ON THE BENEFICIAL EFFECTS OF LIGHT

PROF. G. G. STOKES

BURNETT LECTURES.

ON LIGHT.

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Third Course,

ON THE BENEFICIAL EFFECTS OF LIGHT.

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BY

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ERRATUM.

p. 54, l. 17. *For* "thousandth", *read* "ten-thousandth".

ON THE BENEFICIAL EFFECTS OF LIGHT.

LECTURES ON LIGHT.

THIRD COURSE.

ON THE BENEFICIAL EFFECTS OF LIGHT.

LECTURE I.

Extended signification in which the word "light" will here be used—Different effects produced by light—Mechanical value of sunlight—The existence of winds depends upon light—So also does that of clouds and rain, of streams and rivers—Effects of the radiation from bodies warmed by the sun.

AT the conclusion of the lectures which I had the honour of delivering in this place two years ago, I stated that in accordance with a scheme which had been communicated to and approved by the Burnett trustees, the subject of the entire series of lectures was to be Light, which in each year's course was to be treated from a different point of view; and that in the third year's course light was to be considered in relation to its beneficial effects. Such accordingly is the subject of the present, the concluding, course.

We habitually consider light as an agent external to us which excites in us the sensation of vision. When we study the behaviour of this agent, we learn that it proceeds from some source, travelling with an extremely great, but still finite and measurable velocity, in a course which is straight so long as it lies in the same medium; that on arriving at the confines of this medium and of some other, it is in part reflected and in part refracted, according to definite laws, and so forth as regards other properties. We further find that this agent is not all of the same kind, but that there is some quality about it which admits of continuous variation from one portion to another, though it remains the same in the same portion throughout its whole course. This difference is made known to us through a difference of refrangibility, though not by that alone; and by suitable methods we are able to separate the portions of different refrangibilities from one another, and obtain a pure spectrum.

But we find that there are other effects which the influence emanating from the source is capable of producing besides that of exciting the sensation of vision. It raises the temperature of the body exposed to it, provided at least the body does not let the portion which is not reflected pass freely through; in some bodies it produces chemical changes; in some it excites phosphorescence. These effects might conceivably either be attributed to different agents mixed together in the radiation, or be regarded as different effects which one and the same agent was capable of producing.

If these effects were produced by different agents agreeing in the properties of reflection, refraction and dispersion, and accordingly mixed together even in the same part of a pure spectrum, we should expect that though not separable by refraction they yet would be so by other means, such for example as absorption; or at least that they would be so far separable as that we should be able to extinguish or weaken the agent of a given refrangibility producing one of these effects while that producing another is left in full vigour. If on the other hand the different effects were produced by one and the same agent, it would be impossible so to modify the influencing radiation as to suppress or weaken the agent producing one of these effects without at the same time suppressing or weakening the agent producing any of the others. It is needless to say that in putting these two alternatives to the test of actual experiment we must have regard to the different degrees of sensitiveness of the different effects regarded as indications of the presence or absence of the agent to which they are respectively due.

Now when the experiment is actually made it is found that no matter what may be the treatment to which the influencing radiation may have been subjected, if one of the effects be prevented, so are the others, if one be weakened, so are the others. In accordance therefore with Newton's rule which forbids us needlessly to multiply the causes of natural phenomena, we are led to attribute these various effects to one and the same agent; being ready of course to modify our view should any phenomenon be discovered which would clearly show that it is possible to separate the agents by other means though not by refraction. And the view which our present knowledge leads us confidently to adopt respecting the nature of light—that it consists in undulations propagated through a medium—strengthens the probability, already so high, that these various effects are due to the same agent; for heat is now recognised as a mode of motion, and though we cannot explain in detail how it is that chemical changes and phosphorescence are brought about by the agency of ethereal vibrations, yet vibrations of the kind would seem to be very likely to produce such effects. In fact, the evidence which modern science affords us bearing on the question is such as to lead irresistibly to the conclusion that the different effects mentioned above as produced by something that radiates, are due to one and the same agent.

It follows that the presence of this agent may be evidenced by some of these effects even though others be absent. Thus suppose we use for the scrutiny of the incident radiations a solution of sulphate of quinine, and fix our attention on a particular part of the spectrum, say the neighbourhood of the line *F*. No fluorescence is produced, and no elevation of temperature. Yet radiation is there, and its presence is shown at once by receiving the light into the eye, either directly, or after being scattered by a screen ; or again by the chemical action on a prepared photographic plate. Were we to classify the radiation belonging to the spectrum as a whole into that which did and that which did not produce fluorescence in the solution of quinine, the classification might be convenient in relation to a study of the salts of quinine, but considered purely in relation to the radiations themselves it would be wholly artificial and unmeaning.

Now we are in precisely the same condition if in studying the whole radiation we draw a distinction between that which affects and that which does not affect the eye. With reference to vision the distinction is all-important; with reference to the agent considered in itself, considered objectively, the distinction is perfectly artificial and arbitrary. Beyond both ends of the visible spectrum there lie radiations which do not affect the eye, but are nevertheless, as we have every reason to believe, of the same physical nature as those which do, from which they do not differ by any inherent quality. As the agent which excites vision has been called from time immemorial light, or whatever may be the corresponding term in other languages, it will be convenient to use the same word to designate the agent considered in itself, and irrespectively of its capacity for exciting vision, a capacity which would be regarded as a mere accident of light, in the technical logical sense of that word. Accordingly I shall now use the word "light" to designate what for want of a better term I have just been calling radiation; a word which would more properly denote the process of radiation than the thing radiated, be it material or immaterial, be it matter or undulations.

The use of light in relation to vision is obvious to everybody. But it is only after science has made considerable progress that we learn that the very same agent, in fact light in the more extended sense in which I have now defined the term, has uses of still more vital importance in relation to our well-being, or I should rather say in relation to our existence at all. Some persons are blind from birth, but yet lead tolerably happy lives, receiving it is true much assistance from their fellow creatures who are not subject to such a terrible deprivation. We can imagine ourselves accordingly living in a perfectly dark world, destitute of light of any kind, either natural or artificial, guiding ourselves as best might be by the exercise of the senses of touch and hearing. But the absence of light, of that agent of which the excitement of vision is only one of the offices, entails consequences extending far beyond even this.

Without a certain amount of warmth, men and animals cannot survive. Now what is the great source of warmth upon earth? Clearly the sun. We use indeed fires in our houses; but even if we could have had these fires independently of the sun, the heat thence derived, taking all the world over, is a mere nothing compared with the heat received directly from the sun. But the sun is separated from the earth by the enormous distance of 92 millions of miles, or thereabouts. How then is this supply of heat conveyed to us from such an enormous distance? It is as we familiarly know by radiation; it is therefore to light, in the extended sense in which the word is here used, that we owe this vast supply.

Although the power of the sun's heat is matter of common observation, we are hardly perhaps prepared for the results obtained by an actual measurement of its amount. The quantity received at the earth's surface when the sun is shining clearly can be measured by suitable means, by observing the elevation of temperature produced in a known body which absorbs all the radiation. It must be noted however that the quantity we receive at the earth's surface is not as great as what falls on the earth as a whole, that is, inclusive of the atmosphere, since some portion is stopped in passing through the atmosphere, to allow for which a correction must be made.

Supposing the quantity which falls on a given area of the earth known, the quantity of heat which passes outwards into space in a given time through an equal area of the sun's surface can be got by multiplying by the ratio of the surface of a sphere described round the sun's centre and passing through the earth to the surface of the sun itself; and the mechanical equivalent of this amount of heat can be derived by means of Joule's equivalent, of 772 foot-pounds for the equivalent of the heat required to raise one pound of water through one degree of Fahrenheit's thermometer. About 30 years ago Sir William Thomson availed himself of data given by Pouillet for solar radiation to calculate the amount of energy actually emitted by the sun in the form of radiation. It appeared that for every square foot of the sun's surface the energy of radiation was upwards of 6000 horse power. Yet even this prodigious quantity does not appear to come up to the actual amount; for Professor Langley in America by observations of solar radiation at low and high levels made by a new and delicate instrument of his own devising called a bolometer, which permitted him to operate separately on the different components of the total radiation after they had been separated by a prism, has found that the amount of absorption and scattering which takes place in the earth's atmosphere is greater than had been supposed, and his results lead us nearly to double the above estimate. We may take it then that the amount of energy poured forth into space corresponds to, in round numbers, 12,000 horse power per square foot. When we remember that the sun is a vast globe of about 855,000 miles in diameter, every square foot of the surface of which supplies energy at the above rate, and that that is continually going on from age to age, we cannot help feeling what a prodigious supply the sun must contain.

Of this radiant energy the earth, it is true, receives but a very small fraction. Yet even that represents an immense amount if judged by such quantities as we are in the habit of considering. At the distance of the earth, the amount above mentioned would correspond to about one horse power for every square of five feet the side on the earth's surface, supposing the rays received perpendicularly, or in other words supposing the sun in the zenith; and in case the sun be not vertical, then to one horse power for every area of the size of the shadow of a square board of five feet each side held perpendicularly to the sun's rays. Imagine the earth's surface, whether land or water, studded over with horses as close as above mentioned, all working away with their full strength, and what an immense amount of working power we should thus obtain.

Figures such as these prepare us to expect effects on a grand scale as referable to light. Let us dwell on some of these. The supply of the warmth so essential to the life and growth of plants and animals (though for vegetation as we shall see warmth alone would not suffice) has already been mentioned. But as an accompaniment of this supply physical changes are produced in the atmosphere of the earth which are of vital importance. The surface of the earth, warmed by the sun's rays, in its turn warms the air in contact with it, and generally the lowest portions of the atmosphere. These are it is true to a certain extent warmed directly by the sun's rays, of which a portion, consisting mainly of rays of low refrangibility, are absorbed in their progress towards the earth. But the heat which radiates from the warmed earth consists entirely of rays of low refrangibility, and a far larger proportion of it than of the direct radiation from the sun is affected by absorption in its passage; and thus it is that even independently of the heat communicated by contact from the earth to the air, it is chiefly the lowest portions of the atmosphere that thus get warmed. The warmed air becoming specifically lighter, the equilibrium is disturbed, the heated air ascends, giving place to colder air from above, which gets warmed in its turn. These ascending currents take place at first on a small scale, as we see over a boulder in a grass field on which the sun is shining; and the mixture thus continually going on has the effect of rendering a thicker stratum over the earth's surface warmer, and thereby enabling exchanges to take place on a larger scale. The effect of ascending currents on a larger scale is seen in the phenomenon of land and sea breezes. Where air thus ascends, a horizontal flow must of course take place below, to supply the place of the air which ascends. And when the distance that the air has thus travelled becomes large, another consideration enters which is of great importance in relation to the magnitude of the motion. In consequence of the earth's rotation, any point at the surface describes in the course of the 24 hours a circle of which the radius is the perpendicular let fall from that point on the earth's axis, and it has accordingly a velocity from west to east varying from about 1000 miles an hour for a point at the equator to nothing at the poles. When air which moves along the surface to supply the place of other air which continuously ascends in some different region has travelled some distance in a north or south direction, it gets to a place where the velocity from west to east of the surface of the earth is very decidedly different from what it was at the place from whence the air came; and supposing the air to have been at rest relatively to the surface at the place from whence it started, and accordingly to have been moving with the velocity due to that latitude, so that to a spectator at that place there would be a calm, when it got into the different latitude it would tend by its inertia to preserve the velocity from east to west that belonged to its original latitude*, and accordingly relatively to a spectator at the new latitude to have a velocity from west to east or the reverse according to circumstances.

