JOHN TYNDALL

SIX LECTURES ON LIGHT. DELIVERED IN THE UNITED STATES IN 1872-1873

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Tyndall J.

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PREFACE TO THE FOURTH EDITION

In these Lectures I have sought to render clear a difficult but profoundly interesting subject. My aim has been not only to describe and illustrate in a familiar manner the principal laws and phenomena of light, but to point out the origin, and show the application, of the theoretic conceptions which underlie and unite the whole, and without which no real interpretation is possible.

The Lectures, as stated on the title-page, were delivered in the United States in 1872-3. I still retain a vivid and grateful remembrance of the cordiality with which they were received.

My scope and object are briefly indicated in the 'Summary and Conclusion,' which, as recommended in a former edition, might be, not unfitly, read as an introduction to the volume.

J.T.

ALP LUSGEN: October 1885.

ON LIGHT

LECTURE I

INTRODUCTORY
USES OF EXPERIMENT
EARLY SCIENTIFIC NOTIONS
SCIENCES OF OBSERVATION
KNOWLEDGE OF THE ANCIENTS REGARDING LIGHT
DEFECTS OF THE EYE
OUR INSTRUMENTS
RECTILINEAL PROPAGATION OF LIGHT
LAW OF INCIDENCE AND REFLECTION
STERILITY OF THE MIDDLE AGES
REFRACTION
DISCOVERY OF SNELL
PARTIAL AND TOTAL REFLECTION
VELOCITY OF LIGHT
ROEMER, BRADLEY, FOUCAULT, AND FIZEAU
PRINCIPLE OF LEAST ACTION
DESCARTES AND THE RAINBOW
NEWTON'S EXPERIMENTS ON THE COMPOSITION OF SOLAR LIGHT
HIS MISTAKE AS REGARDS ACHROMATISM
SYNTHESIS OF WHITE LIGHT
YELLOW AND BLUE LIGHTS PRODUCE WHITE BY THEIR MIXTURE
COLOURS OF NATURAL BODIES
ABSORPTION
MIXTURE OF PIGMENTS CONTRASTED WITH MIXTURE OF LIGHTS.

§ 1. *Introduction*

Some twelve years ago I published, in England, a little book entitled the 'Glaciers of the Alps,' and, a couple of years subsequently, a second book, entitled 'Heat a Mode of Motion.' These volumes were followed by others, written with equal plainness, and with a similar aim, that aim being to develop and deepen sympathy between science and the world outside of science. I agreed with thoughtful men[1] who deemed it good for neither world to be isolated from the other, or unsympathetic towards the other, and, to lessen this isolation, at least in one department of science, I swerved, for a time, from those original researches which have been the real pursuit and pleasure of my life.

The works here referred to were, for the most part, republished by the Messrs. Appleton of New York,[2] under the auspices of a man who is untiring in his efforts to diffuse sound scientific knowledge among the people of the United States; whose energy, ability, and single-mindedness, in the prosecution of an arduous task, have won for him the sympathy and support of many of us in 'the old country.' I allude to Professor Youmans. Quite as rapidly as in England, the aim of these works was understood and appreciated in the United States, and they brought me from this side of the Atlantic innumerable evidences of good-will. Year after year invitations reached me[3] to visit America, and last year (1871) I was honoured with a request so cordial, signed by five-and-twenty names, so distinguished in science, in literature, and in administrative position, that I at once resolved to respond to it by braving not only the disquieting oscillations of the Atlantic, but the far more disquieting ordeal of appearing in person before the people of the United States.

This invitation, conveyed to me by my accomplished friend Professor Lesley, of Philadelphia, and preceded by a letter of the same purport from your scientific Nestor, the celebrated Joseph Henry, of Washington, desired that I should lecture in some of the principal cities of the Union. This I agreed to do, though much in the dark as to a suitable subject. In answer to my inquiries, however, I was given to understand that a course of lectures, showing the uses of experiment in the cultivation of Natural Knowledge, would materially promote scientific education in this country. And though such lectures involved the selection of weighty and delicate instruments, and their transfer from place to place, I determined to meet the wishes of my friends, as far as the time and means at my disposal would allow.

[1] Among whom may be especially mentioned the late Sir Edmund Head, Bart., with whom I had many conversations on this subject.

[2] At whose hands it gives me pleasure to state I have always experienced honourable and liberal treatment.

[3] One of the earliest of these came from Mr. John Amory Lowell of Boston.

§ 2. *Subject of the Course. Source of Light employed*

Experiments have two great uses—a use in discovery, and a use in tuition. They were long ago defined as the investigator's language addressed to Nature, to which she sends intelligible replies. These replies, however, usually reach the questioner in whispers too feeble for the public ear. But after the investigator comes the teacher, whose function it is so to exalt and modify the experiments of his predecessor, as to render them fit for public presentation. This secondary function I shall endeavour, in the present instance, to fulfil.

Taking a single department of natural philosophy as my subject, I propose, by means of it, to illustrate the growth of scientific knowledge under the guidance of experiment. I wish, in the first place, to make you acquainted with certain elementary phenomena; then to point out to you how the theoretical principles by which phenomena are explained take root in the human mind, and finally to apply these principles to the whole body of knowledge covered by the lectures. The science of optics lends itself particularly well to this mode of treatment, and on it, therefore, I propose to draw for the materials of the present course. It will be best to begin with the few simple facts regarding light which were known to the ancients, and to pass from them, in historic gradation, to the more abstruse discoveries of modern times.

All our notions of Nature, however exalted or however grotesque, have their foundation in experience. The notion of personal volition in Nature had this basis. In the fury and the serenity of natural phenomena the savage saw the transcript of his own varying moods, and he accordingly ascribed these phenomena to beings of like passions with himself, but vastly transcending him in power. Thus the notion of *causality*—the assumption that natural things did not come of themselves, but had unseen antecedents—lay at the root of even the savage's interpretation of Nature. Out of this bias of the human mind to seek for the causes of phenomena all science has sprung.

We will not now go back to man's first intellectual gropings; much less shall we enter upon the thorny discussion as to how the groping man arose. We will take him at that stage of his development, when he became possessed of the apparatus of thought and the power of using it. For a time—and that historically a long one—he was limited to mere observation, accepting what Nature offered, and confining intellectual action to it alone. The apparent motions of sun and stars first drew towards them the questionings of the intellect, and accordingly astronomy was the first science developed. Slowly, and with difficulty, the notion of natural forces took root in the human mind. Slowly, and with difficulty, the science of mechanics had to grow out of this notion; and slowly at last came the full application of mechanical principles to the motions of the heavenly bodies. We trace the progress of astronomy through Hipparchus and Ptolemy; and, after a long halt, through Copernicus, Galileo, Tycho Brahe, and Kepler; while from the high table-land of thought occupied by these men, Newton shoots upwards like a peak, overlooking all others from his dominant elevation.

But other objects than the motions of the stars attracted the attention of the ancient world. Light was a familiar phenomenon, and from the earliest times we find men's minds busy with the attempt to render some account of it. But without *experiment*, which belongs to a later stage of scientific development, little progress could be here made. The ancients, accordingly, were far less successful in dealing with light than in dealing with solar and stellar motions. Still they did make some progress. They satisfied themselves that light moved in straight lines; they knew also that light was reflected from polished surfaces, and that the angle of incidence was equal to the angle of reflection. These two results of ancient scientific curiosity constitute the starting-point of our present course of lectures.

But in the first place it will be useful to say a few words regarding the source of light to be employed in our experiments. The rusting of iron is, to all intents and purposes, the slow burning of iron. It develops heat, and, if the heat be preserved, a high temperature may be thus attained. The destruction of the first Atlantic cable was probably due to heat developed in this way. Other metals are still more combustible than iron. You may ignite strips of zinc in a candle flame, and cause them to burn almost like strips of paper. But we must now expand our definition of combustion, and include under this term, not only combustion in air, but also combustion in liquids. Water, for example, contains a store of oxygen, which may unite with, and consume, a metal immersed in it; it is from this kind of combustion that we are to derive the heat and light employed in our present course.

The generation of this light and of this heat merits a moment's attention. Before you is an instrument—a small voltaic battery—in which zinc is immersed in a suitable liquid. An attractive force is at this moment exerted between the metal and the oxygen of the liquid; actual combination, however, being in the first instance avoided. Uniting the two ends of the battery by a thick wire, the attraction is satisfied, the oxygen unites with the metal, zinc is consumed, and heat, as usual, is the result of the combustion. A power which, for want of a better name, we call an electric current, passes at the same time through the wire.

Cutting the thick wire in two, let the severed ends be united by a thin one. It glows with a white heat. Whence comes that heat? The question is well worthy of an answer. Suppose in the first instance, when the thick wire is employed, that we permit the action to continue until 100 grains of zinc are consumed, the amount of heat generated in the battery would be capable of accurate numerical expression. Let the action then continue, with the thin wire glowing, until 100 grains of zinc are consumed. Will the amount of heat generated in the battery be the same as before? No; it will be less by the precise amount generated in the thin wire outside the battery. In fact, by adding the internal heat to the external, we obtain for the combustion of 100 grains of zinc a total which never varies. We have here a beautiful example of that law of constancy as regards natural energies, the establishment of which is the greatest achievement of modern science. By this arrangement, then, we are able to burn our zinc at one place, and to exhibit the effects of its combustion at another. In New York, for example, we may have our grate and fuel; but the heat and light of our fire may be made to appear at San Francisco.

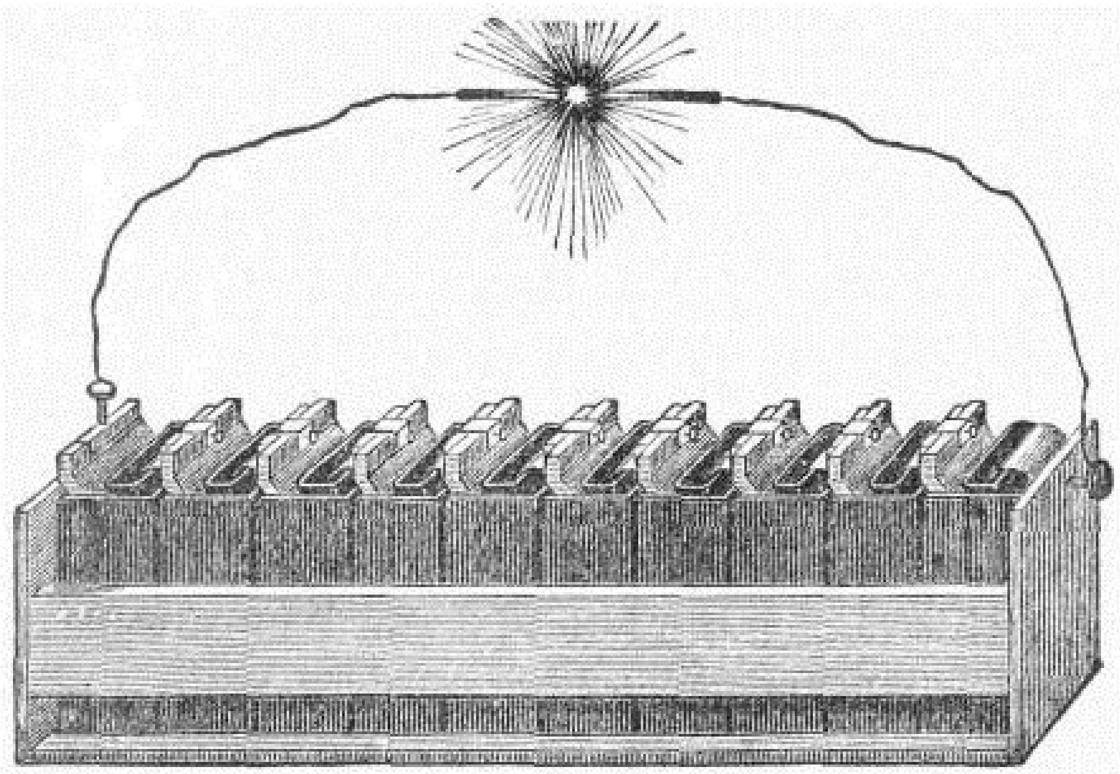


Fig. 1.

