termed the *choroid* coat. Immediately upon this pigment of the choroid lies the retina *c c*, a most delicate reticulated membrane, formed by the expansion of the optic nerve O. At I, I′ is attached a flat circular membrane termed the *iris*, pierced in its centre with a small hole called the *pupil*. The pupil widens or expands when a small portion of light enters the eye, and contracts under the influence of a strong light. The colour of the eye depends on the iris, which is grey, blue, black, &c.; were it transparent as the cornea, the eye would be black as the pupil, and vision could not take place; it is perfectly opaque, and its opacity is insured by the nature of its structure. Behind the iris the *crystalline* lens C is suspended; it is enclosed in a membrane termed the *capsule*, which is firmly attached to the coat of the eye by the ciliary processes, whose nature is not fully understood. The eye is thus divided into two chambers or compartments, as A and B, of very unequal sizes; they are both filled with a liquid; the liquid contained in the anterior, which is the smaller chamber, is called the *aqueous humour;* and that in the posterior or second chamber, the *vitreous* humour. Such is the general formation of the eye; and we shall endeavour to shew how exquisitely even our present imperfect knowledge of its structure shews it and the laws of light to be mutually adapted to each other.

234. *Formation of an Image.*—When a luminous point is placed at the distance of eight or ten inches from the front of the eye on the axis of the crystalline lens, a portion of the pencil falls on the white of the eye, and is irregularly reflected on all sides; a more central part falls on the cornea, and being refracted, penetrates the aqueous humour: of this pencil the exterior rays illuminate the iris, and the central rays passing through the aperture or pupil, the crystalline lens, the aqueous humour, the retina, reach the choroid. The light which the iris receives is irregularly reflected on all sides, and shews us the form and colour of this membrane. The central pencil, which traverses the pupil, is refracted by the crystalline as by a converging or double convex lens; for the crystalline is more strongly refracting than the aqueous, or than the vitreous humour; and, consequently, under certain conditions, this pencil having become convergent, can form an image of the luminous point from which it has emanated. Suppose, for a moment, that a ray from L (Art. 233) is brought to a point exactly on the retina, or on the choroid, at *l*; then it is evident that any other luminous point at L′ will make a similar image at *l′*; thus there will be at the back of the eye a little image *l l′* of the object L L′. This image, being inverted, will present, in all respects, an exact representation of the external object.

This may be verified experimentally by placing the eye of any animal just killed in the aperture of a dark chamber, the posterior surface being pared away, and rendered thin, so as to offer a transparent membrane. An observer within the dark chamber will see very distinctly at the back of the eye the image of any bright object which is placed before it. Hence we cannot doubt but that the images of the external world so faithfully depicted on the retina, is the first condition of vision.

Under this general view, the physical phenomenon of vision appears to be a very simple result of the laws of refraction, and of the power of lenses; but on examining more accurately all the circumstances which accompany the formation of images on the retina or choroid, difficulties present themselves, of which the present state of our knowledge hardly gives any satisfactory explanation. The two following are among the most remarkable.

1°. The eye is achromatic; for objects do not appear surrounded with fringes of different colours.*

In order to solve this question, we must know exactly the indices of refraction, the dispersive powers, and the curvatures of all the media which the light traverses from the cornea to the retina; this question is beset with difficulties, since the different parts of the crystalline have very different refractive and dispersive powers.

2°. The clearness of objects seems to be entirely independent of the distance of objects; for we see distinctly at some inches, and also at some feet—at some miles, and some thousands of miles. The image of a star is as clear and distinct as that of a spark immediately under our eyes.

There is for every eye a distance at which objects are more distinct and clear than at any other; but the eye sees so well at nearly all distances, that it must possess some power of accommodating itself to distances. A great difference of opinion prevails among philosophers on this

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* This is contrary to the opinion of some philosophers: see Brewster's *Optics*, p. 290.

point; some suppose that the eye possesses the property of elongation, or that the crystalline can change its form, or that the iris can, by altering the aperture of the pupil, admit rays only of a proper convergency. Brewster maintains, from direct experiment, that a variation in the aperture of the pupil, produced artificially, is incapable of producing adjustment; and as an elongation of the eye would alter the curvature of the retina, and, consequently, the centre of visible direction, and produce a change of place in the image, that this hypothesis is quite untenable. His experiments lead him to the following conclusions:

1°. That the contraction of the pupil, which necessarily takes place when the eye is adjusted to near objects, does not produce distinct vision by the diminution of the aperture, but by some other action, which necessarily accompanies it.

2°. That the eye adjusts itself to near objects by two actions, one of which is *voluntary*, depending wholly on the will, and the other *involuntary*, depending on the stimulus of light falling on the retina.

3°. That where the voluntary power of adjustment fails, the adjustment may still be effected by the involuntary stimulus of light.

Reasoning on these, he concludes that the adjustment must be effected by the parts in immediate contact with the base of the iris, and that the mechanism of the iris changes the position of the lens, so that the lens is removed from the retina by the contraction of the pupil.*

Pouillet,† on the contrary, considers the motion of the crystalline lens, and its contraction, highly improbable; and agrees in rejecting the hypothesis of the change in the elongation of the eye, and in the curvature of the cornea. Reasoning on the certain fact of the change of the aperture, and from the construction of the crystalline, which he finds to consist, not of concentric layers, but of layers un-

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* *Optics*, p. 302.

† *Elemens de Physique*, Art. 549.

equal, both in thickness and curvature, he arrives at the following explanation.

When we look at a near object, we contract the aperture of the pupil considerably. The effect of this contraction is to stop the rays which would fall too far from the centre of the crystalline, and which would converge to a focus beyond the retina. The rays which are admitted, falling near the centre of the crystalline where the curvature is considerable, are very powerfully refracted.

When a distant object is viewed, we open the pupil as much as possible, so as to admit a very large pencil, the outer rays of which falling on the outer parts of the crystalline, where the curvature is less, will be brought to a focus at the retina.

235. *Defects of Vision.* — A very common defect of vision, especially in elderly persons, is what may be termed long-sightedness, that is, they are obliged to hold a book at two or three feet distance; nearer than this the objects are confused. This infirmity results evidently from a defect in the convergence of the pencils, which pass the humours of the eye, and is generally supposed to result from a flattening of the cornea, and of the crystalline lens. It has been remarked, that those who have too long sight, have in general the pupil a very little open, as if they were making a continual effort to use the centre, where the converging power is the greatest, instead of the edges of the crystalline lens. This defect, when unaccompanied by disease, may be entirely made up by the use of a convex lens, which assists the eye in converging pencils from near objects.

The other very common defect of short-sightedness shews itself in an inability to see distinctly at the ordinary distances; hence objects are held near the eye, as within two or three inches; every object beyond this distance is enveloped in a cloud, and does not form at the back of the eye any distinct image. This defect is exactly the contrary of the preceding, and results from the pencils being brought too soon to a focus; the eye is in these cases too powerfully convergent. We suppose that the cornea or crystalline lens is too convex, and it has been remarked, that in this case the pupil is always dilated, as if the person was endeavouring to use the edges rather than the centre of the crystalline lens. This defect is remedied by using a concave lens, which adds divergency to the incident pencil, so that a distinct image can be formed on the retina.

A most remarkable defect in vision is that arising from cataract, which is a change in the opacity of the crystalline lens; it ceases to transmit light, and the individual becomes perfectly blind. The crystalline lens may, however, be removed, as is done in the operation of couching, and its place can be supplied by a convex lens placed outside the eye. The crystalline lens being as we have seen a convex lens, its effect on a pencil of rays is to increase their convergency; when then this is removed they will not have the requisite convergency; this, however, can be given to them; hence couched people must always wear spectacles; they must also wear different spectacles for different distances; the glasses must be very convex for near objects, as a book or needle-work, and less for distant objects. By the loss of the crystalline lens the eye loses in a great measure its power of adaptation; hence the pencil must be modified and adapted by other means. The judgment of distance also is impaired at first, and the person must learn again to see.

236. *Spectacles.*—The distance of distinct vision is in general from eight to ten inches, but, as we have seen in speaking of long and short-sightedness, the eye has other distances of distinct vision; it is sometimes also necessary for other purposes to be able to view objects at less distances than the above. This is accomplished by the use of spectacles or eye glasses, which consist of a lens set in a frame; the nature of this lens, that is, the curvature of its surfaces, may be readily ascertained from the preceding principles. Suppose, for example, that a person cannot

see distinctly at a less distance than thirty inches. In order that he may see, as well as a person whose sight is good, objects at a distance of ten inches, the light coming from these objects must be modified by a lens so as not to have more divergence than if it had come from a distance of thirty inches. Consequently, the object being ten inches from the lens, the virtual image must be thirty inches, and from these data it is known that the focal length of the lens must be fifteen inches. Hence, a person who naturally sees distinctly only at thirty inches must employ immediately before his eye a converging lens of fifteen inches principal focal distance, in order to see distinctly at ten inches.

Similarly, if a person cannot see clearly except at five inches we shall find the lens which he must use is a diverging lens of ten inches focal distance.*

237. *Microscopes.*—The common magnifying glass or simple microscope is nothing but a converging lens of very short focus. This instrument enables us to see objects which could not possibly be seen by the unassisted sight. The botanist detects by means of it the delicate organs of plants, and workmen in every department of the arts use it for minute adjustments and operations.

The object to be viewed must be placed near the lens at a distance less than its principal focal distance. Let A B be the object before the lens C D, and viewed by an eye at E. The course of the rays will be seen in the figure; the rays from A and B which pass through the centre of the lens come to the eye under the same angle, as if the eye were in the place of the lens. Hence the appearance of the object ought to be the same as if the eye were in the place of the lens, and the apparent magnitude of the object is the same, for this

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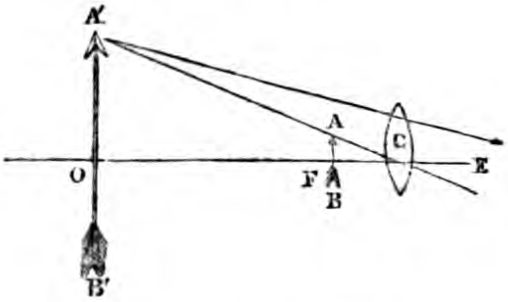
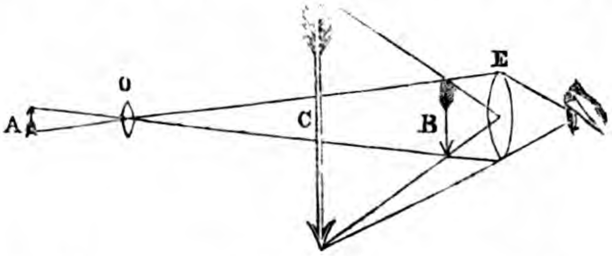
* The mathematical formula for these and all similar cases is $F=\frac{10\,D}{10-D}$ where F is the focal length of the required lens, and D the distance of distinct vision, the natural distinct vision being supposed to be at ten inches. The lens will be a diverging or converging one, according as the resulting value of F is positive or negative.



depends on the angle which the extreme rays make at the centre of the lens. If then the object appears to have the same magnitude as it would have if the eye were in the place of the lens, we may reasonably inquire from what arises the advantage of interposing a lens. This will be seen at once from what has been already said respecting the distance for distinct vision; the rays from any point of the object must meet the retina in one point. But the eye being in the place of the lens the divergence of the rays would render this impossible, and consequently distinct vision could not take place under these circumstances. Objects, however, not being distinctly visible when very near the eye, may be rendered so by the interposition of a lens; and this is the service which the lens renders; it enables us to see an object, when held very near, which must otherwise be held afar off; and the magnifying power of the simple microscope arises entirely from the fact of its enabling us to view, at a very small distance, that is, with the extreme rays making a large angle, an object which must otherwise be held at the usual distance for distinct vision. Thus, suppose the place of distinct vision to be at O, then the object A B will appear as A′ B′, when viewed through the lens C. Now the magnitudes A′B′, A B, are as their distances from the centre of the lens, and, consequently, if A′ B′ be twenty times farther from the lens than A B, it will be twenty times larger than it. But A B is very near the focus of the lens, hence the magnifying power of the simple microscope is measured by the number of times which the focal distance of the lens is contained in the distance at which small objects are seen distinctly by the naked eye.

The *compound* microscope consists, in its simplest form, of two lenses, the object glass and the eye glass. A magnified image of the object is formed by the object glass O,



and the eye glass E enables the eye to view this image very near; thus, suppose the object glass to form an image at B ten times the size of the original object at A, and that the eye glass enables the eye to view this at a distance $\frac{1}{10}$th of that which is necessary for distinct vision with the naked eye, then the original object will, by this compound microscope, be seen represented at C, magnified one hundred times.

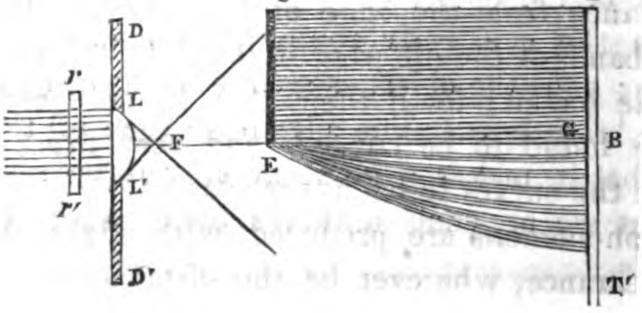
The magnifying power then of the microscope arises from its enabling us to view objects much nearer than we could otherwise do; but we can see them very close with the naked eye by the simple contrivance of piercing a little hole in a thin plate, and viewing through it a small object very close and well illumined; the object will be seen distinctly, and will appear magnified as by the microscope. Here there are no divergent rays whose divergency must be destroyed, the extreme smallness of the passage afforded to the light prevents more than one ray, so to speak, from each point of the object coming to the eye, whence continuing in the eye their route, each makes its distinct impression; thus the object is seen without confusion, but with little brightness. The advantage then of the microscope is, that it makes a great number of rays enter the eye, so that we are enabled to see the object with greater distinctness.

SECTION VII.

DIFFRACTION AND INTERFERENCE OF LIGHT—FRINGES—FRESNEL'S EXPERIMENTS—PRINCIPLE OF INTERFERENCE.

238. The laws of the diffraction of light, that is, the laws of the phenomena which are exhibited when light passes a sharp edge, and through a small hole or slit, are among the most interesting and important phenomena in optics. The beauty of the phenomena must always render them a great object of interest, but the important consequences to which they lead renders them of especial value in the present state of science. It was these which presented the first formidable obstacle to the theory of emission, and which led to the adoption of the theory of undulations. The difficulties of treating this subject in an elementary manner are very great, but we shall endeavour in the present section to point out some of the more important phenomena, and the consequences to which they lead.

239. *Phenomena.* — A pencil of solar light reflected horizontally enters a dark chamber, and is received on a lens L L′ of short focus, and, continuing its course, forms



a very divergent cone. That the light of this cone may not be mixed with extraneous light, a diaphragm or stop D D′ is placed round the lens; and that the light may be as homogeneous and simple as possible, it is transmitted through coloured glass *r r′*, which transmits only the rays of one colour. Then if a screen whose edge is thin and clear be placed at E C, a short distance from the focus F, and its shadow be received on a tablet T T′, or a piece of ground glass, it will be seen,

1°. That the line F E G, which is the geometrical boundary of the shadow, is not the real separation of light and shade.

2°. Above this line the screen is not dark, but has a sensible brightness, which extends to a considerable distance, diminishing in intensity almost uniformly.

3°. Below this line, on the contrary, there are alternately fringes of light and dark, which are extremely remarkable. First, at B is a bright band or fringe, exceedingly brilliant, and parallel to the edge E of the screen, or to the trace of the geometric shadow; then comes a dark band, very black, and parallel to the first; this is a black fringe of the first order. Then comes a second bright band, and then a dark band, which is black of the second order. This succession continues for a great distance from G, so that it is sometimes easy to observe black fringes of the sixth or even of the seventh order. In proceeding from the outline of the geometric shadow the fringes or bands decrease in brilliancy, and the dark bands take a more decided luminous tint. Lastly, they disappear entirely, or rather are lost in the light which passes at a small distance from the edge of the screen. The bright and dark bands of the different orders take their rise at the edge of the screen; for if their path be accurately traced it will be found to be curved, and very exact measures determine the curves to be hyperbolas.

These phenomena are produced, with slight changes in their appearance, whatever be the distance of the screen

T T′, and of the focus F, which is the luminous point, from the edge E; they are produced also with all the colours of the spectrum, but we may observe that from the red light to the violet the bright and dark fringes diminish gradually in breadth, and become in consequence more contracted, and nearer to the geometric shadow. Hence it is, as we shall see presently, that white light does not give bands alternately white and black, but bands coloured alternately with different colours. For each of the simple colours in the white light undergoes the same diffraction as if it were alone; starting from the geometric shadow, it is the violet which will fail first, and the red consequently ought to appear first after the white band which borders the shadow. But at the distance when the red would fail were it alone, the other colours will not fail, and their mixture will give a compound tint. Thus, when the law of the bands is known for each of the simple colours, it will be easy to assign the order and nature of the more or less complex tints, which white light ought to give. These remarkable shadows are, from the name of the philosopher who first wrote upon them, and their variously coloured appearance when made with white light, called Grimaldi's fringes.

240. *Consequences.*— The preceding experiments lead to the following conclusions.

1°. That under certain conditions rays of light exert on each other a mutual action.

2°. From this action arises necessarily the principle of *interferences,* a principle of great extent, and to which all the phenomena of optics are subject.

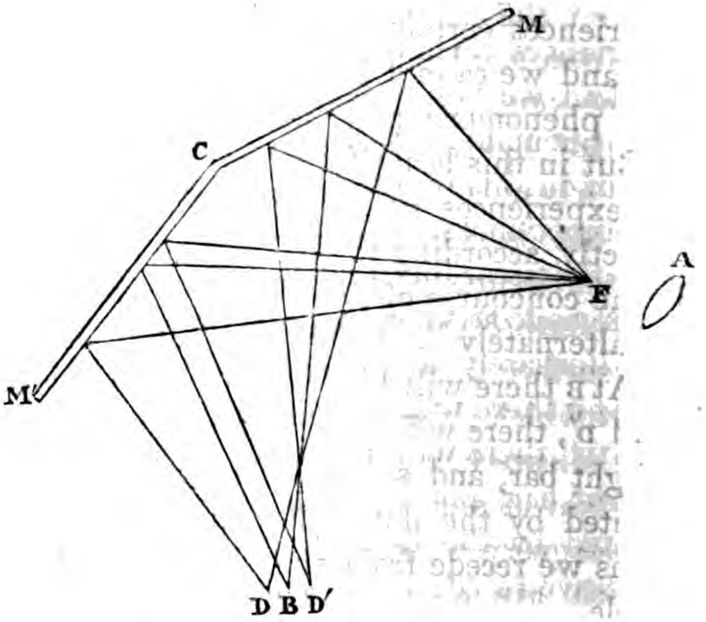
3°. The principle of interference seems inevitably to lead to the system of undulations.

Respecting the mutual action of the rays of light, and their interference, we find it stated by Grimaldi, that a body already illuminated may become less bright by the addition of a new light, besides that which it already receives. This proposition is, at first sight, most improbable and paradoxical, since the characteristic property of light is to illumine, and not to darken, the body it strikes on. Of the truth, however, of this paradox there can be no doubt, as will be seen from a very simple experiment. Let the solar light, reflected horizontally, be admitted into a dark chamber by two small holes, which are near each other, but separated by such an interval that the conical pencils do not intermix, except at a certain distance. A little beyond the point where they intermix let them be received on a screen; then at some points of the illumined part there will be a partial or comparative darkness. If now one of the openings be closed so that the light is not intermixed on the illumined part, but the screen receives light only from one hole, the partial darkness will vanish, parts of the remaining circle will have become brighter by this loss of light. And this darkening of portions of the circles when both holes are open, and the brightening when one is closed, are distinct and certain facts. Under these circumstances, then, it is evident that the addition of fresh light produces darkness, and conversely an obscure surface becomes brighter by the removal of some of the light which shines upon it.

When the preceding experiment is made with great care, and light of one colour is admitted through two fine slits or holes very near each other, the pencil produces bands which are alternately bright and dark, exactly analagous to the bands in the preceding experiments of diffraction. But when either of the apertures is closed the bands disappear, and the space in which they were is occupied by light nearly uniform. Thus the stoppage of the light from one aperture removes the partial obscurity which existed between the bright space: this darkness, therefore, results from the concourse of the two lights meeting obliquely from the two apertures. There are many other experiments equally or even more decisive than these, but of which no account can here be given; the fundamental truth which they all establish is, that two rays of light emanating from the same source, and meeting under a small obliquity, exert on each other a mutual action of such a nature, as alternately totally destroys and doubles the intensity of the light.

The phenomena just quoted furnish strong evidence in favour of the hypotheses which are founded on them, and which will be mentioned hereafter; but the experiment of Fresnel is so simple and decisive, that we cannot altogether omit it.

241. ***Fresnel's Experiment.***—Two metallic mirrors are placed with their edges in contact and inclined to each other at a very small angle, that is, their polished faces containing a very obtuse angle. Let M C, M′ C, represent the two mirrors with their edges in contact at C. At A, in front of these mirrors, is a lens of short focus, which brings the light to a focus at F, whence there issues a diverging cone of light, rendered homogeneous by its passage through some coloured medium which allows but of one colour to pass. This light falls on the different points of the two mirrors, and being reflected forms bars and fringes, which are alternately bright and dark. These bars are subject to the following conditions: they are parallel to the com-



mon intersection of the two mirrors; they are symmetrical with respect to the plane passing through M C M′ and the point F; the central bar, or that which passes through B, is always bright; if one of the mirrors be covered all the bars disappear, and reappear when the obstruction is removed.

This experiment furnishes the most certain evidence of the fact, that two streams of light do, by intermixture, absolutely produce darkness. The phenomena are produced by reflexion at parts of mirrors not near to the line in which their edges meet, or to the edges of the mirrors. In the preceding articles it may be supposed that the light experiences certain modifications from contact with the edges, and we cannot be sure that the internal fringes and other phenomena may not result from some such action. But in this beautiful experiment with the mirrors the light experiences no action from the edges, it is reflected strictly according to the regular laws of reflexion, and it is the concourse of two rays, simply reflected, which produces alternately a double brightness or absolute obscurity. At B there will be a bright bar; on each side of it, as at D and D′, there will be a black or dark bar; then will follow a light bar, and so on, alternately bright and dark, as represented by the dots; they become more and more indistinct as we recede from the centre B, and at last cease to be visible.

Now, it is to be remarked that the light which comes from L to the points B, D, &c. comes by different paths from the mirrors; consequently, the lengths of these paths may be different; that is, the light which comes to the point D by reflexion at the mirror M C, may have travelled over a greater distance in coming from L than the light which comes to the same point D by reflexion at the mirror M′ C. When these paths are equal the intensity of the light is added; when unequal, the light will in some cases be increased, in others diminished, in intensity; that is, there will be a bright bar in some cases and a black bar in others. And the augmentation or diminution of light follows an invariable law, which depends on the excess of the path of the light from one mirror above its path from the other. Whenever this excess is an *even* multiple of a certain constant quantity, the intensities are added, or there is a bright bar; whenever the excess is an *odd* multiple of this same quantity, the intensities are destroyed, or there is a dark bar. Suppose the length of this quantity to be l, then there is brightness at all those points for which the difference of the paths is $2\,l$, $4\,l$, $6\,l$, &c., and darkness at all those points for which the difference of the paths is l, $3\,l$, $5\,l$. This quantity l may be measured, and the fact of the bright and dark points being subject to this law of the difference of the paths is an experimental one, entirely independent of any hypothesis respecting the nature of light. We shall see how the principle of interferences is to be deduced from these phenomena.

242. *Principle of Interferences.*—From the preceding article it appears that two homogeneous rays of light, emanating from the same source, may, after passing over a certain distance, come to a point under such circumstances that the brightness will be almost entirely annihilated. The difference of the paths of the light is the only circumstance on which this remarkable affection of light depends. It can be referred to nothing else but the mutual action of the rays of light, and to this mutual action the term interference is assigned. This term is not here used in the most general sense in which it may be applied; but in a sense exactly similar to that in which it has been already used in speaking of the laws of sound (Art. 137); it may be used in a more general sense, as will be seen hereafter, when we speak of the phenomena of polarization. This statement need only be regarded as a barren fact; that which we call the interference of the rays does produce darkness; we shall see what consequences must necessarily be deduced from these facts.

243. *Consequences.*—The important consequence which

follows from the preceding facts may be stated in the following form: 'The facts of interference are utterly irreconcileable with every known system of emission.' It will generally be admitted that wherever there is light there is motion of some kind or other; the time which light takes to come from the satellites of Jupiter to us is a sufficient proof of this fact. Among all the kinds of motion which exist there are two essentially different, viz. the motion of translation and the motion of vibration. Here it is that the two opinions on light diverge; some assert that it is propagated by translation, others by vibration. The former hypothesis constitutes the system of *emission*, for the luminous substance would in this case be emitted by the sun in all directions. The latter constitutes the system of *undulations;* for the luminous substance would in this case undergo slight displacements, experiencing alternating motions, by which the luminous particle is at one instant removed from the sun, and in the next brought back by the same quantity; a vast number of these backward and forward motions occurring in a very short time. In this case the luminous substance would have an existence independent of the luminous body; just as the air has an existence independent of the sonorous body; this substance at rest would not constitute light any more than air at rest constitutes sound.

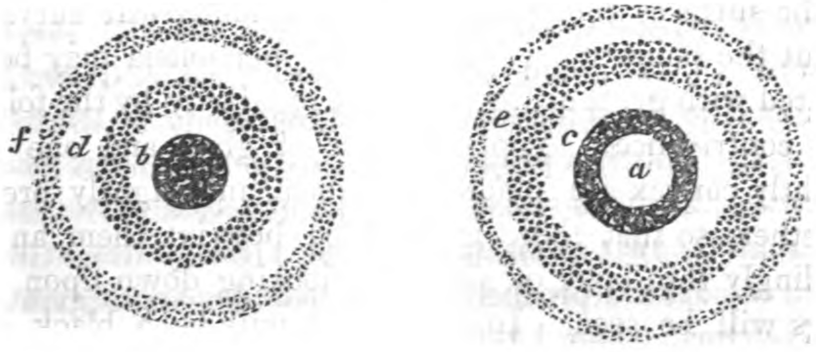
With respect to these two systems we may remark, that the phenomena of interference and the theory of emission are utterly irreconcileable; that two particles endued with the same velocity, and moving very nearly in the same directions, should have their velocities absolutely destroyed on meeting with each other, is a mechanical impossibility. The theory of undulations may be false, but we cannot conceive the theory of emission to be true.

244. *Formation of coloured rings in thin plates.*—All transparent bodies present most vivid colours when reduced into sufficiently thin plates. The thinnest films of glass and mica generally met with, both reflect and transmit

white light; but if the thickness of these substances be sufficiently reduced, the light is in both cases coloured. Thus, if the glass be blown just to the point of breaking their fragments present most vivid colours, the transparency of the substances is not at all a necessary condition, for iron, steel, and all other metals, acquire, by exposure to the air, the power of exhibiting colours.; this arises from the thin layer of oxide which is formed on their surface. If a drop of oil be let fall on pure water, or on water darkened with ink, it rapidly extends over the surface, and forms a thin layer, which exhibits all the colours of the spectrum; the same is seen in a layer of alcohol, or any other fluid which evaporates freely on a polished surface; the instant before it all disappears the layer is sufficiently thin to exhibit colours. The brilliant colours of soap bubbles are very well known; they are only produced when the bubble is extremely thin. Round the point of contact of the surfaces the rings are circular and regular, if the surfaces themselves have a symmetrical curvature about the point of contact. These phenomena may be exhibited with great distinctness and regularity by the following contrivance. A plane piece of glass and one very slightly convex are placed in contact, and slightly pressed together, so that there is included betwixt them an exceedingly thin layer of air. On looking down upon this, rings will be seen. In the centre will be a black spot, then a light ring slightly coloured at the edges, then a dark ring, and so on, growing fainter till they quite disappear. We may remark that these rings continue the same under the vacuum of an air pump. So that in the most complete vacuum which we can produce the circumstances are such that the same rings are produced as by a thin layer of any other substance, whether liquid or gaseous; hence we may infer, that the same rings would be produced, even were the intervening space a perfect vacuum. When homogeneous light, as pure lamp-light, is used, the white and dark rings are exceedingly numerous and distinct; and when the different rays of the spectrum are used, they will be found to be of the same colour as the light. They will be found largest in red light, and contract gradually through all the succeeding colours till they reach their smallest size with the violet rays.

The dark rings are formed by the transmitted light, and the bright rings by the reflected light; for if the glass be held between the eye and the light, the *centre* will appear *bright*, being surrounded by a dark ring, then a bright one, and so on, alternately. Thus it is evident that the thickness which appears black by reflected light, is that which will appear bright by transmitted light, and conversely. Also, the colours formed by the transmitted light are complementary to those formed by the reflected light.