* This statement is not to be interpreted too strictly, as giving more than a general explanation. If an isolated particle were projected on the surface of a smooth gravitating sphere, which we may suppose revolving, though that would not affect the particle's motion, it will describe a great circle with uniform velocity, so that the component perpendicular to the meridian passing through it at any moment would vary as the secant of the latitude, until at the highest latitude attained it became equal to the whole velocity. The variations referred to in the text consequent upon a change of latitude would therefore tend to be even greater than if the velocity in a direction perpendicular to the meridian tended to remain constant.

There is on the whole an ascent of the air in the tropical regions, and the air which has ascended overflows in the upper regions and proceeds towards the poles, while the place of the air which had so ascended is supplied by a flow in the lower regions from higher latitudes. In these movements on a large scale the change of latitude is considerable; and accordingly the difference of velocity from west to east belonging to different latitudes forms a very important factor in determining the actual velocity of the air near the surface at any place relatively to the surface, which constitutes the velocity of the wind that we observe.

It would be beside my object to attempt to enter into the question of the complicated system of currents in the atmosphere; I merely want to call attention to the circumstance that the whole system of winds in our atmosphere has its origin in solar radiation; has its origin accordingly in light. Without light, the atmosphere would be in a state of stagnation, and there would not be a breath of wind to fill the sails of our ships. Perhaps we might say, we should have recourse to steam. Nay, steam would fail us too, for a reason which will be explained in due course; nor failing steam could we have recourse to windmills, which would be useless in a perpetual calm.

When we stand on the coast of the Atlantic, and watch the huge waves which come rolling in and dashing against the rocks in a gale, or it may be as the result of a gale out at sea which never reached us, we are struck by the grand exhibition of mechanical power which we behold. Yet all this power is but a minute fraction of the energy of light which started it; for the waves are due to the long continued action of the gale on the surface of the ocean, and the gale had its origin in currents of convection which themselves originate in solar radiation, that is, in light.

For fear I should be misunderstood in the assertion which I have just made, permit me to make a slight digression. I have said that of the sun's rays which are traversing the atmosphere on their way towards the earth a portion consisting mainly of rays of *low* refrangibility are absorbed in their progress. It may have occurred to some of you to ask whether I should not have said rays of *high* refrangibility. For when the sun is near the horizon and his rays have accordingly a comparatively long space to travel through the atmosphere before they can reach us, the light we receive is orange or red, as we know familiarly from watching sunsets; and examination by the prism confirms what is already shown by the colour, that it is the rays of *higher* refrangibility chiefly that are missing.

In explanation of this apparent contradiction, it must be observed that there are two perfectly distinct causes why the light should fail to reach us:—one, absorption in the strict sense of the word, where light as such is swallowed up, and in lieu of it we have a warming of the air where it is so absorbed; the other a mere scattering of the light by very fine particles of water forming a mist, or by particles of whatever kind they may be which are similarly held in suspension.

When the suspended particles are excessively fine they offer proportionately more obstruction to rays of small wave length and accordingly high refrangibility than to rays of greater wave length and accordingly lower refrangibility. But in this case the obstructed light is reflected back into space (the reflection being of course complicated by diffraction); and light cannot warm a body without disappearing as light and being absorbed. Hence though the obstruction of light by solid particles may greatly exceed its obstruction by true absorption, it does not at all follow that the warming produced by the total obstruction is divided between different parts of the spectrum in anything like the same proportion as the total obstruction. Of course the suspended particles may themselves absorb light, as in a London fog, but I had not in view such purely exceptional cases as that of the smoke about large towns.

After this digression let me resume my subject.

Concurrently with the warming of the earth's surface, another process is going on which is fraught with consequences of the highest importance. By far the greater part of the earth's surface is covered with water, and the surface of the land is in most places more or less moist. Consequently under the influence of the solar radiation evaporation is constantly going on; water is constantly converted from the condition of a liquid into that of an elastic fluid, which mixes with the air. The quantity of water which can be thus sustained in the elastic state in a given volume depends upon the temperature; and when the mixture of air and vapour is sufficiently cooled, whether by radiation, or by the cold accompanying expansion as it ascends, or by being brought in contact with the surface of the earth where cold, or being mixed with colder air from some other quarter, a portion of the water is condensed, forming a vast number of exceedingly minute globules, which fall so slowly in consequence of the resistance of the air due to its viscosity that they may be deemed for all practical purposes to be permanently suspended, and which form the clouds; and when the precipitation is sufficient, or under other circumstances not wholly understood, these globules unite to form larger spheres, and fall as rain. This supply of water, so essential to the growth of plants and the sustentation of animals, is as we see another of the all-important effects brought about through the agency of light. The quantity of water thus raised and let fall again, taken all the earth over, is prodigious. In a dry season we may water the flowers in a garden, but we do not think of watering the fields. Even supposing we had a supply of water at hand, the labour involved in raising, carrying and distributing that water would be so great if we would make any sensible impression that it would not pay, and the fields are left to their fate. An inch of rain, which occasionally may fall in a single day, means 100 tons per acre, and think of the labour of raising and distributing such a weight as this. Yet all this is done for us through the energy supplied by light. And when the fallen rain has fertilised our fields, the overplus collects in rivulets and streams which afford a constant supply of water to men and animals, are used occasionally for supplying energy in water mills, and ultimately collect in rivers which afford one of the cheapest modes of transit for merchandise. When we stand by some mighty waterfall, such for example as Niagara, and are struck by the grand exhibition of power that we see before us, we do not perhaps reflect that while it is through light that we are enabled to see what is going on, it is from light also that the energy is derived that we see thus in action.

The chief effect of light that I have hitherto in this lecture dwelt upon is that of raising the temperature of the body on which it falls. Among the effects which at the beginning of the lecture I enumerated as capable of being produced by it, there is one, the production of phosphorescence, which at first sight might seem to be merely a matter of scientific curiosity, having little relation to our well-being. And yet there is one effect constantly going on, and closely connected with our welfare, which if not identical with is at any rate very closely allied to phosphorescence.

For what is phosphorescence? The term it is true is applied to more phenomena than one, and that from which the name is derived, the shining of phosphorus in the dark, has nothing to do with that to which the name is more commonly applied, and which has been mentioned as an effect of light. This latter consists in the shining of certain substances in the dark, or even in many cases in fairly strong light, after exposure to light of suitable kind and intensity. The duration of the effect after the incident light has been cut off varies immensely in different cases. Sometimes the body will go on shining for hours; sometimes the effect ceases to be sensible at the end of a few seconds; sometimes it remains for only so small a fraction of a second that it requires special instrumental appliances to prove that there is any duration at all; sometimes the duration is shorter even than this, so that it has not at present been rendered sensible in experiment, and it is only from analogy and as a deduction from what we have reason to believe to be the theory of the effect, that we infer that there is any duration at all.

As regards the relation of the light given out to the light that falls upon the body and is the cause of its emitting light, this law appears to be general—that the light given out is of lower refrangibility than the light which excites it*. It is true that sometimes a solar phosphorus emits light in consequence of being shone upon by light of lower refrangibility than that which it emits; but this effect is only temporary, and depends upon a latent condition in which the body was left in consequence of the previous action of light of higher refrangibility than that given out; and when this effect of the higher rays is exhausted, the body refuses to shine though left under the

* When rays of low refrangibility are enormously concentrated they are capable of heating a body so as to make it red-hot, and accordingly cause it to give out rays of higher refrangibility than themselves. This effect, the "calorescence" of Dr Tyndall, is not here under consideration. It is doubtful at present whether the law enunciated in the text is *rigorously* true; some physicists maintaining that in certain cases of "fluorescence" light is emitted of refrangibility extending to *a little* above that of the incident rays, while others hold that that is not the case. Such slight deviations from the law, even if real, will not affect the conclusions drawn in the text.

influence of the lower rays which at first excited it. The exception therefore to the rule first laid down is more apparent than real.

Now when we leave out of sight the distinction between the visible and invisible rays, a distinction which is purely subjective, depending on our own organization, not on the nature of the external object, that is, the radiation presented to us, we find an exceedingly common phenomenon presenting, in some respects at least, a close resemblance to phosphorescence. I refer to the emission of radiant heat as a result of a body's having been shone upon by the sun.

When a body, a stone for instance, is warmed by absorption of the sun's rays, it radiates in its turn, and becomes a source of what in the extended sense of the word may be denominated light. But this light does not affect the eye; it is of lower refrangibility than the extreme red, and its capacity for passing through or on the other hand being absorbed by gases or liquids or homogeneous solids is altogether different from that of the rays to which it owed its origin. Now in the solar radiation, at any rate as it reaches us, a far smaller percentage is made up of invisible ultra-red rays, of refrangibilities which even for such rays are low, than is the case with most terrestrial sources, even flames; while on the other hand the radiation from a body of moderate temperature, such as a warmed stone, consists almost entirely of rays of these very low refrangibilities. But air transmits very freely the visible rays, and also invisible ultra-red rays of not too low refrangibility, and therefore the bulk of the solar radiation passes very freely through it. On the other hand air, in its ordinary state, has a considerable absorbing power for the ultra-red rays of comparatively low refrangibility, which are accordingly stopped, and the temperature of the air is raised thereby. I say air "in its ordinary state," for Tyndall has shown that dry air is highly transparent, even for rays of these low refrangibilities, and that among the normal constituents of the atmosphere it is mainly vapour of water to which the observed absorption is owing; but this is always present more or less, though the quantity contained in a given volume of air may vary very greatly according to circumstances.

Accordingly while the solar radiation falls freely on the earth (assuming of course that there are not clouds in the way to stop it), the radiation from the bodies which it warms is in far greater degree arrested, and goes to warm the air. The atmosphere thus to a certain extent plays the part of the glass in a greenhouse, and the heat is husbanded, to the advantage of those at least who live at a good distance from the equator, not to mention the all-important results of the heating of the atmosphere which have already been dwelt upon. And if we may indulge in speculation as to the condition of a distant body, the telescopic appearance of Jupiter, and his high "albedo," or intrinsic whiteness, favour the idea that his body is mostly enveloped in a dense mantle of cloud, which is absent or much reduced only along the comparatively narrow "belts," where, it may be, we see down to the body of the planet, or at any rate to a considerable depth in a furrow of the ocean of cloud. Being in round numbers four times as far from the sun as we are, Jupiter would receive a radiation only the one-sixteenth part as intense; but it may be that the mantle of cloud acts as an effectual great coat, husbanding the heat derived from such part of the solar radiation as is able to get through it, or at any rate some way into it, perhaps also husbanding some remains of primitive heat. But this as I said is matter of speculation, and I forbear to enlarge on it, being desirous of resting what I have to say to you on well-ascertained facts.