Removing the thin wire and attaching to the severed ends of the thick one two rods of coke we obtain, on bringing the rods together (as in fig. 1), a small star of light. Now, the light to be employed in our lectures is a simple exaggeration of this star. Instead of being produced by ten cells, it is produced by fifty. Placed in a suitable camera, provided with a suitable lens, this powerful source will give us all the light necessary for our experiments.

And here, in passing, I am reminded of the common delusion that the works of Nature, the human eye included, are theoretically perfect. The eye has grown for ages *towards* perfection; but ages of perfecting may be still before it. Looking at the dazzling light from our large battery, I see a luminous globe, but entirely fail to see the shape of the coke-points whence the light issues. The cause may be thus made clear: On the screen before you is projected an image of the carbon points, the *whole* of the glass lens in front of the camera being employed to form the image. It is not sharp, but surrounded by a halo which nearly obliterates the carbons. This arises from an imperfection of the glass lens, called its *spherical aberration*, which is due to the fact that the circumferential and central rays have not the same focus. The human eye labours under a similar defect, and from this, and other causes, it arises that when the naked light from fifty cells is looked at the blur of light upon the retina is sufficient to destroy the definition of the retinal image of the carbons. A long list of indictments might indeed be brought against the eye—its opacity, its want of symmetry, its lack of achromatism, its partial blindness. All these taken together caused Helmholt to say that, if any optician sent him an instrument so defective, he would be justified in sending it back with the severest censure. But the eye is not to be judged from the standpoint of theory. It is not perfect, but is on its way to perfection. As a practical instrument, and taking the adjustments by which its defects are neutralized into account, it must ever remain a marvel to the reflecting mind.

§ 3. *Rectilineal Propagation of Light. Elementary Experiments. Law of Reflection*

The ancients were aware of the rectilineal propagation of light. They knew that an opaque body, placed between the eye and a point of light, intercepted the light of the point. Possibly the terms 'ray' and 'beam' may have been suggested by those straight spokes of light which, in certain states of the atmosphere, dart from the sun at his rising and his setting. The rectilineal propagation of light may be illustrated by permitting the solar light to enter, through a small aperture in a window-shutter, a dark room in which a little smoke has been diffused. In pure *air* you cannot see the beam, but in smoky air you can, because the light, which passes unseen through the air, is scattered and revealed by the smoke particles, among which the beam pursues a straight course.

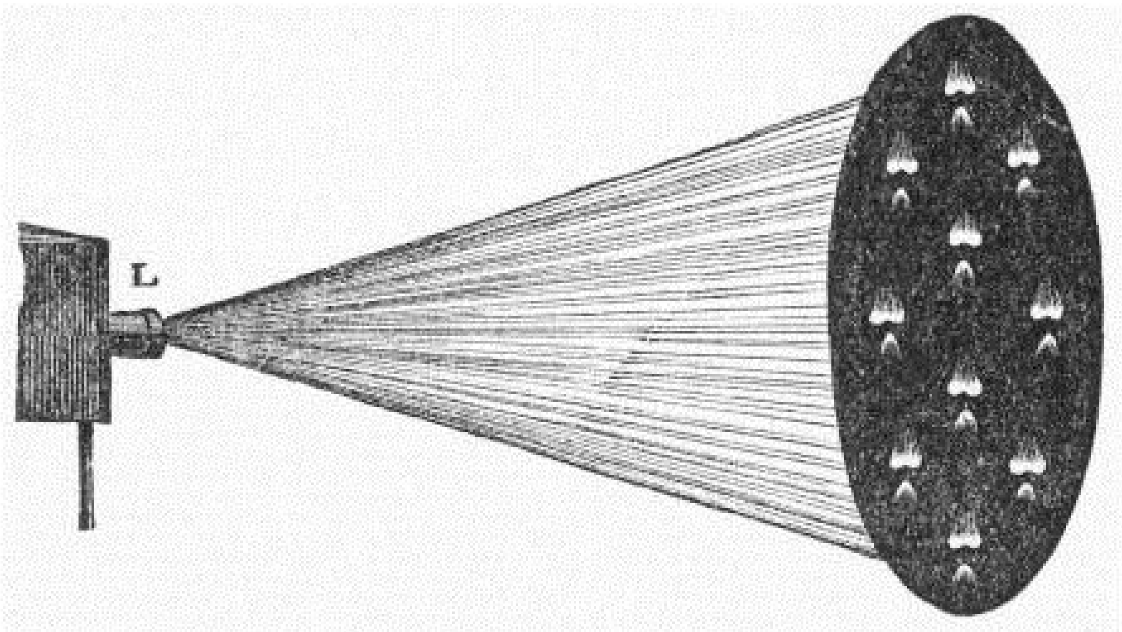


Fig. 2.

The following instructive experiment depends on the rectilineal propagation of light. Make a small hole in a closed window-shutter, before which stands a house or a tree, and place within the darkened room a white screen at some distance from the orifice. Every straight ray proceeding from the house, or tree, stamps its colour upon the screen, and the sum of all the rays will, therefore, be an image of the object. But, as the rays cross each other at the orifice, the image is inverted. At present we may illustrate and expand the subject thus: In front of our camera is a large opening (L, fig. 2), from which the lens has been removed, and which is closed at present by a sheet of tin-foil. Pricking by means of a common sewing-needle a small aperture in the tin-foil, an inverted image of the carbon-points starts forth upon the screen. A dozen apertures will give a dozen images, a hundred a hundred, a thousand a thousand. But, as the apertures come closer to each other, that is to say, as the tin-foil between the apertures vanishes, the images overlap more and more. Removing the tin-foil altogether, the screen becomes uniformly illuminated. Hence the light upon the screen may be regarded as the overlapping of innumerable images of the carbon-points. In like manner the light upon every white wall, on a cloudless day, may be regarded as produced by the superposition of innumerable images of the sun.

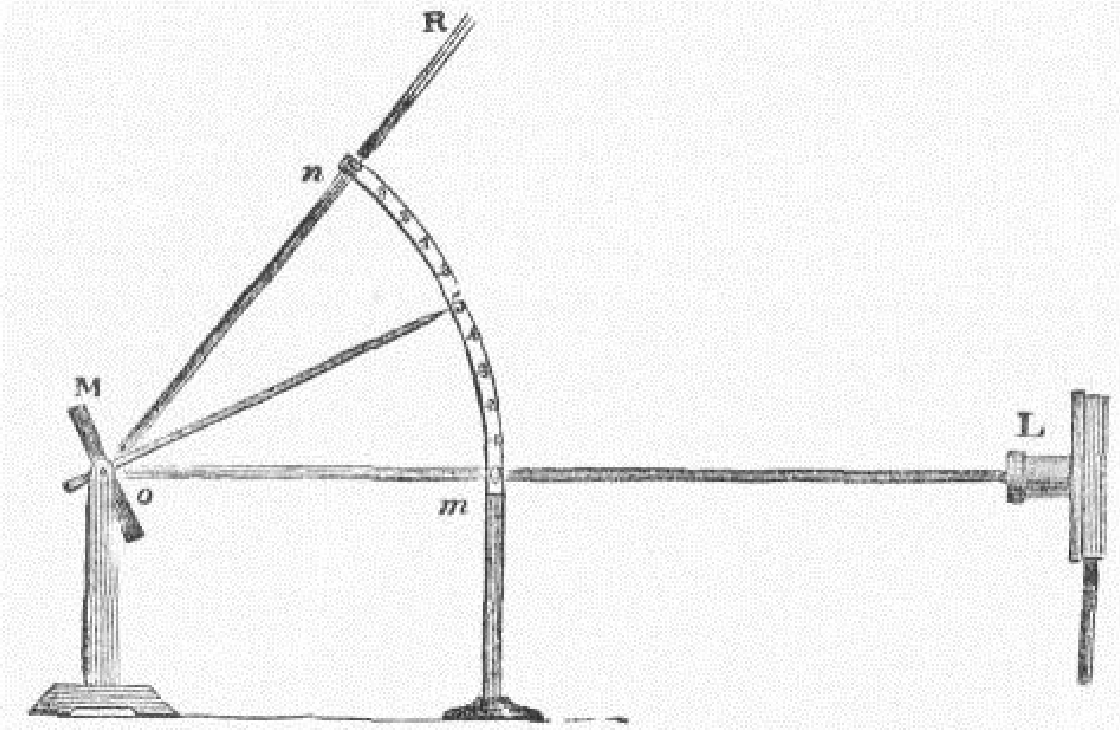


Fig. 3.

The law that the angle of incidence is equal to the angle of reflection has a bearing upon theory, to be subsequently mentioned, which renders its simple illustration here desirable. A straight lath (pointing to the figure 5 on the arc in fig. 3) is fixed as an index perpendicular to a small looking-glass (M), capable of rotation. We begin by receiving a beam of light upon the glass which is reflected back along the line of its incidence. The index being then turned, the mirror turns with it, and at each side of the index the incident and the reflected beams (L *o*, *o* R) track themselves through the dust of the room. The mere inspection of the two angles enclosed between the index and the two beams suffices to show their equality; while if the graduated arc be consulted, the arc from 5 to *m* is found accurately equal to the arc from 5 to *n*. The complete expression of the law of reflection is, not only that the angles of incidence and reflection are equal, but that the incident and reflected rays always lie in a plane perpendicular to the reflecting surface.

This simple apparatus enables us to illustrate another law of great practical importance, namely, that when a mirror rotates, the angular velocity of a beam reflected from it is twice that of the reflecting mirror. A simple experiment will make this plain. The arc (*m n*, fig. 3) before you is divided into ten equal parts, and when the incident beam and the index cross the zero of the graduation, both the incident and reflected beams are horizontal. Moving the index of the mirror to 1, the reflected beam cuts the arc at 2; moving the index to 2, the arc is cut at 4; moving the index to 3, the arc is cut at 6; moving the index at 4, the arc is cut at 8; finally, moving the index to 5, the arc is cut at 10 (as in the figure). In every case the reflected beam moves through twice the angle passed over by the mirror.

One of the principal problems of science is to help the senses of man, by carrying them into regions which could never be attained without that help. Thus we arm the eye with the telescope when we want to sound the depths of space, and with the microscope when we want to explore motion and structure in their infinitesimal dimensions. Now, this law of angular reflection, coupled with the fact that a beam of light possesses no weight, gives us the means of magnifying small motions to an extraordinary degree. Thus, by attaching mirrors to his suspended magnets, and by watching the images of divided scales reflected from the mirrors, the celebrated Gauss was able to detect the slightest thrill of variation on the part of the earth's magnetic force. By a similar arrangement the feeble attractions and repulsions of the diamagnetic force have been made manifest. The minute elongation of a bar of metal, by the mere warmth of the hand, may be so magnified by this method, as to cause the index-beam to move through 20 or 30 feet. The lengthening of a bar of iron when it is magnetized may be also thus demonstrated. Helmholtz long ago employed this method of rendering evident to his students the classical experiments of Du Bois Raymond on animal electricity; while in Sir William Thomson's reflecting galvanometer the principle receives one of its latest and most important applications.

§ 4. *The Refraction of Light. Total Reflection*

For more than a thousand years no step was taken in optics beyond this law of reflection. The men of the Middle Ages, in fact, endeavoured, on the one hand, to develop the laws of the universe *à priori* out of their own consciousness, while many of them were so occupied with the concerns of a future world that they looked with a lofty scorn on all things pertaining to this one. Speaking of the natural philosophers of his time, Eusebius says, 'It is not through ignorance of the things admired by them, but through contempt of their useless labour, that we think little of these matters, turning our souls to the exercise of better things.' So also Lactantius—'To search for the causes of things; to inquire whether the sun be as large as he seems; whether the moon is convex or concave; whether the stars are fixed in the sky, or float freely in the air; of what size and of what material are the heavens; whether they be at rest or in motion; what is the magnitude of the earth; on what foundations is it suspended or balanced;—to dispute and conjecture upon such matters is just as if we chose to discuss what we think of a city in a remote country, of which we never heard but the name.'

As regards the refraction of light, the course of real inquiry was resumed in 1100 by an Arabian philosopher named Alhazen. Then it was taken up in succession by Roger Bacon, Vitellio, and Kepler. One of the most important occupations of science is the determination, by precise measurements, of the quantitative relations of phenomena; the value of such measurements depending greatly upon the skill and conscientiousness of the man who makes them. Vitellio appears to have been both skilful and conscientious, while Kepler's habit was to rummage through the observations of his predecessors, to look at them in all lights, and thus distil from them the principles which united them. He had done this with the astronomical measurements of Tycho Brahe, and had extracted from them the celebrated 'laws of Kepler.' He did it also with Vitellio's measurements of refraction. But in this case he was not successful. The principle, though a simple one, escaped him, and it was first discovered by Willebrord Snell, about the year 1621.