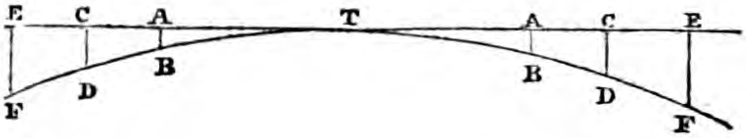
The general appearance of the rings will be understood from the accompanying figure. Looking down on the glass, or viewing it at a small obliquity, with reflected light, there will be seen a black central spot, then a bright ring *b*, then a dark ring, then another bright ring *d*, and so on. On holding the glass up to the light so as to look through it, there is a bright spot *a* in the centre, surrounded by a dark ring, then another bright ring *c*, and so on. The black rings become lighter in receding from the centre, and are finally lost. The rings will only be completely black when homogeneous light is used; for solar light they will be coloured at their edges; and these colours gradually



fade away. The succession of rings and colours has been accurately laid down and described by Newton, and form a most invaluable scale, called 'Newton's scale of colours.'

245. *Breadth of the rings.*—The most favourable combination for exhibiting the rings consists of a convex lens of small curvature, that is, of very large radius, pressed down on a plane surface of glass: the diameters of the rings may then be measured, and the corresponding thickness of the air in which they are produced calculated.

Thus, let the accompanying figure represent a spherical glass of large curvature, in contact at T, with a plane surface. Then the thickness A B, C D, E F, at which the rings of the 1st, 2nd, and 3rd order are produced, are proportional to the squares of the corresponding distances T A, T C, &c. This is a proposition in simple geometry; hence, knowing the diameters of the rings by actual measurement, we shall know the distances between the plates at which these colours are produced. This was done with great care by Newton, when he found, for the first six rings, the squares of the diameters to be as the odd numbers 1, 3, 5, 7, &c., and consequently the intervals at the rings are in the same proportion. Having measured also the diameters of the dark or faint rings between the more lucid colours, he found their squares to be as the even numbers 2, 4, 6, &c.* Thus, where the distances between the glasses are as the numbers 1, 3, 5, &c., the light will be reflected; and when as the numbers 0, 2, 4, 6, &c., it will be transmitted. It is of great importance to observe that these



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* *Optics*, Book II. Obs. 5.

distances are facts of direct observation and experiment; and being entirely independent of any hypothesis respecting the nature of light, will be found of great value in examining the truth of any proposed theory.

246. *Fits of transmission and reflexion.*—On the explanation which can be offered of the preceding remarkable phenomena, we shall not at present make any remarks; but proceed to the subject of Newton's 'Fits,' which have sometimes been supposed as affording a theoretical account of the cause of the phenomena. This they do not; nor were they viewed by their author in the light of a physical theory. They were merely intended as an hypothetical mode of expressing some certain physical facts, as will appear in the account which we shall here add in Newton's own words. These fits are *defined* in the following words:* 'The returns of the disposition of any to be reflected, I will call its Fits of easy Reflexion; and those of its disposition to be transmitted, its Fits of easy Transmission; and the space it passes between every return and the next return the Interval of its Fits.'

This definition is preceded by the following proposition: 'Every ray of light in its passage through any refracting surface, is put into a certain transient constitution or state; which, in the progress of the ray, returns at equal intervals, and disposes the ray at every return to be easily transmitted through the next refracting surface; and between the returns to be easily reflected by it.' 'From the experiments mentioned in the last article, it appears that one and the same sort of rays, at equal angles of incidence on any thin transparent plate, is alternately reflected and transmitted, for many successions, according as the thickness of the plate increases, in arithmetical progression of the numbers 0, 1, 2, 3, 4; so that if the First Reflexion (that which makes the first or innermost of the rings of colours) be made at the thickness 1, the rays shall be transmitted at

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* *Optics*, Book II. Part III

the thicknesses 0, 2, 4, &c., and thereby make the central spot and rings of light which appear by transmission; and be reflected at the thickness 1, 3, 5, and thereby make the rings which appear by reflexion. And this alternate reflexion and transmission, as I gather by the 24th Observation, continues for above a hundred vicissitudes, and by the Observations in the next part of this Book, for many thousands, being propagated from one surface of a glass plate to the other, though the thickness of the plate be a quarter of an inch or above; so that this alternation seems to be propagated from every refracting surface, to all distances, without end or limitation.'

The proposition, a portion of which we have just quoted, concludes in the following remarkable manner: 'What kind of action or disposition this is; whether it consists in a circulating or a vibrating motion of the ray, or of the medium, or of something else, I do not here inquire. Those that are averse from assenting to any new discoveries, but such as they can explain by an hypothesis, may for the present suppose, that as stones, by falling upon water, put the water into an undulating motion, and all bodies, by percussion, excite vibrations in the air; so the rays of light, by infringing on any refracting or reflecting surface, excite vibrations in the refracting or reflecting medium or substance, and by exciting them agitate the solid parts of the refracting or reflecting body, and by agitating them cause the body to grow warm or hot; that the vibrations thus excited are propagated in the refracting or reflecting medium or substance, much after the manner that vibrations are propagated in the air for causing sound, and move faster than the rays, so as to overtake them; and that when any ray is in that part of the vibration which conspires with its motion, it easily breaks through a refracting surface; but when it is in the contrary part of the vibration, which impedes its motion, it is easily reflected; and, by consequence, that every ray is successively disposed to be easily reflected or easily transmitted, by every vibration which overtakes it. But whether this hypothesis be true or false, I do not here consider. I content myself with the bare discovery, that the rays of light are, by some cause or other, alternately disposed to be reflected or refracted for many vicissitudes.'

From the preceding extracts the reader may have some general idea of this most ingenious hypothesis, by which Newton linked together the phenomena of the reflected and transmitted light, and the colours of thin plates. This, as we have stated, has sometimes been regarded as a physical theory, whereas it is merely a general expression of a fact. It is certain that light is alternately transmitted and reflected; but in asserting this, we really make three distinct hypotheses, namely, that it is alternately transmitted at certain thicknesses, and alternately reflected at certain others, and also that the first surface has nothing to do with the phenomena. The theory of undulations shews that it is neither reflexions nor transmissions taking place alternately which originates the rings, but that the rings are produced by the meeting of the two regular reflexions which take place at the first and second surfaces of the thin plates.

SECTION VIII.

PHENOMENA OF DOUBLE REFRACTION—ORDINARY AND EXTRAORDINARY RAY—DIFFERENT PROPERTIES OF THE RAYS—POLARIZATION—POLARIZATION BY REFLEXION.

247. In the ordinary cases of the passage of light through media which have been already treated of (Sect. 3.), a single pencil of incident light gives but a single pencil of emergent light; but in some cases the incident pencil gives two emergent pencils. Those substances which possess the singular property of dividing a single pencil of light into two pencils, are called doubly refracting substances. The phenomena of double refraction have been long observed, but they have now acquired very great importance in consequence of the speculations to which they give rise respecting the nature of light. These pencils possess different properties, and the peculiar properties which will hereafter be shewn to be communicated to them, are expressed by the general term *polarization*.

Liquids and gases are not naturally doubly refracting; and though they may sometimes be rendered so, it is only in an exceeding small degree; solids, on the contrary, may always possess this property; of these, however, there are two distinct classes, the one containing those which possess this property naturally, and in a permanent manner, the other those which possess it accidentally and artificially by physical or mechanical action, as by sudden cooling, or by unequal pressure exerted in different parts. The first class includes all regularly crystallized bodies, whose *primitive* form is not a cube, a regular octahedron, or rhomboidal dodecahedron. The second class includes all other solid transparent bodies, gums, resins, and gelatinous substances. These latter may acquire the property of double refraction, but the former cannot be deprived of it so long as they preserve their crystalline character.

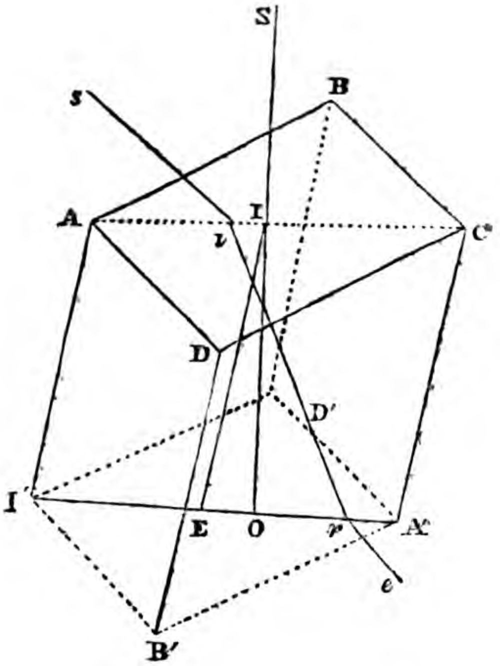
The best substance for shewing the phenomenon of double refraction, is that form of carbonate of lime generally called Iceland Spar: this substance is very common, and exhibits the double refraction in great perfection. The rhomboidal form (Fig. Art. 248.) is the most convenient. Let a black line be drawn on a piece of paper, and let a rhomb of this spar be laid upon it; then, on looking through the upper face of the spar down on the paper two lines will be seen. Again, any object viewed at a distance through the spar will appear double, and the images will be more separated from each other as the distance of the object increases. If the rhomb be turned about so as to complete a revolution, the two images will have a regular motion, so that one will fall twice on the prolongation of the other. And we shall easily see that these coincidences of direction correspond with two exactly opposite positions of the rhomb. If a large object be observed, the two images will still exist, and present the same phenomena of lateral removal or coincidence; the only difference being that they will encroach on each other, and not present a complete separation. The rhomb lying over the line or any dark spot on the paper, there will be two distinct images of every point in the paper, whether the eye looks directly on the face of the rhomb, or obliquely. With a circle traced on paper the phenomena are very distinct; the circles will appear entirely separated, or one will overlay the other, according to the magnitude of the circle viewed.

Any pencil of solar light is divided into two pencils on traversing two parallel faces of the rhomb. The absolute distance between the centres of the images depends on the thickness of the crystal.

From these experiments it is evident that a rhomb of spar crystal gives two images, but that in some positions the pencil of light does not divide; or one image only is formed. There is always either one or two directions in which the division does not take place, and the crystal is accordingly said to have *one* or *two axes.* These particular directions are called the optical axes of the crystals; they have always a symmetrical arrangement with reference to the natural faces of the crystal. It appears that there cannot exist any regular crystals which have more than two axes.

248. *Ordinary and Extraordinary Ray.*—The two rays into which a ray of light is generally divided by a doubly refracting substance, possess remarkable and distinct laws, which we shall now endeavour to render intelligible.

Let the accompanying figure represent a crystal of carbonate of lime. The larger solid angles at A and A′ are



composed of three obtuse angles, each of which is about 101° 32′, and the line joining A and A′ is called the axis of the crystal. If a ray be incident on the face A B C D in a direction parallel to this imaginary line, it is not separated into two; in all other cases it is. Join the shorter diagonals A C, A′ C′, of the upper and lower faces of the crystal, which we will conceive to be horizontal: then the quadrilateral A C A′ C′ is called a principal section or plane of the crystal, since it contains the axis; all our subsequent observations must be confined to rays incident in this plane. We have already said that if a ray be incident on this face parallel to the axis, as *s l*, it will not be doubly refracted, but will pass through the crystal, as represented by *r e*. Let a ray be incident in some other direction in the principal plane, as S I. This ray will be separated into two, namely, I O, I E. If the ray S I be perpendicular to the face A B C D, then the image O will be on the prolongation of S I, as in ordinary cases, and the ray I E will be refracted according to its own laws. But in other cases, the ordinary ray, or I O, is refracted according to the laws of Descartes, that is, the incident and refracted rays are in the same plane, and the sines of the angles of incidence and refraction are to each other in a constant ratio. In this case, that is, when the plane of incidence is a principal plane, the extraordinary ray is subject to the first of these laws, but not to the second. When the ray is not incident in a principal plane, the angle of refraction of the extraordinary ray does not lie in the plane of incidence, nor is its sine in a constant ratio to the sine of the angle of incidence. These results are readily verified by turning the crystal about some vertical axis; the extraordinary image will revolve about the ordinary in a circle, and it will twice lie in the plane of incidence, which will be the case when this plane coincides with the principal plane of the crystal.

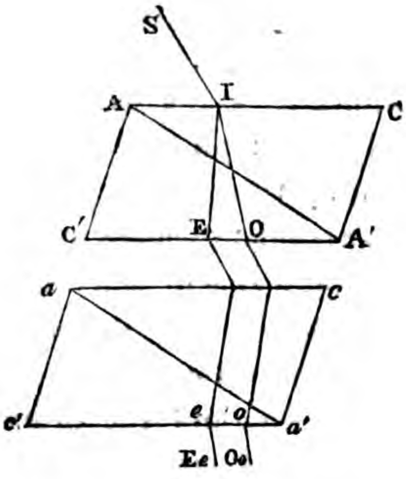
249. ***Properties of the Rays.***—Let two similar rhombs of the crystal be taken; then if the two images formed by one rhomb be viewed by the other, in some cases there will be only two, in others four, and in all cases the pencils exhibit most remarkable properties as regards refraction

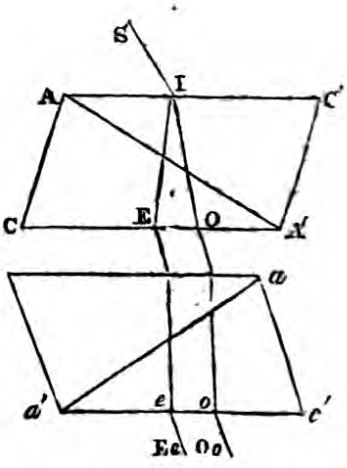
and intensity: these we shall briefly examine. It will be convenient to suppose that we are looking up through the lower surface of the lower rhomb, and that the light is incident on the upper surface of the upper rhomb.

1°. Let the second rhomb be placed on the other, and in exactly the same position, that is, having all similar sections parallel to each other. In this case there will be but two rays; the ordinary ray of the first rhomb will give only an ordinary ray in the second, and the extraordinary ray only an extraordinary ray. This will be seen at once by stopping each of the pencils successively by a piece of paper between the rhombs.

2°. Let the second rhomb be placed in an exactly opposite position, that is, let it be turned 180° from its preceding position; then the same will hold. The ordinary ray will be refracted according to the usual laws, and the extraordinary ray will follow entirely its own laws.

In the two preceding instances the ordinary ray produces only an ordinary ray, and the extraordinary only an extraordinary; there is no farther separation of the light. The course of the pencils will be seen at once by the accompanying figures.





The figure A C A′ C′ is the principal section of the figure in the preceding article, and *a c a′ c′* is another principal section of a crystal, and the two being similarly situated the incident ray S I gives rise to the emergent pencil O *o*, which is the ordinary ray refracted in the ordinary manner, and the emergent pencil E *e*, which is the extraordinary ray refracted in the extraordinary manner. The second figure represents the principal planes parallel to each other, but the one turned 180° about the incident ray, so that their axes, though in parallel planes, are not parallel in direction.

3°. Let the second crystal be turned round 90°; then, the ordinary ray produces only an extraordinary ray, and the extraordinary ray produces only an ordinary ray. In the preceding cases two rays only have been produced.

4°. Let the second rhomb be turned through 45°; then each ray will give both an ordinary and an extraordinary ray, all of apparent equal intensity; so that there are in this case four images.

5°. Let the second rhomb be in any other position, intermediate to those already mentioned; there will always be four images; they will possess, however, very different intensities, brightening up, fading, and utterly disappearing, as the rhomb is turned round.

From these phenomena it is evident that the pencils have some relation to the relative positions of the crystals; when the principal planes of the rhombs coincide, there are but two images, and when they are at right angles there are but two; in every other position there are four; but what is most remarkable, these properties are similar, provided we suppose one pencil to be turned through an angle of 90°. When the principal planes coincide, the ordinary ray produces only an ordinary ray (1° and 2°); when the principal planes are at right angles to each other, the extraordinary ray produces an ordinary ray, and the ordinary ray an extraordinary ray (3°). Thus it appears that the properties of the pencils have relation to the principal plane of the crystal; that whatever properties the ordinary ray may possess with respect to that plane, the extraordinary ray possesses the same properties with respect to a plane at right angles to the preceding; for each acquires the property of the other when the change here indicated has been made in the position of this plane.

250. ***Polarization.***—From the preceding article it is evident that the properties of light have some relation to the planes of the crystal, so as to be influenced by their relative positions. Hence, Newton was led to conceive the idea that a ray of light has *sides* or *poles*, that is, some distinct relation to surrounding space. 'For,' says he,* 'one and the same ray is here refracted, sometimes after the usual, and sometimes after the unusual manner, according to the position which its sides have to the crystals. If the side of the ray is posited the same way to both crystals, it is refracted after the same manner in them both; but if that side of the ray which looks towards the coast of the unusual refraction of the first crystal be 90 degrees from that side of the same ray which looks towards the coast of the unusual refraction of the second crystal (which may be effected by varying the positoin of the second crystal to the first, and by consequence to the rays of light), the ray shall be refracted after several manners in the several crystals. There is nothing more required to determine whether the rays of light which fall upon the second crystal shall be refracted after the usual or after the unusual manner, but to turn about this crystal, so that the coast of this ray's unusual refraction may be on this or on that side of the ray. And, therefore, every ray may be considered as having four sides or quarters; two of which, opposite to one another, incline the ray to be refracted after the unusual manner, as often as either of them are turned towards the coast of unusual refraction; and the other two, whenever either of them are turned towards the coast of unusual refraction, do not incline it to be otherwise refracted than after the usual manner.'

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* *Optics*, Quæry 24.

The preceding remarkable method of stating the phenomena has given rise to the term *polarization*, which is, in the language of modern science, meant to express the properties which each ray has with respect to particular planes. The ordinary ray has properties with reference to the principal plane: this fact is expressed by saying that the 'ordinary ray is polarized in the principal plane of the crystal.' The extraordinary ray has properties with reference to a plane at right angles to the principal plane: this is expressed by saying that the 'extraordinary ray is polarized in a plane perpendicular to the principal plane of the crystal.'

The whole series of experiments on this subject appear to lead to the supposition that polarization is not an alteration of the properties of light, but that common light is of such a nature that it may be separated into two parts.

It does not appear that the polarization of the two pencils is the effect of any polarizing force residing in the crystal, or of any change produced in the nature of light. The crystal merely separates the common light into two elements, just as a prism separates all the seven colours of the spectrum, by its power of refracting these colours in different degrees. The reunion of two oppositely polarized pencils produces common light in the same manner as the reunion of the colours of the spectrum produces white light.

The easiest method of producing polarized light is by transmitting common light through a piece of Iceland spar, and a given pencil will furnish a stronger polarized pencil in this than in any other manner. But it may also be produced by reflexion at unsilvered glass, or at any partially reflecting surface, as we shall proceed to explain.

251. *Polarization by reflexion.*—The preceding phenomena having led Newton to assert that light acquired sides or poles by the refraction of particular substances, have acquired double interest from the fact, that the same properties may be communicated to light by reflexion. In

the year 1810, Malus, while looking through a prism of calcareous spar at the light of the setting sun, reflected from the windows of the Luxembourg, at Paris, observed, on turning the prism round, considerable difference in the intensity of the two images.

From this he was led to other experiments, and found that a pencil of light reflected from glass at an angle of 56°, or from water at an angle of 52° 45′, possesses the very same properties as one of the pencils formed by a rhomb of spar. Thus was a connexion detected between the mysterious phenomenon of double refraction and the ordinary modifications of light, which has given rise to new and startling speculations respecting the nature of light, and promises to place this branch among the most perfect of the physical sciences. At the time of this discovery of Malus, the system of emission was generally adopted; there was nothing in optics but luminous particles endued with different fits and different properties; all the particles experience the same effects when they have been reflected at glass under a certain angle; they were all supposed to be *turned* in the same manner, and consequently, to have their axes of rotation, or the poles about which their motions could take place, under certain influences. Hence, as we have seen, arose the term *polarization*, which indicated that their poles are arranged or directed in the same manner for all the particles.

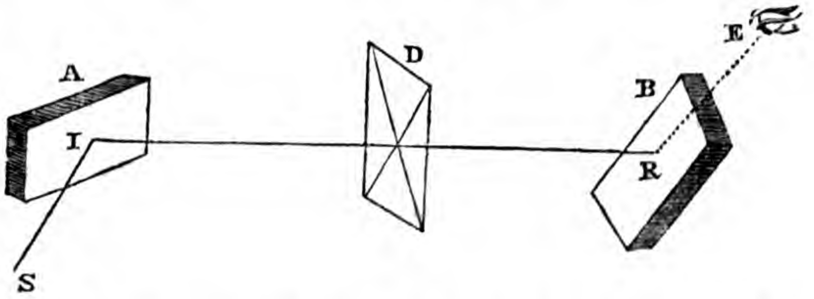
The pencil so reflected possesses the following characteristic properties:

1°. It only gives *one* image after transmission through a doubly refracting prism, when the principal section of this prism is parallel or perpendicular to the plane of reflexion; but in all other positions there are two other images of greater or less intensity.

2°. It is incapable of being reflected at the surface of a second glass mirror at the same angle of incidence, when the plane of incidence on the second mirror is perpendicular to the plane of incidence on the first; but it is partially reflected in all other positions of the planes, and at all other angles of incidence.

3°. It is incapable of being transmitted through a plate of tourmaline in some positions of the plate; but it is partially transmitted in others.

The preceding phenomena will be observed by an apparatus such as is represented in the accompanying figure.



A plate of glass is blackened at its posterior surface to prevent reflexion there; and so placed that a ray S I of light incident at an angle of 56° may be reflected horizontally, and received on another glass surface B, above which an eye E is placed, so as to receive the reflected light. If now the ray I R, so reflected at A, be received on a crystal of Iceland spar, there will only be one image formed when the plane of incidence is coincident or perpendicular to the principal plane of the crystal; in all other cases there will be two images. But suppose the ray I R to be incident on the second surface B, at an angle of 56°, and that the plane of incidence of this surface is perpendicular to the plane of incidence at the former, then the eye at E will receive no light; the ray is extinguished, or it is incapable of reflexion, the angles of incidence having this value, and their planes being at right angles to each other. But if the reflecting plate B be turned through 90°, so that the planes of incidence and reflexion are parallel to each other, then the light will be vividly reflected. And in all other cases, that is, for all values for the angle of incidence on the second surface, besides that of 56°, and for all other relative positions of the planes of incidence, besides that in which they are perpendicular to each other, there will be some reflexion; more or less light will come to the eye. If a plate of tourmaline, as represented at D, be interposed in the path of the ray, the light will sometimes be wholly extinguished. This takes place when the axis of the tourmaline is parallel to the plane of reflexion; the plate being turned round, so as to bring its axis into some other position, a portion of the light is transmitted; and when the axis becomes perpendicular to the plane of reflexion, the whole light can pass.

Such are the general properties of a pencil of polarized light; any one of the preceding laws obtaining, the other two will obtain also; hence we can at once ascertain whether a ray is polarized or not, by observing it through a plate of tourmaline, or a doubly refracting crystal. These phenomena take place whatever be the reflecting surface; the polished surface of a mahogany table will answer extremely well for the production of polarized light. The identity, then, of the phenomena exhibited by light thus reflected with the ordinary ray of a crystal of carbonate of lime, the principal plane of the crystal being parallel to the plane of incidence and reflexion, leads us to refer them to the same cause; hence, the reflected light is said to be polarized in the plane of reflexion. But it is frequently necessary to examine the properties of a polarized pencil whose origin is not known; we must, therefore, have some means of recognising the plane of polarization. This can readily be effected by the plate of tourmaline. When the ray is extinguished by incidence on the tourmaline, its plane of polarization is parallel to the axis of the tourmaline; but when, on the contrary, the ray is transmitted with its maximum intensity, its plane of polarization is perpendicular to the axis of the tourmaline.

SECTION IX.

ON THE UNDULATORY THEORY.

252. In the phenomena of light, as in those of sound, we must distinguish between the impressions received on our organs and the physical cause of those impressions. These two things, in reality most distinct, are frequently confounded; in saying, for example, that there is sound for the deaf, and light for the blind, an incontestable physical fact is enunciated, but yet one which is apparently paradoxical, because, in ordinary language, the words sound and light mean the sensation which is produced in us. In the language of science sound is the vibration of ponderable matter, and light is the vibration of ether, which is an imponderable matter or substance. Thus light exists without us; it is a movement subject to certain conditions. This being supposed, it is evident that wherever there is light there is ether; hence ether pervades all space. It exists between the sun and the earth, among all the bodies of our planetary system, and in the infinite space which separates us and the most distant stars; for there is no part of this immense extent which is not, at each instant, traversed by innumerable rays of light. And not only in the expanse of heaven does this ether exist—it penetrates all bodies, filling the spaces between their ponderable atoms. If the ether does not exist throughout the whole extent of the atmosphere, the light of the stars could never reach us; if it does not exist in water, glass, diamond, and other transparent bodies, the waves of light could not traverse them; lastly, if it does not exist in the intervals which

separate the atoms of our material envelope, light could not affect us, the undulations would never pass through the humours of the eye to the nervous expanse of the retina, the utmost point to which our powers can follow it. All opaque bodies also are full of ether, since they become transparent when reduced to a sufficient thinness.

Thus the system of undulations compels us to admit the existence of a matter, or rather of a substance, in the midst of which are scattered about, subject to invariable laws, the various kinds of ponderable matter which constitutes the universe. Nevertheless, though the ether exists every where, it is not always identical with itself. It is probable that in the void of the celestial spaces, as in the void which can be produced by our machines, there is no difference in the distribution of this substance, and consequently, no difference in the passage of light. But in the interior of bodies light moves differently, the undulations change in velocity and length, consequently the ether has different elasticities. It appears, also, from the experiments of polarization, that in most crystalline bodies the elasticity of the ether is not the same in all directions.

The conception of the existence of this ether is somewhat difficult, since all the reasoning we have respecting it is an exercise of pure intellect unassisted by our external senses. In the production of sound, or in reasonings respecting other elastic fluids, as air, steam vapour, we have evidence from our senses of the existence of something to which we attribute these properties—we are conscious of their effects in diverse ways; but in reasoning with respect to the ether we must resign ourselves entirely to faith in what our own intellect has created, and if the properties with which we invest this imaginary substance would give rise to phenomena of whose existence our senses assure us, then we are compelled to believe the veritable existence of this substance ether. But it is to be remarked, that the first conception of this substance on which the existence of the undulatory theory depends, is in no respect more difficult than the first conceptions on which the theory of emission depends; and when the difficulties besetting the conceptions of an undulation have been removed, it is in every respect most simple. How can we conceive the transfer of particles of the astonishing velocity and minuteness which the theory of emission supposes? We have seen that their velocity is inconceivably greater than any other motion of translation with which we are acquainted; whence the incessant supply of particles? What becomes of them when they have once fulfilled their appointed end, by creating the mental sensation? The existence of ether is not so difficult of conception as the existence of these independent particles. In both cases we have to suppose the existence of a substance; then, since we are compelled to believe that where there is light there is motion, the question is, what is the nature of this motion? Is it one of translation or of vibration? The motion of translation is, as we have already seen (Art. 198), almost inconceivable, but the motion of vibration is in strict conformity with other motions of the same kind; it is precisely such as must take place in an elastic medium. When an elastic medium is disturbed every portion participates in that disturbance almost instantaneously, and the rate at which this disturbance is transmitted, or the velocity of transmission, is in the present instance the velocity of light.

In the reflexion of light on the emission theory it is quite inconceivable how such enormous velocities can be destroyed instantaneously. We know that when the time is short the force exerted must be very great (Art. 37), and since the destruction of all velocities requires time, it is incredible that such velocities can be destroyed in so short a time. Again, in the phenomena of refraction it is necessary to suppose, on the emission theory, that the light moves faster within the denser medium than without it, whereas on the undulatory theory it appears that the waves diverge more slowly in dense media than in others. The latter hypothesis is certainly more conformable to the analogy of nature than the former. A doubt has existed in the minds of some respecting the truth of this theory from considering the extraordinary facts which present themselves in speaking of the number of undulations in a second of time, or an inch of space, as is exhibited by Herschel in the following table.

Colours of the Spectrum.	Lengths of an Undulation in parts of an Inch.	Number of Undulations in an Inch.	Number of Undulations in a Second.
Extreme red	0·0000266	37640	458,000000,000000
Red	0·0000256	39180	477,000000,000000
Intermediate	0·0000246	40720	495,000000,000000
Orange	0·0000240	41610	506,000000,000000
Intermediate	0·0000235	42510	517,000000,000000
Yellow............	0·0000227	44000	535,000000,000000
Intermediate	0·0000219	45600	555,000000,000000
Green	0·0000211	47460	577,000000,000000
Intermediate	0·0000203	49320	600,000000,000000
Blue..............	0·0000196	51110	622,000000,000000
Intermediate	0·0000189	52910	644 000000,000000
Indigo	0·0000185	54070	658,000000,000000
Intermediate	0·0000181	55240	672,000000,000000
Violet	0·0000174	57490	699,000000,000000
Extreme violet	0·0000167	59750	727,000000,000000

But we may remark that whatever theory of light we adopt, these periods and these spaces have a *real existence*, being in fact deduced by Newton from direct measurement, and involving nothing hypothetical but the names here given them.