The nature of the subject in which we have been engaged to-day afforded me but little of novelty to bring before you, and I cannot help fearing that I may have been somewhat wearisome in consequence. Still I am not without hopes that I may have led some of you to appreciate more fully than before the inestimable benefits we owe to light in rendering our earth suitable for a habitation of living beings, even supposing they could themselves exist independently of light. In my next lecture I propose to show how essential light is even to their very existence.

LECTURE II.

Dependence of the various sources of warmth which are available to us on Light—Dependence of the energy of animals on their food, and of the potential energy of the food on the energy of Light—Decomposition of carbonic acid by growing plants—Rays which effect the decomposition—Changes of colour of leaves under the influence of Light.—Effect of an extra supply of Light—Condition of the earth without Light.

ONE of the effects of light which I mentioned in my first lecture is that of producing chemical changes. When the benefits derived from light which depend on the chemical changes which take place under its influence are mentioned, perhaps our thoughts turn to photography, an art which has sprung up within the memory of many now living. How marvellous would it have been thought a century ago that we should be able to obtain in the course of a few seconds, by a purely automatic process, an absolutely authentic picture of a striking landscape of which we wish to preserve a memorial, or portrait of a friend or family group. It is true that hitherto these pictures have been shown only in light and shade. Some little progress has indeed been made towards photographing with colour. M. Edmond Becquerel has succeeded in obtaining on a daguereotype, by a particular process, a delineation of a spectrum the different parts of which showed colours having some resemblance to the colours naturally belonging to these same parts in the actual spectrum delineated. But hitherto it has been found impossible to fix the colours so obtained. Occasionally too indications of colour, chiefly I believe of red, have been obtained in ordinary photographs, but accidentally as it were, doubtless by some variations in the chemical processes involved, or in the mode of exposure, the conditions of which have not been investigated. Enough has been done to show that the idea of photographing with colour may not be wholly chimerical.

But interesting as photographs may be, and glad as we may be to possess a perfectly faithful likeness of a friend or relative, perhaps far separated from us by distance, perhaps removed by death, the advantages we thus derive sink into insignificance compared with others the reference of which to the chemical agency of light is not so obvious.

In my first lecture I pointed out how the source of at least by far the greater part of the warmth which we enjoy is derived from solar radiation. Supposing we were bereft of this, what sources of heat would be available to us?

Perhaps we might say, at least we should have the natural animal warmth. Much as we might suffer from cold, perhaps by warm clothing, and by keeping near one another, we might manage to get on.

But clothing does not originate heat; it merely checks the waste of that which is in some way supplied through the animal organisation. What then is the source of this supply? It is well recognised at the present day that it is derived from the chemical changes which take place in the food. After digestion in the stomach and alimentary canal, the portions available for nutrition are carried into the blood, and circulate through the body. A portion goes to supply the waste of the tissues, but a large part acts as fuel, and by gradual union with oxygen, in fact by slow combustion, furnishes a gentle and continuous supply of heat. At every breath, a portion of the oxygen inspired is absorbed by the blood, which gets access to it in the cells of the lungs. This oxygen enters in the first instance into some sort of chemical combination with the colouring matter of the blood, which now becomes a powerful oxidising agent, and in the course of the circulation oxidises matters contained in the blood. As regards its ultimate elements, the food consists mainly of carbon, hydrogen, oxygen, and some nitrogen; but the quantity of oxygen is not near sufficient to form carbonic acid and water with the carbon and hydrogen respectively which are present; and as the two latter elements are eliminated mostly in these two forms, we infer that the final result is that the absorbed oxygen unites with carbon and hydrogen to form carbonic acid or water as the case may be. In this process heat is given out, just as in actual combustion; so that a sort of slow combustion is always taking place in the lungs and in the circulating blood, resembling actual combustion as regards the heat given out, but differing from it as to the rate at which the chemical changes take place, and not like it accompanied by luminosity and a high temperature.

In carbon and oxygen separately presented, or in hydrogen and oxygen, we have a supply of energy in the potential form; energy which may become actual, and appear it may be in the form of heat, it may be in the form of work done, when the potential energy becomes actual by chemical union, whether quick or slow. Conversely, carbonic acid cannot be converted into carbon and oxygen, nor water into hydrogen and oxygen, without the expenditure of energy in some shape or other.

In seeking for a supply of warmth in default of solar radiation, we have been driven from animal heat to the food of animals, food which contains carbon and hydrogen in great excess of the quantities which by union with the oxygen which the food also contains could form carbonic acid and water. Now the food of animals is derived directly or indirectly from vegetables, indirectly in so far as it consists of the flesh of other animals, through which we come down to vegetable feeders at last.

From whence then do plants derive their carbon and hydrogen? As to hydrogen there is no difficulty. Though it is not found free, and though there is no reason to suppose that plants could assimilate it if it were, it abounds in nature as a constituent of water, which the plants readily imbibe. As to carbon, it exists to a certain extent in the surface soil in which plants usually grow; but it is there in an insoluble state, a state in which the plants could not assimilate it. It is now well ascertained that the source of the carbon found in plants is the carbonic acid which is contained, though in small proportion, in the air.

But the mere absorption of carbonic acid and water would not suffice. They are the ashes, so to speak, which result from the combustion of carbon and hydrogen, and would not be competent in association with oxygen to become a source of energy. How is it then that in plants these elements, in opposition to their chemical affinities, are presented to us in combination with a much smaller proportion of oxygen than in the state in which they were absorbed by the plants?

We are here brought face to face with a very marvellous process, a process which is only imperfectly understood. It is found that living plants when supplied with moderate quantities of carbonic acid, in addition to the water which they have in them or which is supplied from without, are actually able to set oxygen free, and appropriate the carbon and hydrogen, not indeed as such, but in a state or states of combination in which they are combined with much less oxygen than they originally had. But this process *only goes on under the influence of light.* It is, as has been noticed, the very reverse of combustion. In combustion whether rapid or slow, energy is given out; in the reverse process energy must be supplied. It appears from what has been mentioned that this energy is derived from light. To prove this indeed by direct measurement would be a matter of extreme delicacy and difficulty, and I am not aware that the experiment has been attempted. But even without such direct verification the proposition may be regarded as thoroughly well established from what we know at the present day.

This process may be watched by means of a simple experiment which any one can make. Let a few fresh green leaves be put into a vessel of clear glass, such as a finger-glass, or a wide-mouthed bottle, which is filled with water, and inverted in a vessel of water, the water used containing a little carbonic acid in solution, either naturally present or purposely introduced. If the whole be now exposed to the rays of the sun, it will be found that bubbles of gas are formed at the surfaces of the leaves, and these bubbles grow larger, become detached, and rise to the top of the vessel. If now the collected gas be for convenience poured under water into an inverted bottle with a narrow neck filled with water, and this be now stopped with the finger, taken out, held upright, and an extinguished but still glowing splinter of wood be introduced immediately on removing the finger, the red end of the splinter bursts into vivid combustion, indicating that the gas was oxygen, or at least contained oxygen in much larger proportion than in the air.

We see thus how the energy of light becomes in part stored up in plants, which in this way become fitted to be food for animals, man included, by whose muscular movements energy is again given out. For long geological ages this must have been the form in which alone energy was given out by animals. But now that man has appeared upon the scene, and civilization has advanced and science made progress, such stores of energy which have lain buried for ages are opened up to him, and daily employed by him in the execution of the works which he carries on. Far back in geological time the earth teemed with a luxuriant vegetation, of forms which have mostly passed away. The remains of this vegetation, accumulating on the spot where the plants grew, subsequently became buried in the course of the changes which the earth's crust has undergone, and being modified by pressure, and the chemical changes which decaying vegetable matter undergoes, they now form those coal-fields to which our own country owes so much of its greatness, and which we daily make use of in all sorts of ways. The working power which draws our railway trains, and enables us to travel at a rate which our ancestors would have thought chimerical, that which propels our steamers, and carries our merchandize and our travellers across the ocean in spite of calms or adverse winds, that by which the massive engines with which these steamers are furnished were fabricated, the heat and reducing carbon by which the iron of which those engines are made was obtained from the ore, the fires with which we warm our apartments, the gas with which we light our streets, nay even the working power that drives the dynamo machine that supplies us with electric light—all these are derived from the energy of light, stored up in remote geological ages, and now placed ready to our hands.

I have spoken of the fundamental process of the appropriation of carbon from the air by growing plants under the influence of light. But in order that it should be appropriated it must previously have been in the atmosphere, where it is found as we know in the shape of carbonic acid. The supply of carbonic acid contained in the air is constantly drawn upon by growing plants. A small portion is restored at night, for in the dark plants give out a little carbonic acid, and some more is given out in the chemical changes which accompany decay. But the supply thereof from this source is far from meeting the demand, so that if there were no other the carbonic acid in the atmosphere would be exhausted, vegetation would cease, and animals would die of starvation. But in the respiration of animals the opposite process is continually going on, carbonic acid is given out in the lungs, the carbon of which is derived from the vegetables which directly or indirectly form the food of the animals, and fires contribute to the same result. Thus by the coexistence of plants and animals the requisite balance is kept up. Without animals the supply of carbonic acid which is essential to vegetation might in time be exhausted: without plants, supposing that animals could otherwise obtain their food, the atmosphere would in time become so charged with carbonic acid as to be unfit for respiration.

What the particular chemical process may be by which oxygen is removed from carbonic acid by plants under the influence of light, is not at present known. It is believed to be in some way intimately connected with chlorophyll, as the green colouring matter of leaves is called. This substance is known to be a mixture; thus the chlorophyll of land plants consists mainly of three colouring matters; one bluish green, called by Sorby blue chlorophyll, which yields solutions exercising a powerful and characteristic absorption, and exhibiting a lively red fluorescence, another, probably greenish yellow, called by Sorby yellow chlorophyll, possessing very similar characters, though easily distinguishable by its mode of absorption, and another called xanthophyll which yields solutions which exercise a very distinctive mode of absorption in the blue, and are not fluorescent. It is remarkable that if we except the fungi, which we may regard as vegetables of prey, and perhaps a parasite or two, this mixture is always present, though not in all parts of a plant, nor even always throughout the leaves. Thus some variegated leaves are white in parts, and these parts are free from chlorophyll, or yellow in parts, in which parts the green bodies may be absent or nearly so. On the other hand leaves may differ in colour altogether from green, not from the absence of chlorophyll, but from the presence of some other colouring matter which masks its colour. Thus red cabbage owes its red colour to the presence of a red colouring matter, which differs altogether in nature from chlorophyll, being soluble in water; and when this is removed it is found that red cabbage contains chlorophyll just like green leaves in general; and even when we descend to the seaweeds we still find chlorophyll, not it is true in the olive and red series identical with that of land plants, except as regards one constituent of the mixture, namely blue chlorophyll, but this is the most important constituent as an element of coloration.