Less with the view of dwelling upon the phenomenon itself than of introducing it in a form which will render subsequently intelligible to you the play of theoretic thought in Newton's mind, the fact of refraction may be here demonstrated. I will not do this by drawing the course of the beam with chalk on a black board, but by causing it to mark its own white track before you. A shallow circular vessel (RIG, fig. 4), half filled with water, rendered slightly turbid by the admixture of a little milk, or the precipitation of a little mastic, is placed with its glass front vertical. By means of a small plane reflector (M), and through a slit (I) in the hoop surrounding the vessel, a beam of light is admitted in any required direction. It impinges upon the water (at O), enters it, and tracks itself through the liquid in a sharp bright band (O G). Meanwhile the beam passes unseen through the air above the water, for the air is not competent to scatter the light. A puff of smoke into this space at once reveals the track of the incident-beam. If the incidence be vertical, the beam is unrefracted. If oblique, its refraction at the common surface of air and water (at O) is rendered clearly visible. It is also seen that *reflection* (along O R) accompanies refraction, the beam dividing itself at the point of incidence into a refracted and a reflected portion.[4]

[4] It will be subsequently shown how this simple apparatus may be employed to determine the 'polarizing angle' of a liquid.

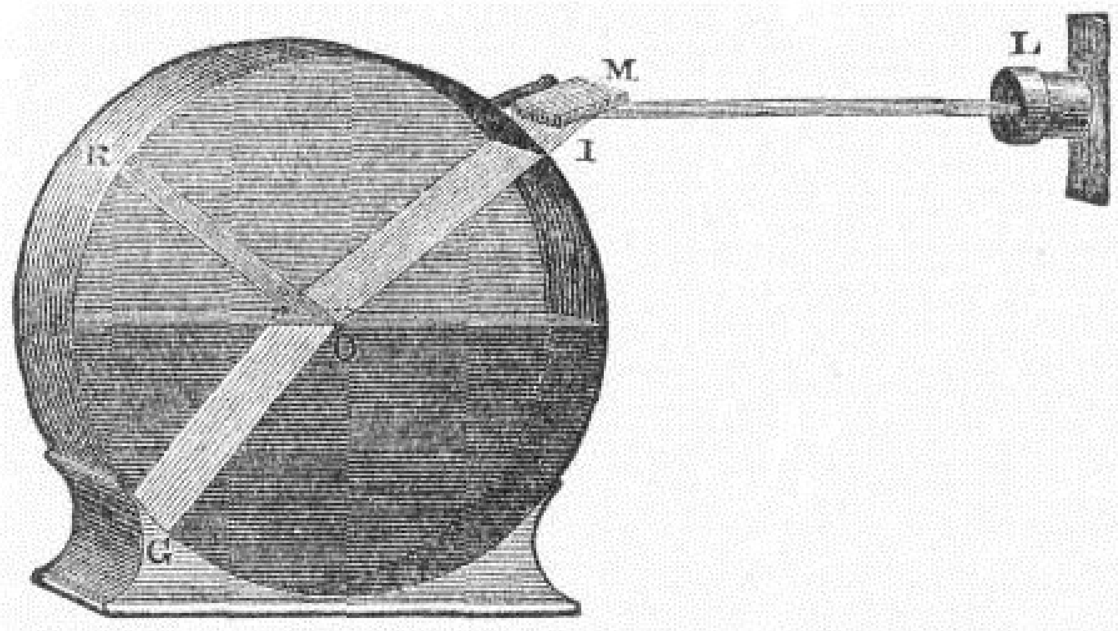


Fig. 4.

The law by which Snell connected together all the measurements executed up to his time, is this: Let A B C D (fig. 5) represent the outline of our circular vessel, A C being the water-line. When the beam is incident along B E, which is perpendicular to A C, there is no refraction. When it is incident along *m* E, there is refraction: it is bent at E and strikes the circle at *n*. When it is incident along *m'* E there is also refraction at E, the beam striking the point *n'*. From the ends of the two incident beams, let the perpendiculars *m o*, *m' o'* be drawn upon B D, and from the ends of the refracted beams let the perpendiculars *p n*, *p' n'* be also drawn. Measure the lengths of *o m* and of *p n*, and divide the one by the other. You obtain a certain quotient. In like manner divide *m' o'* by the corresponding perpendicular *p' n'*; you obtain precisely the same quotient. Snell, in fact, found this quotient to be *a constant quantity* for each particular substance, though it varied in amount from one substance to another. He called the quotient the *index of refraction*.

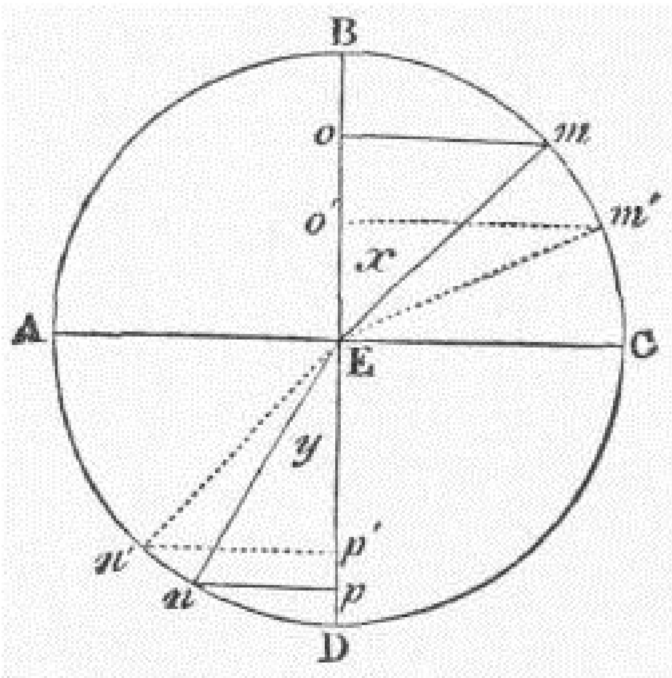
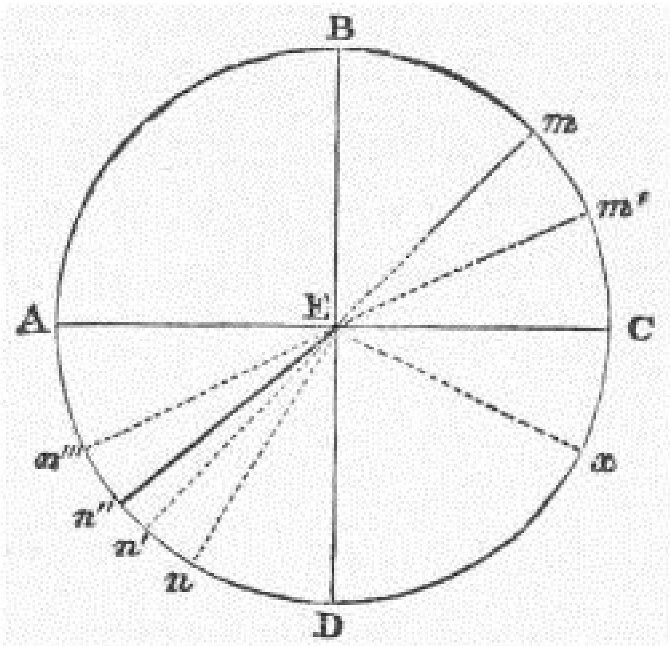


Fig. 5

In all cases where the light is incident from air upon the surface of a solid or a liquid, or, to speak more generally, when the incidence is from a less highly refracting to a more highly refracting medium, the reflection is *partial*. In this case the most powerfully reflecting substances either transmit or absorb a portion of the incident light. At a perpendicular incidence water reflects only 18 rays out of every 1,000; glass reflects only 25 rays, while mercury reflects 666 When the rays strike the surface obliquely the reflection is augmented. At an incidence of 40°, for example, water reflects 22 rays, at 60° it reflects 65 rays, at 80° 333 rays; while at an incidence of 89½°, where the light almost grazes the surface, it reflects 721 rays out of every 1,000. Thus, as the obliquity increases, the reflection from water approaches, and finally quite overtakes, the perpendicular reflection from mercury; but at no incidence, however great, when the incidence is from air, is the reflection from water, mercury, or any other substance, *total*.

Still, total reflection may occur, and with a view to understanding its subsequent application in the Nicol's prism, it is necessary to state when it occurs. This leads me to the enunciation of a principle which underlies all optical phenomena—the principle of reversibility.[5] In the case of refraction, for instance, when the ray passes obliquely from air into water, it is bent *towards* the perpendicular; when it passes from water to air, it is bent *from* the perpendicular, and accurately reverses its course. Thus in fig. 5, if *m* E *n* be the track of a ray in passing from air into water, *n* E *m* will be its track in passing from water into air. Let us push this principle to its consequences. Supposing the light, instead of being incident along *m* E or *m′* E, were incident as close as possible along C E (fig. 6); suppose, in other words, that it just grazes the surface before entering the water. After refraction it will pursue say the course E *n″*. Conversely, if the light start from *n″*, and be incident at E, it will, on escaping into the air, just graze the surface of the water. The question now arises, what will occur supposing the ray from the water to follow the course *n‴* E, which lies beyond *n″* E? The answer is, it will not quit the water at all, but will be *totally* reflected (along E *x*). At the under surface of the water, moreover, the law is just the same as at its upper surface, the angle of incidence (D E *n‴*) being equal to the angle of reflection (D E *x*).



[5] From this principle Sir John Herschel deduces in a simple and elegant manner the fundamental law of reflection.—See *Familiar Lectures*, p. 236.

Fig. 6

Total reflection may be thus simply illustrated:—Place a shilling in a drinking-glass, and tilt the glass so that the light from the shilling shall fall with the necessary obliquity upon the water surface above it. Look upwards through the water towards that surface, and you see the image of the shilling shining there as brightly as the shilling itself. Thrust the closed end of an empty test-tube into water, and incline the tube. When the inclination is sufficient, horizontal light falling upon the tube cannot enter the air within it, but is totally reflected upward: when looked down upon, such a tube looks quite as bright as burnished silver. Pour a little water into the tube; as the liquid rises, total reflection is abolished, and with it the lustre, leaving a gradually diminishing shining zone, which disappears wholly when the level of the water within the tube reaches that without it. Any glass tube, with its end stopped water-tight, will produce this effect, which is both beautiful and instructive.

Total reflection never occurs except in the attempted passage of a ray from a more refracting to a less refracting medium; but in this case, when the obliquity is sufficient, it always occurs. The mirage of the desert, and other phantasmal appearances in the atmosphere, are in part due to it. When, for example, the sun heats an expanse of sand, the layer of air in contact with the sand becomes lighter and less refracting than the air above it: consequently, the rays from a distant object, striking very obliquely on the surface of the heated stratum, are sometimes totally reflected upwards, thus producing images similar to those produced by water. I have seen the image of a rock called Mont Tombeline distinctly reflected from the heated air of the strand of Normandy near Avranches; and by such delusive appearances the thirsty soldiers of the French army in Egypt were greatly tantalised.

The angle which marks the limit beyond which total reflection takes place is called the *limiting angle* (it is marked in fig. 6 by the strong line E *n″*). It must evidently diminish as the refractive index increases. For water it is 48½°, for flint glass 38°41', and for diamond 23°42'. Thus all the light incident from two complete quadrants, or 180°, in the case of diamond, is condensed into an angular space of 47°22' (twice 23°42') by refraction. Coupled with its great refraction, are the great dispersive and great reflective powers of diamond; hence the extraordinary radiance of the gem, both as regards white light and prismatic light.

§ 5. *Velocity of Light. Aberration. Principle of least Action*

In 1676 a great impulse was given to optics by astronomy. In that year Olav Roemer, a learned Dane, was engaged at the Observatory of Paris in observing the eclipses of Jupiter's moons. The planet, whose distance from the sun is 475,693,000 miles, has four satellites. We are now only concerned with the one nearest to the planet. Roemer watched this moon, saw it move round the planet, plunge into Jupiter's shadow, behaving like a lamp suddenly extinguished: then at the other edge of the shadow he saw it reappear, like a lamp suddenly lighted. The moon thus acted the part of a signal light to the astronomer, and enabled him to tell exactly its time of revolution. The period between two successive lightings up of the lunar lamp he found to be 42 hours, 28 minutes, and 35 seconds.