253. *Nature of Light.*—Light, then, according to the preceding theory, consists of the undulations excited in the elastic medium, which we have called ether; these regular vibratory motions being propagated equally in all directions, the ether is disturbed all round the source of light; hence the series of condensations and rarefactions, which are the necessary consequence of this oscillatory motion, give rise to what are termed the waves of light. These waves or disturbances being propagated onwards affect the retina, and thus cause the sensation of light, just as we have already seen in the production and propagation of

sound. Every luminous point then is surrounded at every instant with an infinite number of similar concentric surfaces, in any one of which the particles are in a similar state as to rest or motion, but in a very different state in different surfaces. The remarks which have been already made on the analogous case of the divergence and decay of sound, will shew us how the intensity of light will diminish as we recede from the origin, in consequence of the smaller motion of vibration, which will be communicated to the particles of the ether.

The direction of a ray of light, on the undulatory theory, will be the direction of the wave's motion, that is, it is the line perpendicular to the front of the spherical wave in which the light is propagated. Since from a point of light, as a centre, every straight line is perpendicular to every portion of the wave of light, we see that light is propagated in straight lines, and in every direction. Different colours are produced by waves whose lengths are different; the wave being longest for the red rays and shortest for the violet. The analogy betwixt sound and light is very remarkable; the pitch of a sound depends (Art. 132) on the rapidity of vibration of the particles of air; in the theory of light colour will depend on the rapidity of the vibrations of the particles of ether, and intensity on the extent or magnitude of the vibrations of the particles; stillness and darkness are equally the consequence of the rest of the medium. Every portion of a large wave of light may be taken separately from the rest, and considered as the origin of a new little wave diverging from it. This is the most important principle in the undulatory theory; whenever any portion of a wave is interrupted by any obstacle, it may be considered as the origin of a fresh spherical wave, diverging in every direction.

A *focus* on the undulatory theory is the point at which all the small parts of a wave unite after reflexion or refraction; this point becomes the origin of a fresh series of spherical waves which diverge in every direction, precisely in the same manner as from the luminous body. Thus the image of the sun formed by a lens will excite undulations in exactly the same manner as a luminous body in the same situation.

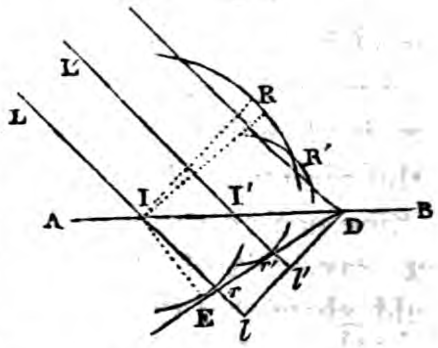
254. *Interference an immediate consequence of the theory of undulations.*—The vibrations of the particles of an elastic medium constituting light, it must happen that the motions of the particles in one-half of the wave are exactly in the opposite direction to those in the other half. Now we can suppose that two waves may be combined so that the motions of the particles may conspire together, or destroy each other; this is what takes place in the interference of light. Two waves which start from two different sources may be so related that they may conspire to augment or diminish the vibrations of the ether. The way in which one wave interferes with another may be well illustrated by waves in a liquid; suppose that there are two liquids, as oil floating above water, and that a disturbance producing an undulation, that is, an elevation and depression of the surface, is excited in each. Then if the undulation be such that the crest of the wave of oil is exactly superposed on the crest of the wave of water, there will be a double elevation, and similarly a double depression. Here one wave is added to the other so as to double the effect, supposing the two waves to be equal. But suppose that the crest of the wave on the oil is exactly over the hollow of the wave in the water; that is, the disturbance being equal, suppose that the oil wave is half a wave either before or behind the water wave; then there will be no undulation on the surface, one wave has interfered with the other so as to produce perfect rest; the surface of the upper fluid instead of being undulated will be level. A similar interference of the waves may take place in the propagation of light; whatever is the nature of the vibration it will happen that the waves of light in crossing each other, or in being superposed, may so interfere as to augment the motion of the particles at some

points, and destroy them at others; the consequence of which will be that the intensity of the light will be increased at some points, and diminished, or absolutely destroyed, at others. When one wave, in advance of another by a distance equal to the length of one, two, &c. waves, is superposed on the other wave, the motions conspire, and the wave is doubled; but if it is in advance only by a distance equal to the length of half a wave, or one and a half, &c. the motions are opposed, and there is absolute rest or darkness.

Thus the principle of interferences is a necessary consequence of the system of undulations, and it is impossible to conceive any other hypothesis which will serve to explain the phenomena. It is quite certain from the experiment with the mirrors which we have detailed (Art. 241), that one portion of light may be so added to another portion as to produce absolute darkness. It is also certain, that whenever this takes place one portion of the light has travelled some odd multiple of a certain quantity more or less than the other (Art. 241); that is, one wave is in advance of the other by some odd multiple of half the length of the wave. If now according to the properties of undulations, one wave be one-half, or any odd multiple of one-half, before another, there will be absolute rest. But, on the contrary, if one wave be any even multiple of half a wave, that is, a whole wave or two whole waves before another, then the motions conspire, the effects are added so as to increase the disturbance.

255. *Theory of Reflexion and Refraction.*—The theory of undulations having been shewn in the preceding article to lead necessarily to the phenomena of interference—facts so utterly inexplicable on any theory of emission—we shall endeavour briefly to point out the explanation which this theory furnishes of reflexion and refraction, phenomena scarcely less inexplicable than those of interference on any theory of emission. When a wave of light meets with any surface its progress is arrested, in some cases almost

entirely, in others only partially. Each point of the wave, as it comes in contact with the surface, may be supposed to be the origin of a fresh series of waves. The way in which these fresh waves diverge so as to cause the phenomena of reflexion and refraction is the point to be explained.



Suppose that L I is any ray of a wave of light which is advancing towards the surface A B. Let the surface be reflecting; then the point I becoming the origin of a fresh series of waves, the light which, had there been no obstructing surface, would have reached the point *l*, will have diverged in a spherical form, the radius of the sphere being equal to I *l*. Hence taking I R=I *l* the light will be at R instead of at *l*. Let us consider any other ray, as L′ I′. This not having reached the surface so soon as L I, will not have diverged so far; but taking I′ R′ = I′ *l*′, we may suppose the light which would have been at I′ as at R′. Similarly, by considering all the waves created by the points of the surface, we shall have a line touching the front of all of them, which will represent the position of the front of the wave, and a line perpendicular to this will be the direction in which the reflected wave is advancing. Instead therefore of having a wave whose front is D *l*′ *l*, advancing in the direction L I *l*, we have a wave whose front is R R′, advancing in the direction I R; and the simplest geometrical construction will shew that the directions L I, I R, are inclined at equal angles to the perpendicular at the point I. The wave then is reflected so that the angles of incidence and reflexion are equal.

The preceding result is founded on the hypothesis, that the waves diverge with the same velocity in every direction in air. But when the surface is a refracting and not a reflecting surface, the wave within the refracting medium is supposed to diverge with less velocity than in air; we shall briefly trace the consequence of this hypothesis.

Let the surface A B be refracting. The wave from the ray L I which enters will, instead of reaching L in a given time, only reach *r*; the wave from L′ I′ will only reach *r*′: and similarly for the rest. Thus the front of the wave, instead of being at a given instant represented by D *l*′ *l*, will be represented by D *r*′ *r*; and drawing the perpendicular upon it, it will be moving in the direction I E instead of in the direction I *l*; that is, the direction of the refracted ray lies nearer the normal than the direction of the incident ray. And the simplest geometrical construction would shew that these directions are related to each other according to the ordinary law of refraction (Art. 207).

Such then are the consequences of the incidence of a wave of light on a surface opposing its motion; whether the surface be reflecting or refracting, the ordinary laws of the resulting phenomena may be deduced in a very simple manner from the theory of undulations. It will be impossible here to dwell on the explanation which may be furnished of the phenomenon of refraction being always accompanied by reflexion; of the phenomena of double refraction as the consequence of the different velocities with which the waves diverge in different directions, owing to the different elasticities of the medium; of the phenomena of polarization, considered as the resolution of vibrations, and of the production of fringes, shadows, and spectra; phenomena which, to use the words of Herschel, are so singular and various, that to one who has only studied the common branches of physical optics it is like entering into a new world, so splendid as to render it one of the most delightful branches of experimental inquiry, so fertile in the views it lays open of the constitution of natural bodies, and the minuter mechanism of the universe, as to place it in the very first rank of physico-mathematical sciences, which it maintains by the rigorous application of geometrical reasoning its nature admits and requires.

In conclusion, a few words must be added on an objection which was supposed to be conclusive against the undulatory theory of light. It was objected, that if light be an undulation, as sound is, then ought light to spread in the same manner as sound. That is, the light entering from a luminous point through a small hole ought to illumine the whole room nearly equally, and not illumine one single spot nearly opposite to it; that it ought, like sound coming through the same hole, to spread in every direction. Now it may be assumed as an experimental fact that the lengths of the waves of light are much less than the aperture (Art. 252); the mathematical investigation for the intensity of a disturbance at any point on the theory of undulations shews, that whenever the waves are much smaller in length than the diameter of the aperture the disturbance must be insensible, excepting in front of the aperture; the lengths of the waves of light are much smaller, and the light ought consequently to be, and is, nearly insensible, excepting in front of the hole. This capital objection to the undulatory theory of light may, consequently, be considered as entirely set aside.

CHAP. XI.

ON ELECTRICITY, GALVANISM, AND MAGNETISM.

SECTION I.

ON ELECTRICITY — TWO SPECIES OF ELECTRICITY — ELECTROSCOPES — ELECTRICITY BY INFLUENCE—DISTRIBUTION OF ELECTRICITY—LEYDEN JAR—ELECTRIC LIGHT.

256. THE branch of physics on which we are now about to enter occupies a most conspicuous place in modern science. Its existence as a science was scarce suspected before the beginning of the last century; but since that period it has been prosecuted with unabated ardour, and promises to unfold to us many of the most obscure and hitherto inexplicable operations of nature. Thales* appears to have studied some of the phenomena of magnetism, but Gilbert† having observed the peculiar phenomena presented by amber, the Greek name for this substance gave rise most naturally to the term *electricity*.

In examining the properties of bodies, there are some apparently so inseparable from them, or essential to their existence, that we cannot conceive their existence independently of these properties. Thus, all matter is supposed to have impenetrability, extension, weight. There are, however, other properties, which do not at first sight appear

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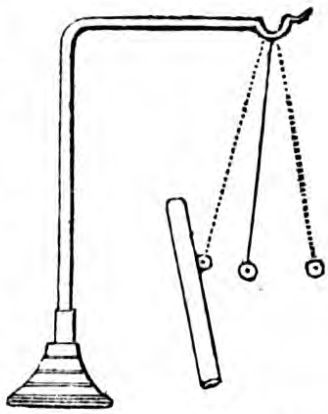
* B. C. 600. † A. D. 1600.

to be so essential to the existence of bodies: thus we might conceive bodies without heat, for this appears to have reference to the particular state in which a body exists, as solid, liquid, or gaseous; and similarly we shall find that electricity is of the same character. It is generally laid down, that no bodies are absolutely devoid of heat, since all appear to be capable of parting with some; it is equally true, that no bodies are devoid of electricity, since all may be made to exhibit signs of it; they may be put into a state capable of exhibiting the phenomena.

257. *Phenomena.*—The characteristic phenomena of the science of electricity are the mutual attractions and repulsions which some bodies exhibit under peculiar circumstances. We know perfectly well that substances in their natural state have no peculiar property of attracting or of repelling small fragments of gold leaf, tinsel, saw-dust, elder pith, feathers, or any other light substance, whatever its nature; but if a tube of glass, as a vial or a wine-glass, a roll of sulphur, a piece of sealing-wax, amber, or any resinous substance, be rubbed with woollen cloth or silk, it immediately acquires these properties; all light substances are attracted by it, and this attraction is so very powerful, that a light substance will rise many inches, or even a foot, to attach itself to the surface of the attracting body. To the cause of this phenomenon the term electricity is assigned, since, as we have already stated, amber was the substance in which the phenomena were first observed. These attractions are not destroyed or interfered with by the interposition of any body; and since their intensity depends on the extent of the surface, and the force with which it is rubbed, various contrivances, called electrical machines, the construction of which is well known, are employed for the production of the phenomena in a striking and convenient manner. Some of the light substances adhere to the substance which has been rubbed, or the *excited body*, as it is termed; others are repelled immediately after contact. The rapidity with which bodies rush from a distance to the

electrified body depends on the degree to which it has been excited; and the fact that some adhere to it, others on coming in contact with it are immediately repelled, is one of the phenomena which particularly deserves notice; of this any one may satisfy himself by a stick of sealing wax, and a few strips of the feather of a pen. If the excited body be brought near the face, a sensation is experienced similar to that produced by the contact of a cobweb; when sufficiently excited, and touched by the knuckle or a metallic ball, there is a slight crack, and a spark passes into the body presented to it. When the experiment is performed in the dark, the spark becomes vivid, and is accompanied with a bluish light. Every one is acquainted with the phenomena which present themselves when the back of a cat is rubbed in the dark; these are electrical phenomena, and to the unknown cause is assigned the term electricity, just as the term caloric was assigned to the unknown cause of heat.



258. *Electroscopes.*—The attraction and the repulsion of a light substance are the characteristics whereby a body is known to be electrified, or excited by friction; and to ascertain this with certainty various instruments, termed electroscopes, have been devised. Of these the most simple is the electric pendulum, which consists of a small ball of elder pith, suspended by a silk, or a very delicate metallic thread. When we wish to discover whether a body is electrically excited, we bring it near the ball; if the ball is neither attracted nor repelled, the body is either not excited at all, or in an exceedingly small degree. The electric needle may also be used for the same purpose; it consists of a most delicate copper needle, poised on its centre, and having a very light pith ball at each extremity. An excited body attracting one ball will make the needle move about

its centre; and since the friction of the point of support is here the only obstacle to motion, this electroscope has great susceptibility.

By means of these and other similar contrivances, we may easily examine all bodies, and see whether they are capable of being electrically excited by friction. This examination is attended with very curious results; and it appears that gum-lac, resin, amber, sulphur, and glass, as well as the diamond and most precious stones, are eminently electric; that baked clay, wood, and charcoal, rarely give any signs of attraction, and that the metals and some other substances never exhibit the least signs of attraction, whatever care is taken in rubbing them. Thus, the productions of nature may be separated into two grand classes, whereof one contains all those substances which are capable of being electrically excited by friction, and which are therefore called electrics; the other contains those which cannot be excited, and which are consequently called non-electrics. This distinction is not, however, well-founded, and the terms non-conductors and conductors are better, since they accord more with the facts.

259. *Conducting and non-conducting or insulating bodies.* --If those substances which we have termed non-electrics cannot be electrified by friction, they may in some other way. It was discovered by Gray,[*] that if a glass tube having its ends stopped with a cork be rubbed, the cork becomes electrified; whereas the cork itself being rubbed exhibits no signs of excitement. A metallic wire inserted into the cork became electrically excited, as well as the cork, and this is the case whatever the length of wire. If the wire have a metallic ball at one end, a body is much more strongly attracted when held near it than near any other part of the wire. A metallic substance, then, has the property of transmitting electricity; and this transmission takes place also instantaneously; thus the effect is the same

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[*] In 1729: see *Phil. Trans.* 1732.

as if electricity were a species of fluid which passes from the glass to the metal, and which diffuses itself immediately over the whole surface. This property is found in all those substances which we have termed non-electric, and they are consequently said to be *conductors* of electricity. On the contrary, those which we have termed electrics are non-conductors, that is to say, the electricity does not diffuse itself over their surfaces; for a tube of glass being rubbed at one extremity, does not exhibit any signs of attraction at the other extremity.

The common electrifying machine may be employed to shew this property of metallic bodies, as the conductors of electricity. This, which consists of a cylinder, or plate, or sphere of glass, made to revolve in contact with the hand, or with a rubber, is a means of producing an abundant supply of electricity. If a metallic bar or wire suspended by silken threads, or sustained on glass props, be placed in contact with the glass, we shall see when the glass is rubbed, 1°. that the metal is electrically excited throughout its whole length, whatever be the number of turns of the wire; 2°. that if it is interrupted any where by a piece of glass or silk, there are no signs of electricity beyond this break in the continuity; 3°. that if it touches the floor, there are no traces whatever of its being electrically excited; for the floor is a sufficiently good conductor to admit of the electricity dissipating itself over the whole surface, and thence extending throughout the whole house, and to the earth itself.

From the preceding it appears that the air is a non-conductor; for had it the properties of a metallic body in this respect, the electricity developed by friction would pass off at once from the rubbed body into the surrounding air, and be instantly dispersed throughout the whole mass of the atmosphere.

Water and its vapour are very good conductors; for an excited body plunged into water or into the vapour of water, parts at once with all its electricity. Hence a substance which will retain its electrical state for a very long time in dry air, loses it almost immediately when the atmosphere is moist; and electrical experiments are very apt to fail on a damp or rainy day. The worst conductors become good ones when moistened, and bodies must in general be warmed before being subjected to friction.

The human body is also a good conductor; a person standing on a bad conductor, as on a cake of resin or sulphur, becomes electrically excited throughout the whole body by touching an excited body; but standing on the ground it is conveyed away into the earth. Hence we see why metals cannot be excited when held in the hand—the electricity is conveyed away as fast as produced.

The electrical conducting power of different substances depends on some permanent cause, as the nature of the substance; but it depends also on several accidental causes, of which it is difficult to ascertain the exact influence. Thus, instead of speaking of bodies as conductors or non-conductors, we should speak with more accuracy of them as good or bad conductors; for there exists no known substance which is an absolute non-conductor. The worst conductors are gum-lac, silk, glass, and resinous substances; hence they are called *insulating* substances, because any body supported upon them is insulated, or has all connexion with the ground cut off, and preserves for a long time the electricity which it possesses. Between the worst and the best conductors lie an infinite diversity of substances, whereof each has its own conducting power.

260. *Two species of Electricity.*—A body which is electrically excited repels any body to which it has communicated any portion of electricity. If an excited body, as a tube of glass, be held near an insulated electric pendulum (Art. 258), the pith ball will be attracted, and will remain in contact with the excited tube for some seconds, but it will then be repelled; the two positions of the ball are represented by the dotted line in the figure just referred to; the angle through which it is repelled is equal

to the angle through which it was previously attracted. That this repulsion of the ball arises from the electricity which it has received from the tube, is evident from the fact, that if the ball be touched by the hand, or by any conductor, it is immediately attracted, and again repelled as before, after contact. If the ball be not insulated, the electricity is conveyed away as soon as communicated, and consequently the ball will remain in contact with the excited body. But if the attracted body be insulated, it is always repelled after contact, whatever be the nature of the excited substance.

But if we have two insulated pendulums, whereof one has been electrically excited by contact with glass, and the other by contact with some resinous substance, the following remarkable phenomenon presents itself; a strong mutual attraction exists between the ball which has been in contact with the glass and the ball which has been in contact with the resinous substance; but if both balls have touched the same substance, they mutually repel each other. It appears then that the electricities of glass and of resinous substances are not identical, since each attracts that which the other repels. These two electricities, different in their origin and in their effects, have received different names, the one being called *vitreous*, the other *resinous* electricity. The vitreous electricity is sometimes called *positive* and the resinous *negative* electricity, in consequence of theoretical views entertained on this subject; we shall use the terms indifferently; and the student must carefully remember, that by positive electricity we mean such as is produced from glass, and by negative electricity such as is produced from a resinous substance, as amber, or gum-lac.

Whatever theoretical views we may adopt, the effects are such as may be produced by *two* electricities, whereof each attracts the other and repels its own kind. And this is the test whereby we distinguish the kind of electricity; the excited body is brought near a pendulum, the electricity of whose ball is vitreous; if the ball is repelled the unknown electricity is proved to be vitreous—*if* attracted, resinous.

261. *Natural state of bodies with respect to Electricity.*—Such is the rapidity with which electricity spreads itself over the whole surface of the conducting body, that we must conclude that, if a fluid at all, it is one of excessive mobility; and from the opposite nature of the electricity developed in glass and in resinous substances, the opinion is strongly forced upon us that there are *two* fluids. When these two fluids are combined by their mutual attraction, or by one neutralizing the other, the body is in its *natural* state with respect to electricity; but the electricities becoming decomposed or separated by any cause, the contrary actions which they exert on some outward body cannot be exactly compensated, and the body in which this decomposition has taken place is said to be electrically excited. It is electrized vitreously, or positively, if the vitreous fluid predominates—and resinously, or negatively, if the resinous fluid predominates.

Whenever one electricity is developed in a body which was previously in its natural state, there must be a corresponding development of the other electricity, or it must be destroyed by the decomposing cause. But the destruction of a natural agent or a force being no less inconceivable than the destruction of matter itself, we may be assured that one electricity is never developed without the other. Of this we may convince ourselves by rubbing two discs of any substance against each other, the discs being insulated by glass handles. If after the friction they be held together there will be no signs of any electricity, but if they be separated we shall at once recognise that one possesses vitreous and the other resinous electricity. These plates may be of glass, wood, resin, metal, or covered with fur, paper, silk, &c. and we shall obtain the same result.

If a body in its natural state possesses the two electricities in equal quantities, there seems no reason why on being rubbed it should take one fluid in preference to the other; and take at one time the positive, at another the negative electricity. Such is however the fact; glass acquires positive electricity when rubbed with a piece of silk, and negative electricity when rubbed with a piece of cat's skin, and some other furs. It is, moreover, universally true, that the rubbed and the rubbing substances acquire opposite electricities, and it will be of service to remember, that glass rubbed by silk or wool acquires positive, the rubbers consequently acquiring negative electricity; that resin rubbed by silk or wool acquires negative, the rubbers, on the contrary, acquiring positive electricity.

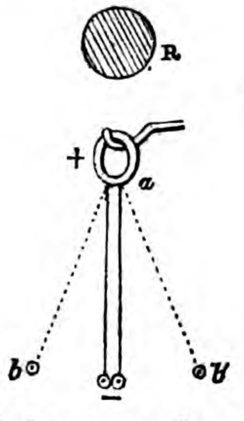
262. *Communication of Electricity.*—Electricity is communicated by contact; but it may be communicated also without actual contact, at a small distance; in all cases, however, the conducting power of the body and its form has great influence on the mode in which it is communicated. Bad conductors part with their electricity only at those points at which the contact takes place; but the best conductors gain or part with electricity throughout the whole extent of their surface; and other bodies acquire or lose their electricity from a portion of their surface of greater or less extent about the point of contact, according to the goodness of their conducting powers. Thus balls of glass, sulphur, and resin, are, by contact with excited glass, sulphur, or resin, electrized only at the points of contact. Pieces of paper or card a little moistened are electrized through a small extent of surface about the point of contact; and an insulated metallic body is electrized instantly throughout its whole surface; their electricity is consequently less sensible according as the extent of their surface is greater. If the metallic body communicates with the ground, the surface over which the electricity may extend is infinite, and the electrical state of its surface will be scarcely sensible. In this case the electricity is said to have flowed into the soil, or into the common reservoir, because it is in fact diffused over the whole globe of the earth. If the

electrized body is itself a conductor, it is perfectly immaterial at what point the contact takes place; the loss of electricity will be instantly sensible over the whole surface.

The electricity which is communicated without contact, or at a distance, expands itself over a conducting body in the same manner as that which is communicated by contact; but in its passage, the curious phenomenon of the *electric spark* presents itself. For the production of this spark we do not require a tube to be electrically excited in any great degree; whatever be the degree of excitement, a small spark will be seen when a metal bar or the knuckle is brought near to the excited tube; together with the spark a smart crack is heard. When the electrized body is metallic, and of considerable surface, as the conductor of an electrical machine, the spark will pass between it and another body at more than a foot distance; the light is in this case exceedingly brilliant, and the crack somewhat like that of a whip.

263. *Induction.* — In the preceding articles we have spoken of the phenomena of attraction and repulsion, and considered that each electric fluid attracts the fluid of a different name, and repels the fluid of the same name; these attractions and repulsions do not take place simply between the free fluids, that is, when the fluids are already decomposed or separated; they are also exerted on the combined fluid, that is, when a body is in its natural state; hence it follows that a conducting body may, without losing or without receiving any electricity, be brought into an electrical state, due simply to the action of some external cause, and which state will cease with the removal of this cause. This electrical state produced at a distance is termed electricity by influence, or induction.

Suppose that a copper ring *a*, having two pith balls suspended to it by very delicate metallic threads, is sustained on a glass support. A body R, electrized resinously, is placed near it, at a foot distance suppose; then the two balls will repel each other and take the positions *b b′*. The less the distance of R from the ring the greater will be the divergence of the balls, provided R is not brought so near that the spark passes. The balls *b*, *b′* are charged with the same electricity, and this electricity will be found to be resinous, or the same as that of the body R, whose presence causes their divergence. If the body R be removed, the divergence diminishes as the distance increases, and ceases entirely when R is removed to a sufficient distance; this would not be the case if R had imparted any electricity to the ring or to the balls; we cannot therefore suppose that there is any communication of electricity across the air. The whole phenomenon is due to what takes place in the ring, the wire, and the balls, and may be explained by saying, that the natural state of this system is disturbed by the influence of the electrized body; that the fluids are separated, and the vitreous fluid is attracted to that part which is nearest R, or is comprised in the ring—that the resinous is repelled to the most distant point, and is collected in the balls. Thus the two fluids are simply displaced, and on the removal of the disturbing electrized body they become reunited by their mutual attraction.



There is a little instrument termed a *proof plane*, which serves to shew the nature of the electricity at any point of a body. It consists of a very small disc of tinsel or gilt paper attached to the extremity of a good insulator, usually a piece of gum-lac. This being applied by contact at any point of an excited body will take a quantity of electricity proportional to the intensity of the electricity at that point; this must then be brought near a delicate electrometer, that the amount and nature of the charge may be ascertained. The disc of a proof plane being made to touch any portion of the copper ring, will be found to have acquired vitreous electricity, whilst that from the balls will be resinous.

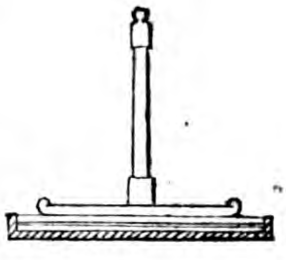
A body is sometimes said to be situated within or without the *sphere of activity* of an electrized body, according as it does or does not experience its influence. This statement is, however, not strictly correct; for the influence of an electrized body really extends to infinity, but the distance at which we can detect it, or render its effects sensible, must depend on the delicacy of the means which we employ.

264. *Return Stroke.*—A body which has been electrized by induction returns to its natural state the instant the influence ceases. Now, since the decomposition by influence is instantaneous in conducting bodies, the recomposition ought also to be instantaneous when the decomposing cause has ceased; the decomposing cause may be destroyed in two ways—gradually, by drawing small sparks from the electrized body with an insulated body, or suddenly, by removing it all at once by a single spark. In the former case the recomposition is gradual, since the influence which causes the separation is continually diminished; in the latter, the two electricities unite by their mutual attraction, and unite entirely, as is seen by the sudden and complete approach of the balls. In these phenomena neither of the fluids leaves the mass which is the subject of the electrical influence, but each experiences a motion of translation throughout the whole mass, both in their separation and in their reunion. These rapid motions of electricity produce in the particles of matter most remarkable mechanical and chemical effects. The effects of this sudden reunion of the two electricities, or of the return stroke, are quite sensible in the human frame. Suppose that two persons stand one at each end of a large conductor; then while it is being charged they experience no peculiar sensations; but if one of them approaches sufficiently near to draw sparks, the other immediately experiences a shock,

although there is no trace of any spark or light having passed betwixt him and the charged conductor.

265. *Electricity of bodies communicating with the earth.*—When a body, as an insulated conductor, is electrized by influence, either kind of electricity may be procured from it; but if the body communicate with the ground, it can never be charged with more than one of the electric fluids. If we examine the electricity at the two ends of the conductor in which the fluids have been separated by influence, the vitreous fluid will be collected at one end, as at V, and the resinous at R, and betwixt them will be a *neutral* line, as at *n*, which separates the two fluids. On applying a proof plane we shall find vitreous electricity throughout the whole portion V *n*, and resinous throughout R *n*; but no sensible electricity near this point *n*. If however any communication be made with the ground, the results will be altogether different; if the communication take place any where in the portion *n* V, the whole vitreous electricity will disappear; if any where in *n* R, the whole resinous electricity will disappear; the resinous remaining unaffected in the former case, and the vitreous in the latter. The explanation of this phenomenon is simple; the chain by which the communication takes place has its electricity decomposed by influence; its vitreous fluid is repelled into the ground, whereas the resinous is attracted on to the cylinder, and neutralises the vitreous fluid which it meets with; the result being precisely the same as if the cylinder had communicated with the ground previous to its being electrized by influence.