This universal presence of chlorophyll in self-sustaining plants indicates that it fulfils some very important office, and leads us to suppose that it is connected with that all-important function, the appropriation of carbon and elimination of oxygen.

The absolute necessity of light for the life of self-sustaining vegetables may be illustrated by an easy experiment. Let seeds, say of cabbage or turnip, be sown in pots which are placed in a dark cellar. Presently the seeds germinate, and send up stalks surmounted by a small pair of seedling-leaves, which however are yellow instead of green. If now the pots be left where they were, the stalks grow longer and longer, remaining however thin, white and watery, and the little pair of seedling leaves at their summits seem to grow no more, and retain their yellow colour; and presently the stalks can no longer sustain their own weight, and fall over, and the little plants die.

But if when the seeds have germinated a pot be carried into the open air, so as to be freely exposed to the light, and left there, the result is very different. The yellow seedling leaves soon become green, and the growth of the plant continues in the usual manner.

The effect of an extra supply of light on vegetation was strikingly shown by an experiment, the result of which was exhibited by the late Sir William Siemens at a meeting of the Royal Society of London. Three pots were sown at the same time with seeds of the same kind, mustard I believe. One was kept under the usual conditions, having daylight by day and being in the dark at night. Another was kept in darkness during the day and exposed to the electric light at night. The third had daylight during the day and electric light all night. The plants in the first two pots were much alike, but those in the third pot which had light night and day were strikingly different. The plants were stouter looking, with larger leaves, and of a darker green, but they were not so tall.

This experiment illustrates a phenomenon with which those who have sojourned in the Arctic regions (not too far north) have been struck, namely, the rapidity with which vegetation comes on when once summer has fairly set in. In those high latitudes the sun of course remains above the horizon in summer-time for by far the greater part of the 24 hours; and so the growing plants are somewhat in the same condition as the plants that were worked day and night in Siemens's experiment.

These two processes, the elimination of oxygen and appropriation of carbon, and the turning green of the yellow leaves of etiolated plants, take place as we have seen only under the influence of light. But light is heterogeneous, and in the wide sense in which the word has been defined contains not only visible rays differing from one another in colour and refrangibility, but also invisible rays lying beyond both ends of the visible spectrum. An interesting question now arises, are all these rays efficient alike in the production of these two effects, or of either of them, and if not, in what manner is the activity in either case distributed in the spectrum?

This question has been subjected to experiment by several persons, and notably by the late Dr John Draper, and at his suggestion by Dr Gardner, who worked with all the advantage of a Virginian sun. Instead of trusting to coloured glasses, the light transmitted by which is of a compound character, and usually includes invisible rays from one or both ends of the spectrum, they used sunlight which was reflected horizontally into a perfectly darkened room, and passed through a prism placed in the window. The spectrum thus formed was not it is true pure, but still the colours were not greatly mixed, and it could only be quite neighbouring parts of the spectrum that overlapped. The result was very decided; the evolution of oxygen by green leaves placed in water charged with carbonic acid, and the turning green of leaves which had germinated in the dark, and so before exposure presented only yellow seedling leaves, both one and the other were strongest about the brightest part of the spectrum, about the greenish yellow, and from thence decreased in both directions; the blue and violet rays in particular, which act so powerfully on most photographic preparations, being almost wholly if not wholly inactive in producing the phenomena now under consideration. The accordance between the parts of the spectrum which produce these two effects respectively makes it probable that the process by which oxygen is separated from carbonic acid under the influence of light has for result, or at least for one result, the formation of the green colouring matter.

Besides the greening of the yellow leaves of etiolated plants there is another action of light in relation to chlorophyll which we shall do well to consider, as having in all probability a most important connection with the growth of the plant. The mixture of substances called chlorophyll is soluble in alcohol, and if the mixed solution be exposed to light it is soon bleached, and there is nothing left whereby chlorophyll or products of its decomposition can be traced by their peculiar action on the spectrum. In order to insure the success of this experiment, it is necessary to be careful to guard against any decomposition of the chlorophyll, especially by even a trace of acid. For acids decompose it extremely easily, and the products of decomposition, at least of the green bodies, show like the parent substances a powerful and highly distinctive absorption (though differing from that of the parents) and a red fluorescence, but unlike them are bodies of great stability, and in particular are not readily affected by light. The same action of light in discharging the green colour is found in the chlorophyll grains themselves; and the action of the different parts of the spectrum in producing this effect was studied by Sir John Herschel, who received a spectrum on paper coloured green by crushed leaves. He found that the effect was mostly confined to the visible spectrum, or at least parts of it, and that the most powerful action of all took place far on in the red, at the place where chlorophyll exercised its most energetic absorption.

Now is there any natural phenomenon attending the growth of plants which puts in evidence this power of light to discharge the green colour? I believe there is. We are familiar with the change from green to yellow which takes place in the leaves of trees shortly before they fall in autumn. We are not to suppose, as we might at first sight have been disposed to do, that the green substance is changed into a yellow. Chlorophyll is, as I have said, a mixture, the constituents of which can be more or less completely separated from one another by suitable means. In this way it can be shown that the yellow substance found in the sere leaf was there already; the change consisted in the disappearance of the green constituent or rather constituents of the mixture—those constituents which exhibit the powerful absorption in the red and the red fluorescence. Now as it is only by light that we are able to discharge the colour of the green constituent without the formation of products of decomposition which the prism at once detects, unless indeed we have recourse to somewhat violent chemical agents, the like to which we can hardly suppose to be naturally present, we are authorised to conclude, at least with the highest probability, that the disappearance of the green constituent in the autumnal change is due to the action of light.

But if these changes from yellow to green and from green to yellow so readily take place, why is it that during nearly the whole of the life of a leaf it retains its green colour unaltered? The most natural supposition to make is that the two processes are always going on simultaneously; that there is a perpetual formation and a perpetual destruction of the green matter under the influence of light. This mode of viewing the change leads us to suppose that the green which is constantly present is not identically the same matter throughout, but is rather a phase or state of chemical combination through which matter passes, different molecules of matter in succession, probably on the road from the inorganic forms of water, carbonic acid, nitrates &c., to the organic chemical constituents of which the plant is made up.

But be the steps of the process whereby plants are enabled to assimilate carbon and eliminate oxygen what they may, this much is certain, that it is only under the influence of light that they are able to do so. Let us pause now to consider some further consequences, besides those dwelt on in the first lecture, which would follow from the absence of light. It was then pointed out how we should be deprived of our main source of warmth. But even subsidiary sources would fail us too. Animal heat would not be available, for animal heat and life are dependent upon food, and food we could not have without plants, and plants could not grow without light. Fires we could not have, for the wood or peat or coal which we might burn is derived from plants. The atmosphere would be in a state of stagnation; no wind to impel our ships, if ships we could have; nor in the absence of wind would steamers be available, for our steamers are impelled by means of coal, and what is coal but the relics of extinct vegetation, dependent therefore for the energy which in association with the oxygen of the air it supplies on the energy derived from sunshine, we know not how many thousands of years ago? In the absence of sunshine, of fuel, of wind, of rain or descending streams, we might perhaps think of tide-mills as a conceivable source of energy. But this too would fail, for the whole earth would be in a worse plight than the Arctic regions, and the ocean would be covered by more than palaeocrystic ice; would in fact be a frozen mass. Our earth would be a silent abode of darkness and of death, the stillness only interrupted by the occasional noise produced by volcanic explosions, and the darkness by the occasional lurid glare in some few places of lava streams issuing from a volcano, or of the red hot stones which it ejects; though even this there would not be if not only were our earth destitute of sunlight, but there were no such thing as light at all.

LECTURE III.

Light as subservient to vision—General structure of the eye in relation to the formation of images—Theoretical imperfections of the image formed of no practical importance in a normal eye—Structure of the retina—Rods and cones—Probable seat of the perception—Photochemical changes in the retina—Analogy of fluorescence—Power of adjustment for focus—Perception of colour—Theory of distinct primary sensations of colour—Coloured globules: their possible function—Single vision with the two eyes—Theory of corresponding points—Muscles for turning the eye-ball in all directions—Functions of these muscles in procuring singleness of vision.

WE so habitually use light for our guidance, for informing ourselves of what is passing at a distance, for enriching our minds with the thoughts of others by reading, for conveying information by writing to those at a distance, that we probably think of such things as these as forming the use of light. Yet inestimable as these uses are, there are others of still more vital importance; and in the two preceding lectures I have endeavoured to point out how absolutely essential light is to our very being, constituted as we are; how without it the earth would be a silent abode of darkness and of death.

But supposing light to be supplied as it is, and that under its influence plants grow and animals are fed on them, and obtain the warmth which they require, still light would be useless for purposes of guidance and information were we not furnished with organs adapted to its reception and to the utilisation of it for such purposes as those above mentioned. To-day I would draw your attention to some points connected with the construction and functions of that marvellous organ for the reception of light with which we are furnished. I shall mainly confine myself to the human eye.

The general construction of the eye is so familiarly known that I need not dwell upon it. The eye-ball is approximately spherical, fitting into a bony socket lined with fat and connective tissue, in which it is free to turn in all directions with hardly any friction. It is invested with a very tough covering, the sclerotic. The investing membrane is mostly white and opaque, but in front it is beautifully transparent, forming the cornea. This front portion is not exactly a continuation of the general nearly spherical surface of the eye-ball, but is slightly more protuberant, so that its surface resembles that of a prolate spheroid of revolution rather than that of a sphere, the axis of revolution being the axis of the eye. Unlike the other parts of the body, which are opaque, or merely translucent, the body of the eye is beautifully transparent and colourless. It is divided into two chambers by the crystalline lens and its support; the anterior chamber being filled with the so-called aqueous humour, the posterior with the vitreous humour. The refractive indices of these humours very little exceed that of water. The crystalline lens, which is shaped in a general way very much like a lens formed by the optician, is more refractive, its refracting power placing it at about two-thirds of the way from water to crown glass. It has been found that the refractive power of the substance of which the lens consists, varies a good deal in different parts, increasing on the whole from the external layers to the centre. The breadth of the pencil of light from any luminous point which enters the cornea, in proportion to the diameter of the eyeball, is enormous compared with anything we have in a telescope, but it is stopped down to a suitable aperture by an opaque screen, the iris, in the centre of which is a hole, the pupil, circular in man, though of different forms in some other animals, for example cats and horses. It is hardly necessary to mention what is so familiarly known, that the pupil contracts or expands spontaneously, that is involuntarily, according as more or less light enters the eye, remaining, in man, circular at all sizes.