This measurement of time was so accurate, that having determined the moment when the moon emerged from the shadow, the moment of its hundredth appearance could also be determined. In fact, it would be 100 times 42 hours, 28 minutes, 35 seconds, after the first observation.

Roemer's first observation was made when the earth was in the part of its orbit nearest Jupiter. About six months afterwards, the earth being then at the opposite side of its orbit, when the little moon ought to have made its hundredth appearance, it was found unpunctual, being fully 15 minutes behind its calculated time. Its appearance, moreover, had been growing gradually later, as the earth retreated towards the part of its orbit most distant from Jupiter. Roemer reasoned thus: 'Had I been able to remain at the other side of the earth's orbit, the moon might have appeared always at the proper instant; an observer placed there would probably have seen the moon 15 minutes ago, the retardation in my case being due to the fact that the light requires 15 minutes to travel from the place where my first observation was made to my present position.'

This flash of genius was immediately succeeded by another. 'If this surmise be correct,' Roemer reasoned, 'then as I approach Jupiter along the other side of the earth's orbit, the retardation ought to become gradually less, and when I reach the place of my first observation, there ought to be no retardation at all.' He found this to be the case, and thus not only proved that light required time to pass through space, but also determined its rate of propagation.

The velocity of light, as determined by Roemer, is 192,500 miles in a second.

For a time, however, the observations and reasonings of Roemer failed to produce conviction. They were doubted by Cassini, Fontenelle, and Hooke. Subsequently came the unexpected corroboration of Roemer by the English astronomer, Bradley, who noticed that the fixed stars did not really appear to be fixed, but that they describe little orbits in the heavens every year. The result perplexed him, but Bradley had a mind open to suggestion, and capable of seeing, in the smallest fact, a picture of the largest. He was one day upon the Thames in a boat, and noticed that as long as his course remained unchanged, the vane upon his masthead showed the wind to be blowing constantly in the same direction, but that the wind appeared to vary with every change in the direction of his boat. 'Here,' as Whewell says, 'was the image of his case. The boat was the earth, moving in its orbit, and the wind was the light of a star.'

We may ask, in passing, what, without the faculty which formed the 'image,' would Bradley's wind and vane have been to him? A wind and vane, and nothing more. You will immediately understand the meaning of Bradley's discovery. Imagine yourself in a motionless railway-train, with a shower of rain descending vertically downwards. The moment the train begins to move, the rain-drops begin to slant, and the quicker the motion of the train the greater is the obliquity. In a precisely similar manner the rays from a star, vertically overhead, are caused to slant by the motion of the earth through space. Knowing the speed of the train, and the obliquity of the falling rain, the velocity of the drops may be calculated; and knowing the speed of the earth in her orbit, and the obliquity of the rays due to this cause, we can calculate just as easily the velocity of light. Bradley did this, and the 'aberration of light,' as his discovery is called, enabled him to assign to it a velocity almost identical with that deduced by Roemer from a totally different method of observation. Subsequently Fizeau, and quite recently Cornu, employing not planetary or stellar distances, but simply the breadth of the city of Paris, determined the velocity of light: while Foucault—a man of the rarest mechanical genius—solved the problem without quitting his private room. Owing to an error in the determination of the earth's distance from the sun, the velocity assigned to light by both Roemer and Bradley is too great. With a close approximation to accuracy it may be regarded as 186,000 miles a second.

By Roemer's discovery, the notion entertained by Descartes, and espoused by Hooke, that light is propagated instantly through space, was overthrown. But the establishment of its motion through stellar space led to speculations regarding its velocity in transparent terrestrial substances. The 'index of refraction' of a ray passing from air into water is 4/3. Newton assumed these numbers to mean that the velocity of light in water being 4, its velocity in air is 3; and he deduced the phenomena of refraction from this assumption. Huyghens took the opposite and truer view. According to this great man, the velocity of light in water being 3, its velocity in air is 4; but both in Newton's time and ours the same great principle determined, and determines, the course of light in all cases. In passing from point to point, whatever be the media in its path, or however it may be refracted or reflected, light takes the course which occupies *least time*. Thus in fig. 4, taking its velocity in air and in water into account, the light reaches G from I more rapidly by travelling first to O, and there changing its course, than if it proceeded straight from I to G. This is readily comprehended, because, in the latter case, it would pursue a greater distance through the water, which is the more retarding medium.

§ 6. *Descartes' Explanation of the Rainbow*

Snell's law of refraction is one of the corner-stones of optical science, and its applications to-day are million-fold. Immediately after its discovery Descartes applied it to the explanation of the rainbow. A beam of solar light falling obliquely upon a rain-drop is refracted on entering the drop. It is in part reflected at the back of the drop, and on emerging it is again refracted. By these two refractions, and this single reflection, the light is sent to the eye of an observer facing the drop, and with his back to the sun.

Conceive a line drawn from the sun, through the back of his head, to the observer's eye and prolonged beyond it. Conceive a second line drawn from the shower to the eye, and enclosing an angle of 42½° with the line drawn from the sun. Along this second line a rain-drop when struck by a sunbeam will send red light to the eye. Every other drop similarly situated, that is, every drop at an angular distance of 42½° from the line through the sun and eye, will do the same. A circular band of red light is thus formed, which may be regarded as the boundary of the base of a cone, with its apex at the observer's eye. Because of the magnitude of the sun, the angular width of this red band will be half a degree.

From the eye of the observer conceive another line to be drawn, enclosing an angle, not of 42½ °, but of 40½°, with the prolongation of the line drawn from the sun. Along this other line a rain-drop, at its remote end, when struck by a solar beam, will send violet light to the eye. All drops at the same angular distance will do the same, and we shall therefore obtain a band of violet light of the same width as the red band. These two bands constitute the limiting colours of the rainbow, and between them the bands corresponding to the other colours lie.

Thus the line drawn from the eye to the *middle* of the bow, and the line drawn through the eye to the sun, always enclose an angle of about 41°. To account for this was the great difficulty, which remained unsolved up to the time of Descartes.

Taking a pen in hand, and calculating by means of Snell's law the track of every ray through a raindrop, Descartes found that, at one particular angle, the rays, reflected at its back, emerged from the drop *almost parallel to each other*. They were thus enabled to preserve their intensity through long atmospheric distances. At all other angles the rays quitted the drop *divergent*, and through this divergence became so enfeebled as to be practically lost to the eye. The angle of parallelism here referred to was that of forty-one degrees, which observation had proved to be invariably associated with the rainbow.

From what has been said, it is clear that two observers standing beside each other, or one above the other, nay, that even the two eyes of the same observer, do not see exactly the same bow. The position of the base of the cone changes with that of its apex. And here we have no difficulty in answering a question often asked—namely, whether a rainbow is ever seen reflected in water. Seeing two bows, the one in the heavens, the other in the water, you might be disposed to infer that the one bears the same relation to the other that a tree upon the water's edge bears to its reflected image. The rays, however, which reach an observer's eye after reflection from the water, and which form a bow in the water, would, were their course from the shower uninterrupted, converge to a point vertically under the observer, and as far below the level of the water as his eye is above it. But under no circumstances could an eye above the water-level and one below it see the same bow—in other words, the self-same drops of rain cannot form the reflected bow and the bow seen directly in the heavens. The reflected bow, therefore, is not, in the usual optical sense of the term, the *image* of the bow seen in the sky.

§ 7. *Analysis and Synthesis of Light. Doctrine of Colours*

In the rainbow a new phenomenon was introduced—the phenomenon of colour. And here we arrive at one of those points in the history of science, when great men's labours so intermingle that it is difficult to assign to each worker his precise meed of honour. Descartes was at the threshold of the discovery of the composition of solar light; but for Newton was reserved the enunciation of the true law. He went to work in this way: Through the closed window-shutter of a room he pierced an orifice, and allowed a thin sunbeam to pass through it. The beam stamped a round white image of the sun on the opposite wall of the room. In the path of this beam Newton placed a prism, expecting to see the beam refracted, but also expecting to see the image of the sun, after refraction, still round. To his astonishment, it was drawn out to an image with a length five times its breadth. It was, moreover, no longer white, but divided into bands of different colours. Newton saw immediately that solar light was *composite*, not simple. His elongated image revealed to him the fact that some constituents of the light were more deflected by the prism than others, and he concluded, therefore, that white light was a mixture of lights of different colours, possessing different degrees of refrangibility.

Let us reproduce this celebrated experiment. On the screen is now stamped a luminous disk, which may stand for Newton's image of the sun. Causing the beam (from the aperture L, fig. 7) which produces the disk to pass through a lens (E), we form a sharp image of the aperture. Placing in the track of the beam a prism (P), we obtain Newton's coloured image, with its red and violet ends, which he called a *spectrum*. Newton divided the spectrum into seven parts—red, orange, yellow, green, blue, indigo, violet; which are commonly called the seven primary or prismatic colours. The drawing out of the white light into its constituent colours is called *dispersion*.

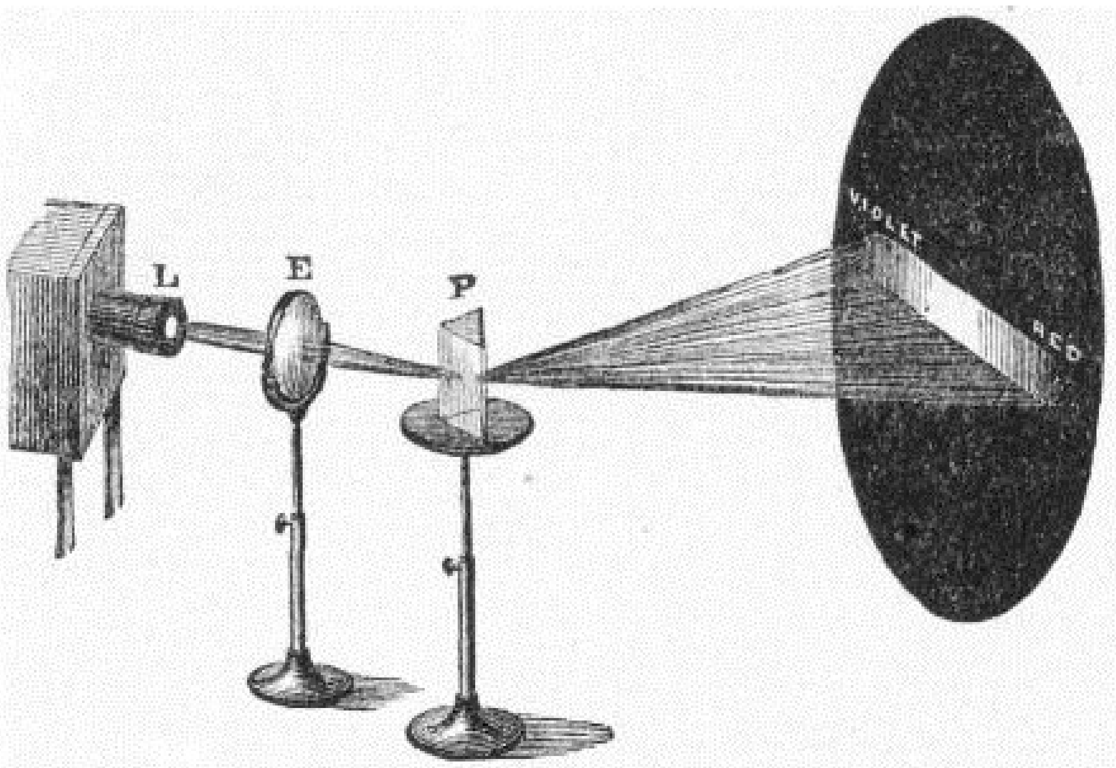


Fig. 7.

This was the first *analysis* of solar light by Newton; but the scientific mind is fond of verification, and never neglects it where it is possible. Newton completed his proof by *synthesis* in this way: The spectrum now before you is produced by a glass prism. Causing the decomposed beam to pass through a second similar prism, but so placed that the colours are refracted back and reblended, the perfectly white luminous disk is restored.