266. *The Electrophorus.*—This instrument is founded on the laws of electrical excitation by influence, which we have just attempted to explain. It consists of three parts, whereof the most important is a plate



of resin, sulphur, or some other electric, which is poured in a melting state on some conducting substance termed the *sole*, and formed with a rim so as to retain the melted electric until it has cooled. The third part is a metallic plate of somewhat smaller diameter than the electric, and insulated by a handle fastened to its upper surface; it is termed the *cover*. The surface of the cake is electrically excited by friction, with fur or flannel, and the cover is placed upon it. The contact which takes place is not sufficiently intimate for the plate to acquire the electricity of the cake; but the plate is electrized by influence, acquiring an *opposite* state at its lower surface, and a *similar* state at its upper surface. If, now, the upper plate be touched by the finger, or by any other conductor which communicates with the ground, a spark will pass to the cover, so as to restore the electric equilibrium; the quantity of electricity thus superadded being retained in the cover by the inductive influence of the cake. When the plate is raised, provided it be held by its insulating handle, the cover will be charged with positive electricity, which may be imparted to an insulated conductor, or to a Leyden jar (Art. 269). This operation being repeated, a charge may be communicated to the jar of an intensity equal to that of the cover of the electrophorus when raised.

On the same principle the *condenser* is constructed, and employed for collecting weak electricity spread over a large surface, so that the electricity, being increased in intensity, may be examined.

267. *Dissipation of Electricity.*—The electricity of all bodies disappears after a certain time; it is either dissipated into the air or into the soil, as all electrical experiments shew. The prevention of this dissipation is not in our power, but we may render it more slow, more regular, and capable of being measured. Unless this can be effected it would be impossible to establish any laws respecting the electric forces, since they would be ever variable, and change according to unknown laws. The loss which is

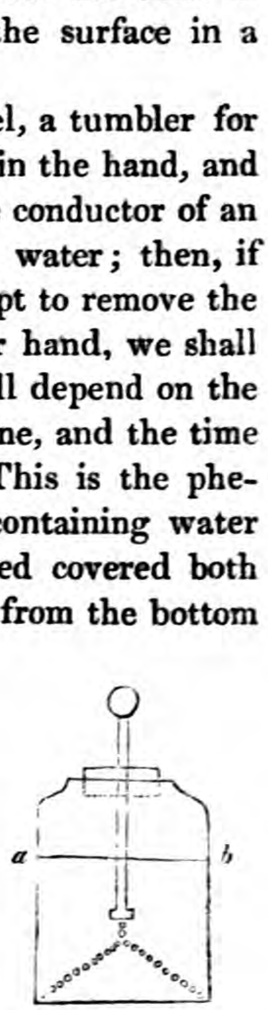
due to the imperfect insulation of the supports, arises partly from their conducting power and partly from the thin stratum of moisture with which they are covered. The surface of glass condenses the vapour of the atmosphere with great rapidity; hence a glass support must always be covered with gum-lac; and silk threads must be dipped in this substance for the same reason. These precautions being taken, glass or silk may insulate nearly as well as gum-lac itself; and it appears from some experiments of Coulomb, that the insulation is complete when the supports are about fifteen or twenty inches in length, and well warmed before each experiment, so as to evaporate any moisture which may be on their surfaces. Since, however, the insulation is not complete except the supports have considerable length, it is evident that they always contain a certain quantity of electricity, and that the fluid becomes repelled to the extremity of the support, and thence passes into the ground by a slow but continuous discharge. A body is perfectly insulated when it experiences the same loss of electricity from one as from several supports; and the loss which then takes place must be due to the contact of the air. The loss due to the air arises in a great measure from the watery vapour which is always diffused through it; the effect of moisture in dissipating electricity is so great, that all traces of electricity are lost if we breathe on electrized glass or resin, or on an insulated conductor. The electricity which is thus removed by vapour diffuses itself continuously through one particle after another in the surrounding atmosphere, and it may be conjectured that the molecules of vapour are considerably influenced by it. The loss of electricity is not, however, entirely due to the vapour, since air completely deprived of its vapour by muriate of lime, sulphuric acid, or any other substance for which water has a strong affinity, suffers a small portion of the electric fluid to escape.

268. *Distribution of Electricity at the surfaces of bodies.*—The electric fluids, in the natural state of bodies,

are uniformly diffused throughout the whole mass of a conductor, and seem to be accumulated there in infinite abundance. But when the fluids are separated, or the electricity is free, the particles repel each other, and disperse in every direction until they meet with some obstacle which can arrest their progress. A perfect conductor would present no impediment to this diffusion, and the fluid extending instantly through the whole of its surface would extend itself still farther if it met with any space equally permeable. An electrized body placed in a perfect vacuum would lose instantly all its free fluids, since a void would present no impediment to the passage of electricity.

Thus the earth is, perhaps, the only planetary body which can be electrized at its surface, supposing it alone to have an enveloping atmosphere. The metals do not possess conducting power in perfection, but the electrical state passes with such rapidity through them, that we may suppose the fluid to experience little or no resistance in passing through their substance. It follows from this hypothesis that free electricity, developed at any part of a metallic conductor, always spreads to the surface, when its farther progress is arrested by the surrounding air. There are some simple experiments which may elucidate this most important hypothesis. 1°. An insulated sphere is covered with two hemispheres of some metallic leaf or tinsel, which fit accurately, and may be removed at pleasure by insulating handles. The sphere is electrized, and the hemispheres being removed suddenly, the surface will be entirely deprived of its electricity. The fluid then had expanded over the surface, and accumulated there without entering at all into the interior. 2°. A sphere of seven or eight inches in diameter, with a very small slit of about an inch deep, is insulated and electrized; the whole electricity will be confined to the surface, none whatever being at the bottom of this small hole. 3°. If two spheres of the same radius and conducting material be electrized together, and separated; and one be touched by a solid metal sphere, and the other by a sphere of the same radius, but made with tinsel or gold paper, that is, by gumming a leaf on a sphere of resin; the two spheres will be found to have lost the same quantity of electricity; thus the solid metal sphere removes no more than the superficial shell. Hence we may conclude, that the fluid does not exist in the interior of bodies, but is confined to the surface in a stratum of insensible thickness.

269. *The Leyden Jar.*—If a glass vessel, a tumbler for example, partly filled with water, be held in the hand, and a conductor communicating with the prime conductor of an electrical machine be introduced into the water; then, if after a few turns of the machine we attempt to remove the conductor, holding the vessel in the other hand, we shall receive a shock, the violence of which will depend on the size of the vessel, the power of the machine, and the time during which it is continued in action. This is the phenomenon of the Leyden jar; but a jar containing water being extremely inconvenient, a jar is used covered both inside and outside with tin foil, pasted on from the bottom to within a third of the top, as up to *a b*. The upper portion of the jar is coated with lac-varnish, or if not varnished it must be rubbed over with tallow to prevent the deposition of moisture. A cork covered over with lac-varnish, or with sealing-wax, is fitted into the mouth of the jar, and a brass wire passes through it, terminated at one extremity by a ball or knob, and divided at the other into two or three fine wires, which are in contact with the inside coating of the jar. The jar being held in the hand by the outside, if the knob is brought within the striking distance of the conductor of an electrical machine, sparks pass between the conductor and the knob as the machine is worked, and the vitreous electricity which passes into the jar becomes expanded over the whole



interior surface of the jar. The electricity cannot pass through the glass; but acting by influence on the exterior surface, it decomposes the electricities of the external surface, attracts the resinous, which becomes accumulated and condensed on the external surface, and repels the vitreous, which passes off through the body into the ground. The jar may also be charged by holding the knob in the hand and presenting the external surface to the prime conductor; but in all cases the communication of one of the surfaces with the ground is no less essential than the communication of the other with the prime conductor. Every spark which passes from the conductor of the knob occasions an increase of vitreous or positive electricity on the inside, and of resinous or negative on the outside surface. Suppose now that any good conductor, as a metallic body, touches at once the knob and the outside coating of the jar, the two electricities will immediately rush together, there will be a crack and a brilliant light, the two electricities will combine, and almost all traces of a vitreous or of a resinous electricity will disappear. If the medium of communication be the human body instead of a metallic wire, as if the jar be held by the bottom with one hand and the knob be touched by the other, the two electricities will combine in the human body, and their union will be attended with a smart shock of greater or less violence, according to the size of the jar and the amount of the charge.

270. *The Electric Light.* — Whatever may be the amount of electricity accumulated in a body, there is no luminous appearance when the fluid is at rest. Hence the first condition for the electric light is, that the fluids must be in motion, or that their equilibrium must be disturbed in some manner. This, though a necessary, is not a sufficient condition, the tension of the fluids must also be of a certain amount. The electricity of an ordinary machine, for instance, gives no luminous appearance in its passage into the earth by a metallic conductor; but light is visible when

the machine has very great power. The tension requisite for the production of the light depends on the state, the form, and the conducting power, of the medium in which the fluid moves; sometimes electricity of very low tension will give a brilliant light, at others the most powerful tension which we can produce is unattended with any luminous appearance.

The distance from which an electric spark can be drawn depends on the conducting power of the substance, the extent of the surface, and the thickness of the stratum of electricity with which it is charged; for the single condition that the spark may be drawn is, that the tension of the electricity must be greater than the pressure of the air. In bodies with angular points this condition is satisfied for extremely small charges of electricity; and the fluid diffuses itself spontaneously, forming bunches of light which are exceedingly brilliant in the dark, and whose divergent rays are several inches long. Bodies of a round form must have a very powerful charge before a spark can leave them; but if a conductor communicating with the ground be brought near them, the action by influence takes place immediately: the fluids are displaced in consequence of the conducting power of the bodies, are accumulated in a manner which depends on the extent of the surfaces, and the spark bursts forth as soon as the elastic force of the atmosphere is more than counterbalanced by the tension of electricity on either of the bodies which are subjected to influence.

A machine has great strength when it can, without the assistance of conductors acting by influence, give sparks at a distance of twenty or twenty-five inches. At these distances the electric light forms a line of fire, the sinuosities of which are strikingly analogous to the flashes of lightning. The luminous flashes furnished by a machine may be increased indefinitely by making interruptions in the continuity of the conductor, which communicates with the ground; on this principle many interesting phenomena may be exhibited by electric light. Small grains of metal may be laid very near together in silk, but not in immediate contact, so as to form chains, garlands, and patterns, which will appear luminous as long as the machine with which they communicate is worked. The last and first particle of metal will appear illumined equally at the same instant, so sudden is the communication of electricity, whatever be the length of the line.

The phenomenon of the electric light in a partial vacuum is very remarkable. If a tube of any length, as for example six or eight feet, have the air exhausted from it, and be made to communicate at one end with an ordinary machine, and at the other with the ground, there will be a vivid light throughout the whole of its interior. The electricity experiencing but a feeble resistance from the air which remains, is diffused throughout the whole tube, and flows through, marking its passage at every point by a luminous appearance. When the communications are good, the light appears fixed and steady; but if a conductor be brought near the exterior of the tube, the light is attracted towards it, appearing at the same time more vivid. It generally also happens, that a tube which has been used for these experiments exhibits similar phenomena long after it has been separated from the machine.

With respect to the theory of the Electric Light, nothing which is satisfactory can be at present advanced. Two hypotheses have been started, whereof one supposes the light to be the consequence of the heat produced by the sudden condensations which are known to take place when the electric spark passes; the other supposes that the light proceeds from successive decompositions and recompositions of electricity between the atoms of ponderable matter.

271. *Motion of electrized bodies.* — All the preceding experiments lead us to consider the electric matter as an extremely subtile fluid, which envelopes the atoms of bodies, and perchance fills up the void spaces which the bodies naturally contain. This fluid, in its neutral state,

exerts beyond all doubt some actions on itself; but at present it is a perfect mystery what those actions are; it is only when the fluids are decomposed or separated, that we become sensible of the phenomena. Again, it exerts some action on ponderable matter; it impresses various motions upon it, and seems at first to act on it by attractive or repulsive forces. A more attentive examination, however, will convince us, that if the atoms of matter are acted on by electric fluids, it can only be by some indirect action of pressure or impulse; so that the movements of electrized bodies are not secondary motions in which matter has no direct power, but a simple resistance, receiving passively all the motions impressed upon it by the electric fluid. It is a curious question for our consideration, how ponderable masses may be displaced and transferred by an imponderable fluid.

There does not appear to be any attraction at a distance, or any affinity between the electric fluid and the substance of non-conductors; for all these bodies lose their electricity in a vacuum. If, now, we consider two balls, of gum-lac for example, charged with the same electricity, and brought near each other, the only active force is the repulsive force of all the molecules of the fluid with which they are covered; the immediate effect of this force would be to separate the molecules, and to disperse them in all directions in which they could move freely; if, for example, the two balls were in a vacuum, they would remain immoveable, whilst their electricity, obeying its repulsive power, became disseminated in all directions; but suspended in air, which is a bad conductor, the fluid which covers them is checked on all sides, or rather it finds on all sides a resistance which must be overcome. Those molecules of the electric fluid which rest themselves against the air cannot move without repelling the air before them, and those which support themselves against the surface of the gum-lac cannot move without moving the ball as an obstacle which opposes their progress. Thus, by a double effect, the balls are put in motion, and separated.

We shall have a more distinct conception of the phenomena, by conceiving the balls of gum-lac, after having been electrized, to have had their surface covered with a layer of some substance impermeable to electricity, so that the fluid with which they are charged is, as it were, imprisoned betwixt the two non-conducting materials. It is evident, that all the repulsive actions which are exerted betwixt the electric molecules are transmitted immediately to the ponderable matter, by the simple fact of the passive resistance which they present. The layer of air which envelopes the bodies produces precisely the same effect as this imaginary shell impermeable to electricity.

Just as the balls charged with the same electricity repel each other, those charged with the contrary fluids ought to be dragged and attracted towards each other, by the effort which the molecules make to be reunited. The same reasoning applies to all bodies, whatever their forms; and it is evident, that if a non-conducting body, taken in its natural state, is neither attracted nor repelled by an electrized body, it is simply because its fluids not being decomposed by influence, and separated the one from the other, there are two contrary actions, the one attractive, the other repulsive, which are invariably equal, and consequently counteract each other.

The motion of electrized conductors is the result of the pressure which the fluid exerts against the air, or in general against the impermeable envelopes which limit their surfaces; for the air may be considered as an impermeable envelope. A conducting body is, in its natural state, always attracted by an electrized body, because the fluids being separated by influence, and the one of contrary name being always attracted to the nearest part, the attraction which is exerted on it is always more efficacious than the repulsion which is exerted on the other at a greater distance.

SECTION II.

GALVANISM, OR VOLTAIC ELECTRICITY—ELECTROMOTIVE FORCE—VOLTAIC PILE—DIFFERENT KINDS OF PILE—FORCES AND EFFECTS OF THE PILE.

272. The experiments of Galvani of Bologna paved the way for a new branch of Physics, which is termed Galvanism, after the illustrious philosopher with whom it originated, or Voltaic Electricity, from the vast extension and generalization which this science received from the researches of Volta.

Galvani, about the year 1790, observed convulsive motions produced in the limbs of a frog which had been recently killed, when a metallic connexion was established between the nerves and muscles. This phenomenon was observed not to be confined to frogs; but similar convulsive motions were produced after death in many other animals, insects, reptiles, and fishes. Previously to the observation of these phenomena, Galvani had conceived some peculiar notions respecting a nervous or vital fluid, and he consequently readily invented an explanation of the phenomena, which was in accordance with his preconceived hypothesis. The commotions of the frog, he said, were excited by a fluid which passes along the nerves and muscles, in consequence of the external communication which is established among them. He made many experiments with the view of ascertaining whether this fluid existed in the nerves or in the muscles; but not succeeding in these researches, he considered the muscles as a Leyden jar, whereof the interior, charged with electricity, is constantly tending to an equilibrium with the exterior; the nerves were conceived to act as conductors; any conducting substance, then, being brought into contact with the nerve, so that a communication is established between it and the surface of the muscle, the equilibrium is instantly restored, and a sudden contraction of the fibres is the consequence. This explanation appeared so plausible, that it was received, and the new fluid termed the Galvanic. The phenomena themselves excited great admiration throughout the whole of Europe; but the theory of Galvani, and the hopes of discovering a new fluid, the principle of life, added a charm to the inquiry which existed in few other pursuits.

The hypotheses of Galvani gave a most powerful stimulus to philosophers; but inasmuch as they could not be followed out without admitting the most vague conjectures, they were soon successfully opposed by the genius of Volta. Celebrated by numerous discoveries in electricity, Volta repeated, with great care, all the experiments of Galvani and his followers; full of enthusiasm respecting the facts, he gave but a conditional consent to the hypotheses, and soon, with great sagacity, seized on a fact which had escaped the most acute observers. When the conductor which establishes the communication betwixt the muscle and the nerve is a single metal, the contraction is always exceedingly small, sometimes scarcely sensible; on the contrary, when the conductor is composed of two metals, it is always very powerful. From this fact Volta drew the following inference; that though there is a fluid concerned in the phenomenon, the animal is not a Leyden jar; the fluid which causes the excitement is neither in the muscles nor in the nerves, it is in the metals; it is developed by their contact; it is nothing else than the common electric fluid.

Galvani endeavoured to support his hypothesis of animal electricity, by urging the convulsions excited by a single metal, and Volta, so far from disputing the phenomena, announced them himself, and drew from them support to his own opinions. There is some heterogeniety in every part of a conducting arc; this is inseparable from bodies; some extraneous substance will always be present, either in the conductor, or in the nerve of the animal, introduced during its preparation; and when apparent convulsions are not produced, as is sometimes the case by a single metal, they will always occur, if one part be rubbed by any foreign metallic substance. The imperceptible particles which attach themselves give a heterogeniety which is sufficient; the contact of the metal with these strange particles gives rise to the electricity which is developed. That which is homogeneous to chemical analysis, is not absolutely so; and could art or nature furnish a conductor of perfect purity, the effect would still be produced, for the nerves and muscles would not be homogeneous at the points of contact. The difference of their structure is sufficient to produce the phenomena; for Galvani having prepared a frog, with great care, obtained contraction by mere contact between the muscles and nerves of the animal itself; which was strongly urged against the theory of Volta. But it was subsequently shewn that electricity may be produced by the mere contact of two metals; so that the new facts urged by Galvani tended to generalize and establish the opposing theory; thus the animal electricity of Galvani might with equal propriety be called metallic electricity. Volta soon established the fact, that the kind of action, or new force, which is brought into play when two different metals touch each other, and are connected by any moist body, depends entirely on the metals.

273. *Electromotive force.*—The new force just spoken of, which is exerted betwixt metallic and other heterogeneous substances, is termed *electromotive;* it is produced when contact takes place; it resides in the surface at which the juncture is effected, and there decomposes the natural electricity, and may be said to separate the two fluids, so that the vitreous passes into one body, and the

resinous into the other. The characteristics of this force, in the language of the modern theory of electricity, are the following: it produces the decomposition of the natural fluids, and prevents their recomposition; by the former effect the vitreous fluid is driven into the zinc, and dispersed throughout its whole extent in virtue of its proper repulsion, whilst the resinous fluid is in a similar manner repelled, and dispersed in the copper; by the latter effect the contrary fluids are kept near each other, the one to the right, the other to the left of the surface, which is in contact, without the power of passing over this surface, and of being recompounded in virtue of their mutual attraction. To form a more distinct idea of this resistance or obstacle, let us suppose for an instant that there is no decomposition on contact, and that some vitreous fluid is communicated artificially to the zinc: this fluid will not then pass to the copper, the electromotive force will present itself as an obstacle to arrest it; but if, on the contrary, some resinous fluid be communicated to the zinc, it is probable that this fluid passes entirely to the copper. The converse phenomena will present themselves if the copper be electrized resinously or vitreously.

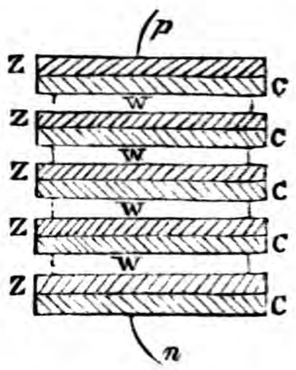
Considered as opposing an obstacle to recomposition, the electromotive force has its limits; that is, it is unable to stop some charges of vitreous fluid in the zinc, and some of resinous fluid in the copper. So soon as these charges, acquired naturally by contact, or communicated artificially, attain a certain tension, they can pass the surface of the junction, and expand in all directions, or recombine; but in this case the electromotive force arrests all that it has the power of doing. The electromotive force when it produces decomposition acts instantaneously and permanently; permanently, because it is always ready to act when the tension is not what is necessary for Galvanic equilibrium; and instantaneously, because only an inappreciable portion of time is requisite for the tension to attain its maximum. The tension is found to be small, for a plate of zinc does not charge the condenser when insulated, whereas it charges it instantly when in communication with the ground. The electric tensions developed and retained by the electromotive force are not the same for all bodies. The metals are good *electrometers*, although there is a marked difference in these, and in general other substances are said not to be electrometers, because they produce only very small effects; but when examined with very delicate instruments they also are found to develop electricity by contact; only the tensions produced are incomparably more feeble than those produced by metals.

The electromotive force thus discovered by Volta must be considered as a force universally operating on the contact of all the molecules of heterogeneous substances, incessantly decomposing the electric fluids, and giving rise to new forces whose effects are sensible on ponderable matter. The elements of which the mass of our globe is compounded, whether at the surface or at depths below, are mixed up in such a manner that there is every where heterogeneity amongst the particles in contact; what an infinity of different substances are in contact in the masses of organized and unorganized matter, and what a multitude of electrical actions, if these views be correct, must every where develop themselves! The vegetable mould of the earth's surface, the stones, the rocks, the leaves, the various strata, are but an aggregation of different principles, among which the electromotive force must act with greater or less intensity. A single glance will shew the fecundity of this principle, and that the first observers were not presumptuous in their belief, that the laws of Galvanism, or Voltaic electricity, would furnish a key to innumerable phenomena.

274. *Construction of the Voltaic pile.*—The pile is constructed with three different substances, whereof two are metallic and good electrometers, and the third is non-metallic, but a good conductor, and of very feeble electromotive power.

The metals which serve best for the purpose are zinc and copper; the former furnishing the *positive elements* of the pile, and the latter the *negative elements;* two elements, united or soldered together, compose what is termed a *pair* or *couple.*

The non-metallic substance is called the *conductor*; sometimes it is a *moist cloth,* that is, a roll of cloth or paper dipped in pure water, or in an acid, alkaline, or salt solution; sometimes the solution itself is the conductor; sometimes a dry body, and then the pile is called the *dry pile.*



Let us conceive now a plate c of copper, that is, a negative element, communicating with the ground by a non-metallic conductor, as *n*. On its upper surface let a plate z of zinc be placed, of the same dimensions; at the instant of contact the electromotive force exerts its action—the resinous fluid which is developed passes over the copper and flows into the ground; the vitreous fluid, on the contrary, passes over the zinc, and is thus accumulated until it has acquired the maximum tension which the electromotive force is capable of retaining: this takes place instantaneously; the tension, or rather the thickness of the electricity which produces it, being represented by unity, we say that the copper is in its natural state whilst the zinc is covered with a thickness unity of vitreous electricity. If by any means we remove from the zinc a part of the fluid with which it is covered, it will no longer have the thickness unity which it ought to have; the electromotive force will, however, by a new development, reproduce exactly that which will make up the loss, and there will be an equal development of the resinous fluid, which will pass into the ground. For each portion of the fluid which is in that way removed from the zinc, there will be a sudden reparation, whereby the thickness unity, which is the state of Galvanic equilibrium, will be immediately restored. If a communication be made also between the zinc and the ground by a non-metallic thread, the vitreous fluid will flow away in a never-ceasing current, and be as incessantly restored; the resinous fluid also developed on the copper will flow away in the same manner; so that if the two non-metallic threads which touch the zinc and the copper be brought near each other, the fluids will be recomposed at the point of contact, and there will be a continuous *circulation* or current of electricity: the fluids will be separated during the contact of the metals, and recompounded at the point of contact of the conducting threads.

Let the copper only be in communication with the ground, and let there be placed on the zinc a piece of moist cloth or card. Vitreous electricity will be developed and separated from the zinc; but the loss being instantly restored, the thickness which we have called unity on the cloth and zinc will be the same as at first. The same state of things will be obtained if a plate of copper be placed on the moist cloth, for no electromotive force exists between these substances. If now a second plate of zinc be placed on this second plate of copper, the phenomena are more complicated, and it is here that the true principle of the accumulation of the electricity in the pile shews itself. Suppose for an instant that the action of the electromotive force is suspended in this second couple; it is evident that the zinc will receive a thickness unity of the vitreous fluid, just as the moist cloth and the plate of copper had previously done, and as soon as the electromotive force acts, this thickness will become equal to two on the second zinc, because it must always exceed by unity that of the copper with which it is in contact. At the same time the resinous fluid, which will be developed on the copper, will be destroyed by the vitreous fluid, which already exists, and there will be in the first couple a fresh development, by which the first zinc, as well as the first cloth and the second copper, will be restored to the state expressed by the thickness unity of electricity. By means of this arrrangement the second zinc must have for its equilibrium a thickness of the vitreous fluid double that which exists on the first.

On the same principles the 2nd linen fold and 3rd copper will have the same thickness 2, whilst the 3rd zinc will have a thickness 3. The 4th zinc will have a thickness 4, the 10th a thickness 10, and the 1000th a thickness 1000.

Thus there exists no limit to the thickness which may be accumulated at the surface of a pile of this kind, since there is no limit to the number of elements which may be superposed; and the first zinc being, as we have seen, an inexhaustible source of vitreous electricity, whose thickness is unity, the 1000th zinc will be an inexhaustible source for electricity whose thickness is 1000. Such is the admirable contrivance by which Volta was enabled to develop and accumulate an indefinite thickness of electricity without either friction or pressure, and by simply placing in contact certain bodies disposed in a determinate order. The pile of which we have just explained the construction is termed the columnar pile.

275. *The insulated pile.*—The extremity of the pile which is terminated by a plate of zinc, is called the zinc or the positive extremity, or the positive pole. That terminated by the copper is called the copper or negative extremity, or the negative pole. In the arrangement of which we have just spoken, the negative pole communicates with the ground, the positive pole being insulated, and on the whole pile there is vitreous fluid, the thickness of which goes on increasing from the 1st zinc, where it is unity, to the 100th, where it is 100, supposing the pile to consist of 100 couples. Let us conceive now another pile with this only difference, that the positive pole communicates with the ground, the negative pole remaining insulated; it is evident that there will be every where resinous fluid, of which the thickness goes on increasing from the 1st copper, that is, the one touching the zinc in communication with the

ground, where it will be unity, to the last, where it will be 100. If now these two piles be placed end to end, a moist cloth only being placed between the two poles which communicate with the ground, there will be a single pile of 200 couples, whereof each half will preserve the equilibrium of electricity which it had at first. Thus the middle will be in its natural state, the communication by the threads having been broken. Starting from that point there will be on one side vitreous, on the other resinous electricity: these electricities cannot be reunited, and their thicknesses always increasing by equal differences for each couple, will be 100 at each pole. If now this equilibrium be disturbed by removing some electricity from one of the poles, the zero, or the point which is at its natural state, will be for the instant displaced; the pole which is touched will have a thickness less than 100, and the other pole will have a thickness greater than 100; soon, however, the loss by the air diminishing more rapidly the electrical thickness of the more powerful pole, the zero will return to the middle, and the equilibrium will be restored. Thus, in every insulated pile, the final arrangement of the electricity is such that the middle is in the natural state, whilst the two halves are charged with different fluids, the thickness of these fluids increasing by unity as we pass from each couple to the next succeeding.

276. *The active pile.*—The poles of the insulated pile being inexhaustible sources of opposite electricities, it is evident that if each be placed in communication with a metallic wire, the wire will partake of the fluid of the pole with which it is in contact, and thus we shall have two conductors, the one positive, the other negative, which, being brought together, will occasion a continual recomposition. Betwixt the two wires there will be a spark, and others will follow in succession at small intervals; thus there is a perpetual current of fire: this pile is an inexhaustible battery, which is constantly being discharged. When the wires are placed in contact, and the circuit of the

pile is thus closed, the sparks disappear, but the electrical effects are nevertheless not destroyed. The fluids continue to develop themselves in every couple, between all the elements, and are recompounded at all points of the conducting wires, which join the two poles of the pile. Thus, while without every thing appears immoveable, within every thing is in activity and motion. One of the most striking proofs of this rapid circulation of electricity, is the phenomenon presented by a thin metallic thread, interposed between the conductors, so as to close the circuit: it will become suddenly heated, or even red hot, and if the metal be easily fusible it will fall in drops. The remarkable effects produced on water and other substances when placed betwixt the poles of this pile, so as to complete the circuit, are well known.