Up to the formation of distinct images on the retina, which, as is well known, is the condition of distinct vision, the eye acts simply as an ordinary optical instrument, and we can give a full account of its functions according to the ordinary laws of refraction. In a similar optical system formed of media bounded by spherical surfaces, the image of a point would be approximately a point, but would be a little diffuse, from the effects of spherical and chromatic aberration. The question arises, do these exist in the eye, and do they impair sharpness of vision?

First, as to spherical aberration. The principal refraction takes place at the surface of the cornea, where the light passes out of air into a medium slightly more refractive than water, whereas the media it encounters in its subsequent passage do not any of them greatly surpass water in refracting power, and therefore the refraction in passing out of one into another is not nearly so great, for equal angles of incidence, as in the former case. Now when light from a distant radiant point falls on a homogeneous medium bounded by a surface of revolution in the axis of which the radiant point is situated, it may be shown that the form of the surface necessary to cause the refracted pencil to converge accurately to a point is that of a prolate spheroid of revolution, the axis of revolution passing through the radiant point, and the eccentricity of the generating ellipse being the reciprocal of the refractive index. Now it is remarkable that the cornea is approximately just such a surface.

Again, the defect of spherical aberration in an ordinary lens bounded by spherical surfaces, when used for refracting to a real focus light proceeding from a radiant point in its axis, consists in this, that the rays which fall nearer to the edge are too much refracted to be brought exactly to the same focus as those refracted nearer to the centre. One way in which this defect might conceivably be remedied would be by making the density of the medium increase, in a suitably continuous manner, in passing from the edge to the centre. It is not within the power of the glass manufacturer and of the optician to produce such a lens, but in the crystalline lens of the eye we have one of that character, and accordingly more or less approximately fulfilling the desired condition.

The result is that, though there is still a certain quantity of residual spherical aberration, its amount is not such as to cause any serious departure from perfect sharpness of definition in the image; in fact, it is only by somewhat refined modes of observation that we can establish the existence of that residual spherical aberration of which I spoke.

Next, as to chromatic aberration. This arises from the fact that when light enters glass, water, &c., the refraction increases from the red to the blue, and therefore in a convex lens the blue rays are brought to a focus before the red, and the rays of intermediate refrangibilities at intermediate distances, so that at no one distance are all the rays collected in a common focus. Hence at the best focus for the rays coming from a radiant point of white light, that namely where the rays from the brightest part of the spectrum are collected, the red and the blue rays are somewhat diffused, the red rays not yet having reached their focus, while the blue rays have passed theirs. Before the discovery of the different dispersive power of different media, this constituted a most formidable obstacle to the improvement of telescopes. Object glasses of most inconveniently great focal lengths were used, in refracting telescopes, in order to diminish the imperfections of the image which were due to chromatic dispersion. For example, an old object glass of Huyghens's is in possession of the Royal Society of London which is 9 inches in aperture and no less than 122 feet in focal length. Nowadays a telescope of similar aperture would be made with a focal length of about 9 feet only. If then chromatic dispersion caused such a serious inconvenience in the construction of telescopes, and the eye we know acts as a telescope, is there some such compensation in the eye as that which we have in the achromatic object glass, and if not, must not the want of it be a most serious inconvenience?

To the first question the answer is, there is no such compensation in the eye, and the eye is not achromatic. A pretty way of showing this is by throwing a pure spectrum on a page of small print, in an otherwise darkened room. At the ordinary distance of reading the words are seen quite sharply in the brightest part of the spectrum, but somewhat indistinctly in the red from long-sightedness, and very indistinctly in the violet from short-sightedness.

Are we then to regard the want of achromatism as an imperfection in the eye? The answer to that question depends on what we regard as the object of the eye. If the answer be, to guide us in the daily wants of ordinary life, then the want of achromatism ought not to be deemed an imperfection unless it diminished the sharpness of vision for ordinary purposes. But in reality it requires some rather refined experiments, such as that mentioned above, or some very unusual condition as regards the use of the eyes, such as viewing objects through a deep cobalt blue glass, to render the fact of the want of achromatism in the eye sensible at all. Of the twelve hundred millions or so of human beings who inhabit our earth, how few are the philosophers who concern themselves with optical experiments! And for those who do, what a small portion of their time is occupied in experiments of the kind compared with the time during which they are using their eyes for common purposes! And even in experiments there are very few indeed where the non-achromatism of the eye is any disadvantage; and if in some special case inconvenience should arise in the first instance, the man has only to set his wits to work to devise some plan for getting over it. As regards the ordinary requirements of life, the want of achromatism in the eye is of no consequence whatsoever.

Up to the formation of images on the retina we can fully explain the functions of the eye, provided at least, so far as the iris is concerned, that we confine our attention to the effect produced by the varying limitation of the pencil, and do not mean to include an explanation of the mode in which the motions of the iris are brought about. But now we come to a part of the structure respecting the functions of which we have only a very imperfect knowledge; that part, namely, which is destined to receive the impression of the external agent, and convey the influence to the sensorium.

The coating of the eye from the outside at the back of the eye-ball to the vitreous humour, is distinguished into three coats; the hard, white outer coat called the sclerotic, already mentioned, an intermediate coat called the choroid, and inside this again, between it and the vitreous humour, the retina. These coats are further subdivided into layers, the retina more especially presenting a highly complex and curious structure. I am no anatomist or histologist myself, and I do not propose to describe to you at second hand, except very briefly, the microscopic structure of this curious organ. As we proceed from the centre of the eye-ball outwards, that is, towards the socket, and accordingly in the direction in which the light travels, we first meet with a plexus of extremely fine nerve fibres, the general course of which is parallel to the surface of the eye-ball, and which unite in the optic nerve, which runs into the brain. This layer of nerve fibres is followed by several other layers, containing "granules," or "ganglionic cells," or "molecules," until at last we come to a remarkable and very peculiar structure, the "bacillary layer." This series consists of a set of elongated bodies, arranged radially, and closely set in lateral directions. They are of two kinds, which are denominated respectively rods, and cones. Each of these consists of two portions, an outer, highly refracting portion or outer limb, and an inner portion or inner limb not thus highly refracting, the two portions further differing as regards the effect produced on them by certain reagents. Each inner limb on its inner side runs into a fibre, apparently a nerve fibre, which proceeds in a direction towards the nerve plexus, but runs into certain roundish bodies "granules" &c., on the way. On the other hand the nerve fibres of the plexus turn on the outer side into an oblique direction, running on in the direction of the rods and cones. There seems every reason to believe that the nerve fibres of the plexus are continuous with the fibres seen running out of the inner limbs, though the continuity has not actually been traced quite the whole way.

Consider for the present the action of a single eye, reserving for future consideration the joint action of the two eyes. We know that the image of a point on the retina gives rise to the sensation of a point in the field of view, and that the part of the field that the point seen appears to occupy depends on the part of the retina on which the image fell. The images of a variety of points in the field of view necessarily follow the same order of sequence with regard to lateral direction as that of the actual points from whence the pencils come, the image of a point to the right of the axis of the eye falling on a point of the retina to the left of that on which falls the image of a point in the axis; the image of a point above the axis falling on a point of the retina below the axis, and so on. The order of sequence of the sensations is that of the sequence of the points of the retina affected; and that an inverted image should give rise to the sensation of an erect object need not create any difficulty, as there is no reason *a priori* that we can see why the order of the sensation as to up and down, right and left, should be the same as the order of the points of the retina affected rather than the opposite. It remains to enquire whether there is anything in the structure of the retina which appears calculated to give rise to separate sensations when separate points of the retina are stimulated, even though those points should lie very close to each other, and again whether there is anything which appears calculated to receive impression from light, at the expense of energy on the part of the light so impressing it, and thus to become an organ of perception.

Now there is just this one part of the retina, the bacillary layer, where we have a vast number of separate elements closely set in lateral directions, while elongated comparatively speaking in a radial direction. These elements are provided with fibres, which, there is every reason to believe, are nerve fibres, running towards the layer of nerve fibres which forms the first layer of the retina as we proceed from the centre of the eye outwards. Moreover the lateral distance between the cones in the part of the human retina immediately about the axis, where the vision is most distinct, agrees very closely with the distance on the retina of the images of two points which can just be seen as two. It is found that the smallest angle subtended at the eye by two points which can just be seen as two is about 1′, from whence the distance of the two images on the retina can be calculated. It comes out about 4 thousandths of a millimetre, and the lateral distance apart of the cones near the axis of the eye is according to Schultze about 3 thousandths of a millimetre, or very little over the thousandth of an inch. There are still further arguments leading to the same conclusion, namely, that the rods and cones are the percipient organs.

I have said rods *and* cones; for that both are concerned in vision, which is possible with either, is shown by the fact that some animals (as for example lizards) have got only cones, while in others (as the owl) there is little else than rods, and in bats, nothing but rods. In the human eye, we have over the greater part of the yellow spot cones only, while over the greater part of the rest of the retina the rods are much more numerous than the cones; and we know that while we see most distinctly over a small portion of the field of view surrounding the point to which we direct our eyes, we do see simultaneously over a very large field. But while it is certain that either structure is adapted to vision, it is at present only a matter of conjecture, or perhaps I should say probable inference, in what respect the functions of the rods and cones differ from each other.

It is to be remarked that the layer of nerve fibres is the first thing the light meets with after passing across the vitreous humour. Hence the light must go right across the layer of nerve fibres (as well as certain other intermediate layers) before it can reach the bacillary layer. Hence the mere passage of the light across these nerves, nerves of vision though they be, produces no sensation of vision, nor indeed sensation of any kind. If it did, light might be perceived as such, but there could be no distinct vision. For it appears to be a rule that the stimulation of a given nerve produces a given sensation, no matter to what part of the nerve the stimulus be applied. Hence if one of these visual nerve fibres were capable of being stimulated directly by light, the visual sensation corresponding to it ought to be produced (mixed it may be with other sensations) when the point from which the light came occupied not merely one but a whole series of positions, becoming a line when projected on the visual sphere, those namely whose images on the retina lay on the various points of the nerve fibre in question.

The same conclusion, namely, that the nerves of vision are not directly stimulated by light, follows from the well-known phenomenon of the blind spot of the retina. The nerve fibres belonging to the layer mentioned above unite in the optic nerve, which runs into the brain, being led out of the eye through a hole in the sclerotic, not in the axis of the eye, but to one side towards the nose. Now images of points in the field of view must be formed on this spot as well as elsewhere on the retina, but the common experiments in relation to the *punctum cœcum* show, that no visual sensation is produced by the light which falls here. This oblique position of the optic nerve is accordingly a matter of the utmost importance to us. We might perhaps have expected at first sight that the fibres would have been arranged symmetrically with respect to the axis, and have been led out into an optic nerve at the centre of the back of the eye-ball. Had this been so, we should have been blind to the point of the field at which we looked, and for a little way round it. As it is, the centre of the field, which is the place where vision is most distinct, is seen with both eyes, and though there is a small patch to the right of the centre of the field for which the right eye is blind, it is taken up by the left eye; and similarly as regards the blind spot of the left eye.