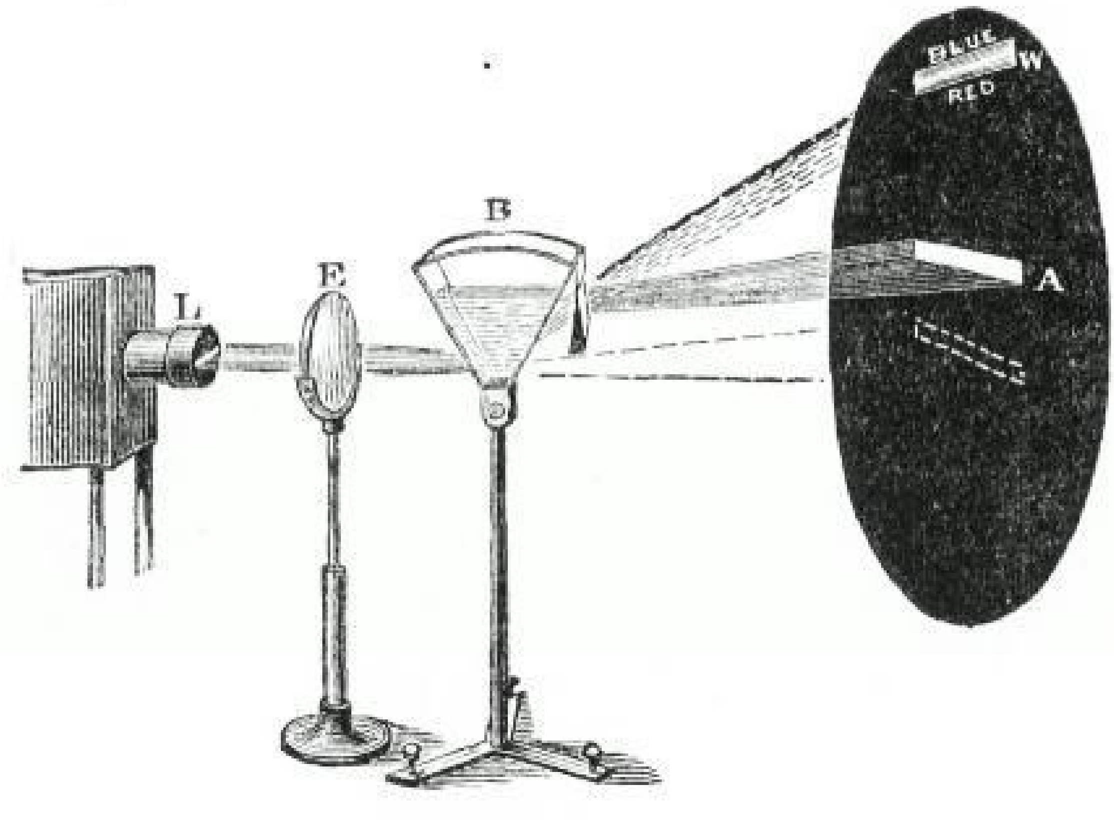


Fig. 8.

In this case, refraction and dispersion are simultaneously abolished. Are they always so? Can we have the one without the other? It was Newton's conclusion that we could not. Here he erred, and his error, which he maintained to the end of his life, retarded the progress of optical discovery. Dollond subsequently proved that by combining two different kinds of glass, the colours can be extinguished, still leaving a residue of refraction, and he employed this residue in the construction of achromatic lenses—lenses yielding no colour—which Newton thought an impossibility. By setting a water-prism—water contained in a wedge-shaped vessel with glass sides (B, fig. 8)—in opposition to a wedge of glass (to the right of B), this point can be illustrated before you. We have first of all the position (dotted) of the unrefracted beam marked upon the screen; then we produce the narrow water-spectrum (W); finally, by introducing a flint-glass prism, we refract the beam back, until the colour disappears (at A). The image of the slit is now *white*; but though the dispersion is abolished, there remains a very sensible amount of refraction.

This is the place to illustrate another point bearing upon the instrumental means employed in these lectures. Bodies differ widely from each other as to their powers of refraction and dispersion. Note the position of the water-spectrum upon the screen. Altering in no particular the wedge-shaped vessel, but simply substituting for the water the transparent bisulphide of carbon, you notice how much higher the beam is thrown, and how much richer is the display of colour. To augment the size of our spectrum we here employ (at L) a slit, instead of a circular aperture.[6]

[6] The low dispersive power of water masks, as Helmholtz has remarked, the imperfect achromatism of the eye. With the naked eye I can see a distant blue disk sharply defined, but not a red one. I can also see the lines which mark the upper and lower boundaries

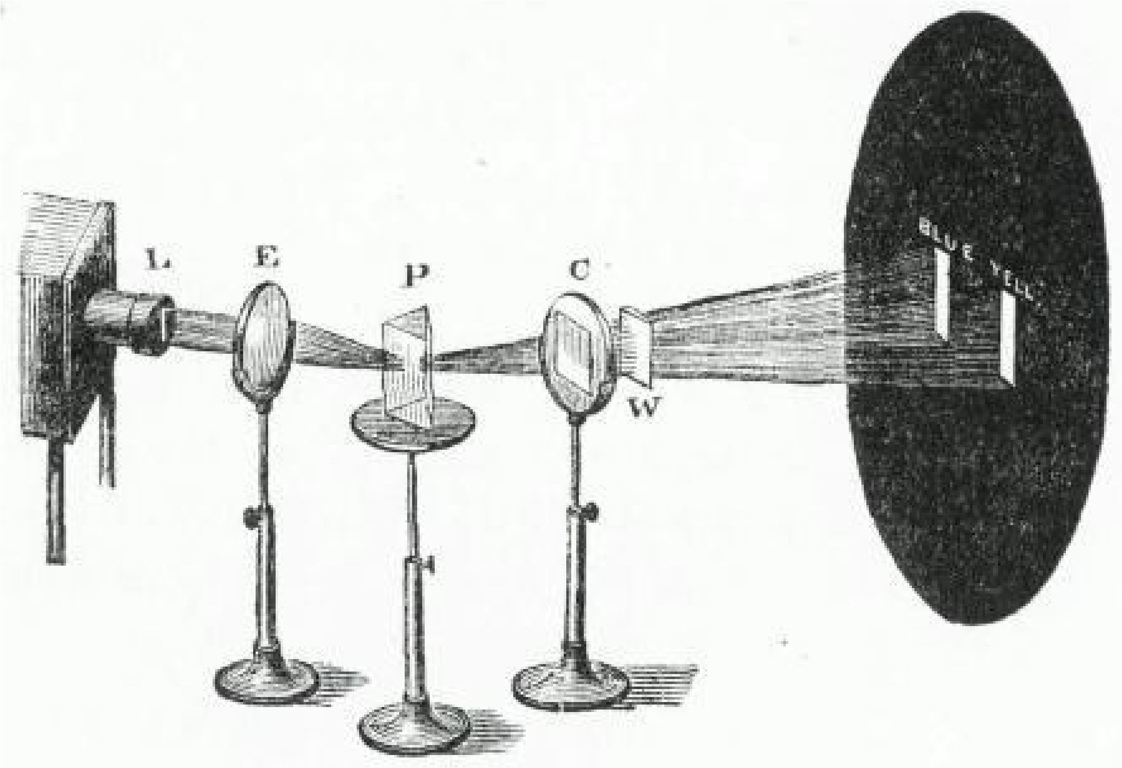


Fig. 9.

The synthesis of white light may be effected in three ways, all of which are worthy of attention: Here, in the first instance, we have a rich spectrum produced by the decomposition of the beam (from L, fig. 9). One face of the prism (P) is protected by a diaphragm (not shown in the figure), with a longitudinal slit, through which the beam passes into the prism. It emerges decomposed at the other side. I permit the colours to pass through a cylindrical lens (C), which so squeezes them together as to produce upon the screen a sharply defined rectangular image of the longitudinal slit. In that image the colours are reblended, and it is perfectly white. Between the prism and the cylindrical lens may be seen the colours, tracking themselves through the dust of the room. Cutting off the more refrangible fringe by a card, the rectangle is seen red: cutting off the less refrangible fringe, the rectangle is seen blue. By means of a thin glass prism (W), I deflect one portion of the colours, and leave the residual portion. On the screen are now two coloured rectangles produced in this way. These are *complementary* colours—colours which, by their union, produce white. Note, that by judicious management, one of these colours is rendered *yellow*, and the other *blue*. I withdraw the thin prism; yellow and blue immediately commingle, and we have *white* as the result of their union. On our way, then, we remove the fallacy, first exposed by Wünsch, and afterwards independently by Helmholtz, that the mixture of blue and yellow lights produces green.

Restoring the circular aperture, we obtain once more a spectrum like that of Newton. By means of a lens, we can gather up these colours, and build them together, not to an image of the aperture, but to an image of the carbon-points themselves.

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of a horizontally refracted spectrum sharp at the blue end, but ill-defined at the red end. Projecting a luminous disk upon a screen, and covering one semicircle of the aperture with a red and the other with a blue or green glass, the difference between the apparent sizes of the two semicircles is in my case, and in numerous other cases, extraordinary. Many persons, however, see the apparent sizes of the two semicircles reversed. If with a spectacle glass I correct the dispersion of the red light over the retina, then the blue ceases to give a sharply defined image. Thus examined, the departure of the eye from achromatism appears very gross indeed.

Finally, by means of a rotating disk, on which are spread in sectors the colours of the spectrum, we blend together the prismatic colours in the eye itself, and thus produce the impression of whiteness.

Having unravelled the interwoven constituents of white light, we have next to inquire, What part the constitution so revealed enables this agent to play in Nature? To it we owe all the phenomena of colour, and yet not to it alone; for there must be a certain relationship between the ultimate particles of natural bodies and white light, to enable them to extract from it the luxury of colour. But the function of natural bodies is here *selective*, not *creative*. There is no colour *generated* by any natural body whatever. Natural bodies have showered upon them, in the white light of the sun, the sum total of all possible colours; and their action is limited to the sifting of that total—the appropriating or absorbing of some of its constituents, and the rejecting of others. It will fix this subject in your minds if I say, that it is the portion of light which they reject, and not that which they appropriate or absorb, that gives bodies their colours.

Let us begin our experimental inquiries here by asking, What is the meaning of blackness? Pass a black ribbon through the colours of the spectrum; it quenches all of them. The meaning of blackness is thus revealed—it is the result of the absorption of all the constituents of solar light. Pass a red ribbon through the spectrum. In the red light the ribbon is a vivid red. Why? Because the light that enters the ribbon is not quenched or absorbed, but in great part sent back to the eye. Place the same ribbon in the green of the spectrum; it is black as jet. It absorbs the green light, and renders the space on which that light falls a space of intense darkness. Place a green ribbon in the green of the spectrum. It shines vividly with its proper colour; transfer it to the red, it is black as jet. Here it absorbs all the light that falls upon it, and offers mere darkness to the eye.

Thus, when white light is employed, the red sifts it by quenching the green, and the green sifts it by quenching the red, both exhibiting the residual colour. The process through which natural bodies acquire their colours is therefore a *negative* one. The colours are produced by subtraction, not by addition. This red glass is red because it destroys all the more refrangible rays of the spectrum. This blue liquid is blue because it destroys all the less refrangible rays. Both together are opaque because the light transmitted by the one is quenched by the other. In this way, by the union of two transparent substances, we obtain a combination as dark as pitch to solar light. This other liquid, finally, is purple because it destroys the green and the yellow, and allows the terminal colours of the spectrum to pass unimpeded. From the blending of the blue and the red this gorgeous purple is produced.

One step further for the sake of exactness. The light which falls upon a body is divided into two portions, one of which is reflected from the surface of the body; and this is of the same colour as the incident light. If the incident light be white, the superficially reflected light will also be white. Solar light, for example, reflected from the surface of even a black body, is white. The blackest camphine smoke in a dark room, through which a sunbeam passes from an aperture in the window-shutter, renders the track of the beam white, by the light scattered from the surfaces of the soot particles. The moon appears to us as if

> 'Clothed in white samite, mystic, wonderful;'

but were it covered with the blackest velvet it would still hang as a white orb in the heavens, shining upon our world substantially as it does now.