277. *The force of a pile.*—There are three things to be distinguished from each other in a pile—the force of production, the force of propagation, and the force of tension.

1°. The force of *production* depends on the electromotive force, that is, the energy with which the fluids are separated on the contact of the elements. We have already seen that all the metals do not take on contact equal electrical charges, or an equal thickness of electricity; thus two piles altogether similar, but constructed with different metals, cannot produce in the same time the same quantity of fluid. It fortunately happens, that two of the cheapest metals, namely, zinc and copper, are of all known substances those which acquire the strongest electrical charges on contact. Consequently, the piles constructed with these metals, other circumstances being similar, possess the greatest force of production.

2°. The force of *propagation* of the pile depends only on the nature and on the dimensions of the conductor which separates the couples; for the electricity cannot reach the poles previously to its being transmitted along the wire without first having traversed all the moist cloths, or all the intervals which exist between the couples: if it is retarded in this motion by the imperfect nature of the conductor, the pile gives at first a discharge, in consequence of the tension which it possesses at the two extremities, but after this first shock the propagation slackens; on the contrary, if the conductor is sufficiently good to offer a free passage to the fluid, which is incessantly developed between its elements, the propagation is rapid and always equal. In all these cases, the length of the circuit of the pile must be considered as a species of canal, along which the electric fluids move with greater or less velocity and ease, according as the conductors are more or less perfect: the wire which joins the poles only permits that quantity of fluid to pass in a given time, which has traversed the pile in the same time; whence it follows, that the force of propagation of the pile is in the inverse ratio of the thickness, and in the direct ratio of the breadth of the conductor of the pile; these being the laws which the conducting powers of bodies are found to follow. Water is a bad conductor; every pile, consequently, charged by pure water, has a small force of propagation. Hence saline or alkaline solutions are employed, and generally acid solutions; water containing $\frac{1}{16}$th of sulphuric or $\frac{1}{20}$th of nitric acid is the liquid generally employed; this liquid gives a sufficient passage to the electric fluids, and at the same time does not exert a chemical action of sufficient power to corrode too fast the elements of the pile.

3°. The force of *tension* changes with the nature of the elements of the pile, but is always proportional to their number, unless the conductors are bad. We have seen that the tension on the 2nd zinc is double that which it is on the 1st, that it is triple on the third, and so on; but if the electromotive force which is exerted on the contact of the zinc and the copper can accumulate on the zinc a tension of vitreous electricity double the tension which it would accumulate on any other metal, on iron for instance, it is evident, that for the same number of elements, the tension of a pile of zinc and copper would always be double the tension of a pile of iron and copper. It is thus that the tension depends on the nature of the elements. But it does not depend either on their magnitude or on the extent of the touching surface, as may easily be shewn by constructing two similar piles; that is, two piles of the same number of couples, with the same conductor, but with elements of different sizes; as, for instance, the surface of the plate being one and three inches square, then with a proof plane, or with a condenser, we may examine the electricity at their poles, and we shall find it of the same tension in both cases, whether the piles be insulated or not. Lastly, if two piles be constructed, whereof the elements of one are in contact throughout their whole extent, while those of the other touch only at small portions, the tensions will be the same, provided there be no defect in the conductors.

278. *Different kinds of pile.*—It would be foreign to our present purpose to describe the different forms and kinds of pile, or the infinite variety of modifications in the mode of bringing into operation the preceding principles, or of developing Voltaic electricity. The columnar pile, which we have just explained, though convenient for illustrating the principle of the construction of all piles, has great practical inconveniences. The lower cloths or cards, compressed by the weight of the upper elements, will dry quickly, and the running out of the liquid establishes a communication betwixt the couples, which diminishes the total effect. For these and various other points on which our limits will not permit us to enter, we must refer to other treatises, and that by Dr. Roget* will be exceedingly useful to the student.

The pile employed almost exclusively is the *trough pile;* the construction is well known, and we shall only say a few words upon the principle of its construction.

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* On Electricity, Galvanism, &c. forming part of the Library of Useful Knowledge.

The elements being rectangular, and soldered together, will thus form a couple: all the couples may be arranged similarly and parallel, in a wooden case, of which the inner surface is covered with some non-conducting substance, as mastic varnish. The space between two couples forms a trough into which the acid solution is poured; these thin strata of water supply the place of the moist cloths in the columnar pile; hence great care must be taken that these successive troughs do not communicate in any manner. Or the trough pile may consist of several cells, into which the acid solution is poured, and the elements are plunged, when the pile is to be put into activity. Several similar piles united together compose the Galvanic or Voltaic battery. The piles may be united in two ways; the piles consisting, for example, of one hundred couples, each three inches square; if two of these be united by making the two negative poles communicate at the same time, and also the two positive, there will be a battery of one hundred couples, each consisting of six square inches; the force of the surfaces of propagation will be doubled: if, on the contrary, they be united, the positive pole of the first communicating with the negative pole of the second, they will form a battery of two hundred couples, each couple being three inches square; in this case the tension will be doubled.

279. *Effects of the pile.*—The application of the Voltaic pile is the most powerful means of research with which we are acquainted; it has opened a completely new field to the modern chemist. The effects which are generally referred to may be distinguished into the three classes of physiological, chemical, and physical. With respect to the physiological effects, we may refer to the marvellous cures which are said to have been effected by currents of electricity—to the facts which are recorded of animals recently killed exhibiting many of the phenomena of life, so long as they are placed betwixt the poles of the pile. These convulsive movements cease, however, with the current. Similarly, animals stupified by breathing the fumes of charcoal

may be brought at once to life by placing them betwixt the poles of the pile. Among the chemical effects produced by the pile, the decomposition of water, of oxides, and the alkalies, are the most remarkable. The discovery, by Davy, in the year 1807, that the alkalies soda and potash could be decomposed by a very powerful Voltaic battery, was a grand step in the progress of science.

Among the physical effects of the pile, we may remark the production of heat, light, and magnetism. This last effect, and the mutual action which the currents exert on each other, constitutes the science of electro-magnetism, which we shall consider hereafter.

SECTION III.

MAGNETISM — NEUTRAL LINE — NATURE OF MAGNETISM — MAGNETIZATION OF METALS — OSCILLATIONS AND PERTURBATIONS — TERRESTRIAL MAGNETISM.

280. There exist in most countries of the world mineral substances possessing the property of attracting iron. These substances, whatever be their force or composition, are called natural magnets, or loadstones; for their structure has more a stony than a metallic appearance. Loadstones are naturally extremely feeble, that is, they exert on iron an attraction which is in some cases scarcely sensible; when placed in contact with fine iron filings, they may have scarce power enough to attract any; but their power may be concentrated, so that a mass of two or three cubic inches may be capable of sustaining masses of many pounds weight.

The different degrees of energy which exist in loadstones depend on some peculiar arrangement of their molecules. If the force were proportional to the mass, there would be instances of a most prodigious intensity, since whole mountains exist composed of the attracting substance.

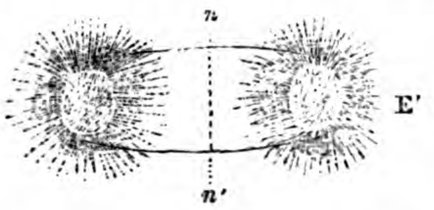
The attractive force which exists between iron and loadstone is seen at once on immersing one extremity of a piece of loadstone into iron filings or turnings; the particles of the iron will adhere to the surface, and to each other, so as to form films or rays of metal. This adherence of the particles to each other, and their peculiar arrangement, is a phenomenon deserving great attention, and one to which we shall return hereafter; at present we shall simply regard them as proofs of an attractive force. We may also present to a loadstone, according to the degree of energy which resides in it, masses of greater or less bulk; at a certain distance below it they will appear lighter, and being forcibly attracted will come into contact with the surface, and remain suspended from it; and an effort depending on the energy of the attraction must be made to detach the body. A small ball of iron being suspended by a delicate thread, and brought near a loadstone, we shall readily recognise the following characteristic qualities of the attractive force—1°, it is exerted at a distance; 2°, that it is exerted through the air, a vacuum, and all bodies, provided they be not of iron; 3°, it diminishes as the distance increases.

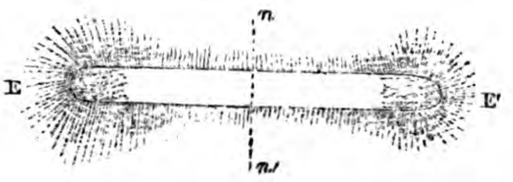
All attractions being reciprocal (Art. 33), it follows, that if the loadstone attracts the iron, the loadstone is itself attracted with the same energy, and according to the same laws. This principle may be verified experimentally by suspending the loadstone, and bringing pieces of iron to act upon it at different distances. This attractive force being distinct from all other natural forces, has received the distinct name of the *magnetic force,* from the word which the Greeks applied to the substance exhibiting the phenomena.

281. *Neutral line and poles.*—Iron seems to be related to a magnet much as heavy bodies are to the globe of our earth: the mass of the globe attracts bodies on all sides, and presses them to its surface: let us see whether the magnet possesses the same properties, and whether all its points exert a similar action on the particles of iron, attracting them to its centre. For this purpose we may employ an instrument called a magnetic pendulum, that is, a small ball or bar of iron suspended by a fine thread. If a magnet be held at the same distance from the pendulum, we shall immediately perceive that some points of its surface impress a great deviation on it, whilst others produce no effect; there are two opposite portions which shew a most energetic action, and in the intermediate space which separates these the effect is exceedingly small. The same conclusion is arrived at, whether we make use of a natural magnet of exceedingly irregular form, or of an artificial magnet (Art. 285) of the form of a cylinder, or an elongated prism. In this latter case we may see distinctly that the transverse sections near the middle produce no sensible effect on the pendulum, whilst the extreme parts act with great force. On the surface, then, of a magnet, and about its middle, may be traced a line, the points of which exert no attractive action; this line is called the *neutral line* of the magnet. The section through this line is the *neutral plane* of the magnet. This plane divides the magnet into two portions, each of which contains a *pole.* This term pole denotes that point in each portion at which the attraction is most powerful; or it may denote an ideal point situated in the interior of the magnet, just as the centre of gravity is conceived in the interior of bodies, or in the mass of the globe which attracts them; for the particles of iron are not acted on only by the part of the magnet to which they attach themselves, they are solicited by all the portion which

is on one side of the neutral line, and the resultant of all these attractions may be considered as applied at a certain point which is called the pole of this portion of the magnet. There can never be any difficulty in distinguishing the sense in which this word is employed; we shall in many cases employ the term *end* in preference to the preceding term pole, since it expresses all that is required, without involving any hypothesis, or requiring any explanation. There are, moreover, objections to the employment of the term pole as an imaginary point at which the forces are applied; since this point has none of that fixity which characterizes the point termed the centre of gravity; its position shifts continually with the position of the attracting bodies.

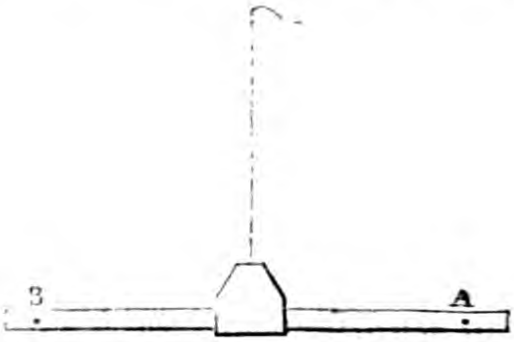
The statement which we have just made may be verified and illustrated by a very simple experiment. If a magnet be rolled in iron, the way in which the filings adhere will shew the nature of the forces. The accompanying figures, for instance, may be supposed to represent a natural and an artificial magnet; we have at the extremities, E and E′, large clusters of filings arranged perpendicularly to the surfaces; at the middle parts they become smaller and shorter, and at a line *n n′*, which may be called the mean or neutral line, none will adhere. The same effects will take place if a piece of card be laid on a magnet, and iron filings be sifted on the card; the filings will arrange themselves about the two ends or poles of the magnet.





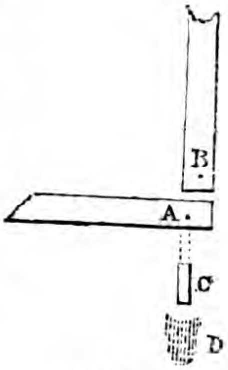
One remarkable phenomenon of magnetism is, that if we break a magnet into two or more pieces, every piece will have a neutral line and two poles. This division may be carried on as far as we please—each portion will be a complete magnet.

282. *Attraction and repulsion of poles.*—If a magnet be suspended horizontally by a fine thread, as represented in the figure, and to each of its ends we present successively



the same end of another magnet, one end will be attracted and the other repelled; the ends are said to have different names, because the action betwixt them and the same pole of a magnet presented to them is in different directions. If the two ends of the first magnet have different names, it is natural to suppose that those of the second magnet will similarly have different names, and that the same is the case with all other magnets. In fact, if the second magnet be turned, so that its other end acts on the suspended needle, we shall see that the effects are exactly contrary to the preceding; namely, A is repelled, and B attracted: the ends, then, of the free magnet which we hold in our hands have also different names, since the one attracts that which the other repels, and conversely. Every magnet presents the same phenomena. Those ends which act in the same manner, either on the end A or B of the suspended needle, have the *same name*. These ends being marked for the sake of distinction, if one magnet be suspended so that the others may rest upon it, we shall see that all the ends of the same name repel each other, whilst all the others of contrary names attract each other. We shall hereafter, (Art. 286), for the sake of distinction, and according to the suggestion of Mr. Christie, speak of the two ends of the magnet as the *marked end* and the *unmarked end;* the adoption of these terms will prevent confusion in the present state of science.

Thus, on each side of the neutral line, in the two halves of a magnet, there exist two forces, which at first seem identical because they act in the same manner on iron, and which are in reality two opposite forces, because they act in different directions on the magnet, the one attracting the point which the other repels. The neutral line is the limit of these two opposing forces; it is the passage from the one to the other; and hence arises the neutrality which is observed. These two forces tend incessantly to neutralize or to destroy; and if we could, for example, incorporate in a given magnet another of the same force and dimensions, so that the ends with different names should correspond, instead of two equal magnets we should have an inert mass entirely deprived of its magnetic qualities. The simple superposition is not sufficient to complete the destruction of effects, since the different parts of one of the magnets do not act at the same distance as the corresponding parts of the other; but nevertheless, there is in this case a sensible reduction in the intensity of the force, as may be shewn at once in the following manner.



A horizontal magnet sustains at its extremity, A, a mass of iron, C, whereof the weight is nearly as much as it can bear: an equal magnet is brought near it, the other end B being brought near A: when the distance is sufficiently small, the mass c becomes detached, and falls down; the system composed of the two magnets cannot carry near so much as either of them, because of the contrary action of the two ends, which neutralizes the effects. If some iron filings be presented, so as to form a cluster D, these will immediately be detached on the application of the second magnet.

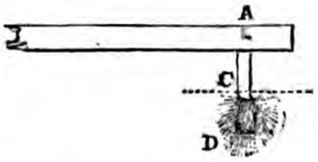
It is almost unnecessary to add, that if the end of the same name of the second magnet corresponds with the end of the same name in the first, the mass c will not fall down, but we may augment it, and almost double it, without its falling; since those of the same name produce conspiring actions, the total effect is, with some modifications, the sum of the particular effects.

283. *Magnetic action may be attributed to a fluid.*—In attempting to ascend to the origin of the forces which produce the phenomena of magnetism, we readily recognise that they are not like gravity, some property inherent in ponderable matter. Chemical analysis shews that natural magnets are oxides of iron, or mixtures containing different proportions of oxide of iron; the oxigen and the iron are the only ponderable elements which enter into the composition of these remarkable substances. But neither of these substances has the property of exerting actions similar to the magnetic, and it is hardly conceivable that their molecules take by combination essential properties which they did not possess before their combination; for it does not appear that the form or arrangement and disposition of the molecules of ponderable matter give rise to new forces, which are exerted at sensible distances. On the other hand, the forces inherent in ponderable matter may be augmented, diminished, or modified in a thousand ways, but they can never be destroyed or disappear; whereas in magnets the magnetic forces appear to be, as it were, accidental. If a magnet be heated to a red heat, it loses none of its material elements, yet all its magnetic properties vanish. On being cooled, it is, so far as its matter is concerned, exactly what it was before; but so far as its magnetism is concerned, it is absolutely nothing, for it no longer exerts any action on iron. And what is more, we may restore its magnetic properties without adding or subtracting any ponderable matter. For these and similar reasons we are, on viewing the whole class of phenomena, led to consider magnetism as due to a peculiar fluid diffused through the heavy particles of the oxide of iron which constitutes the magnet. And since we have distinguished two magnetic forces opposed to each other, we are led to the hypothesis of two fluids of contrary character, whereof one predominates

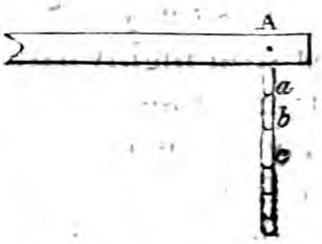
in each end of the magnet. In all magnets the same ends have the same predominant fluid; and since they repel each other, we must conclude that each fluid repels itself: the different ends have different fluids, and, since they attract each other, we must conclude that each fluid attracts the other fluid. Thus we are conducted to the hypothesis, that there are two distinct magnetic fluids, each repelling itself and attracting the other.

On this remarkable hypothesis we may remark, that it is to be viewed as a possible explanation of the phenomena; the phenomena are such as may be conceived to result from such a cause; but we are far from asserting such to be the true cause, though at the same time we feel, that of the hypotheses which at present exist, this is the only one which can be admitted. Before the hypothesis can be considered as fully established, the known results must be unfolded by mathematical analysis, with great accuracy, and others must be predicted, of which we are at present in ignorance (Art. 3). Something has already been effected in this way; we do see distinct reasons and theoretical explanation of some phenomena; but the mathematical analysis is of a character to be grappled with by none but minds of the most superior order.

284. *Iron rendered magnetic.* — The influence of the natural magnet or loadstone will attribute similar properties to iron, as may be shewn by the simplest experiments. If to the lower extremity of an iron cylinder, sustained by magnetic attraction, we present some iron filings, they will form a cluster D, which will remain attached as long as the iron is suspended from the magnet; but if it be detached, the filings immediately fall, and the attractive force is no longer exerted. It is not the attractive force of the magnet which acts in this case at a distance on the iron filings, and retains them; for if the attached cylinder be not of iron, the phenomenon cannot be produced; and the following facts shew the cor-



rectness of this conclusion:—1°, the fillets of filings diminish in length as we recede from the extremity of the cylinder; 2°, there is a point in the upper part where they cannot attach themselves, and which is the situation of the neutral line; 3°, beyond this point they attach themselves, but in a contrary direction. Thus the small cylinder is most truly a magnet, for it attracts iron filings, has a neutral line and two ends or poles; the only exception being that the neutral line does not occupy the middle.



But we may attach a series of cylinders as represented at *a*, *b*, *c*, &c. and so form a sort of chain; if the first link of this chain be removed, the whole breaks up.

Thus we must conclude that iron, as well as the natural magnet, contains the two fluids; but the two fluids are here combined, that is, neutralized by each other. Hence we see why iron does not act magnetically on iron, for that which is attracted by one of the fluids is repelled by the other with a force equal and opposite, so that the resultant action is nothing. But when, on the contrary, it is subject to the action of a natural magnet, these two fluids are decomposed; the one is attracted and the other repelled; a separation is effected betwixt them; the former flows towards the magnet, the latter flows to the opposite end of the mass of iron, and there, becoming predominant, attracts the filings which are presented to it. We are then led to consider the natural state of iron as nothing else than a state of combination of the two fluids, the one neutralizing the other; and the magnetic state, as resulting from the more or less complete separation of the two fluids by the attraction and repulsion which they experience from the magnet. The phenomenon, however, of the decomposition of the fluids may be produced in several ways, and the question arises, whether the fluids really experience a motion of translation by which they pass from one extremity to the other of the mass, or whether they experience only a molecular displacement; many facts seem to shew that there is no motion of translation; but on this subject we cannot now enter.

285. *Magnetization of Steel.*—The filings of steel are attracted by a magnet as well as those of iron; they attach themselves to magnets in small fillets or loops of sensible length. Very fine steel wire is preferable to iron wire of the same dimensions, but it receives the magnetic action more slowly. Small pieces of steel, and especially pieces of steel highly hardened, present properties entirely distinct from those of iron, for they appear at first not to receive any influence from the action of magnets. If we attempt to form by small cylinders of hardened steel a chain, such as described in the last article, the first cylinder will not attach itself, and the experiment which succeeds so easily with iron will in this case fail. Since, however, small particles of steel can be attracted, we cannot suppose that the magnetic sensibility is destroyed by employing larger masses, but rather that some precautions only are requisite to render apparent what we expect to take place. If the steel be kept in contact with the magnet during a quarter of an hour, or for a longer period, this substance which at first seemed insensible to magnetism becomes magnetic; in time it acquires magnetism, and at last is as powerfully attracted as iron. The time which appears requisite to develop this force may be supplied by other means, namely, by the method of touching, as it is termed, that is, by exerting friction for several times in the same direction, and along the whole length of the mass of steel; either by passing the steel along the magnet, or the magnet along the steel. If, for example, the small cylinders of which we have just spoken, and which the magnet has never touched, be treated in this manner, they will, after the friction has been repeated several times, attach themselves to the surface and to one another, and form a magnetic chain, like the small cylinders of iron. In order thus that tem-

pered steel may become magnetic, we must employ either prolonged contact with a magnet or friction frequently repeated. Another characteristic quality of steel with respect to magnetism is, that after these operations steel *always* preserves its acquired magnetism. This is at once proved by rolling in filings steel which has been *touched* by the magnet; it will be seen at once to possess a neutral line, and two ends or poles; or, in a word, all the properties of natural magnets; if it be again tried after a day, a month, or a year, it will appear to have lost none of its force. Lastly, if the ends of these artificial magnets be brought near so as to act on each other, those of the same name will repel each other, whilst those of different names will attract each other, just as the ends of natural magnets.

From the former characteristic of comparative slowness with which steel yields to the action of magnets, we may conclude, that there exists in the substance some force, or rather some sort of resistance, which opposes the immediate separation of the magnetic fluids, and this force is called the *coercive force*. From the faculty which it has of preserving its acquired magnetism, we may conclude, that there exists also a force, or some resistance, opposing the reunion of the two fluids; for the contrary fluids attract, and tend incessantly to be recompounded or to neutralize each other; and if there were no opposing force, these two fluids would be actually recomposed, and the steel would return to its natural state, until the fluids are again separated by the magnet exerting its decomposing action upon it. This resistance to the recomposition may also be called the coercive force, the same term as we applied to the resistance to separation. From this we may infer, that if the magnetic fluids experience in certain substances some resistance or some friction, or, in general terms, some obstacle to their separation, they must encounter the same obstacles on returning to each other, so as to resume their natural state.

286. *Magnetic action of the Earth.*—A magnetic needle suspended horizontally by a silk thread, or on a pivot, is not in equilibrium in all positions, as a needle not magnetized would be; it takes a determinate direction towards some point in the horizon, and if displaced, returns after a number of oscillations to that position. The force which draws it back is due to its magnetization, for an unmagnetized needle experiences no similar action. At first we might suppose that this phenomenon is but a local one, depending perhaps on some masses of iron or natural magnets situated near it; for a common sewing needle, or the end of a piece of iron wire, is sufficient to attract the magnetic needle out of one position, and to keep it in some other position; and there is nothing to prevent powerful masses acting at a distance from soliciting and directing it towards one particular side. But the same phenomenon is recognised every where. Travellers have carried a magnetic needle into all the countries of the world, and there is no known place at which it does not assume a fixed direction, and return invariably to the same position when drawn from it. In the polar, as well as in the equatorial regions, at the tops of the highest mountains, and at the bottoms of the deepest ravines and mines, the magnetic needle always presents the same phenomenon. There exists then a magnetic force of which the effects are sensible at all points of the terrestrial globe; for a directive action is necessarily relative as well as all actions at a distance; and a body can no more take of itself a determinate direction than it can move itself. In both cases there is some external force to which it is subject.

The simplest experiments will serve to shew that this force has the essential character of a force emanating from a magnet, and not of a force emanating from a mass of iron; for if the poles of the needle be reversed by turning it half round, or through 180°, it does not rest in equilibrium in this new position; it wheels about, and describes on one side or the other the whole semi-circumference by which it was removed from its primitive position. This directive force then acts in opposite directions on the two ends, and, similar to the force which resides in a magnet, it acts by attraction on one, and by repulsion on the other, whereas iron attracts both with the same energy.

Where now is the centre of the magnetic action so universally diffused throughout the globe? The solution of this question has ever formed a great subject of discussion. Some, like Cardan, have placed it in a small star which forms the tail of the bear; others in the pole of the zodiac; and some others, finding perhaps the heaven too narrow for them, imagine beyond the heavens and the stars an attractive centre, whence arises the force giving direction to magnets. But Gilbert, the father of the sciences of magnetism and electricity, put an end to these vain hypotheses, by demonstrating, as clearly as could at that period be done, that the globe of the earth is magnetic, and that it is its action which directs the magnetic needle.

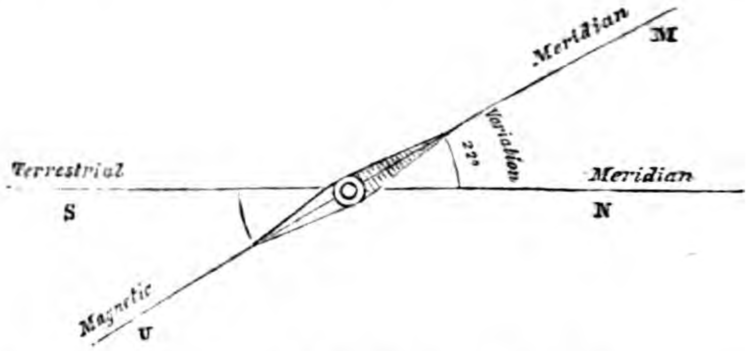
A discussion of the observations made in different climates will lead us to view the earth as a vast magnet, having its neutral line near the equator, and its *ends* on either side towards the poles of rotation. Also the phenomena appear to indicate that the poles considered as centres of force are near the centre of the earth; at all events at some considerable depth below the surface. Thus, with respect to mangetism, the earth has two distinct regions, a north and a south; but these do not accurately coincide with the astronomical northern and southern hemispheres; because the neutral line which separates these does not coincide with the equator. We may, however, characterize and define these two fluids by saying, that the northern fluid predominates in the northern region of the earth, and the southern fluid in the southern; and since the fluids of contrary names attract each other, it is the south pole of the needle which is directed towards the north pole of the earth, and the north pole of the needle which is directed towards the south pole of the earth.

These statements are evidently in danger of introducing confusion; hence the terms boreal and austral fluid have been introduced; the former being that which is supposed to prevail in the northern hemisphere, and the latter that which is supposed to prevail in the southern; and that end of the needle which points to the north pole of the earth is called the *marked end*. Thus we may avoid speaking of the north and south ends or poles of needles.

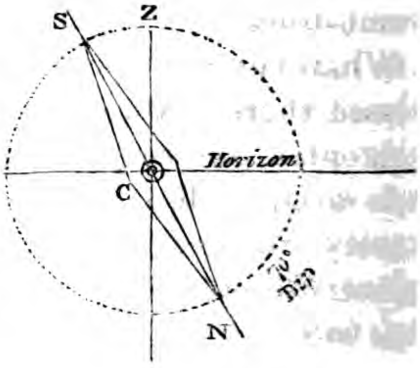
Needles situated at the same place on the earth's surface, but sufficiently distant to prevent their mutual actions, take directions which are sensibly parallel; but needles at places removed from each other by several degrees of latitude and longitude, are not parallel to each other; we must consequently possess some means of defining the direction of the magnetized needle, that is, we must have the power of referring it to lines of known and invariable position, that we may be able to determine, 1°. what changes this direction undergoes with time; 2°. what relations exist between the directions observed at different places. For this purpose the following definitions of terms have been adopted.

287. *Terms defined.* — The *plane of the magnetic meridian* is the plane which passes through the centre of the earth, and the direction of the horizontal needle; this plane will cut the heavens and the earth in a certain line, which is the trace of this plane, or the magnetic meridian. The terrestrial or astronomical meridian of a place is the plane which passes through the place and the axis of the earth, and the meridian line, or simply the meridian, is the trace of this plane on the surface of the earth. The magnetic meridian and the terrestrial meridian lie in two vertical planes, since the planes of both pass through the centre of the earth, or rather through the vertical of the place which we are considering; but these two planes may be inclined to each other at an angle of greater or less magnitude.