The well-known experiment of Purkinje's figures affords a further proof that the nerves are not stimulated by the light which crosses them. In this experiment the forms of the blood-vessels of the retina are seen in the field of view, in consequence of the partial interception of the light which falls upon them. This shows that they must be situated in front of, and not far from, the percipient organ, so that their shadows may fall on it as on a screen; and their motion, when the candle used in the experiment is moved, shows on the other hand that they do not actually touch it. Now it is found on dissection that the blood-vessels run among the nerve fibres, and therefore the percipient organ must be situated a little further back, that is, a little outwards, reckoning from the centre of the eye-ball. Such is the situation of the layer of rods and cones.

The office of the nerve fibres appears to be simply one of conveyance, notice of a change of condition of the recipient organ at the nerve end being conveyed in some way by the nerve to the brain, and then in some manner which seems likely always to remain a mystery, giving rise to the sensation. Perhaps the subject may be made clearer by a rough analogy drawn from common life. Take the sending of a telegram. The image painted on the retina is analogous to the message handed in to the telegraph clerk, the percipient organ to the instrument manipulated by the clerk, the nerve to the line wire, the sensation to the delivery of the message at the other end.

The general surface of the outer ends of the rods, or in the central part of the retina where there are no rods, of the cones, is in contact with a layer of cells containing a black pigment; cells which also extend some way inwards so as to come between the rods, and still further inwards when stimulated by light, so as in that case to reach to the cones, with which they are in contact independently of the stimulus of light, in that part of the retina where there are no rods to keep them off. The office of the black pigment is generally supposed to be to absorb stray light, like the lamp black with which the optician coats the inside of the tubes of his telescopes. Since however light must be more or less absorbed in order to produce a change in the percipient organ, and there is no substance in the neighbourhood, at least in the case of the human eye, capable of exercising so intense an absorption as the black pigment, it has been doubted whether its office may not be more direct. But that it is not at any rate essential to vision is shown by the fact that it is wanting in albinos, who nevertheless are able to see.

What the particular part of the rods or cones may be at which the change takes place from light to some effect produced by light which gives rise to the sensation of vision, and what the nature of that effect may be, are questions to which we are not at present able to give determinate answers. It has I believe been suggested that the outer segments are the seat of the change, and that the change is of a photochemical nature; that is to say, that under the influence of light certain chemical decompositions take place, and that the new products thus formed act as a stimulus on the nerves.

It is noteworthy that in most vertebrates the outer limbs of the rods are suffused with a purple colouring matter, which has been called visual purple, which has the property of being turned yellow and then bleached under the influence of light, while in the dark the purple colouring matter is regenerated provided the eye is sufficiently fresh, and the rods are in contact with the choroidal epithelium. The visual purple possesses accordingly some of the properties which we should expect on the supposition that vision is produced by a photochemical action: but its changes are not sufficiently prompt to allow us to suppose that it is through its means that vision is obtained, besides which it has not been found in the cones, but only in the rods, and some animals are destitute of rods, nor are there rods, but only cones, in the part of the human retina which is in the immediate neighbourhood of the axis, though objects in the corresponding part of the field of view are not only seen but seen with special distinctness.

There are several arguments which may be urged in support of the photochemical view, which has much to commend it. At the same time I confess that it seems to me not altogether exempt from difficulty. The sensation remains as long as the eyes are kept open and light supplied, with no apparent change beyond a somewhat greater sensitiveness of the organ on the first admission of light after it has been kept for some time in the dark; and yet when the light is cut off, as by removal or failure of the source or by closing the eyelids, the sensation seems immediately to stop. I am not speaking, you will understand, of the phenomenon of so-called after-images, but of the ordinary sensation of vision. It is true that the cessation of the sensation is not instantaneous, for the steadiness of the impression produced by a rapidly fluctuating light shows that the sensation lasts for a finite though short time, which has been estimated at the tenth of a second, and it is much enfeebled in a considerably shorter time. It may be remarked in passing that the duration depends upon the colour; being distinctly longer for blue than for red light. We cannot of course say for certain that this demonstrates a brief finite duration in the change of state produced in the percipient organ, though that appears to be the most probable explanation, for it might depend on the time that the influence on the end of a nerve takes to travel along it, though the time seems much too long for that if we may judge by the time an influence takes to travel along nerves of touch; or again it might depend on the sensation of impressions in the sensorium.

Now, supposing the duration of the impression to depend on the duration of a change of state in the percipient organ, it seems to me that there is one physical phenomenon in which a change of state is produced by the action of light, the behaviour of which in respect of duration is strikingly analogous to what we require in the percipient organ. I allude to phosphorescence of brief duration, of such duration that it might be called indifferently phosphorescence or fluorescence. Take for example uranium glass. The glass is yellow by transmitted light, from the absorption of the most refrangible rays. But if we regard it in such a direction as to look across the rays, as soon as the light is let on we see a green colour, which is due to phosphorescence. This remains as long as the light continues to fall upon the glass; and when the incident light is cut off, the green phosphorescence seems immediately to cease. It lasts however an appreciable time, the thousandth of a second or so, as may be shown by Becquerel's phosphoroscope and by other means.

Now the change of state in the glass, the existence of which is made known to us by the phosphorescence, is, so far as the relation between the time of action of the exciting causes and the duration of the effect goes, precisely such a change as we require in the percipient organ. This tempts us to enquire whether possibly the change in the latter case may not be of a similar nature to the change in the former. Now, what takes place in the glass is doubtless this: the incident ethereal vibrations throw the ultimate molecules of the uranium compound into a state of internal agitation, and they in turn become centres of disturbance to the ether, and so give out light. When the incident light is cut off the molecular agitation does not at once cease, but rapidly dies away, partly by communication to the ether, but mainly, as I have long thought, by communication of an agitation to continually widening groups of neighbouring molecules of the glass, which form vibrating systems of greater extent and increased period of vibration. When the light falls continuously on the glass the molecular agitation tends to be renewed as fast as it tends to die away, and a permanent condition is maintained. Now, if a similar kind of molecular agitation is excited in the ultimate molecules of the substance or substances of which the percipient organ is composed, and if being excited it is able to affect the nerves, we have just such an apparatus as we require.

I throw out this conjecture for the consideration of physiologists, of whom I have no pretensions to be one myself, and merely as a conceivable alternative to the photochemical theory which it seems worth while to bear in mind, even though the latter should appear the more probable. I would just observe that the presence or absence of fluorescence in the percipient organ would not by itself alone go far either to confirm or to refute the suggested explanation. For fluorescence is so common in organic substances that it might very well be present without having anything to do with vision. On the other hand, molecular agitations similar in their nature to those in uranium glass might very well be present, and yet not give rise to any visible light, as their period or periods might be such as to belong to rays beyond the red.

When a person uses a telescope for viewing objects at different distances, and some of them not far off, he is obliged to re-focus his instrument in passing from one object to another, as otherwise he would not see them all distinctly. Now the eye acts as a telescope, and if it remained invariable in form we could not see quite distinctly objects at very different distances. The focal length of the eye being but small, an object at a moderate distance would be as good as at an infinite distance so far as sharpness of vision is concerned, and therefore a person who could see distant objects distinctly, would also see distinctly objects at a moderate distance without any change in the eye. But when we come to nearer objects, as in reading, the vision would be indistinct, unless assisted by spectacles, if there was not some change in the eye itself answering to the re-focussing of a telescope. But we are provided with such an adjustment (at least during youth and middle age, for the power is diminished or lost in old age), by the exercise of which we can see distinctly at very different distances. What the changes are which constitute the adjustment has given rise to some conjectures, but it is now ascertained to consist essentially in an alteration of curvature of the anterior surface of the crystalline lens. The lens being somewhat more refractive than the aqueous humour, an increased curvature of the anterior surface shortens the focus, which is what is required for distinct vision of a nearer object. The adjustment ordinarily accompanies, apparently automatically, the voluntary act of making the axes of the two eyes converge on a nearer or more distant object, though some persons appear to have the power of altering the adjustment at will independently of an alteration in the convergence of the axes.

Hitherto I have spoken only of the perception of light as such. But the objects which we see are not presented to us simply in light and shade as in a photograph; we see them with a great variety of colours, which contributes very much to our enjoyment, and helps us in the ordinary concerns of life by the means of discrimination which it affords. The means whereby the difference of sensation produced by lights of different composition as regards refrangibility is brought about, are far from being understood; we can only feel our way towards a partial explanation.

It has long been recognised that there appears to be a triplicity of some kind about the various colours which we are able to perceive, as if they were referable to a mixture of three primary colours, though some confusion was formerly made in the subject from regarding the colour produced by a mixture of coloured pigments as the same thing with a mixture of the colours which the pigments separately exhibit, which in fact is a totally different thing. Now, assuming the existence of say three primary colours, the difference between them might be objective or subjective; that is to say, there might be three kinds of light, usually mixed together in any light presented to us, each affecting us with the same sensation as to colour, different from that with which the two others affect us; or else we might have as it were three senses in relation to light, such that if one were alone affected we should have a particular sensation as to colour, which would remain the same though other circumstances, such for example as the refrangibility of the light, might change. On the former supposition, an element of a pure spectrum would contain three kinds of light though not separable by refraction, the proportions of which would change from one part of the spectrum to another; on the latter, the light of the element would be homogeneous, but would be capable of exciting our colour senses simultaneously, but in proportions differing according to the place of the element in the spectrum.

Of these two suppositions, the second, which is that of Dr Young, is by far the simplest. For even if there were a triplicity in the object, we should still require a triplicity in our organization in order that the objective difference might be subjectively perceived as a difference; whereas, if a triplicity in the organization be admitted, we have no need to assume a triplicity in the object, of which we have no experimental evidence. It is true indeed that Brewster thought that he had succeeded by the use of absorbing media in modifying the tint of a given part of a pure spectrum. But the phenomena on which Brewster relied have since been shown to be due to illusions of contrast. There are cases indeed in which the apparent tint of a given part of the spectrum changes somewhat with the intensity of the light, independently altogether of contrast. But this affords no proof that light homogeneous as to refrangibility is nevertheless heterogeneous as to colour.

The experiments of Helmholtz and Maxwell appear to show, that the supposition of the existence of three primary colour sensations suffices to account by their union for the various shades of colour which we perceive. In particular Maxwell has shown by his colour top, and more recently by mixing colours of the spectrum, that if we take three standard colours X, Y, Z, any colour C may be expressed by the formula

$$C = aX + bY + cZ,$$

where a, b, c are numerical coefficients which may be positive or negative; $=$ means matches in colour and intensity; $+$ means superposed on, and $-$, in case any of the coefficients should be negative, means that the term must be transferred to the other side of the equation. If the standard colours are well chosen the coefficients a, b, c in most cases will be positive. The best colours to choose for standards appear to be red, green and blue.