§ 8. *Colours of Pigments as distinguished from Colours of Light*

The second portion of the incident light enters the body, and upon its treatment there the colour of the body depends. And here a moment may properly be given to the analysis of the action of pigments upon light. They are composed of fine particles mixed with a vehicle; but how intimately soever the particles may be blended, they still remain particles, separated, it may be, by exceedingly minute distances, but still separated. To use the scientific phrase, they are not optically continuous. Now, wherever optical continuity is ruptured we have reflection of the incident light. It is the multitude of reflections at the limiting surfaces of the particles that prevents light from passing through snow, powdered glass, or common salt. The light here is exhausted in echoes, not extinguished by true absorption. It is the same kind of reflection that renders the thunder-cloud so impervious to light. Such a cloud is composed of particles of water, mixed with particles of air, both separately transparent, but practically opaque when thus mixed together.

In the case of pigments, then, the light is *reflected* at the limiting surfaces of the particles, but it is in part *absorbed* within the particles. The reflection is necessary to send the light back to the eye; the absorption is necessary to give the body its colour. The same remarks apply to flowers. The rose is red, in virtue, not of the light reflected from its surface, but of light which has entered its substance, which has been reflected from surfaces within, and which, in returning *through* the substance, has had its green extinguished. A similar process in the case of hard green leaves extinguishes the red, and sends green light from the body of the leaves to the eye.

All bodies, even the most transparent, are more or less absorbent of light. Take the case of water. A glass cell of clear water interposed in the track of our beam does not perceptibly change any one of the colours of the spectrum. Still absorption, though insensible, has here occurred, and to render it sensible we have only to increase the depth of the water through which the light passes. Instead of a cell an inch thick, let us take a layer, ten or fifteen feet thick: the colour of the water is then very evident. By augmenting the thickness we absorb more of the light, and by making the thickness very great we absorb the light altogether. Lampblack or pitch can do no more, and the only difference in this respect between them and water is that a very small depth in their case suffices to extinguish all the light. The difference between the highest known transparency and the highest known opacity is one of degree merely.

If, then, we render water sufficiently deep to quench all the light; and if from the interior of the water no light reaches the eye, we have the condition necessary to produce blackness. Looked properly down upon, there are portions of the Atlantic Ocean to which one would hardly ascribe a trace of colour: at the most a tint of dark indigo reaches the eye. The water, in fact, is practically *black*, and this is an indication both of its depth and purity. But the case is entirely changed when the ocean contains solid particles in a state of mechanical suspension, capable of sending the light impinging on them back to the eye.

Throw, for example, a white pebble, or a white dinner plate, into the blackest Atlantic water; as it sinks it becomes greener and greener, and, before it disappears, it reaches a vivid blue green. Break such a pebble, or plate, into fragments, these will behave like the unbroken mass: grind the pebble to powder, every particle will yield its modicum of green; and if the particles be so fine as to remain suspended in the water, the scattered light will be a uniform green. Hence the greenness of shoal water. You go to bed with the black water of the Atlantic around you. You rise in the morning, find it a vivid green, and correctly infer that you are crossing the Bank of Newfoundland. Such water is found charged with fine matter in a state of mechanical suspension. The light from the bottom may sometimes come into play, but it is not necessary. The subaqueous foam, generated by the screw or paddle-wheels of a steamer, also sends forth a vivid green. The foam here furnishes a *reflecting surface*, the water between the eye and it the *absorbing medium*.

Nothing can be more superb than the green of the Atlantic waves when the circumstances are favourable to the exhibition of the colour. As long as a wave remains unbroken no colour appears, but when the foam just doubles over the crest like an Alpine snow-cornice, under the cornice we often see a display of the most exquisite green. It is metallic in its brilliancy. The foam is first illuminated, and it scatters the light in all directions; the light which passes through the higher portion of the wave alone reaches the eye, and gives to that portion its matchless colour. The folding of the wave, producing, as it does, a series of longitudinal protuberances and furrows which act like cylindrical lenses, introduces variations in the intensity of the light, and materially enhances its beauty.

We are now prepared for the further consideration of a point already adverted to, and regarding which error long found currency. You will find it stated in many books that blue light and yellow light mixed together, produce green. But blue and yellow have been just proved to be complementary colours, producing white by their mixture. The mixture of blue and yellow *pigments* undoubtedly produces green, but the mixture of pigments is a totally different thing from the mixture of lights.

Helmholtz has revealed the cause of the green produced by a mixture of blue and yellow pigments. No natural colour is *pure*. A blue liquid, or a blue powder, permits not only the blue to pass through it, but a portion of the adjacent green. A yellow powder is transparent not only to the yellow light, but also in part to the adjacent green. Now, when blue and yellow are mixed together, the blue cuts off the yellow, the orange, and the red; the yellow, on the other hand, cuts off the violet, the indigo, and the blue. Green is the only colour to which both are transparent, and the consequence is that, when white light falls upon a mixture of yellow and blue powders, the green alone is sent back to the eye. You have already seen that the fine blue ammonia-sulphate of copper transmits a large portion of green, while cutting off all the less refrangible light. A yellow solution of picric acid also allows the green to pass, but quenches all the more refrangible light. What must occur when we send a beam through both liquids? The experimental answer to this question is now before you: the green band of the spectrum alone remains upon the screen.

The impurity of natural colours is strikingly illustrated by an observation recently communicated to me by Mr. Woodbury. On looking through a blue glass at green leaves in sunshine, he saw the superficially reflected light blue. The light, on the contrary, which came from the body of the leaves was crimson. On examination, I found that the glass employed in this observation transmitted both ends of the spectrum, the red as well as the blue, and that it quenched the middle. This furnished an easy explanation of the effect. In the delicate spring foliage the blue of the solar light is for the most part absorbed, and a light, mainly yellowish green, but containing a considerable quantity of red, escapes from the leaf to the eye. On looking at such foliage through the violet glass, the green and the yellow are stopped, and the red alone reaches the eye. Thus regarded, therefore, the leaves appear like faintly blushing roses, and present a very beautiful appearance. With the blue ammonia-sulphate of copper, which transmits no red, this effect is not obtained.

As the year advances the crimson gradually hardens to a coppery red; and in the dark green leaves of old ivy it is almost absent. Permitting a beam of white light to fall upon fresh leaves in a dark room, the sudden change from green to red, and from red back to green, when the violet glass is alternately introduced and withdrawn, is very surprising. Looked at through the same glass, the meadows in May appear of a warm purple. With a solution of permanganate of potash, which, while it quenches the centre of the spectrum, permits its ends to pass more freely than the violet glass, excellent effects are also obtained.[7]

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[7] Both in foliage and in flowers there are striking differences of absorption. The copper beech and the green beech, for example, take in different rays. But the very growth of the tree is due to some of the rays thus taken in. Are the chemical rays, then, the same in the copper and the green beech? In two such flowers as the primrose and the violet, where the absorptions, to judge by the colours, are almost complementary, are the chemically active rays the same? The general relation of colour to chemical action is worthy of the application of the method by which Dr. Draper proved so conclusively the chemical potency of the yellow rays of the sun.

This question of absorption, considered with reference to its molecular mechanism, is one of the most subtle and difficult in physics. We are not yet in a condition to grapple with it, but we shall be by-and-by. Meanwhile we may profitably glance back on the web of relations which these experiments reveal to us. We have, firstly, in solar light an agent of exceeding complexity, composed of innumerable constituents, refrangible in different degrees. We find, secondly, the atoms and molecules of bodies gifted with the power of sifting solar light in the most various ways, and producing by this sifting the colours observed in nature and art. To do this they must possess a molecular structure commensurate in complexity with that of light itself. Thirdly, we have the human eye and brain, so organized as to be able to take in and distinguish the multitude of impressions thus generated. The light, therefore, at starting is complex; to sift and select it as they do, natural bodies must be complex; while to take in the impressions thus generated, the human eye and brain, however we may simplify our conceptions of their action,[8] must be highly complex.

Whence this triple complexity? If what are called material purposes were the only end to be served, a much simpler mechanism would be sufficient. But, instead of simplicity, we have prodigality of relation and adaptation—and this, apparently, for the sole purpose of enabling us to see things robed in the splendours of colour. Would it not seem that Nature harboured the intention of educating us for other enjoyments than those derivable from meat and drink? At all events, whatever Nature meant—and it would be mere presumption to dogmatize as to what she meant—we find ourselves here, as the upshot of her operations, endowed, not only with capacities to enjoy the materially useful, but endowed with others of indefinite scope and application, which deal alone with the beautiful and the true.

[8] Young, Helmholtz, and Maxwell reduce all differences of hue to combinations in different proportions of three primary colours. It is demonstrable by experiment that from the red, green, and violet *all* the other colours of the spectrum may be obtained.Some years ago Sir Charles Wheatstone drew my attention to a work by Christian Ernst Wünsch, Leipzig 1792, in which the author announces the proposition that there are neither five nor seven, but only three simple colours in white light. Wünsch produced five spectra, with five prisms and five small apertures, and he mixed the colours first in pairs, and afterwards in other ways and proportions. His result is that red is a *simple* colour incapable of being decomposed; that orange is compounded of intense red and weak green; that yellow is a mixture of intense red and intense green; that green is a *simple* colour; that blue is compounded of saturated green and saturated violet; that indigo is a mixture of saturated violet and weak green; while violet is a pure *simple* colour. He also finds that yellow and indigo blue produce *white* by their mixture. Yellow mixed with bright blue (Hochblau) also produces white, which seems, however, to have a tinge of green, while the pigments of these two colours when mixed always give a more or less beautiful green, Wünsch very emphatically distinguishes the mixture of pigments from that of lights. Speaking of the generation of yellow, he says, 'I say expressly *red and green light*, because I am speaking about light-colours (Lichtfarben), and not about pigments.' However faulty his theories may be, Wünsch's experiments appear in the main to be precise and conclusive. Nearly ten years subsequently, Young adopted red, green, and violet as the three primary colours, each of them capable of producing three sensations, one of which, however, predominates over the two others. Helmholtz adopts, elucidates, and enriches this notion. (*Popular Lectures*, p. 249. The paper of Helmholtz on the mixture of colours, translated by myself, is published in the *Philosophical Magazine* for 1852. Maxwell's memoir on the Theory of Compound Colours is published in the *Philosophical Transactions*, vol. 150, p. 67.)

LECTURE II

ORIGIN OF PHYSICAL THEORIES
SCOPE OF THE IMAGINATION
NEWTON AND THE EMISSION THEORY
VERIFICATION OF PHYSICAL THEORIES
THE LUMINIFEROUS ETHER
WAVE THEORY OF LIGHT
THOMAS YOUNG
FRESNEL AND ARAGO
CONCEPTION OF WAVE-MOTION
INTERFERENCE OF WAVES
CONSTITUTION OF SOUND-WAVES
ANALOGIES OF SOUND AND LIGHT
ILLUSTRATIONS OF WAVE-MOTION
INTERFERENCE OF SOUND-WAVES
OPTICAL ILLUSTRATIONS
PITCH AND COLOUR
LENGTHS OF THE WAVES OF LIGHT AND RATES OF VIBRATION OF THE ETHER-PARTICLES
INTERFERENCE OF LIGHT
PHENOMENA WHICH FIRST SUGGESTED THE UNDULATORY THEORY
BOYLE AND HOOKE
THE COLOURS OF THIN PLATES
THE SOAP-BUBBLE
NEWTON'S RINGS
THEORY OF 'FITS'
ITS EXPLANATION OF THE RINGS
OVER-THROW OF THE THEORY
DIFFRACTION OF LIGHT
COLOURS PRODUCED BY DIFFRACTION
COLOURS OF MOTHER-OF-PEARL.

§ 1. *Origin and Scope of Physical Theories*

We might vary and extend our experiments on Light indefinitely, and they certainly would prove us to possess a wonderful mastery over the phenomena. But the vesture of the agent only would thus be revealed, not the agent itself. The human mind, however, is so constituted that it can never rest satisfied with this outward view of natural things. Brightness and freshness take possession of the mind when it is crossed by the light of principles, showing the facts of Nature to be organically connected.

Let us, then, inquire what this thing is that we have been generating, reflecting, refracting and analyzing.