The *variation* of the needle at any place is the angle which the magnetic makes with the terrestrial meridian of any place; or, which is the same thing, it is the angle which the direction of the needle makes with the meridian. This is sometimes called the magnetic declination. The variation is said to be east when the *marked end* of the needle passes to the east side of the meridian, and west when to the west. Suppose, for example, that S N is the meridian of Greenwich,* and U M the direction of the horizontal needle at the same place; the variation is west, being now† about 24°, for we shall see that it changes gradually. There are some places on the earth at which the magnetic meridian coincides exactly with the meridian; at these places the variation is nothing, and the assemblage of successive points at which this phenomenon takes place constitute the line of no variation. We shall see hereafter that there are, betwixt the two poles, at least two lines of no variation, traversing the sea and land in a sinuous and irregular course.



The *dip* is the angle which a needle, having free motion in the vertical plane of the magnetic meridian about its centre of gravity, makes with the horizon. Let N C S be a needle moveable about its centre C, and able to describe



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* The situation of the Royal Observatory.

† 1837.

a circumference in the vertical circle S Z N, that is, in the plane of the magnetic meridian the angle M C H is the *dip*. At Greenwich the dip is now about 70°, the marked end being below the horizon. The needle makes four angles with the horizon which are equal, two and two; but it is convenient to take the least of the two angles which its lower end forms; so that the dip is always less than 90°.

As we advance towards the north pole the dip increases regularly with the latitude, and the voyagers who, in the midst of ice, have penetrated nearly to the north pole, found dips very near 90°; that is, the needle rests nearly in a vertical position. There are then in these parts points at which the needle will coincide exactly with the plumb-line; no observer has ascertained the position of these places of verticity, above the magnetic poles of the earth, but it appears probable that there is more than one such pole, and that besides the principal poles considered as centres of force, there must be others depending on local causes. If now we advance in the other direction, or towards the equator, the dip continually diminishes, and near this line we find that the needle is horizontal. Passing beyond this line into the southern hemisphere, the dip has again a sensible value; but now the marked end of the needle is above the horizon, and rises more and more as the latitude increases. There are then towards the south pole of the earth other points at which the needle will rest vertically, its direction coinciding with that of the plumb-line.

Whatever may be the meridian at which the equator is crossed there is always some point at which the needle is horizontal, and the series of points where there is no dip form a curve termed the magnetic equator. This curve is very regular at some points of its course; and the tracing these lines on the earth's surface is a most interesting problem.

288. *Points of application of the magnetic force of the*

earth.—Since the earth acts in the same manner as a natural magnet, it is certain that it attracts one pole and repels the other; for it is a general law of magnetism, that if a force does not act indifferently on the two poles, as in the case of soft iron, it acts always on one by attraction and on the other by repulsion. But without knowing any thing respecting this magnetic force, it is sufficient to remark, that it is a universal force acting at all parts of the globe, so that we may conclude that its centre of action is at an infinite distance when compared with the needles or magnets which serve for our experiments, and that consequently this direction may be considered as parallel to itself throughout the whole extent of the body. By the action which is exerted on all the molecules of the fluid which are on one side of the neutral line of a magnet, there is compounded a system of parallel forces; and by the action on all the particles on the other side of the neutral line, there is compounded another system of forces parallel to themselves and to the former. These two systems, the one attractive and the other repulsive, have each a single resultant, the determination of the intensity and point of application of which is a simple proposition in mechanics, and is as follows.

1°. Each resultant being parallel to its component forces, there will be two resultants parallel to each other; thus the whole magnetic action of the earth is reduced to a system of two opposite parallel forces. 2°. Each resultant being equal to the sum of its components, the two resultants will be always equal in intensity, provided the quantity of the two fluids is the same. But since the development of magnetism may be considered only as the separation of these fluids, each remaining enclosed in the substance of the magnet and unable to quit it, the preceding condition will always be fulfilled, and the resultant forces of the two fluids will always be equal. These two resultants being opposite, parallel, and equal, constitute a couple, the intensity whereof depends on the energy of the magnet and of the magnetic force of the earth (Art. 22).

This fundamental fact, that a needle experiences from the earth a repulsion and an attraction which are always equal, the result of which is, consequently, always directive, and not attractive or repulsive, may be confirmed by the most simple experiments. If a needle be weighed before being magnetized, and after having received all the magnetic power which can possibly be communicated to it, there will be no difference in the weight; hence the terrestrial action adds no vertical resultant to the forces, for such a resultant would produce an augmentation of weight if it acted from above downwards, or a diminution if it acted from below upwards. Again, if a magnetized needle be attached to a small piece of cork which floats on the surface of water, the cork will present no sensible resistance to the motion; hence, if there were any horizontal resultant, it would constantly draw the cork and needle to the same side until it met some obstacle; but no such motion is observed, the needle takes a definite direction, and, when once directed, it rests in the middle of the surface, without having the least tendency to move to one side or to the other.

3°. The points of application of these magnetic resultants of the earth, or of the terrestrial couple in a magnet, cannot be determined unless we know the distribution of magnetism on each side of the neutral line. The needles used are generally symmetrical with respect to a longitudinal axis, and a transverse plane at right angles to this axis; being generally cylindrical, prismatical, or of the form of a very elongated lozenge, or some similar figure; and when the magnetization is regular, the neutral line divides it into two equal parts, and in each half the opposite fluids are distributed in exactly the same manner. The points of application of the resultants of the terrestrial magnetism will be on the axis of the figure, and at the same distance from the centre or extremities of the needle;

that is, they are symmetrically placed with respect to the neutral line. Thus much we know respecting their relative positions; but their absolute position cannot at present be determined; it will be seen that the magnetic intensity increases as we recede from the neutral line, and the point of application of each resultant is nearer to the extremities than to the middle. These two points of the application of the resultants of the terrestrial magnetism are sometimes called the *two poles* of the needle; and in this sense the poles are considered with respect to magnetism what the centre of gravity is with respect to gravity. The line which joins these poles is called the axis of the needle. On the supposition which we have just made of perfect and regular magnetization, the magnetic axis will coincide with the axis of the figure; but there are always some practical errors which disturb these mathematical conditions, and since the direction of a magnet or of a needle is the direction of its magnetic axis, this must not be considered as coincident with the axis of the figure.

289. *Diurnal Oscillations.* — The needle experiences daily certain motions either to the east or to the west of the magnetic meridian; sometimes these motions are sudden and accidental, at other regular and periodic; the former are called perturbations, the latter diurnal oscillations. On days not distinguished by any perturbations, the following phenomena may generally be observed; the needle is nearly stationary during the night, it begins to move at sunrise, its marked end going towards the east, the maximum east being attained about nine o'clock. The oscillation is then westerly, the maximum west being about half-past one.

Then, by a contrary motion, it returns towards the east till about nine, after which time a second maximum west is attained. Starting from a position nearly coinciding with that of the preceding day, it performs, during the next day, a similar oscillation. The amplitude of the diurnal oscillation is the angle which the needle traverses from its morning position to its next western position after midday. This angle is variable most days, but from a great multitude of observations it appears to be greatest during summer, from the spring to the autumnal equinox, and least during the winter, from the autumnal to the spring equinox. Its value during the months of April, May, June, July, August, and September, is about 13′ or 15′, and only about 8′ or 10′ during the other months. On some days it is as much as 25′, on others not more than 5′ or 6′.

In the northern regions, as Denmark, Iceland, and parts of America, the diurnal oscillations are generally more considerable and less regular; the needle does not preserve the same stationary position during the night as in these latitudes, nor does it attain its maximum variation east or west at the same hours. In going from the north towards the magnetic equator the amplitude of the diurnal oscillations continually decreases, and at the magnetic equator it is nothing. It appears, however, that this depends on the position of the sun to the north or to the south of the terrestrial equator. South of the magnetic equator the oscillations take place in the contrary order, the marked end of the needle turns towards the east at the hours at which it would turn to the west in the northern hemisphere.

290. *Perturbations of the Magnetic Needle.*—Several natural causes act on the magnetized needle, either deranging it suddenly from its position or disturbing the regularity of the diurnal oscillation. Among these causes the aurora borealis appears the most certain and infallible; when this meteor expands itself from the northern regions, the whole heaven is lighted up, and while it lasts, which is frequently for several hours, the needle undergoes a continual agitation and a considerable deviation. The summit of the bright arch generally coincides with the magnetic meridian, and its crown, that is, the focus to which the streaks of flame which seem to start from the horizon or the arch itself tend, is always very near the prolongation of

the dipping needle. But not only is the needle agitated at or near the places where the aurora is visible, but it extends to great distances and places at which no aurora is visible. In general, however, the perturbations are greater the nearer the phenomenon; but there are instances in which a sudden perturbation, amounting to 1°, has taken place in London, without any apparent cause; and it was afterwards discovered that a similar perturbation took place at the same time at Paris and Petersburg, there being a most brilliant aurora visible in northern places. Thus an observer in his study is apprised by the needle of what is passing in the regions of the north, just as he is by the barometer of what is going on in the upper strata of the atmosphere.

Earthquakes and volcanic eruptions act also on the needle, and these phenomena sometimes permanently derange it. It seems probable that lightning produces similar effects; by it magnetism is frequently changed, destroyed, or exactly reversed; many lamentable instances of this kind have occurred in vessels; some part of the ship being struck, the compass has been reversed, and the navigators mistaking the south for the north, have run upon rocks or shoals, and been shipwrecked. We shall return to the preceding subject in speaking of the phenomena of electro-magnetism.

291. *Magnetic Intensity of the Earth.*—One of the most important points in the theory of terrestrial magnetism, is the determination of its intensity at different parts of the earth, or at the same place at different periods. It is only recently that the methods employed have been capable of leading to accurate results; and the method now universally adopted is to observe the number of oscillations made by a needle moved slightly from its position of rest, and left to itself. If regularly magnetized, and its axis of suspension pass through its centre of gravity, it will oscillate by the action of the magnetic couple of the earth, just as each of its ends would oscillate separately when solicited by

one of the forces of the couple. Thus we have a true compound pendulum, which remains perfectly identical, the distribution of magnetism remaining exactly the same at all points of the substance; for if the fluid experienced any change either in quantity or in arrangement, the resultant would have a different intensity and a different point of application, and the same needle would in reality constitute a different pendulum. Suppose, however, that a needle remains both magnetically and materially the same, any difference in the duration of its oscillations will depend only on some difference in the intensity of the forces which solicit it; and gravity remaining the same, this difference can only depend on a difference in the intensity of the magnetic force. But under these conditions, the intensity of the force and the duration of the oscillations are connected by the law, 'that the forces are as the square of the number of oscillations performed in a given time.' Now the number of oscillations can be readily observed; hence this method can be applied by making a needle oscillate either in the plane of the magnetic meridian, about the line of dip, or perpendicularly to the magnetic meridian, about the line of variation.

The result of these observations with the compass and dipping needle made in different parts of Europe and America, in the islands of the Indian and Pacific Ocean, is, that the intensity is least at the magnetic equator, and increases gradually towards each pole. The law which this increase appears to follow would give the intensity at the poles one-half greater than at the equator.

292. *Action of the earth on soft iron.*—The earth exerts a perpetual action on all substances which contain magnetism; it acts as a vast magnet, which is incessantly endeavouring to decompose the natural state of the fluid, or incessantly attracting and repelling the separated fluids. The different magnetic bodies which exist on the surface of the earth resist more or less this universal power, according to the intensity of their coercive force; but all bodies ex-

perience some modification from it. Soft iron is, under this point of view, the substance most worthy of attentive examination, because it offers no resistance to the separation of the fluids, and does not preserve any of the magnetic actions to which it has been subjected. The following experiments will serve to give us some idea of the phenomena which occur.

A bar of soft iron two or three feet in length is brought near a small needle. When the bar is held vertically, or nearly in the direction of the dip, it acquires the properties of the marked end, that is, of the end which will point to the north pole of the earth at its lower extremity, and of the unmarked end at its other extremity. This is seen at once by the attractive and repulsive actions which are exerted on one or other end of the needle, as the bar is moved vertically, so as to bring all its parts successively opposite the needle. To be convinced that the soft iron is without coercive force, and that its magnetism is decomposed by the terrestrial action, we need only turn the bar suddenly upside down, so that its extremity, which before was uppermost, should now be lowest; the lower end will still have the properties of the marked end, and the upper of the unmarked end. Thus the fluids have been instantaneously recompounded by their mutual action, and decomposed by the terrestrial action.

All magnetic bodies become real magnets by the influence of the terrestrial magnetism, but their poles are moveable, and perpetually changing; thus the poles are reversed by turning them upside down, and for every slight change in their position the poles in the interior of their substance experience corresponding displacements. This result shews us that great care is requisite in making experiments; for the iron which is employed in the construction of buildings acts in two ways on magnetized needles; it acts by the magnetic decomposition which it experiences from the needle itself, and principally by the free fluid which the earth keeps in a state of permanent separation. The local perturbations due to this cause may with care be discovered, for in a space of some extent, as a mile square, the difference in the terrestrial action will be exceedingly small.

293. *Causes influencing the coercive force.*—When a bar of soft iron is submitted to the magnetic action of the earth, it is sufficient to give it one or two strokes with a hammer at either of its extremities, to fix partially one of the two separated fluids by which it acts on the needle. After the percussion it is a magnet with fixed properties, and in whatever direction it is turned, the same fluid always shews itself at the same extremity. Thus coercive force is given to soft iron by percussion; this force is undoubtedly local, and exists only in the molecules which have received the blow; for the bar being turned, and struck in this inverted position, becomes magnetized in the opposite direction. The pole may thus be reversed as often as we please, and it is peculiarly deserving of remark, that though the coercive force will disappear after some hours or days, it may be reproduced by fresh strokes.

The preceding curious fact furnishes a key to several phenomena. It is well known that all magnetic substances are in a state of magnetization of greater or less degree. For instance, as early as 1590 it was remarked, that an iron bar fixed in the brick-work of a steeple was magnetic, and in 1630 a cross, completely rust-eaten, was powerfully magnetic at its lower end. Since these periods similar phenomena have been frequently observed, and it is found that a piece of rusty iron is almost always a magnet of greater or less power: the same is true of cast-iron, steel, and other magnetic substances. But oxidation is not necessary for the magnetization of a substance; this may be effected by some mechanical action, as twisting, beating, filing, or any similar process: the tools of a locksmith's shop, for example, are nearly always magnets, and sharp instruments kept generally in the same position generally present traces of polar magnetism. In all these cases it is neither the chemical nor the mechanical action which magnetizes the bodies; but the incessant action of the earth, which decomposes the fluids; and the decomposition once made is maintained by the coercive force resulting from the chemical and mechanical displacements of the molecules of the bodies. A strong confirmation of the preceding remarks is derived from a comparison of the quantity of magnetism which bodies receive in different positions, with respect to the direction of the force of the earth. In a vertical position they become powerfully magnetic by oxidation or mechanical action, and the marked end is always downwards. In more oblique positions the effect is less, but the same law may still be detected. Thus we may manufacture various kinds of magnets either with iron wire, or bars of iron and steel.

Natural magnets being an oxide of iron, may in some measure owe their magnetic properties to the action of the earth exerted upon them at the moment of their formation. For the mines of iron which exist in our day are not as old as the world; and without admitting that at its origin iron was in a pure and metallic state, it is certain that the combinations in which it is engaged at the surface of the earth, and in that part of the crust which we can explore, were not always what they are at present. The chemical actions which have been going on incessantly for centuries of ages, cause the most inactive molecules to pass through innumerable combinations, and change in ten thousand ways their primitive aggregations. The magnetic masses, like all ponderable elements, are subject to perpetual mutations, and we may say that at every instant some are being decomposed, others are being formed, and having their poles arranged according to the laws of the general magnetic action of the earth. These are probably the causes which first develop the magnetism of natural magnets, whether of those possessed by the Chinese three thousand years ago, or of those observed by Pythagoras and Plato, or of those which we employ at the present day. Magnetism already developed is the great agent in the development of magnetism, but the discoveries of Œrsted shew us that electricity also can develop magnetism.

294. *Iron of vessels.*—Large masses of iron are employed in the construction and equipping of vessels; some as permanent parts, others being moveable, as the cannons, anchors, cables, and tools. All these bodies are magnetic, and being situated at different parts of the vessel exert a considerable action on the needle. The deviations produced by this cause may sometimes amount to fifteen or twenty degrees, and two or three degrees would be quite sufficient to expose navigators to the greatest risk and danger. It appears that Wales, a companion of Cook the circumnavigator, was the first to point out this source of error in observations at sea. Since that period the attention of the officers of the navy has been constantly directed to this phenomenon, and many observations have been made at Woolwich by Barlow and Christie for the purpose of determining and correcting the errors which must arise from this source. The needle in a vessel may be made to deviate by any of the following causes:—

1°. By the decomposition which itself creates in magnetic substances.

2°. By the permanent magnetic state which these substances have in virtue of their coercive force.

3°. By the transient magnetic state which they acquire from the magnetism of the earth.

The first of these causes can produce only very small effects, which may be effectually guarded against by placing the needle at a sufficient distance from all masses of iron.

The second cause may also be guarded against; for the magnetized needle being situated from the different magnetic poles of the vessel at distances which bear a considerable ratio to the length of the needle, each of these centres will act upon the needle by a couple. By the composition of all these partial couples there will be a resultant couple, remaining the same in all climates and in all positions of the vessel. This couple will be compounded with the terrestrial couple, and hence the deviation in the needle is produced. But at the same place where the vessel turns about a vertical axis, the terrestrial couple will always preserve the same direction in space, and the couple of the vessel turning with it, there will result a variable deviation susceptible of one maximum to the right of the magnetic meridian, and of another to the left; and these maxima will be such that the mean of these two positions of the needle will give its true position.

The third cause is most powerful, and its effects, incessantly variable, are most difficult to appreciate and correct. Let us, for instance, suppose that the only action is to cause a deviation in the needle. Now it is clear that every magnetic body in the vessel becomes a magnet with shifting poles; when the vessel turns to one side or the other, these present themselves in a different manner to the action of the earth, and experience different decompositions. These phenomena, so complicated at the same place, become much more so when the vessel passes to different countries where the terrestrial couple changes both in direction and in intensity.*

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* See *Nautical Magazine*, April, 1837.

SECTION IV.

ELECTRO-MAGNETISM—ITS DISCOVERY—CHARACTER OF THE FORCES—THEORY OF CURRENTS—MULTIPLIER—MAGNETIZATION—ROTATION OF A NEEDLE—THERMO-ELECTRICITY.

295. Prior to the great discovery of Œrsted, which firmly established this new branch of science, there had existed generally in the mind of philosophers a strong conviction of the identity of the electric and magnetic fluids. The analogies between the phenomena of electricity and magnetism, as they had been long observed, were so extensive and remarkable, that no one could help conceiving the notion of the agencies to which they were owing being connected by some close and intimate relation. Several of the phenomena which led to this conclusion have already been noticed, but till Œrsted's discovery, there were many anomalous appearances which bid defiance to the general theory, that the principles of electricity and magnetism are merely modifications of each other, and that both may be regarded as ultimately identical in their nature, and arising from a single instead of two separate powers. The evidence on which this conclusion is founded will be best seen in the details which will be offered respecting the phenomena.

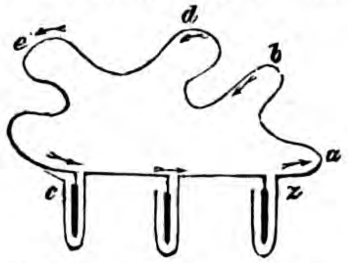
296. *Discovery of Electro-Magnetism.* — The fundamental phenomena on which this branch of physical science must be considered as resting, were observed by Œrsted in 1820. Guided by profound views on the identity of the electrical and chemical forces, this distinguished philosopher succeeded in making electricity act as magnetism in a sure and permanent manner. Hitherto the results had been

most uncertain and indefinite. Some experimenters asserted that an electric discharge imparts a southern polarity, that is, the properties of the marked end of a magnetic needle, to that part of a steel bar at which it enters, and a northern polarity to that at which it leaves the bar; others conceived that they had observed an invariable connexion between the negative electricity and the southern polarity; while other very laborious experiments seemed only more deeply to embarrass the results. But the mode of action having been once discovered and defined with precision by Œrsted, the fundamental phenomena were reproduced without any discrepancies.

The only condition for the action of the electric fluids on a magnetic needle is, that they must be in motion. If a metallic conducting thread be traversed by the electric currents of the Voltaic pile, and a magnetic needle, delicately suspended, be brought near to this conductor, the needle will be disturbed, and make oscillations. This was the first discovery of Œrsted. The existence of an action so powerful on a needle at the distance of several feet, could not fail to create astonishment.

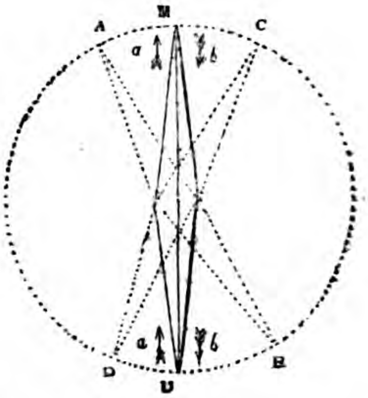
The force by which these oscillatory motions are produced in the needle is called the *electro-magnetic force*. It is evidently some force very distinct from mere attraction or repulsion, and diminishes as the distance between the current and the needle increases; and is exerted on all sides and through all interposed substances, except those which are magnetic. It is, moreover, an active force exerting itself not only on the free magnetism of the needle, but also on combined magnetism, so as to effect a decomposition whenever it can overcome the coercive force. If iron filings are brought into contact with the conductor traversed by the electric fluids, they arrange themselves round it, not only adhering to its surface as a common magnet, but forming transverse layers, or species of rings, which envelop it. The thickness of the layer of filings depends on the intensity of the pile, and when the action of the electric fluid is checked, they instantly detach themselves, and fall down. Thus the electro-magnetic force exerts itself on soft iron, and decomposes the natural magnetism; it also exerts itself on steel, and has great influence in overcoming the most powerful coercive forces.

297. *Definitions.* — Before proceeding to give any account of the experiments, it may be well to make some suppositions which will serve to characterize the phenomena in a convenient and precise manner. For this purpose we shall suppose the current to possess a determinate direction, and define its direction by saying, that it always goes from the positive pole to the negative pole, passing along the conductor which joins the poles. Thus, when the communications are established, and the circuit is complete, we shall say, speaking of the arc *z a*, which touches the positive pole, that the current traverses it passing from *z* to *a*; similarly, that *a b* is traversed from *a* to *b*, *b d* from *b* to *d*, and so on, as indicated by the arrows; and lastly, *c z* from *c* to *z*; and the circuit being complete, we shall always say that the current passes from *c* to *z* in passing through the pile, and from *z* to *c* in passing through the conductor. The current, also, is frequently designated by the form and dimensions of the conductor which it traverses; when it passes by a rectilinear conductor, it is called a rectilinear current; when by a hollow cylinder, a cylindrical current; thus also we shall speak of a curvilinear, a circular, and an indefinite current; and when the conductor returns to itself, and forms a complete circuit, it is called a closed current. None of these expressions, however, must be interpreted literally; when it is said that there is a current along the conductor which joins the two poles, it must not be understood that there is a motion of translation along the conductor; that the vitreous or positive fluid travels from the positive to the negative pole, and that there is a



corresponding motion of the resinous or negative fluid in the opposite direction; for it is probable, on the contrary, according to the present theoretical views entertained on this subject, that a recomposition of the electricities takes place about all the ponderable molecules of the bodies, and in all the spaces which separate them. Thus the current is said to have a direction from the positive to the negative pole; it is not meant that the fluids move solely along the axis of the conducting line without experiencing any deviations, lateral or oblique, to the axis; but that, in a given conductor, since the effects are not the same if one extremity be made to communicate with the positive pole, and the other extremity with the negative pole, or if this takes place in the contrary order, it is convenient to express in what order the communications are established, by saying that in one case the current is directed from *a* to *d*, and in the other from *d* to *a*.

298. *Effect of the force.*— The effect of the electro-magnetic force on a magnetized needle at rest in its natural position, as in the plane of the magnetic meridian, is to place it in some cross position, the marked end being turned to the left. The particular direction of the motion of the needle and of the current will require to be illustrated at some length, but they are all included in one compendious formulary of Ampère's, which will enable us to embrace the action in every particular case.



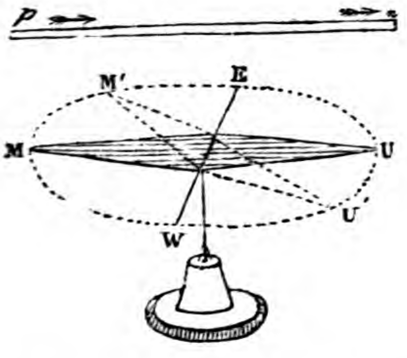
Let the accompanying figure represent a magnetic needle situated in the plane of the magnetic meridian, and let a conductor be placed horizontally above it, so that a rectilinear current passes in the direction indicated by the arrows *a a*. The needle will deviate from its original position, its marked end being turned towards the west, and after some oscillations it will settle in the position indicated by A B, the amount of deviation being measured by the arc M A. This deviation augments as the current is lowered, so as to approach near the needle, and diminishes as the conductor is raised, so that the current is at a greater distance above the needle.

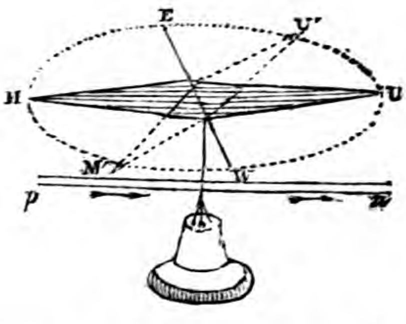
The needle being in its original position, if the conductor be turned, so that the current travels in the opposite direction, as indicated by the arrows *b b*, the side of the deviation is changed; the needle is turned so that its unmarked end travels towards the west, and after some oscillations the needle will take the position C D.

Thus the current above the needle deflects the marked end towards the west when the course of the current is from south to north, and towards the east when its course is from north to south.

If these experiments be repeated, the conductor being placed below the needle, suspended horizontally in the magnetic meridian, the effects are precisely inverted; that is, the unmarked end is turned towards the east when the current goes from the south to the north, and to the west when it goes from the north to the south.

The results just stated will be perfectly intelligible on inspecting the two accompanying figures, in one of which the conductor is above the magnetic needle, and in the other below it.





The current being in the direction of the arrows, the needle M U assumes the position M′ U′ in the respective figures; if the conductor be reversed, so that the current may be considered as moving in the opposite direction, the marked end of the needle will, in the first case, move towards the west, and in the second towards the east. The effects on the needle for other positions of the conductor are very remarkable, but on these we cannot dwell.

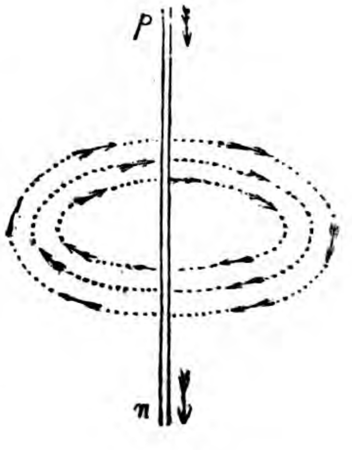
299. *Character of the force.*—In the preceding phenomena the electro-magnetic force is impeded by the directive action which the earth exerts on the needle; and to observe the separate effect of this power, whose action is so energetic and singular, we must neutralize the terrestrial action. This may be effected in several ways, either by placing a bar horizontally in the plane of the magnetic meridian, or by two equal magnets, with their poles reversed. These precautions being taken, the true character of the electro-magnetic force is discovered, and it appears to be neither an attractive force, nor a repulsive force, but a *directive* force, that is, a force which always turns the needle in a direction perpendicular to the conductor, without attracting one pole in preference to the other; hence the line joining these poles always arranges itself across the current. To form a distinct idea of this direction, let us conceive a hollow cylinder of any length, and a foot, for example, in diameter. Along the axis of this cylinder let there pass a conductor traversed by the current of electricity, and on the upper-side surface of this cylinder let a magnetic needle move freely in a horizontal plane; the effect of the electro-magnetic force is such as to place the needle in the direction of a tangent to the upper point of the cylinder, and of a perpendicular to the upper side; or in other words, if a perpendicular be let fall from the point of suspension of the needle to the conductor, the needle will be at right angles to the plane which contains this perpendicular and the conductor. It is not, however, sufficient to define the direction of the current; we must assign also the position of the ends of the needle, determining on which side the marked end is situated, and on which

the unmarked end, according to the direction of the current. This is apparently somewhat difficult, but an ingenious comparison of Ampère has rendered it exceedingly simple; he supposes the current to have head, feet, hands, and consequently a right and a left side. Suppose, now, the observer to conceive himself placed in the current with his feet towards the zinc, and his head towards the copper end, so that, according to our definition, the current will enter by his feet, and go out at his head; and that he has his face always turned towards the middle of the needle on which the current is to act; then the current will always turn the needle so that the marked end will be on the observer's left hand. The motion, then, of the needle is expressed, by saying it turns itself across the current, its marked end being on the left.