Microscopic examination of the retinas of the eyes of mammals has not hitherto revealed the existence of a difference of structure in the different elements which would naturally suggest a triplicity of function. We have it is true rods and cones, but in the central parts of the human retina there are only cones, which appear alike; and yet in the centre of the field our appreciation of colour is specially good. But it is remarkable that in the retinas of birds and reptiles the inner limbs of the cones are furnished with highly coloured globules, which the light has to pass through on its way to the outer limbs. The actual colours appear to vary somewhat from one kind of animal to another, but to be generally yellow, ruby, colourless, and a few green. The globules of one colour may be more numerous than those of another, but the globules of the different colours appear to be very equally mixed among one another. So remarkable a structure can hardly be imagined to be destitute of function, and it has naturally been supposed to be connected with the perception of colour by these animals. The cones in the same species of animal may be classified according to the colour of their globules, and it seems not unreasonable to suppose that the sensation excited by the stimulation of the fibres coming from cones of one class may differ from that produced by the stimulation of those from cones of another class, and that this difference may correspond to a difference of the colour perceived.

It can hardly be doubted that when light produces vision it is absorbed in doing so. Now the coloured globules absorb the rays of part of the spectrum and let pass those of another part. The ruby globules, for example, let through the red rays and absorb those that are more refrangible. If we suppose the globule and its immediate neighbourhood to be the percipient organ, the stimulating rays will be those above the red, the assemblage of which would excite in us the sensation of green. But if, as seems more probable, the organ in which light first produces those changes that result in vision be the outer limbs of the cones, the globule would stand as a porter at the gate, letting through none but the red rays, which on this latter supposition would be the stimulating rays.

The retinas of mammals however are not provided with these coloured globules, which shows that at any rate colour vision may be obtained without them. They are nevertheless so far confirmatory of the theory of three primary sensations of colour as that they show the existence, in certain races of animals, of different classes of cones, those of each class being on the whole very equally mixed among those of the other classes; and it seems not at all unlikely that the nerves which end in the cones of these different classes respectively may on stimulation give rise to sensations of different kinds respectively. In the human eye the cones on being traced inwards lead to a sort of fine thread, which at its base divides into excessively fine fibres. It has been conjectured that of these different fibres may on stimulation give rise to different colour sensations, so that each cone would as a rule furnish fibres of each class: and a plausible conjecture might be offered to account for the proportion between the stimulation of the fibres of different classes being different with exciting lights of different refrangibility. On this supposition, the parts of objects which were only distinguishable from one another by colour would be more sharply defined with man than with those classes of animals where different colour sensations belong to different cones, if indeed such be the case with those animals which are provided with coloured globules. But I fear I have been indulging too much in what is only speculative.

I have hitherto considered almost exclusively the action of a single eye with reference to vision. But though we have two eyes, each of which gives us perfect vision of an object, which for the present I will treat as a point, when we use both eyes together we do not ordinarily see the object as two but one. It is perfectly easy, however, to see it as two. We have only to squint, or if we prefer it, to hold a small object in a line with the first, but at a different distance, and direct our eyes to it, and instantly the first object is seen double. In the first case, the axes of the two eyes were directed to the object, and its images fell on the centres of the two retinas, in which case as we have seen the sensation is that of a single point in the field of view. In the second case the axes are directed to the second object, which I will suppose to be nearer than the first, and will treat as a point, and it accordingly is now seen single in the centre of the field. But as the first object lies to the right of the axis of the right eye, its image falls to the left of the centre, and it is accordingly seen by the right eye to the right of the second object. Similarly it is seen by the left eye to the left of the object. In a similar way it appears that if the eyes be directed to the first object, the second is seen double; but now, as seen by the right eye, it appears to the left of the object seen single, and similarly as regards the other eye.

Suppose now, that while the eyes are directed to the near object the further one is moved to the right.

Both its images will appear to move to the right, and presently they will both appear to the right of the second object but at very unequal distances from it, the one previously to the right, which is the one seen by the right eye, being the more distant. Suppose now, the first object brought nearer to the eyes than the second and placed in a line with it. Then, of its two images, it is now the one to the left that is seen by the right eye. Hence, if the first object be moved to the right, till both its images are seen to the right of that of the second, the one seen by the right eye is now the *less* distant from it. Now suppose the first object held always to the right of the second, so that both its images appear to the right of the second, and let it be moved from a distance from the eyes decidedly greater than to a distance decidedly less than that of the second object. Then the distance of the image seen by the right eye from that of the second object will at first be the longer, and at last the smaller of the two distances. Hence, as the first object is moved continuously from the first to the second position, for some intermediate position the two distances will be the same, and the first object will appear single though it is to the second that the eyes are directed. Hence, not only do the centres of the two retinas correspond, in the sense that when the images of a point fall on them the point is seen single, but other pairs of points possess the same property. In fact, to each point of one retina corresponds a point in the other in the sense above indicated.

According to this definition it would be a matter of experiment to determine the relations between the positions of corresponding points in the two eyes; and as we cannot at all accurately judge of the coincidence or non-coincidence of position of two points when they are well out of the axis, near which only we see with full distinctness, the experimental determination could not be very accurately made. When however we look straight forward at one point of a distant object the rest of the object appears single. Hence, the two points on which fall the images of any one point of the object are corresponding points, at least within the limit of errors of observation. This condition is accordingly usually taken as the *definition* of correspondence; though I confess it seems to me that the natural definition is that derived from singleness of vision; and the fact that under the condition named, the two images of the same point in the object fall on corresponding points of the two retinas, is to be taken as a proposition established by experiment.

There can be no doubt that the stimulation of a given point of the retina of either eye by the image of a point falling upon it, produces a given sensation no matter how the eye-ball be turned in its socket. Suppose then, we have single vision of an object, say a distant object, using both our eyes. Then the pairs of foci from the various points of the object fall on pairs of corresponding points on the two retinas. If now, while one eye-ball remained fixed, the other rotated round any axis, immediately the pairs of points on which pairs of foci fell would become non-corresponding, and we should have double vision. Hence, there must be a determinate adjustment between the angular positions of the two eyes in order that vision may be single.

Now the most general angular displacement of a body, and accordingly of either eye-ball, may be given by three rotations about determinate axes, suppose vertical, horizontal running right and left, and horizontal running forwards. Now it is remarkable that the eye-ball is provided with six muscles, one straight pair in a horizontal plane the contraction of one or other of which turns the ball in one direction or the contrary round a vertical axis; one straight pair in a vertical plane, which similarly turn it round a horizontal axis running right and left, and a third pair of oblique muscles, which turn it round its own axis. By means of these the requisite relative adjustment of the eye-balls can be and is effected.

The horizontal muscles are in constant use for not merely turning but turning unequally the two eye-balls, as we have occasion to make the axes converge on objects at various distances, from a few inches up to a large distance for which the axes may be deemed parallel. We have no occasion to make them diverge, but there is no difficulty in doing so up to a few degrees of divergence, by holding before one eye a slender prism with its edge vertical and its thick side next the nose, and viewing a distant object till it appears single.

Unlike the horizontal, the vertical straight muscles are not called upon in ordinary life to act differently for the two eyes. But that they are capable of doing so may be shown by looking at an object and holding a slender prism with its edge horizontal before one eye. The object is at first seen double, one image being above the other, but if the separation be not too great they can be readily united after a little. The experiment, as Maxwell showed me, can be made with still simpler apparatus, nothing but a pair of common spectacles being required. Viewing an object through the spectacles, turn them gradually and not too much round an axis passing through the ridge and perpendicular to the planes of the glasses. One can easily maintain single vision, and if the spectacles be now suddenly removed the vision is found to be double at first, one image being over the other. This shows that the vertical muscles afford sensible play for adjustment.

Lastly, the use of the oblique muscles in adjustment may be shown by a simple experiment which I have not seen mentioned. Take two slips of glass varnished at the back to stop the second reflection, and holding them one under each eye view by reflection at a high angle of incidence the images say of the string of a blind as it hangs down and is seen against the sky. Adjust the glasses to make the images blend into one in the most comfortable manner, and then turn one of the glasses slightly round an axis pointing forwards. The two images are seen to cut at a small angle, but on continuing to gaze at them they presently blend into one.

How the unity of sensation between corresponding points is brought about, is more than we can tell. The optic nerves after entering the brain unite in the optic commissure, from whence run nerves to the right and left sides of the brain. The course of the fibres in the commissure, and the extent to which the fibres from the right eye cross over to the left side of the brain or keep to their own side, are not I believe as yet made out for certain, so difficult is the histological investigation of these fine and complex structures. What the object of this mode of crossing may be, and whether it has anything to do with singleness of vision, is not at present known. But whatever be the mode in which the unity of sensation is brought about, there appears to be no doubt that as a matter of fact the elements of the retinas of the two eyes do correspond in pairs, and that the six muscles of the eye-balls supply the mechanism required for adjustment to single vision.

LECTURE IV.

Original object of the Burnett Trust—Possibility at first sight of contemplating the motions of the heavenly bodies as having gone on as they are from a past eternity—Such a view negatived by their physical condition—This scientific conclusion greatly strengthened when we consider living things—Scientific investigation is adverse to the hypothesis of the spontaneous origination of life—Our inability to explain by mere natural causes the vast variety of forms of life, and their changes in geological time—Difficulties of the Darwinian theory if regarded as a solution of the problem—Evidences of design afforded by an examination of the structure of living things—Marvellous adaptation of the eye to its uses—Self-existence, beyond which we cannot go, not attributable to the visible universe—The evidence of design leads to the contemplation of a designing mind, of whom self-existence has been affirmed—Further evidence derived from the study of mind—Inadequacy of the human mind to take in together the ideas of personality and exemption from limitations of time and space—The character of God revealed to us through the Son.

In the order of the Home Secretary by which a new direction was given to the Burnett Foundation, it is prescribed that the Trustees shall instruct the lecturer to have regard, in treating of the special subject prescribed, to the illustration afforded by it to the theme proposed by the testator. Hitherto I have touched only incidentally on this topic; but I think that I shall not be acting otherwise than in accordance with the wishes of the Trustees by devoting the present lecture, the last I shall deliver as Burnett Lecturer, to this special subject.