In doing this, we shall learn that the life of the experimental philosopher is twofold. He lives, in his vocation, a life of the senses, using his hands, eyes, and ears in his experiments: but such a question as that now before us carries him beyond the margin of the senses. He cannot consider, much less answer, the question, 'What is light?' without transporting himself to a world which underlies the sensible one, and out of which all optical phenomena spring. To realise this subsensible world the mind must possess a certain pictorial power. It must be able to form definite images of the things which that world contains; and to say that, if such or such a state of things exist in the subsensible world, then the phenomena of the sensible one must, of necessity, grow out of this state of things. Physical theories are thus formed, the truth of which is inferred from their power to explain the known and to predict the unknown.

This conception of physical theory implies, as you perceive, the exercise of the imagination —a word which seems to render many respectable people, both in the ranks of science and out of them, uncomfortable. That men in the ranks of science should feel thus is, I think, a proof that they have suffered themselves to be misled by the popular definition of a great faculty, instead of observing its operation in their own minds. Without imagination we cannot take a step beyond the bourne of the mere animal world, perhaps not even to the edge of this one. But, in speaking thus of imagination, I do not mean a riotous power which deals capriciously with facts, but a well-ordered and disciplined power, whose sole function is to form such conceptions as the intellect imperatively demands. Imagination, thus exercised, never really severs itself from the world of fact. This is the storehouse from which its materials are derived; and the magic of its art consists, not in creating things anew, but in so changing the magnitude, position, grouping, and other relations of sensible things, as to render them fit for the requirements of the intellect in the subsensible world.[9]

Descartes imagined space to be filled with something that transmitted light *instantaneously*. Firstly, because, in his experience, no measurable interval was known to exist between the appearance of a flash of light, however distant, and its effect upon consciousness; and secondly, because, as far as his experience went, no physical power is conveyed from place to place without a vehicle. But his imagination helped itself farther by illustrations drawn from the world of fact. 'When,' he says,' one walks in darkness with staff in hand, the moment the distant end of the staff strikes an obstacle the hand feels it. This explains what might otherwise be thought strange, that the light reaches us

[9] The following charming extract, bearing upon this point, was discovered and written out for me by my deeply lamented friend Dr. Bence Jones, when Hon. Secretary to the Royal Institution:—'In every kind of magnitude there is a degree or sort to which our sense is proportioned, the perception and knowledge of which is of the greatest use to mankind. The same is the groundwork of philosophy; for, though all sorts and degrees are equally the object of philosophical speculation, yet it is from those which are proportioned to sense that a philosopher must set out in his inquiries, ascending or descending afterwards as his pursuits may require. He does well indeed to take his views from many points of sight, and supply the defects of sense by a well-regulated imagination; nor is he to be confined by any limit in space or time; but, as his knowledge of Nature is founded on the observation of sensible things, he must begin with these, and must often return to them to examine his progress by them. Here is his secure hold: and as he sets out from thence, so if he likewise trace not often his steps backwards with caution, he will be in hazard of losing his way in the labyrinths of Nature.'—(*Maclaurin: An Account of Sir I. Newton's Philosophical Discoveries. Written 1728; second edition*, 1750; pp. 18, 19.)

instantaneously from the sun. I wish thee to believe that light in the bodies that we call luminous is nothing more than a very brisk and violent motion, which, by means of the air and other transparent media, is conveyed to the eye, exactly as the shock through the walking-stick reaches the hand of a blind man. This is instantaneous, and would be so even if the intervening distance were greater than that between earth and heaven. It is therefore no more necessary that anything material should reach the eye from the luminous object, than that something should be sent from the ground to the hand of the blind man when he is conscious of the shock of his staff.' The celebrated Robert Hooke at first threw doubt upon this notion of Descartes, but he afterwards substantially espoused it. The belief in instantaneous transmission was destroyed by the discovery of Roemer referred to in our last lecture.

§ 2. *The Emission Theory of Light*

The case of Newton still more forcibly illustrates the position, that in forming physical theories we draw for our materials upon the world of fact. Before he began to deal with light, he was intimately acquainted with the laws of elastic collision, which all of you have seen more or less perfectly illustrated on a billiard-table. As regards the collision of sensible elastic masses, Newton knew the angle of incidence to be equal to the angle of reflection, and he also knew that experiment, as shown in our last lecture (fig. 3), had established the same law with regard to light. He thus found in his previous knowledge the material for theoretic images. He had only to change the magnitude of conceptions already in his mind to arrive at the Emission Theory of Light. Newton supposed light to consist of elastic particles of inconceivable minuteness, shot out with inconceivable rapidity by luminous bodies. Optical reflection certainly occurred *as if* light consisted of such particles, and this was Newton's justification for introducing them.

But this is not all. In another important particular, also, Newton's conceptions regarding the nature of light were influenced by his previous knowledge. He had been pondering over the phenomena of gravitation, and had made himself at home amid the operations of this universal power. Perhaps his mind at this time was too freshly and too deeply imbued with these notions to permit of his forming an unfettered judgment regarding the nature of light. Be that as it may, Newton saw in Refraction the result of an attractive force exerted on the light-particles. He carried his conception out with the most severe consistency. Dropping vertically downwards towards the earth's surface, the motion of a body is accelerated as it approaches the earth. Dropping downwards towards a horizontal surface—say from air on to glass or water—the velocity of the light-particles, when they came close to the surface, is, according to Newton, also accelerated. Approaching such a surface obliquely, he supposed the particles, when close to it, to be drawn down upon it, as a projectile is deflected by gravity to the surface of the earth. This deflection was, according to Newton, the refraction seen in our last lecture (fig. 4). Finally, it was supposed that differences of colour might be due to differences in the 'bigness' of the particles. This was the physical theory of light enunciated and defended by Newton; and you will observe that it simply consists in the transference of conceptions, born in the world of the senses, to a subsensible world.

But, though the region of physical theory lies thus behind the world of senses, the verifications of theory occur in that world. Laying the theoretic conception at the root of matters, we determine by deduction what are the phenomena which must of necessity grow out of this root. If the phenomena thus deduced agree with those of the actual world, it is a presumption in favour of the theory. If, as new classes of phenomena arise, they also are found to harmonise with theoretic deduction, the presumption becomes still stronger. If, finally, the theory confers prophetic vision upon the investigator, enabling him to predict the occurrence of phenomena which have never yet been seen, and if those predictions be found on trial to be rigidly correct, the persuasion of the truth of the theory becomes overpowering.

Thus working backwards from a limited number of phenomena, the human mind, by its own expansive force, reaches a conception which covers them all. There is no more wonderful performance of the intellect than this; but we can render no account of it. Like the scriptural gift of the Spirit, no man can tell whence it cometh. The passage from fact to principle is sometimes slow, sometimes rapid, and at all times a source of intellectual joy. When rapid, the pleasure is concentrated, and becomes a kind of ecstasy or intoxication. To any one who has experienced this pleasure, even in a moderate degree, the action of Archimedes when he quitted the bath, and ran naked, crying 'Eureka!' through the streets of Syracuse, becomes intelligible.

How, then, did it fare with the Emission Theory when the deductions from it were brought face to face with natural phenomena? Tested by experiment, it was found competent to explain many facts, and with transcendent ingenuity its author sought to make it account for all. He so far succeeded, that men so celebrated as Laplace and Malus, who lived till 1812, and Biot and Brewster, who lived till our own time, were found among his disciples.

§ 3. *The Undulatory Theory of Light*

Still, even at an early period of the existence of the Emission Theory, one or two great men were found espousing a different one. They furnish another illustration of the law that, in forming theories, the scientific imagination must draw its materials from the world of fact and experience. It was known long ago that sound is conveyed in waves or pulses through the air; and no sooner was this truth well housed in the mind than it became the basis of a theoretic conception. It was supposed that light, like sound, might also be the product of wave-motion. But what, in this case, could be the material forming the waves? For the waves of sound we have the air of our atmosphere; but the stretch of imagination which filled all space with a *luminiferous ether* trembling with the waves of light was so bold as to shock cautious minds. In one of my latest conversations with Sir David Brewster, he said to me that his chief objection to the undulatory theory of light was, that he could not think the Creator capable of so clumsy a contrivance as the filling of space with ether to produce light. This, I may say, is very dangerous ground, and the quarrel of science with Sir David, on this point as with many estimable persons on other points, is, that they profess to know too much about the mind of the Creator.

This conception of an ether was advocated, and successfully applied to various phenomena of optics, by the illustrious astronomer, Huyghens. He deduced from it the laws of reflection and refraction, and applied it to explain the double refraction of Iceland spar. The theory was espoused and defended by the celebrated mathematician, Euler. They were, however, opposed by Newton, whose authority at the time bore them down. Or shall we say it was authority merely? Not quite so. Newton's preponderance was in some degree due to the fact that, though Huyghens and Euler were right in the main, they did not possess sufficient data to *prove* themselves right. No human authority, however high, can maintain itself against the voice of Nature speaking through experiment. But the voice of Nature may be an uncertain voice, through the scantiness of data. This was the case at the period now referred to, and at such a period, by the authority of Newton, all antagonists were naturally overborne.

The march of mind is rhythmic, not uniform, and this great Emission Theory, which held its ground so long, resembled one of those circles which, according to your countryman Emerson, the intermittent force of genius periodically draws round the operations of the intellect, but which are eventually broken through by pressure from behind. In the year 1773 was born, at Milverton, in Somersetshire, a circle-breaker of this kind. He was educated for the profession of a physician, but was too strong to be tied down to professional routine. He devoted himself to the study of natural philosophy, and became in all its departments a master. He was also a master of letters. Languages, ancient and modern, were housed within his brain, and, to use the words of his epitaph, 'he first penetrated the obscurity which had veiled for ages the hieroglyphics of Egypt.' It fell to the lot of this man to discover facts in optics which Newton's theory was incompetent to explain, and his mind roamed in search of a sufficient theory. He had made himself acquainted with all the phenomena of wave-motion; with all the phenomena of sound; working successfully in this domain as an original discoverer. Thus informed and disciplined, he was prepared to detect any resemblance which might reveal itself between the phenomena of light and those of wave-motion. Such resemblances he did detect; and, spurred on by the discovery, he pursued his speculations and experiments, until he finally succeeded in placing on an immovable basis the Undulatory Theory of Light.

The founder of this great theory was Thomas Young, a name, perhaps, unfamiliar to many of you, but which ought to be familiar to you all. Permit me, therefore, by a kind of geometrical construction which I once ventured to employ in London, to give you a notion of the magnitude of this man. Let Newton stand erect in his age, and Young in his. Draw a straight line from Newton to Young, tangent to the heads of both. This line would slope downwards from Newton to Young, because Newton was certainly the taller man of the two. But the slope would not be steep, for the difference of stature was not excessive. The line would form what engineers call a gentle gradient from Newton to Young. Place underneath this line the biggest man born in the interval between both. It may be doubted whether he would reach the line; for if he did he would be taller intellectually than Young, and there was probably none taller. But I do not want you to rest on English estimates of Young; the German, Helmholtz, a kindred genius, thus speaks of him: "His was one of the most profound minds that the world has ever seen; but he had the misfortune to be too much in advance of his age. He excited the wonder of his contemporaries, who, however, were unable to follow him to the heights at which his daring intellect was accustomed to soar. His most important ideas lay, therefore, buried and forgotten in the folios of the Royal Society, until a new generation gradually and painfully made the same discoveries, and proved the exactness of his assertions and the truth of his demonstrations."

It is quite true, as Helmholtz says, that Young was in advance of his age; but something is to be added which illustrates the responsibility of our public writers. For twenty years this man of genius was quenched—hidden from the appreciative intellect of his country-men—deemed in fact a dreamer, through the vigorous sarcasm of a writer who had then possession of the public ear, and who in the *Edinburgh Review* poured ridicule upon Young and his speculations. To the celebrated Frenchmen Fresnel and Arago he was first indebted for the restitution of his rights; for they, especially Fresnel, independently remade and vastly extended his discoveries. To the students of his works Young has long since appeared in his true light, but these twenty blank years pushed him from the public mind, which became in time filled with the fame of Young's colleague at the Royal Institution, Davy, and afterwards with the fame of Faraday. Carlyle refers to a remark of Novalis, that a man's self-trust is enormously increased the moment he finds that others believe in him. If the opposite remark be true—if it be a fact that public disbelief weakens a man's force—there is no calculating the amount of damage these twenty years of neglect may have done to Young's productiveness as an investigator. It remains to be stated that his assailant was Mr. Henry Brougham, afterwards Lord Chancellor of England.