300. *Law of the force.*—The intensity of the electro-magnetic force, that is, of the action of the current, is inversely as the distance. To establish this law, a delicate magnetic needle is suspended by a very fine thread, as the silk of a silk-worm, and covered with a glass to prevent its being disturbed by the air. The action of the earth is completely neutralized by a bar suitably placed, so that the needle, having no directive force, can obey without any resistance the new forces to which it is subjected. A conductor, traversed by a current of electricity, is arranged so that it can be placed at different distances from the needle, and the different effects being observed for these distances, the law of the action of the force may be detected. The needle will, according to the law which we have stated (Art. 298), place itself across the current, and remain at rest; but on being moved from this position, it will make isochronous oscillations during a shorter or longer period, according to the intensity of the electro-magnetic force. The quantities which can be observed are the distance of the current from the needle, and the number of oscillations made in a given time; from these the intensity of the force is to be calculated. It appears from the results that the in-

tensity of the electro-magnetic force is inversely as the distance of the current. But the law thus discovered corresponds only to the particular case of a current whose length may be considered as indefinite, compared with the length of the needle and the distance; the more general law is determined by Laplace to be that of the inverse square of the distance, and, like the other known laws of Physics, proportional to the sine of the angle contained between the direction of the current and the line drawn from the middle of any section to the centre of the needle.

301. *Theory of the Currents.*—The peculiar character of the electro-magnetic force, or the force emanating from the conducting wire, is its directive property. It is in this respect different from all other forces in nature with which we are at present acquainted; there is nothing attractive or repulsive in its nature, nor does it act at all in a direction parallel to that of the current, nor in any plane passing through that direction; but it is evidently exerted in a plane perpendicular to the wire, without, however, any tendency to move the poles either directly towards, or directly from, the wire. But the motion which it does produce is in a circular direction all round the wire, that is, the motion is in the direction of the tangent of a circle, described round the wire in a plane perpendicular to it. This Mr. Barlow expresses by saying, that the electro-magnetic force exerts a tangential action. The nature of this action will be understood by conceiving a current to circulate about the wire, and the action of the force as in a plane at right angles to the wire's direction to be such as is represented by the arrows in the accompanying figure. The conducting wire $p\ n$ is supposed vertical, and the current of positive electricity to be descending. The action of the current on

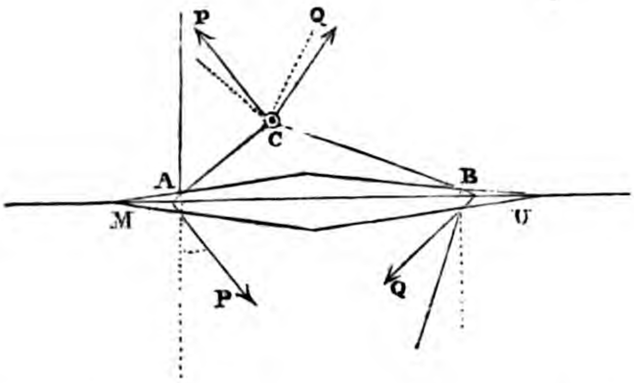


the needle will then be such as may result from forces of this character.

302. *Equilibrium of a Needle subject to a rectilinear Current.*—The vertical conductor being placed in different positions and near to the needle, several phenomena occur which give rise to fresh speculations respecting the natural action of the needle and currents. It was observed by Œrsted that the current brought very near to the needle exerted singular actions upon it, sometimes attracting or repelling it according to its position, sometimes turning it the wrong way, that is, turning the marked end to the right. This observation, followed out by Farraday, led to his beautiful discovery of the rotation of magnets, of which we shall speak hereafter. But the question now was to explain the cause of this apparent change in the character of the actions, these alternations, and, so to speak, reversions of the electro-magnetic forces. It was natural to suppose that the current acted always in the same manner on the same end, and that the changes from attraction to repulsion, and conversely, might result from some circumstances which rendered the action more powerful at one end than at the other. On considering the separate action of the current on each end of the needle, the conclusion is arrived at, that the action which subsists between an indefinite rectilinear current and the end of a needle consists of two equal parallel and opposite forces, which constitute a couple. These forces are perpendicular to the current, and to the shortest distance between the current and the pole of the needle, and their direction is such that the marked end is always turned to the left, and the unmarked end to the right; the intensity of the forces being in the inverse ratio of the distance of the current from the pole of the needle. This principle is also true when any small section of the current is considered; in this case the couple is perpendicular to the line which joins the centre of the section and the pole of the needle, and its intensity always as the inverse square of the distance is proportional to the

sine of the angle which the direction of this line makes with the direction of the current.

In the accompanying figure let A B represent a horizontal section of a needle, and C of a vertical conductor,



traversed by an ascending current; the total action of this current on the marked end M will constitute a couple, that is, two equal opposite parallel forces, P P; similarly, the mutual action of the current and the end U will constitute another couple Q Q. If the current is fixed, and the needle is moveable, the two forces, A P, B Q, will be the only ones which produce motion; their relative intensity, their obliquity, and the length of the arms at which they act, determine the side to which the rotation takes place, or the position of equilibrium. On these principles the general problem of the mutual action which subsists between an electric current and a needle may be resolved, and the various phenomena which will present themselves for known relative positions of the conductor and of the needle may be predicted.*

303. *Electro-Magnetic Multiplier.*—Soon after the discoveries of Œrsted, Schweigger suggested a galvanometer, or multiplier, which multiplying the electro-magnetic force enables us to detect the least traces of electricity or

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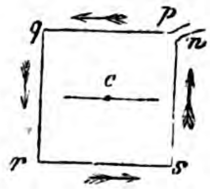
* For several beautiful illustrations, see Dr. Roget's *Electro-Magnetism*, Art. 30.

Galvanism in motion. The multiplier is founded on the principle, that a circular or polygonal current, or one which has any form returning into itself, acts throughout its whole length to turn a needle, which it entirely envelops, in the same direction. Thus every part of the current which traverses the sides of the square *p q r s n* acts in the same manner on a needle moveable about an axis at the centre *c* of the figure, and in a direction perpendicular to its plane. The side *p q* tends to turn the marked end in front of this figure and the other end behind. The side *q r* produces precisely the same effect, as also the sides *r s* and *s n*. Thus, the needle ought to turn itself with a great energy perpendicularly to the plane of the figure, the north end being in front of the figure. A second circuit of the same intensity placed by the side of this will produce the same effect, and so on for any number. A conducting wire, then, rolled up in a hundred coils must, when traversed by the same current, produce an effect a hundred times as great as that of a single coil, provided the current is prevented from passing laterally from one coil to another during the circumvolution. This is effected by winding silk round the conducting wire so as entirely to cover the metal. The wire so prepared may be placed on a wooden frame, a portion being left bare at each extremity so as to serve for the two threads of the multiplier, by which the current is to enter.*



304. ***Magnetization by Electric Current.***—Since a magnetized needle places itself at right angles to the direction of the current, we may naturally suppose that an iron or steel needle will be magnetized in proportion as its position coincides more or less nearly with this. In fact, a current produces a very small quantity of magnetism in needles which are parallel to itself, but magnetizes with great

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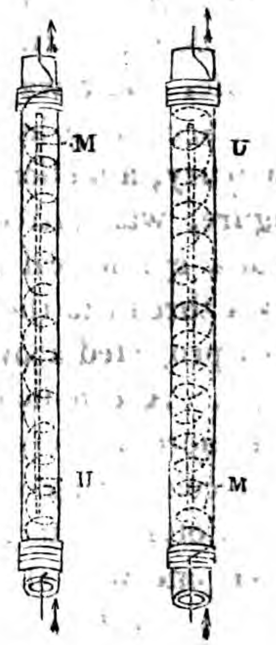
* *Electro-Magnetism*, Art. 115.

energy, and almost to saturation, those of which the direction is across, that is, having nearly the same position as they would themselves assume if previously magnetized. Hence it is evident that in order to develop with a given current successive degrees of magnetism, we must make the current act not only on the middle of the needle, but on all the transverse sections, and at distances successively less and less. To effect this a wire is wound, as a helix, on a glass tube, in the interior of which is placed a needle, and a current is passed from one end of the helix to the other; the development of magnetism which takes place under these circumstances is instantaneous; for after a contact which but just takes place, the needle situated in the tube perpendicular to the plane of the magnetic meridian is magnetized as powerfully as after a contact of several minutes. The rapidity, or rather the instantaneous manner, with which the current overcomes the coercive force is a very remarkable phenomenon.

There are two kinds of helices, one termed the right-handed helix, or the one in which the thread winds to the right, as in the common screw; and the left-handed helix, in which the thread goes to the left. The accompanying figures shew the two kinds of helix. Now, in the right-handed helix the unmarked end of the needle, or that having the property of pointing to the south, is always that at which the current enters, or at the positive end of the wire; but in the left-handed helix, on the contrary, the marked end of the needle is always that which was at the positive wire.

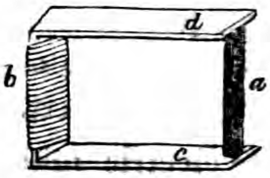


The field which is thus opened to research is boundless; to detail even briefly the various experiments and discoveries of Œrsted, Ampère, and Farraday, would alone require a large volume, and we can only mention one very striking experiment. Soft iron does not, as we have stated (Art. 285), retain its magnetism; but its magnetic properties while under the influence of an electric current are very surprising. A piece of soft iron, about a foot long and an inch in diameter, is bent into the form of a horseshoe; a copper wire is twisted round the bar at right angles to its axis. On connecting the ends of the wire with a simple Voltaic circle, even of small size, the soft iron instantly becomes a powerful magnet, capable of supporting fifty or sixty pounds. Nearly a ton weight has been supported by a connexion with a battery of five square feet.

305. *The rotation of a needle subject to a current.*—The remarkable phenomena of the rotation of magnets were suggested by Wollaston and produced by Farraday at an early period of the science of electro-magnetism; they are a consequence of the principles which have been already laid down (Art. 302.) respecting the equilibrium of a needle. The way in which the rotation was first produced by Farraday is as follows. Into the bottom of a cup full of mercury, a section of which is shewn in the figure, was introduced a copper wire *c d*, and a cylindrical magnet *m u* was attached by a thread to the wire, so that the end is just projected above the surface of the mercury. A conductor *a b* was then fixed in the mercury perpendicularly over the wire. The conducting wires being connected with the Voltaic battery, a current is transmitted from one wire through the mercury to the other. If the positive current descend, the marked end of the magnet, if uppermost, will rotate round the wire *a b*, passing from east through the south to the west, in conformity with the law already stated. If the current

be reversed, the rotation will take place in the opposite direction; and if the magnet be reversed the south end will rotate, but in a direction exactly opposite to that in which the north end will rotate under the same circumstances.

306. *Thermo-Electricity.*—One of the most important consequences of the discovery of electro-magnetism is the means which it affords us of detecting the presence of electricity where it was never suspected; the electrical currents which are excited in metals simply by variations of temperature, are a proof of this; the existence of these phenomena, consequent on the development of heat, or thermo-electric phenomena, as they are termed, would never have been suspected, much less established, but for the delicate test which the magnetic needle supplies of the presence of an electric current. Seebeck discovered that if a bar of bismuth, as *a*, have its two extremities soldered in any manner to a piece of copper *c b d*, this circuit in its natural state produces no effect on the needle, but if one part be warmed it becomes instantly capable of acting on a needle. These motions indicate the existence of an electric current which traverses the whole metallic circuit, and always in the same direction, so long as the heated portion preserves its temperature above the rest. The part at *b* may be covered with silk or stuff, so that it can be held in the hand; if then the part *c* be applied to a candle, or warmed by the hand, the needle will be acted on as by a current which traverses the circuit in the direction *c a d b*. From the identity of effects we must infer an identity of cause, and conclude that the heat excites in the metals a current of electricity. If the part *c* be allowed to cool and to return to its natural temperature, and the part *d* be heated, we have the same result, but in a different direction; the current then passes



in the direction *d a c b*. The two extremities being raised to the same temperature, the effects ought to counteract each other, and experiment shews this to be the case.

It is found also that cooling one end of the bar of bismuth, and leaving the other at its natural temperature, produces the same effects as warming the other. Thus it is the unequal temperature at the two extremities which occasions this remarkable phenomenon of the electric current. It appears also that thermo-electric effects may be produced without two different metals; a single metal will answer, provided there be dissimilarities in its texture and constitution. Rings of antimony, bismuth, and zinc, were cast by Seebeck, and cooled suddenly in some parts, the other parts being left to cool gradually. The internal structure and constitution will be different at these portions of the rings. If now heat be applied to any parts at which the difference of constitution may be conceived to be greatest, the needle will be acted upon as in the preceding case of two metals. This was also shewn by Becquerel in the following manner; he heated one end of the wire of the electric multiplier to redness, and bringing it into contact with the other end, which was cold, the needle was immediately affected as by a current of electricity. Seebeck concludes from his experiments that the same substance, unequally heated, always exhibits electrical currents, and two pieces of moist clay, one of which is hotter than the other, appear, on being brought into contact, to exhibit the same phenomena.

SECTION V.

ATMOSPHERIC ELECTRICITY—LIGHTNING—EFFECTS—SOURCES OF ELECTRICITY IN THE ATMOSPHERE—LIGHTNING CONDUCTORS—AURORA BOREALIS.

307. The phenomena connected with the electricity of the atmosphere are among the most interesting applications which can be made of the laws of Physics, both on account of the phenomena themselves and of the important part they bear in the science of Meteorology. We shall endeavour to give a brief outline of the present state of our knowledge respecting them. The discovery of the electrical state of the atmosphere is due to Otto Gueriche, the illustrious inventor of the air-pump. He and Dr. Wall about the same period observed a vivid spark and sharp crack as they were exciting the electricity of a large cylinder of amber. It is somewhat remarkable that this, the first spark known to have been produced by the hands of man, was instantly compared to the lightning; this crack and this light, says Wall, appear to resemble in some manner thunder and lightning. The analogy was very striking, and such as the imagination could not fail to dwell upon; but to demonstrate the truth of it, to ascend from phenomena so small and insignificant to the causes and laws of one of the grandest phenomena of nature, required a series of proofs which could only be traced out by a superior genius. Various resemblances, more or less striking, served for some time to exercise the ingenuity of philosophers. Thus, some remarked that the spark was crooked, as the lightning; others thought that lightning and thunder are in the hands of nature what electricity is

in our hands. This idea, said the Abbé Nollet, would please me much were it well supported, and how many specious reasons are there for its support. Reasonings, however, of this nature can lead to no satisfactory conclusion, since actual experiment is the only test on which we can with confidence rely. While, however, these speculations were going on in Europe, Franklin, a philosopher of the New World, devised means of bringing lightning from heaven to decide for itself the much agitated question. After several discoveries in electricity, particularly with respect to the Leyden phial and the influence of points, he had the boldness of idea to conceive means of fetching electricity from the bosom of the clouds; he suspected from some decisive experiments that a pointed bar of metal, raised to a great height above the top of an edifice, ought to receive the electricity of a stormy cloud. He waited with great anxiety for the construction of a steeple which they were about to erect at Philadelphia, but wearied with waiting and impatient to perform an experiment which was to remove all his difficulties and resolve all his doubts, he had recourse to a device which was more expeditious and not less certain in its results. Since he only wanted to convey a body into the region of thunder, that is, to a sufficient height in the air, a kite would serve his purpose better than a steeple. He prepared a kite and a cord of suitable length, and waiting for the first storm, this great philosopher, in June, 1752, went out into the fields to fly his kite. His son was the only person who accompanied him, for to him alone had he imparted the knowledge of his design, through fear of the ridicule which might attend an unsuccessful attempt. The kite was raised, and a key being attached to the lower end of the hempen cord, he insulated it by fastening it to a post with a silken string, and waited with intense anxiety for the result. A dense cloud of a most promising appearance passed without producing any effect; the apparatus gave no signs of electricity; other clouds passed with no better success, and Franklin was just beginning to despair when his attention was arrested by some of the loose fibres of the hempen cord bristling up and appearing to repel each other; a slight clap was now heard; encouraged by these appearances he applied his knuckle to the key and received a vivid spark. Thus, for the first time, did the genius of man connect together, by indisputable evidence, the phenomena of lightning and electricity. Overcome by the emotions consequent on the consciousness of the immortality thus achieved, he felt that he could have been content had that moment been his last. The rain now fell in torrents, and wetting the string, rendered it a conductor throughout its whole length, so that electric sparks were collected in great abundance.

This decisive experiment of Franklin, made in June, 1752, was immediately repeated in every civilized country, and every where with the same success. About a month prior to this date electrical indications had been obtained by some French philosophers, in consequence of their pursuing a plan which Franklin had recommended, and which had been published in France. In 1752, De Romas, a French magistrate, raised a kite, and having conceived the happy idea of attaching a metal wire all the length of the hempen string, obtained electrical indications of a very decided character in fine weather. Subsequently, in 1757, the same philosopher repeated his experiments during a storm, when he obtained sparks of a surprising size. 'Imagine,' says he, 'lines of fire ten or eleven feet long and an inch in thickness, and attended with as loud a report as the discharge of a pistol. In less than an hour I had most certainly thirty flashes of these dimensions, not to mention thousands of others of seven or eight feet in length and under.'* This admirable experimentalist, in spite of all the precautions which he took, was once knocked down by the violence of the shock. The risk which

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* *Savans Etrangers,* tome ii.

is run in experiments of this nature was shewn by a fatal catastrophe which occurred immediately after the announcement of Franklin's discovery. In August, 1753, Richman, while intent on examining an electrometer, was struck dead by a large globe of fire which flashed from the insulated conducting rod. A red spot was found on his forehead where the electricity had entered, his shoe was burst open, and part of his clothes singed. His companion was struck down and remained senseless for some time. The door-frame of the room was half split through, and the door torn off and thrown into the room.

From these experiments it is clear that the thunderbolt or fire-ball is identical with the electric spark. Great precautions must be taken in using a kite for these purposes, and an experimenter should never hold the string in his hand, even if the end be silk; since a humid atmosphere may render this portion a conductor.

308. *Action of Electricity during storms.*—If the electrical state of the clouds which pass successively over a raised kite be examined, we shall find that some are charged with positive or vitreous, others with negative or resinous electricity, while others are in their natural state. Now, although we know nothing of the arrangement of electricity in the interior of the clouds, and at their surfaces, yet we may conclude with certainty, that when they are charged with the same electricity they repel each other, and when with different electricities they attract each other. These attractions and repulsions have a considerable share in the extraordinary motions which are observed in the sky during storms; the wind is not the sole power which influences the motion of the clouds; its action must be modified by the electrical actions which are going on with greater or less energy on a vast mass of vapour: hence the clouds are seen to approach or recede with great rapidity, as if they were impelled in opposite directions, or whirling about amongst each other, as if the wind which drove them on was a vast whirlwind. It is from the

midst of this general disturbance that the lightning is seen to glare forth, and that the claps of thunder are heard. We must endeavour to give some account of the flash, and of the report by which it is succeeded.

309. *Lightning.* — The lightning is frequently seen piercing the clouds, and darting through a great extent of heaven; when this phenomenon is observed from the top of a mountain, a more correct opinion can be formed of the extent of it, and all observers agree in stating, that they have seen flashes of much more than a mile in length. We know also that the same clouds suspended in the same regions of the sky can give several flashes in succession; thus in returning to their natural state they follow very different laws to those of electrified conducting bodies. Lastly, every one knows that the line of the flash is nearly always a curve, or more properly a zig-zag. These three phenomena, the form of the flash, its sudden repetition, and its length, cannot be completely explained in the present state of our knowledge.

The zig-zag form is common to the lightning and the electric spark; one and the same explanation will apply to both, but at present there does not appear to be any thing satisfactory on the subject. The masses of vapour, which constitute the clouds, are not conducting bodies, like metallic masses; we know not how the electricity is distributed, and brings itself to equilibrium on imperfect conductors which have several square miles of surface; but it is not probable that their discharge can be effected completely by a single and instantaneous contact with the soil, or that a single spark can restore them to their natural state. Hence we see a reason for so many flashes issuing from the same cloud. The length of the flash appears to be a consequence of the imperfect conducting powers of the clouds, and of the mobility of their constituent parts. The electricity of the clouds must not, in this respect, be closely compared to the electricity of a battery. In this, when the two dissimilar electricities attempt to reunite themselves, they can only traverse a very small space; as, for example, a battery charged to the utmost is not discharged at a greater distance than six or eight inches. The reason of which is, that when the points which are to close the circuit between the interior and the exterior of the battery are at some little distance, the electricities are very feeble, since they are retained in the interior of the jars by mutual attraction exerted through the thickness of the glass. The electricity of the clouds must, then, be compared to the free electricity at the surface of bodies, which are in a greater or less degree conductors. Our best machines will give a spark at a distance of thirty or thirty-six inches through dry air; but if some metallic dust be sprinkled on a piece of cloth, the spark may be taken at a greater distance. If we had at our disposal machines sufficiently powerful, it is evident that the conducting particles suspended in the air might produce the same effect as the metallic particles in the preceding experiment. It seems, then, that the length of the flash may be explained by conceiving that the particles of vapour, and probably also the particles of the air on the line of the lightning, are already partially electrized by the contrary influences of the electricity which tend one towards the other; and that at a given instant the equilibrium is disturbed, not by a transfer of fluid from one cloud to another, but by a successive transfer or successive vibration from layer to layer throughout the whole line which the lightning traverses.

The crash of the thunder, in its greatest intensity and peal, presents no difficulty but that which it has in common with the feeble crack of the smallest spark. They differ in no respect but in the intensity with which the air is set in vibration. When the discharge of a battery passes through a liquid mass, it scatters it on all sides, and when the discharge of a single Leyden phial passes through a gas, the fluid is disturbed and set in vibration, and experiences an augmentation of volume. These facts are perhaps sufficient to shew a probable cause of the crack of the electric spark, and the peal of thunder; and of these, two explanations may be offered. We may conceive that the electric fluid opens a passage through the matter, as a projectile would do, in consequence of its impenetrability, and that the instant after the air, rushing into the void formed by the instantaneous passage of the fluid, produces a sound, as in the experiment of a bladder bursting over an exhausted receiver. If we follow in imagination the course of the lightning, and conceive a tube of glass exactly filling up every bend of the chasm and void of air, and exactly occupying the course of the flash, at a given instant let this tube be broken from end to end, the crash which takes place is the crash of thunder. This explanation is, however, liable to an important objection. Though the passage of a bullet or cannon-ball through the air produces an audible sound, the supposition of an electric fluid being transferred by a motion of translation in a manner analogous to that of projectiles of ponderable matter, is contrary to the positive evidence of many experiments, as has already been stated. The principles which we have adopted in the explanation of the passage of electricity along good and bad conductors, will furnish another and much less objectionable explanation. When the spark quits a body there is a decomposition and a recomposition of electricity among all the parts of the layers where it appears, and consequently vibrations of greater or less rapidity in their ponderable matter; there is a sudden tearing and hasty separation, as may readily be shewn by passing a charge of electricity through a sheet of paper. It is this vibration propagated through the whole surrounding mass which produces the sound. Let us now conceive a flash of lightning extending two or three miles in length. The light glares at the same instant throughout the whole extent; the sound, therefore, is generated at the same instant in the whole line. But sound travels slowly; it is, as we have seen, propagated only at about 1200 feet per second; consequently, an observer whose distance from the nearest point of the line of lightning is 1200 feet, will not hear any sound for at least a second; the roar will then commence; and the sound arriving continuously from the points which are successively more and more distant, will continue ten or fifteen seconds if the most distant point of the line be two or three miles distant. Thus it is the length of the line which determines the duration of the thunder, and to an ear placed near the middle of the line, the same peal will seem only of half the duration which it does to an ear at either extremity; thus one person may hear but one crash, another hears two, one on the right and the other on the left, or the sound may reach his ear from many quarters at once.

310. *Effects of Lightning.*—When the lightning is seen to leap forth and pass betwixt a cloud and any body on the earth, we say, in ordinary language, that the body is struck by lightning. In the language of science this statement does not necessarily convey the idea of any destructive agency; for the thunderbolt does not necessarily destroy every thing which it strikes. A discussion might be raised on the question, whether the thunderbolt descends from the sky, or ascends from the earth; so instantaneous is the effect, that the eye cannot decide; but from what has been already said, it appears that the lightning sometimes passes from the clouds to the earth, and sometimes from the earth to the clouds; for in neither case is there any transfer of electric fluid from one to the other of the extreme points of the flash of lightning. In conformity, however, to common usage, we shall say that the lightning descends to the earth, but the sense in which this term is used must be carefully borne in mind.

Suppose, now, that there is a thunder cloud, charged with vitreous electricity for example, at a considerable elevation above the surface of the earth, as two or three miles high, of any form, and of considerable extent and thickness. Suppose, moreover, that it is suspended above the sea or a large lake. Its presence decomposes the natural electricities of the liquid, repelling the vitreous, and attracting the resinous; making the former recede into the depths of the soil, and the latter approach the surface of the water. The accumulation of the fluid may be sufficient to cause a sensible rise in the water, and we may see a considerable wave or elevation of the water, which will remain suspended above the rest so long as the electrical action continues. This phenomenon may, however, cease in any of the three following ways. First, if there is no explosion in the thunder cloud, it will recede with a more or less rapid motion until, the intensity of its action diminishing as the distance increases, the resinous electricity, becoming less and less attracted, repasses by degrees into the interior of the earth, and the whole mass of water returns to its natural state. Secondly, if an explosion takes place between the thunder cloud and some other point of the earth at a distance from the surface of the water which we have just considered, it is evident that the cloud, deprived suddenly of its electric fluid by this explosion, will suddenly cease to exert any action on the surface of the water which it has raised, and the liquid, suddenly suffered to return to its natural state, will collapse with violence, and its resinous electricity will become recombined with the vitreous, from which it had just been separated. In this case the water is struck by the *back stroke*, of which we have already spoken (Art. 264). It is struck by lightning without any lightning having fallen, that is, without any explosion having taken place between it and the thunder cloud. Thirdly, if the thunder cloud is near enough, of sufficient magnitude, and so highly charged with electricity that a spark may pass between some point in its surface and in the surface of the water electrized by influence, the water is then struck directly, or, in common language, a thunderbolt or fire-ball falls from the clouds into the water. Such an explosion produces in general more disturbance and ebullition in the water than the return or back stroke; such an union cannot take place between the electric fluids without a corresponding violent mechanical action among the particles of the ponderable matter. Each of these effects, which it has taken us so long to describe, may be produced in an instant, and an instant is sufficient to produce them all successively.

From the preceding example, in which we have considered the effect produced on a moveable homogeneous mass of equal conducting power in all its parts, we may form some conception of the effects of a thunder-cloud suspended over an extended plain, the soil of which is composed of heterogeneous elements of different conducting powers. The natural electricity of the soil will here too be decomposed by influence; the vitreous fluid will be repulsed to the interior, and the resinous attracted towards, and accumulated near, the surface of the soil. In this instance, however, we must not confine our views to the surface; we must penetrate into the interior through many of the strata which constitute the soil; we must separate the good and bad conductors, distinguish their form, their extent, and their arrangement. All these circumstances will bear an important part in the phenomena. It is evident, for example, that if there is at some feet below the surface of the soil a metallic stratum of great extent, the action of the cloud will be very great, the quantity of electric fluid accumulated will be much greater, and the spark will be given out much sooner; the upper crust of the soil will then be perforated by lightning in several places, as a card or square of glass is perforated by a charge from the Voltaic battery. This instance will be sufficient to shew us that the nature of the soil, its state of dryness or moisture, and the conducting power of the various component masses, must be carefully considered; hence we may learn what are the elements which determine the nature of the action, and of the various extraordinary effects which lightning is known to produce. The cloud, for instance, may in this case exert no action but that of influence—there may be only a back stroke, and no fall of fire.

With respect to the first of the above-mentioned phenomena, it does not appear that it can ever produce any apparent effect; there are never any violent actions when the electric fluids are slowly separated and slowly reunited; these changes are, however, undoubtedly sensible to organized beings; the peculiar sensations which are in many nervous affections consequent on these changes in the electric equilibrium of the earth cannot be doubted, whatever may be the insuperable difficulties of explaining the way in which the effects are produced. This subject is, however, at present involved in the greatest obscurity. With respect to the two other visible phenomena, it is important to remark, that the back stroke is always much less intense than the direct stroke. There do not appear any authenticated instances of combustion by the back stroke; but it is certain that men and animals have been killed by it; but in death thus produced there are no traces of burning or fracture.