§ 4. *Wave-Motion, Interference of Waves, 'Whirlpool Rapids' of Niagara*

Our hardest work is now before us. But the capacity for hard work depends in a great measure on the antecedent winding up of the will; I would call upon you, therefore, to gird up your loins for coming labours.

In the earliest writings of the ancients we find the notion that sound is conveyed by the air. Aristotle gives expression to this notion, and the great architect Vitruvius compares the waves of sound to waves of water. But the real mechanism of wave-motion was hidden from the ancients, and indeed was not made clear until the time of Newton. The central difficulty of the subject was, to distinguish between the motion of the wave itself, and the motion of the particles which at any moment constitute the wave.

Stand upon the seashore and observe the advancing rollers before they are distorted by the friction of the bottom. Every wave has a back and a front, and, if you clearly seize the image of the moving wave, you will see that every particle of water along the front of the wave is in the act of rising, while every particle along its back is in the act of sinking. The particles in front reach in succession the crest of the wave, and as soon as the crest is past they begin to fall. They then reach the furrow or *sinus* of the wave, and can sink no farther. Immediately afterwards they become the front of the succeeding wave, rise again until they reach the crest, and then sink as before. Thus, while the waves pass onwards horizontally, the individual particles are simply lifted up and down vertically. Observe a sea-fowl, or, if you are a swimmer, abandon yourself to the action of the waves; you are not carried forward, but simply rocked up and down. The propagation of a wave is the propagation of a *form*, and not the transference of the substance which constitutes the wave.

The *length* of the wave is the distance from crest to crest, while the distance through which the individual particles oscillate is called the *amplitude* of the oscillation. You will notice that in this description the particles of water are made to vibrate *across* the line of propagation.[10]

And now we have to take a step forwards, and it is the most important step of all. You can picture two series of waves proceeding from different origins through the same water. When, for example, you throw two stones into still water, the ring-waves proceeding from the two centres of disturbance intersect each other. Now, no matter how numerous these waves may be, the law holds good that the motion of every particle of the water is the algebraic sum of all the motions imparted to it. If crest coincide with crest and furrow with furrow, the wave is lifted to a double height above its sinus; if furrow coincide with crest, the motions are in opposition and their sum is zero. We have then *still* water. This action of wave upon wave is technically called *interference*, a term, to be remembered.

[10] I do not wish to encumber the conception here with the details of the motion, but I may draw attention to the beautiful model of Prof. Lyman, wherein waves are shown to be produced by the *circular* motion of the particles. This, as proved by the brothers Weber, is the real motion in the case of water-waves.

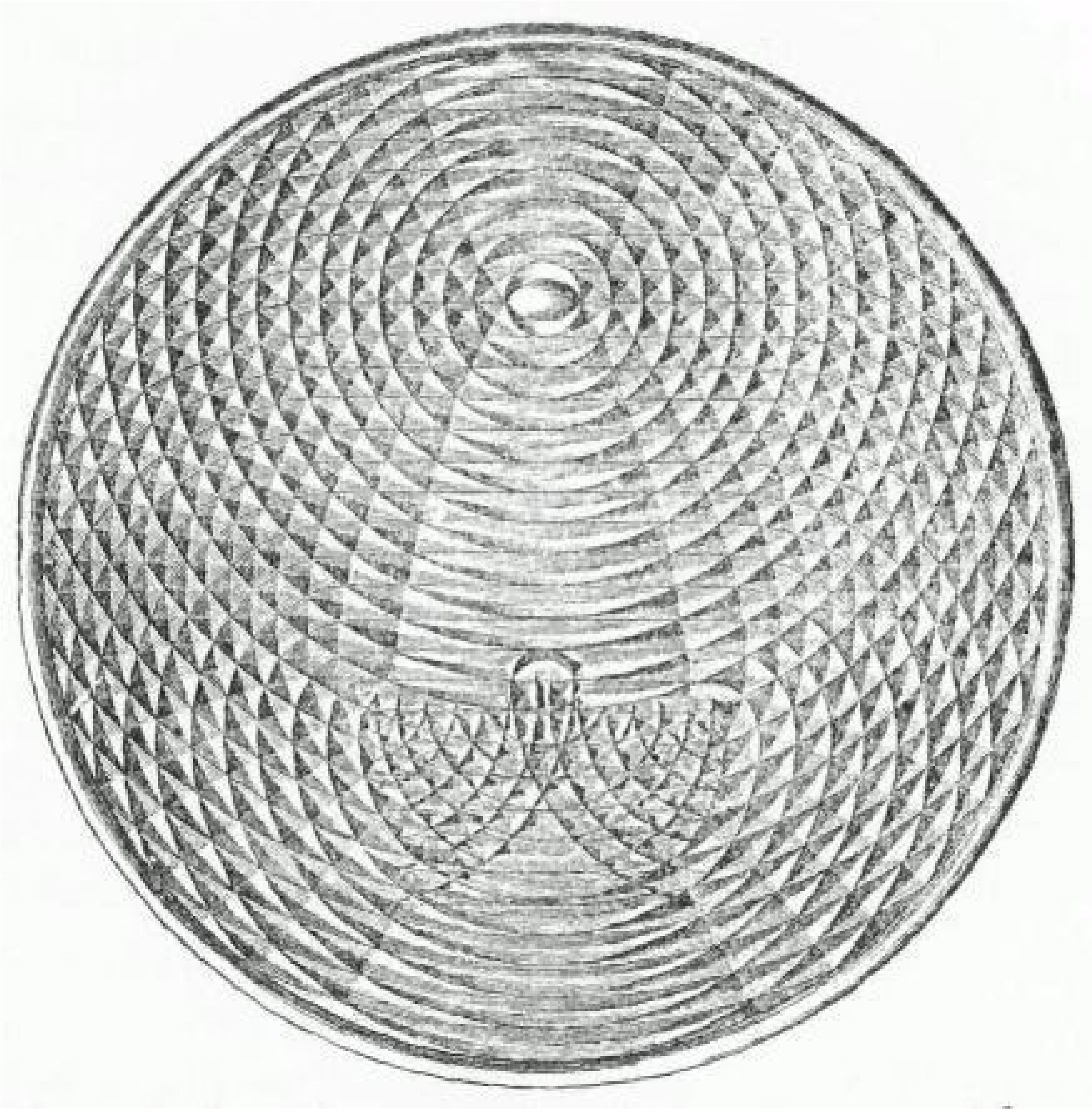

Fig. 10.

To the eye of a person conversant with these principles, nothing can be more interesting than the crossing of water ripples. Through their interference the water-surface is sometimes shivered into the most beautiful mosaic, trembling rhythmically as if with a kind of visible music. When waves are skilfully generated in a dish of mercury, a strong light thrown upon the shining surface, and reflected on to a screen, reveals the motions of the liquid metal. The shape of the vessel determines the forms of the figures produced. In a circular dish, for example, a disturbance at the centre propagates itself as a series of circular waves, which, after reflection, again meet at the centre. If the point of disturbance be a little way removed from the centre, the interference of the direct and reflected waves produces the magnificent chasing shown in the annexed figure.[11] The light reflected from such a surface yields a pattern of extraordinary beauty. When the mercury is slightly struck by a needle-point in a direction concentric with the surface of the vessel, the lines of light run round in mazy coils, interlacing and unravelling themselves in a wonderful manner. When the vessel is square, a splendid chequer-work is produced by the crossing of the direct and reflected waves. Thus, in the case of wave-motion, the most ordinary causes give rise to most exquisite effects. The words of Emerson are perfectly applicable here:—

[11] Copied from Weber's *Wellenlehre*.

'Thou can'st not wave thy staff in the air,
Or dip thy paddle in the lake,
But it carves the brow of beauty there.
And the ripples in rhymes the oars forsake.'

The most impressive illustration of the action of waves on waves that I have ever seen occurs near Niagara. For a distance of two miles, or thereabouts, below the Falls, the river Niagara flows unruffled through its excavated gorge. The bed subsequently narrows, and the water quickens its motion. At the place called the 'Whirlpool Rapids,' I estimated the width of the river at 300 feet, an estimate confirmed by the dwellers on the spot. When it is remembered that the drainage of nearly half a continent is compressed into this space, the impetuosity of the river's escape through this gorge may be imagined.

Two kinds of motion are here obviously active, a motion of translation and a motion of undulation—the race of the river through its gorge, and the great waves generated by its collision with the obstacles in its way. In the middle of the stream, the rush and tossing are most violent; at all events, the impetuous force of the individual waves is here most strikingly displayed. Vast pyramidal heaps leap incessantly from the river, some of them with such energy as to jerk their summits into the air, where they hang suspended as bundles of liquid pearls, which, when shone upon by the sun, are of indescribable beauty.

The first impression, and, indeed, the current explanation of these Rapids is, that the central bed of the river is cumbered with large boulders, and that the jostling, tossing, and wild leaping of the waters there are due to its impact against these obstacles. A very different explanation occurred to me upon the spot. Boulders derived from the adjacent cliffs visibly cumber the *sides* of the river. Against these the water rises and sinks rhythmically but violently, large waves being thus produced. On the generation of each wave there is an immediate compounding of the wave-motion with the river-motion. The ridges, which in still water would proceed in circular curves round the centre of disturbance, cross the river obliquely, and the result is, that at the centre waves commingle which have really been generated at the sides. This crossing of waves may be seen on a small scale in any gutter after rain; it may also be seen on simply pouring water from a wide-lipped jug. Where crest and furrow cross each other, the wave is annulled; where furrow and furrow cross, the river is ploughed to a greater depth; and where crest and crest aid each other, we have that astonishing leap of the water which breaks the cohesion of the crests, and tosses them shattered into the air. The phenomena observed at the Whirlpool Rapids constitute, in fact, one of the grandest illustrations of the principle of interference.

§ 5. *Analogies of Sound and Light*

Thomas Young's fundamental discovery in optics was that the principle of Interference was applicable to light. Long prior to his time an Italian philosopher, Grimaldi, had stated that under certain circumstances two thin beams of light, each of which, acting singly, produced a luminous spot upon a white wall, when caused to act together, partially quenched each other and darkened the spot. This was a statement of fundamental significance, but it required the discoveries and the genius of Young to give it meaning. How he did so will gradually become clear to you. You know that air is compressible: that by pressure it can be rendered more dense, and that by dilatation it can be rendered more rare. Properly agitated, a tuning-fork now sounds in a manner audible to you all, and most of you know that the air through which the sound is passing is parcelled out into spaces in which the air is condensed, followed by other spaces in which the air is rarefied. These condensations and rarefactions constitute what we call *waves* of sound. You can imagine the air of a room traversed by a series of such waves, and you can imagine a second series sent through the same air, and so related to the first that condensation coincides with condensation and rarefaction with rarefaction. The consequence of this coincidence would be a louder sound than that produced by either system of waves taken singly. But you can also imagine a state of things where the condensations of the one system fall upon the rarefactions of the other system. In this case (other things being equal) the two systems would completely neutralize each other. Each of them taken singly produces sound; both of them taken together produce no sound. Thus by adding sound to sound we produce silence, as Grimaldi, in his experiment, produced darkness by adding light to light.

Through his investigations on sound, which were fruitful and profound, Young approached the study of light. He put meaning into the observation of Grimaldi, and immensely extended it. With splendid success he applied the undulatory theory to the explanation of the colours of thin plates, and to those of striated surfaces. He discovered and explained classes of colour which had been previously unnoticed or unknown. On the assumption that light was wave-motion, all his experiments on interference were accounted for; on the assumption that light was flying particles, nothing was explained. In the time of Huyghens and Euler a medium had been assumed for the transmission of the waves of light; but Newton raised the objection that, if light consisted of the waves of such a medium, shadows could not exist. The waves, he contended, would bend round opaque bodies and produce the motion of light behind them, as sound turns a corner, or as waves of water wash round a rock. It was proved that the bending round referred to by Newton actually occurs, but that the inflected waves abolish each other by their mutual interference. Young also discerned a fundamental difference between the waves of light and those of sound. Could you see the air through which sound-waves are passing, you would observe every individual particle of air oscillating to and fro, *in the direction of propagation*. Could you see the luminiferous ether, you would also find every individual particle making a small excursion to and fro; but here the motion, like that assigned to the water-particles above referred to, would be *across* the line of propagation. The vibrations of the air are *longitudinal*

Конец ознакомительного фрагмента.