The terrible effects of the direct stroke are too well known to require any detailed account on the present occasion. Innumerable instances are on record of the loss of lives, of conflagration, fracture, and disruption. Large masses of stone and iron have been carried many feet; rocks and mountains bear marks of fusion from the intense heat; and vitreous tubes of many feet in length have been dug out of the sandy plains of Silesia and Prussia—thus marking the path of the electric fluid. It is worthy of remark, that these frequently terminate in small reservoirs of water below the sand, and we may conceive that it is the water which determined the course of the electric fluid.

All elevated objects are more liable to be struck than those which are near the surface of the soil. An eminence in the midst of an extensive plain is much nearer a passing thunder-cloud than the surface of the plain, and a few feet of elevation is sufficient to determine an explosion. Hence it is that trees and animals are so frequently struck in the midst of open fields; all other circumstances, however, being the same, objects situated on a soil which is a bad conductor, are in much less danger than those which are on a soil which is a good conductor. Let us now, for the sake of illustration, consider the action of an electric cloud which passes over an elevated object, as a tree, a tall chimney, or a steeple. If these objects were non-conductors, their presence produces no influence; the cloud would exert no action on them, but only on the soil; but since all bodies are more or less conductors, their natural electricity undergoes separation, and the amount of separation depends on the conducting power, the form, and the nearness, of the objects. Trees, in consequence of their nature, and, above all, in consequence of the excessive moisture of their leaves, are in general very good conductors, and their tops receive a considerable accumulation of the electric fluid. Hence it is that trees *attract* the lightning, and the tallest are struck the first. In a storm, then, no person ought to approach a tree, or even a bush, which stands in the midst of a plain, for if a stroke takes place, it is the tree or the bush which will suffer. In a place abounding with trees and bushes the danger is not the same; the lightning will not strike all or any number of trees, it will strike some one, and almost certainly the tallest; but still an individual seeking shelter would be somewhat embarrassed as to which he should choose, and his only safe course is to avoid them all, and to lie down on the ground in an open place.

Buildings are in general composed of metal, stone, and wood; now each of these receive very different actions from an electric cloud, in consequence of the difference of their conducting powers. But we can readily conceive that the stroke will most probably take place on good conductors; it is of little consequence whether they are uncovered or completely surrounded by some substance which is not so good a conductor. The action by influence is not impeded by any intervening obstacle; it takes place as well on a nail enclosed in a mass of stone as on a weather-cock exposed to a cloud; on this principle we may explain a host of phenomena otherwise inexplicable, which are observed in the explosions of lightning. This power seems to act with a degree of discernment, and to make a selection of particular objects; it seems to flee from or to avoid some object which is in its regular course, that it may strike some other one which is perhaps concealed at a distance; none of these phenomena, however marvellous they may appear, can embarrass an observer who has paid attention to the laws of the conductibility of substance, and of the electrical action by influence.

311. *Effects of discharge.*—In the preceding articles we have endeavoured to point out the principal causes on which the explosion of a charge of electric fluid in the atmosphere depends; we shall make a few remarks on the mechanical, the physical, and the chemical effects of these electric discharges. The mechanical effects are, as has been already stated, of incredible intensity; when lightning strikes any part of a room, the furniture is generally displaced, and strewn in all directions; a tree is frequently cleft down and broken in several places; generally, however, there is a regular channel of several inches in depth and breadth, extending from the top to the roots, the bark and smaller branches being torn off and projected to a considerable distance. At the foot of the tree there is frequently a hole by which the electric fluid entered the soil.

The physical effects are far more analogous than the preceding to those which we can produce with our batteries; they resolve themselves into a greater or less elevation of temperature. When lightning falls on a heap of stubble or a stack of straw, on dry timber, or even on green wood, it either sets it on fire, or carbonizes, that is, chars the parts which it strikes. Metals, being better conductors, experience a much greater elevation of temperature from the passage of the electric fluid; sometimes they are melted or volatized. Thus, in a house which has been struck by lightning the bell-wires have been melted; hence care should be taken not to place good conductors, as metallic wires, in contact with combustible substances, unless the house is protected by lightning rods.

The chemical effects are incomparably more intense than any which we can produce with the strongest batteries. The frequent strokes of lightning on the elevated summit of a lofty mountain ridge leave evident traces of fusion. Saussare observed them in the schist on the top of Mont Blanc, Ramond in the micacious schist on the peak of Midi, and Humboldt saw at the top of the volcanic mountain Toluca the surface of the rock vitrified for an extent of several square feet; and there are many other places in which the surface is covered with a vitreous crust.

The three preceding effects are in general simultaneous in explosions; there is always collision of parts, elevation of temperature, and a consequent chemical combination, if the neighbouring elements are of a nature to unite and separate under these influences. When organized bodies, for example, are struck by lightning, the heat and the mechanical violence are the phenomena which most arrest our attention. In one instance of the death of two individuals by the same stroke of lightning in the midst of a field, when one was killed instantly, the other survived some hours; the clothes of both were burnt, and deep burnings marked the course of the fluid, and the skull of one was broken in pieces as if by the blows of a hammer; and effects very similar to these are observed in all the cases of death from this cause.

The authentic records of most surprising mechanical effects, as the disruption of massive buildings, stone steeples, and of the scattering the stones as some light substances before the wind, are exceedingly numerous; we shall select a remarkable one recorded by the pen of Smeaton* for a few extracts; this will shew distinctly that the effects produced are such as no other forces with which

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* *Phil. Trans.* 1757.

we are acquainted can be conceived capable of producing. 'About five o'clock in the evening, Jan. 25, 1757, returning home from the Edystone works, I observed four flashes of lightning, within the space of six or seven minutes, towards the west; but heard no noise of thunder. A few days after I was informed that the same evening the lightning had shattered a church, thirty miles distant, in a very surprising manner. The steeple is carried up square to about 49 feet, surmounted by a lantern, a spire, and a vane, so that the whole together was about 113 feet. I do not affirm that the lightning entered the spindle or vane, but will suppose it for the sake of methodizing the facts. The socket of the vane was rent open, as if burst by gunpowder; under the spindle which carried the vane was a bar about four feet long, and one inch square, which run through the centre of several of the uppermost stones, successively, all which stones, except one, were broken off. The shell of the spire as far down as 35 feet from the top was no more than 7 inches thick, and the courses about the same height; joined with mortoise and tenon in a curious manner. Above 20 feet of the upper part was entirely thrown down and dispersed in all directions, and some pieces were found at the distance of 200 yards. At the top of the lantern is a bell for the clock to strike on; it is hung upon a cross bar. The cross bar was so bent that the clock hammer would not touch the bell by above two inches. As to the wire which drew the hammer, as I was informed, not one bit could be found. The crutch that lays hold of the pendulum looked as if it had been cut off by a blunt tool, and heated by the blow until it was coloured blue at the place where it was cut. As to the pendulum, which hung pretty near the wall, the upper part of the rod was struck with such violence against the wall, that a smart impression thereof was made in the plaster; and near the upper part of the impression appeared a circular shady ring, of a blackish colour, something like as if a pistol had been discharged of powder, and the muzzle held near the wall. The casing of boards round the clock remained unhurt.' 'At the basement story there was the appearance of a hole reaching through both wall and buttress, which is together 8 feet. Besides this hole, the wall was pierced in several places; at one place was a hole 14 inches square, pierced 6 inches in the wall; and so near square that I inquired whether it had not been made by art, but was assured of the contrary.' 'The vapour seems to have divided itself into three branches, one moving directly towards the east window, consisting of five lights divided by stone mullions; two of the lights were in a manner wholly destroyed, and several large holes in those remaining; the glass and lead being carried outward, like as if an harlequin had leaped through the window.'

The following account of some extraordinary effects of lightning given by Withering* is very remarkable. 'A thunder-cloud formed in the south, in the afternoon of Sept. 3, 1789, and took its course due north. In its passage a field of standing corn was set on fire, but the rain presently extinguished the fire. Soon afterwards the lightning struck an oak tree in the Earl of Aylesbury's park at Packington. The height of this tree is 39 feet, including its trunk, which is 13 feet. It did not strike the highest bough, but that which projected farthest southward. A man who had taken shelter against the north side of the tree was struck dead instantaneously, his clothes set on fire, and the moss on the trunk of the tree where the back of his head had rested was likewise burnt. Two men, spectators of the accident, ran immediately towards him on seeing him fall; and as it rained hard and a small lake had collected almost close to the spot, the fire was very soon extinguished; but the effects of the fire on one-half of his body and on his clothes were such as to shew that the whole burning was instantaneous, not progressive. Part of the electric matter passed down a walking-stick which

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* *Phil. Trans.* 1790.

the man held in his hand, sloping from him; and where the stick rested on the ground it made a perforation about 2½ inches in diameter and 5 inches deep. All observation would probably have ended here had not Lord Aylesbury determined to erect a monument on the spot, not merely to commemorate the event, but with an inscription to caution the unwary of the danger of sheltering under a tree during a thunder-storm. In digging the foundation for this monument, the earth was disturbed at the perforation before mentioned, and the soil appeared to be blackened to the depth of about 10 inches. At this depth a root of the tree presented itself which was quite black; but this blackness was only superficial, and did not extend far along it. About two inches deeper some melted quartzose matter began to appear, and continued in a sloping direction to the depth of 18 inches.' Several pieces of melted matter and perforated stone were sent with this account to the Royal Society.

312. *Sources of atmospheric electricity.*—The question of the origin and supply of the electricity which we know to exist at all times in the atmosphere, but at some times in much greater abundance than at others, is of the greatest interest to the meteorologist, and involved in very great difficulties. This subject has been recently investigated with great ability by Pouillet, and he is of opinion, that vegetation and evaporation are the two great sources of atmospheric electricity. It appears from his experiments that gases always disengage electricity on combination, whether they combine with each other, or with solids, or with liquids: and in these combinations oxigen always disengages positive electricity, and every combustible, whatever be its nature, negative electricity; also, that pure water, whether slowly or rapidly evaporated, gives no signs of electricity; but when the water contains foreign ingredients, as salts, so that this change of state is accompanied by the separation of some heterogeneous elements with which they are chemically combined, there is

always a development of electricity consequent on this separation; the heterogeneous elements assuming one electricity, and the vapour the other. Now since, in all the evaporations which are going on in nature, whether by land or by sea, there is this separation of heterogeneous elements, electricity of one kind or the other must always be produced. Thus, in vegetation and evaporation we may trace two great sources of atmospheric electricity; these causes are in operation with greater or less activity in every place, in every country, at all seasons, and we may reasonably expect that they act according to some invariable, but at present undetected, law. Into the details of these most interesting experiments we cannot possibly enter;* and we regret to say that other philosophers have come to results extremely discordant with the preceding; thus De La Rive and Becquerel cannot agree with Pouillet in regarding vegetation as a great source of positive electricity.

Admitting, however, for the present, the preceding views of the share which evaporation has in producing atmospheric electricity, we may at once comprehend the fact of the existence of clouds in different electric states. The vapour which collects from any one source, and forms a cloud, having the electricity which belongs to the circumstances under which it was formed, will communicate to the cloud the character of positive or negative electricity.

313. *Lightning Rods.*—These rods consist of a pointed iron bar, which is raised above the object to be protected, and of a conductor from this bar to the ground. The requisite properties for a good protector are, that the bar should be well pointed, and that the conductor should communicate perfectly with the soil without any interruption of continuity throughout its whole length. Suppose now that an electric cloud comes near the top of this rod; its natural electricities will be decomposed, that of the same

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* See *Annales de Physique et de Chimie,* 1827.

kind as the cloud will be repelled, and diffuse itself into the ground, with which the conductor freely communicates: the electricities of the different kind to that with which the cloud is charged will be attracted towards the point of the rod, and be dissipated in the air. Thus the two opposite electric fluids experience no obstacle to their circulation throughout the whole extent of the conductor, or to their dissipation, the one into the earth, and the other into the air; there will consequently be no accumulation on the rod, and an explosion therefore will be impossible. Whilst the rod is thus traversed by the different electricities in opposite directions, we may approach it or grasp it with the hand with perfect impunity; where there is no tension of electricity there is no danger. Not only under the circumstances which we have supposed will no lightning strike the rod, but it will not strike any object for a certain distance round about the rod; there is a certain sphere of activity of the rod within which the lightning has no power. But suppose that the rod is not a good one, that the point is blunted, that the conductor communicates imperfectly with the ground, or that it has some defect whereby its continuity is destroyed; in such a case it is evident that an accumulation of electricity is not only possible, but inevitable; it is then a conductor which can become charged with a very great quantity of electricity; and sparks may be drawn by the hand which will be feeble or powerful according to circumstances. In all these cases there is danger, but its character is different according to circumstances. If the point is blunted and the lightning strikes it, the point may be melted, and in general the electric fluid will follow the conductor, and do no mischief to the building. But if the continuity be incomplete, if the free communication with the ground be interrupted, the lightning may still strike and melt some part of the rod, but it will also be conveyed laterally to all the neighbouring conductors, and will exert its destructive energy just as if the rod did not exist. But besides this, a rod possessing these defects is extremely dangerous even when the lightning does not strike it; for the instant there is sufficient accumulation of electricity on the conductor, the fluid has a tendency to escape, and the sparks may be most dangerous and destructive; as we have already seen in the instance of the death of Richmann—the spark, or rather globe of fire by which he was killed was from a lightning rod which he had insulated for the purpose of making experiments.

314. *Aurora Borealis.*—The phenomenon of the Aurora Borealis, or northern lights, is not of very frequent occurrence in our latitudes, but in proportion as we advance towards the north it becomes more frequent, and in high latitudes it is so regular and permanent, that the aurora may with some propriety be called the sun of the polar regions. Travellers who have visited the north of Scotland, Norway, Lapland, and the northern parts of Asia and America, state that the light of the aurora is exceedingly brilliant, and exhibits many vivid colours—that the expanse of heaven to a great distance seems to be on fire. This phenomenon does not resemble lightning in the rapidity with which it passes away, but it lasts for several hours, and frequently throughout the whole night; its brilliancy is not however constant and steady as the brilliancy of the stars, but it may be compared to immense flames which are lighted up suddenly, expand themselves on all sides, are partially extinguished, and restored again almost immediately. The inhabitants of our latitudes have no conception of the brilliancy of these lights as they are seen in northern regions, but the auroras which we witness in these latitudes furnish a grand spectacle, and one which cannot fail to attract the attention of every beholder. The Transactions of the Royal Society* contain a faithful record of a very beautiful one seen in November, 1835, by Mr. C. Christie. It may be remarked, that on those

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* *Philosophical Transactions*, 1836.

evenings on which an aurora has appeared there has generally been visible after sun-set a confused bright light towards the north, accompanied by sudden jets of bright light. In conformity with this general observation, Mr. C. Christie remarked at 9 o'clock a bright light, exactly as if the moon were about to rise in that quarter. From a more elevated position he saw a perfect and very bright arch to the north; the lower edge being sharply defined on the dark cloud beneath, the upper shaded off into the sky. The sky, except beneath the lower arch, was perfectly cloudless, the stars shining brightly down to its upper edge. The arch was motionless, but large bodies of faint vapoury light continually ascended from it, and whirled in every direction across the zenith, &c. as if by the wind, and with such rapidity as scarcely to be followed by the eye. These frequently rose perpendicularly, and were then sharply whisked off towards the south-east. At a quarter past nine there was a fine outbreak of pencils from the centre and eastern extremity of the arch; none of them stationary or in straight lines, but waving more or less, and flickering, as if with the wind; masses of vapoury light whirled up occasionally; the whole presenting the appearance of an immense and not distant conflagration; while the paleness of the light and the absence of noise gave it a spectral and unearthly character which was very striking. The gusts of wind increased the illusion. 'At 9^h 25^m the western extremity suddenly blazed up; one very broad pencil of rose-coloured light forming the western boundary to the rest; through it α Aquilæ shone with great brilliancy.' At half-past nine the arch was entirely broken up, and then in five minutes restored, but of an irregular undulating form; and in this state it continued with slight changes for nearly an hour: the observer was unable to wait for the total disappearance of the phenomenon. It is necessary to remark, that the term arch is applied to the under surface of the body of light, which appeared to be defined by or to rest on a dark cloud.

Mr. C. Christie remarks, that the centre of the arch was very near magnetic north, so that the arch would be at right angles to the magnetic meridian: that the body of light was nearly colourless, and its brightness similar to that seen on the edge of a cloud when the moon is about to rise behind it; with, however, this striking difference, that the stars were seen distinctly through the diffused light of its upper surface, and those in the tail of the Bear shone clearly in the very body of the light on the right hand. One very remarkable phenomenon recorded by Mr. C. Christie, is the darting of pencils of light through the dark cloud. The first appearance of the aurora at nine o'clock was that of a dark convex cloud cutting the luminous arch and concealing a body of light behind, the eye naturally referring the light to a more distant region, while the sharp line of division threw the clouds forward. Subsequent appearances, however, did not seem to confirm this notion, but, on the contrary, induced him to consider whether the dark cloud might not be a *substratum* of matter differing in nature and density from the superincumbent arch of light. Mr. C. Christie having drawn several inferences from the appearance and state of the arch, comes to the following conclusion. 'All the circumstances struck me as so closely resembling the disturbance of two fluids, the one superposed on the other, mutually repulsive, but compelled to mingle by forces of whose action the vividness of the pencillings seemed to indicate the intensity, and requiring intervals of repose to re-collect their scattered energies, that I cannot but conclude the luminous matter of an aurora to be a superincumbent stratum, and consequently, that its altitude is dependent on that of the dark mass beneath.'

The reader who has never witnessed the phenomenon will have an accurate conception of it from the beautiful drawings accompanying the paper from which the preceding has been extracted. Their accuracy will be borne testimony to by every one who has witnessed the phenomenon. Sometimes two or several luminous arches are seen parallel to each other, and the colours which accompany the streamers sent up towards the zenith are most variegated and beautiful. The breaking up and restoring of the arch is a very curious fact; the luminous matter collects in large masses at different parts of the arch, and then returns again into its original state. In the present state of our knowledge we seem only to be assured of the fact, that the aurora is an electrical phenomenon; on this point all are agreed; but of the laws which govern it we are at present exceedingly ignorant.

CHAP. XII.

THEORY OF GRAVITATION—THEORY OF HEAT—THEORY OF LIGHT—THEORY OF ELECTRICITY AND MAGNETISM—CONCLUSION.

315. IN the concluding chapter of this work the student's attention may with advantage be directed to some considerations of very great value, and to some features especially in the theory of the Physical Sciences, which ought not to be wholly omitted. The great object in view being to ascend from particular facts to general laws, and to form theories from which the phenomena may be reproduced, we may with advantage consider what is the actual state of our knowledge in this respect.

The theory of gravitation will first claim our consideration; on the evidence of the truth of this theory it is unnecessary to add any farther remarks to those which have been already made (Art. 3); we have traced in considerable detail in the chapters on Gravity and on Fluids the consequences which flow from this law, and the phenomena which are included in it as exhibited at the surface of the earth. The truth of the laws of gravity is so wound up with our belief, that we can scarcely conceive them otherwise than they are believed to be. But it is a most interesting and instructive question, if conducted in a proper spirit, to inquire whether there is any necessity for the law being such as it is. That any such necessity exists is quite contrary to our general belief; we are bound to believe that the Great Author of all things could have made matter subject to any other law had it so seemed good; but very strong reasons are to be pointed out why, for the beauty and advantage of the system of the universe, this law seems immeasurably superior to every other. Reflections of this nature would furnish a most proper conclusion to the preceding work: but our limits will not admit of it, and we could scarcely hope to present any thing worth notice when compared with the beautiful remarks of Mr. Whewell on this subject.*

The universality of the law of the inverse square is most remarkable; this particular law presents itself in almost every department of Physics. Thus we are led to look for some more general principle, which may include every phenomenon in nature. Some surprising generalizations to this effect have within the last year been announced to the world by Mosotti.

It is a most important exercise for the student to contemplate the process by which a general law is arrived at. A mass of facts which previously appeared entirely unconnected, nay incoherent, stand at once in a clear relation to each other. This step, to quote the words of Mr. Whewell,† so much resembles the mode in which one intelligent being understands and apprehends the conceptions of another, that we cannot be surprised if those persons in whose minds such a step has taken place, have been most ready to acknowledge the existence and operation of a superintending Intelligence, whose ordinances it was their employment to study—when they had first read a sentence of the table of the laws of the universe, they could not doubt whether it had a Legislator.

On quitting the subject of universal gravitation we enter on a field of some uncertainty, so far as the physical theory is concerned. The theories of heat, light, electricity and magnetism, are far from settled, and we encounter much

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* *Bridgewater Treatise*, book ii. chap. x.

† *Ibid*, book iii. chap. v.

that is involved in uncertainty. We cannot, however, doubt but that here too are general laws, though we have not yet established them; indeed much has already been done in the theory of light, and some little advance has been made in the theory of the other imponderable agents; but the Newton is yet to arise who shall place these sciences on the same rank as to certainty of evidence with the theory of universal gravitation. We shall endeavour to point out the state of the theory of these sciences.

316. *Theory of Heat.*—We have already (Art. 187) hinted at the hypothesis, that heat consists in the vibrations of an imponderable fluid, or ether. The phenomena of conduction and radiation, on which we have dwelt at considerable length, are so obviously consistent with the notion of the flow or transmission of some material particles, that it is not the least a matter of surprise that the hypothesis of heat, consisting in the transfer of material particles, should be generally received. But the two cases of the material theories of heat and light are remarkably analogous. The material theory did exceedingly well for a long time; but at last some phenomena presented themselves apparently utterly inexplicable on any such hypothesis. These phenomena are the interference of rays of heat, so that cold is produced, and the polarization of heat;* so that we may say of the theory of heat as we have already said of the undulatory theory of light (Art. 243), that a theory of undulations may be false, but we cannot conceive any theory of emission to be true.

Here then, as in the case of light, some other hypothesis is forced upon us, and under these circumstances there is no difficulty in entertaining the hypothesis of the vibrations of an ether; nay, of the same ether by whose motion light is supposed to be produced. We cannot suppose that the different phenomena of light and heat are produced by

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* See Professor Forbes 'On the Refraction and Polarization of Heat,' *Philosophical Magazine,* March and November, 1835.

vibrations of the same kind; but we may conceive that heat may be produced by vibrations in one plane, and light by vibrations in another, or we may conceive two entirely different kinds of vibrations.

Melloni is said to have succeeded in separating the luminous and calorific rays of light, by passing light through some transparent substances which absorb all the calorific rays. The light so transmitted, being concentrated, is said to be as intense as the direct light, but to produce no effect on the most delicate thermometer. Should the experiments of this distinguished philosopher be confirmed, a wide field is at once opened for our speculations.

317. *Theory of Light.*—In the theory of light considerable progress has been made, and we have already (Arts. 252—255) endeavoured to set forth the general principles of the undulatory theory. To have applied these principles to the explanation of double refraction and polarization, to diffraction, to dispersion, and to the other phenomena of Physical Optics, would have on the present occasion been impossible. Indeed the theoretical explanation of these phenomena can hardly be attempted in ordinary language, and the student who would enter fully into this most delightful inquiry, must have made considerable progress in mathematical science. We can only bear testimony to the apparent sufficiency of the principles to explain all the phenomena, and shall conclude this subject in the words of Mr. Whewell:—

'In the undulatory theory all tends to unity and simplicity. We explain reflexion and refraction by undulations; when we come to thin plates, the requisite "fits" are already involved in our fundamental hypothesis, for they are the length of an undulation: the phenomena of diffraction also require such intervals; and the intervals thus required agree exactly with the others in magnitude, so that no new property is needed. Polarization for a moment checks us, but not long, for the direction of our vibrations is hitherto arbitrary;—we allow polarization to decide it. Having done this for the sake of polarization, we find that it also answers an entirely different purpose, that of giving the law of double refraction. Truth may give rise to such a coincidence; falsehood cannot. But the phenomena became more numerous, more various, more strange; no matter: the theory is equal to them all. It makes not a single new physical hypothesis; but out of its original stock of principles it educes the counterpart of all that observation shews. It accounts for, explains, simplifies, the most entangled cases; connects known laws and facts; predicts and discloses unknown ones; becomes the guide of its former teacher, observation; and, enlightened by mechanical conceptions, acquires an insight which pierces through shape and colour to force and cause.'*

318. *Theory of Electricity and Magnetism.*—It now only remains to say a few words on the theories of the sciences of electricity and magnetism, and of the various branches which have arisen from a great number of kindred and analogous phenomena. The great question for consideration is, whether the phenomena may with certainty be referred to a fluid, and next, whether to one or to two fluids. In treating this subject we stated that the phenomena were such as might result from supposing two fluids endued with the properties assigned to them; the reproduction of the phenomena from the hypothesis, in a manner sufficiently simple, is the coincidence on which the hypothesis must be considered as resting. And the hypothesis of two fluids was till recently generally considered by most who had examined the mathematical calculations—the only certain evidence which can be furnished—that the question of two fluids was, in simplicity of hypothesis, incomparably superior to the hypothesis of one fluid. But the researches of M. Mosotti,† published last year, exhibit

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* *History of the Inductive Sciences*, book viii. chap. xi.

† Sur les Forces qui regissent la Constitution Interieure des Corps. Turin, 1836.

the theory of one fluid under a far more favourable aspect than it previously possessed.

The theory of terrestrial magnetism is too important to be wholly omitted. The analogies betwixt heat and magnetism are in many respects so remarkable, that we may reasonably inquire whether magnetism, and that to a considerable extent, is not excited by the unequal distribution of heat amongst metallic, and possibly amongst other bodies. 'Is it improbable that the diurnal variation of the needle, which follows the course of the sun, and therefore seems to depend upon heat, may result from the metals and other substances which compose the surface of the earth being unequally heated, and consequently suffering a change in their magnetic influence?'* And Dr. Traill considers 'that the disturbance of the equilibrium of the temperature of our planet, by the continued action of the sun's rays on its intertropical regions, and of the polar ices, must convert the earth into a vast thermo-magnetic apparatus,' and 'that the disturbance of the equilibrium of temperature, even in stony strata, may elicit some degree of magnetism.'† Mr. Christie having conducted a series of observations bearing on this subject comes to the conclusion, that one part of the earth with its atmosphere being more heated than another, two magnetic poles, or rather electric currents producing effects referrible to such poles, would be formed on each side of the equator, poles of different names being opposed to each other on the contrary sides of the equator; and that different points in the earth's equator becoming successively those of greatest heat, these poles would be carried round the axis of the earth, and would necessarily cause a deviation in the needle.‡ And Mr. Christie says, 'Upon a review of all the phenomena of terrestrial magnetism, and considering the intimate relation which has been established between magnetism and

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* Professor Cumming, *Camb. Phil. Tran.* vol. ii. p. 64.

† *Edin. Phil. Tran.* 1823, p. 392.

‡ Christie, *Phil. Tran.* 1827.

electricity, by which it appears that, if not identical, they are only different modifications of the same principle, there can, I think, be little doubt that they are due to electric currents circulating round the earth. How these currents are excited, whether by heat, by the action of another body, or in consequence of rotation, we are not at present able to determine; but however excited, they must, though not wholly dependent upon it, be greatly modified by the physical constitution of the earth's surface.'*

Respecting the views of Ampère on the theory of electro-magnetism, or the splendid discoveries of Farraday of the development of electricity by magnetism, which has led to the establishment of a new branch of science, termed magneto-electricity, we can at present say nothing. For the profound views of these most distinguished philosophers, and the startling phenomena which they have linked together, we must refer to other works, and especially to the papers by Farraday in the Transactions of the Royal Society from 1832 to the present time.

319. *Conclusion.*—The conclusion then which we must draw from a review of the preceding is, that Heat, Light, Electricity and Magnetism, which pervade in so mysterious a manner every department of nature, have a most intimate connexion, and must be referred to one common cause; and we cannot say whether Gravitation itself be not an electrical phenomenon; whether it be not also the very same agent which arranges and binds together the constituent elements of bodies; that thus the whole universe of matter is governed by one pervading principle, harmonizing and controlling every thing.

Notwithstanding all that has been done every one must respond to the sentiments of Herschel, that 'Science, in relation to our faculties, still remains boundless and unexplored; and after the lapse of a century and a half from the era of Newton's discoveries, during which every

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* *Third Report of British Association*, p. 127.

department of it has been cultivated with a zeal and energy which have assuredly met their full return, we remain in the situation in which he figured himself—standing on the shore of a wide ocean, from whose beach we may have culled some of those innumerable beautiful productions it casts up with lavish prodigality, but whose acquisition can be regarded as no diminution of the treasures which remain.'* Nor can the reflection fail to force itself upon us, that this universe, disposed and upheld by the superintendence of Infinite Wisdom, will be an inexhaustible object for the research and meditations of man; that each successive generation will add its mite to the store of useful knowledge, but that in this imperfect state of being it will not be given to man to 'find out the work that God maketh from the beginning to the end.'

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* Herschel, *Study of Nat. Phil.* Art. 391.

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