Let us in imagination so separate ourselves from ourselves as to use our intellect, while conceiving ourselves unconscious of our own existence and of all that that involves; and under this restriction let us contemplate the heavenly bodies, more especially those of the Solar System, from the point of view of an astronomer who observes and records the places of these bodies from time to time, and reduces their motions, at first complicated and to a considerable extent lawless, to order under the guidance of the law of universal gravitation, but who avoids, as foreign to his subject, any speculation as to the physical condition of the bodies other than that they consist of matter obeying the law of gravitation. Such a person ascertains that the motions of those bodies take place in accordance with the results of his calculations. He finds that he is able to determine years beforehand what the places of those bodies shall be, and when the time comes they are found in their predicted places; or, if there be minute discrepancies beyond the limits of casual errors of observation, he finds that by revising his calculations, which are excessively complicated, and can only be carried out approximately, though there is no limit to the accuracy to which the calculations may with patience be carried, these minute discrepancies gradually disappear; or if there be still a slight outstanding error the presumption is that it only needs a yet still more refined and laborious calculation to account for it. There is no intimation of any error in the principles on which the calculation is founded; and it is proved mathematically that according to those principles the motions are periodic, and capable of indefinite continuation. It is true that the orbits in which the planets move are subject to very slow variations, but these secular changes are themselves found to be periodic, though the periods are enormous compared with those of the bodies in their orbits. And just as the motions of the bodies are capable (in accordance with the principles to which we have hitherto confined our attention) of indefinite continuance in time to come, so they may be determined from our formulæ for any past time however remote. For anything that appears so far, the heavenly bodies may be self-existent, in the sense that they are capable of continuing as they are for ever, and may have existed as they are from a past eternity.

But when from considering merely the motions of the heavenly bodies we examine into their physical condition, even though we still continue to ignore the existence of plants and animals, ourselves included, the case is very different. The geological examination of the superficial portions of our earth, to which alone we can get access, points to a succession of changes extending indeed over vast periods of time, but progressive rather than periodic in their nature. There are indications of volcanic agency in remote times on an immense scale; and various considerations, derived in part from a study of the figure of the earth independently of geological speculations, lead to the probable inference that the earth was originally in a molten state. The telescopic appearance of the surface of the moon points to the former existence of powerful volcanic forces now extinct. In the case of the moon, and to a great extent in the case of the earth, we are without evidence of the present existence of a residue of primitive heat; but the sun is always pouring forth heat into space by radiation. This, as was observed in a former lecture, is analogous to a continual expenditure of capital, and is not therefore a process calculated to last for ever, or which can have been going on from a past eternity. Similar conclusions as regards the earth might be deduced from a consideration of the effects of tidal friction, which must tell in the long run; but the consequences of this are less easily followed, and what has already been mentioned is sufficient for our purpose.

The upshot is that even if we leave out of account all organization, whether of plants or animals, we fail to find in the material system of nature that which we can rest on as self-existent and uncaused. The earth saith it is not in me, and the sun saith it is not in me.

When from the contemplation of mere dead matter we pass on to the study of the various forms of life, vegetable and animal, the previous negative conclusion at which we had arrived is greatly strengthened. We can conceive of suns and systems as formed, under the operation of laws open to our investigation, from masses of matter previously in the condition of fiery nebulæ. I do not say that they were actually so formed, but only that there is nothing opposed to what we know of the laws of nature in the supposition that they were; and modern researches have even lent some additional degree of probability to the supposition that such was their origin.

But as regards living things the case is different. As I have already remarked, a physical examination of the condition of our earth gives us reason to think that the earth was at one time in a molten state, a state accordingly in which no living thing, be it plant or animal, such as we know, could exist. How then did it become furnished with the abundance of life in various forms that we see around us at the present day, and that the examination of fossil remains shows to have existed in ages far back in geological time?

Two questions are here involved; first, that of the origin of life on earth in any form, and secondly that of the origin of the various forms in which we find it, forms that have changed from one geological age to another.

As to the first, some of the ancients imagined that maggots were spontaneously generated in decaying flesh, and that carcases bred bees. It needed however no great study of natural history to dispel such notions as these, and as to the larger animals there could never be any question that they were the offspring of others like them. We have however animals varying in size from the whale or the elephant to creatures so minute that it requires a microscope to show them at all. It stands to reason that the germs of these last, if germs there be, would be of such minuteness that even the microscope could hardly if at all reveal them. Such organisms are constantly found in connexion with putrefying substances, even though the closest search fails to reveal the germs, if germs there be, from which they spring; and the question has been seriously debated, even in recent times, whether creatures of such a kind may not sometimes at least arise spontaneously from dead matter. The experimental investigation of this question, as will readily be understood, is beset with great difficulties, so hard is it to effectually exclude germs so excessively minute as must be those of these microscopic organisms, if indeed they do come from germs. The result of the experiments which have been made in this subject by the most careful workers is such that most persons are I think now agreed that the evidence of experiment is very decidedly against the supposition that even these minute creatures can be generated spontaneously.

Here then, in the origin of life, we have a problem which science fails to give any account of. It differs from that of the origin of the celestial bodies in this respect, that it does not send us back to a time so remote that we are unable to contemplate any orderly system of nature anterior to it. On the contrary, if, as science seems to indicate, our earth were at one time in an incandescent state, very considerable progress must have been made towards the condition in which we find it at present before it would be adapted for a habitation to even the simplest forms of living things that we see around us or find remains of in a fossil condition. We have then evidence in the commencement of life on earth of the operation in time—and not merely at some indefinitely remote time which we please to contemplate as that of the origin of things—of a cause which for anything that we can see, or that appears probable, lies altogether outside the ken of science.

One conjecture has indeed been thrown out which if it were seriously entertained would invalidate the evidence of the operation in time of some ultra-scientific cause, that is derived from contrasting a former azoic condition of the earth with its present condition and that which it has had during geological ages now long since passed, but subsequent to the azoic period. In his presidential address at the meeting of the British Association in Edinburgh in 1871, Sir William Thomson suggested as a conceivable mode of conveying some form of life to the earth that possibly a meteorite containing the germs of some low organism might have fallen on the earth, and that these germs might have given rise to a living progeny. Of course such a supposition if adopted would leave untouched the problem of the origin of life; it would merely invalidate the argument for the origination of life on our earth within geological time.

I need not however dwell on the many formidable difficulties which stand in the way of any such hypothesis; for example the intense superficial incandescence produced in a meteorite by its rapid passage through the air, for I do not conceive that the hypothesis was ever meant to be adopted. I can say for my own part that as I listened to the address I did not suppose that the distinguished speaker threw out the hypothesis as one to be really entertained; he was only, as I understood him, illustrating in a graphic manner the nature of a *vera causa* as distinguished from would-be explanations which refer the origin of life to something of the nature of an occult quality.

But the existence of life upon earth is not the only problem which presented itself to us; there is a vast variety of forms of life upon earth; can we give any scientific account of the origin of these forms?

I need hardly remind you that one famous theory has been put forth to account for the origin of species, which is due to a most distinguished naturalist who has not long since departed from among us. In this theory there are postulated, first, the existence of life to start with, secondly the continuation of life by reproduction, thirdly, the general resemblance of offspring to parents, whether of plants or animals, combined however with minor variations which we are obliged to regard as accidental, fourthly, a tendency towards the hereditary transmission of any special peculiarity, any deviation, that is, from the average normal type.

These postulates being assumed, it is held that in the struggle for existence consequent on the limitation of space and food supply, individuals with such variations from the average type as are advantageous in the struggle will have a better chance than those that are otherwise constituted, and are likely to live longer and produce a more numerous progeny; and as the progeny have on the whole a tendency to inherit the peculiarities of their parents, there is thus a one-sided tendency towards an improvement in the race, improvement in the sense of its becoming better fitted for its environment. This change may be conceived to be continued till a maximum is reached, when any slight deviation from the normal type would be disadvantageous rather than otherwise, and thus the form of maximum advantage would tend to be perpetuated; and just as, to use a mathematical illustration, a function of several independent variables may admit of a variety of maxima, so on this hypothesis we may conceive of a variety of forms of life, each possessing the quality of a maximum of adaptation to its environment, these forms answering to different species.

The amount of transmutation of form which can be obtained in actual experiment is small indeed compared with the interval which separates remote forms of life; nor is it by a process analogous to the survival of the fittest that the more remarkable even of these transmutations have experimentally been brought about. But it is held that the time at our disposal is merely infinitesimal compared with the ages which such changes required in the natural way. In fossil remains however we have records, fragmentary it is true, and more or less discontinuous, of forms of life which have existed far back in geological ages. We might have expected to find here evidence of a continuous change from one of what we call species into another, if such there were. While however there is a general progress in the character of forms of life, when looked at in the large scale, the links which might have been expected are for the most part wanting. This the advocates of continuous transmutation account for by supposing that the records of intervening forms have been swept away and destroyed by the convulsions which from time to time wrought great changes in the earth's crust in the past. Some on the other hand are of opinion that an examination of the records of the past is unfavourable to the hypothesis of continuous transmutation. Thus Sir William Dawson expresses the opinion that an examination of fossil remains points rather to outbursts of fresh forms of life from time to time in past ages; forms which seem to tend rather to deteriorate than to improve*.

It would ill become me to express an opinion of my own in branches of science which like geology are out of the track of my own studies. Suffice it to observe that if as regards the first origin of life on earth science is powerless to account for it, and we must have recourse to some ultra-scientific cause, there is nothing unphilosophical in the supposition that this ultra-scientific cause may have acted subsequently also.

Hitherto I have spoken of living things and the various forms of living things merely in relation to their existence. They cannot it is true be thought of wholly without regard to their structure; but hitherto the structure has been kept out of view, being reserved for separate consideration. Let us now turn our attention to this point.

The most cursory examination of living things, especially the higher animals, cannot fail to impress us with the adaptation of their structure to their mode of life and their wants. This is perhaps most strongly felt when some one organ is taken, and studied in considerable detail. Let us take then the

* The chain of life in geological time. Published by the *Religious Tract Society*.

eye, suppose the human eye, the structure of which in relation to its functions was to some extent dwelt upon in my last lecture. What a wonderfully refined organ it is that we are here presented with. While the other parts of the body are opaque or merely translucent, we have here a ball an inch or so in diameter as clear as crystal. The form of the cornea, the form of the crystalline lens, are such as an optician would choose for the refraction of pencils of light that were to be brought to foci on the spherical surface of the back of the eye itself, and that, even including refinements which are neglected when as is usual in elementary books we confine our attention in the first instance to the so-called geometrical foci to which extremely slender pencils would be brought, but the neglect of which would entail imperfections of vision not indeed fatal to the use of the eye, but interfering with its full efficiency. Then we have that delicate self-acting screen, the iris, which regulates within wide limits the quantity of light that is allowed to fall upon the retina, and so guards that network from permanent injury or temporary dulling of sensibility which might be occasioned by an excess of light, while at the same time allowing a marvellous sensitiveness to feeble light. Then we have that close set carpet of ends of nerve fibres with their rods and cones, forming an exquisite mosaic which it requires a microscope to reveal, bodies the operation of which is not understood, but which appear to be adapted to convey to the sensorium individual sensations corresponding respectively to individual points in the field of view. Then we have a remarkable arrangement of muscles adapted to permit of the adjustment necessary for single vision, by causing the images of a point looked at to fall on corresponding points in the retinas of the two eyes: though why it is that the stimulation of the nerve fibres leading from corresponding points should produce the same sensation, is more than we can explain.

When we contemplate the mosaic of the human retina, with its elements regularly arranged, and set at distances of only one or two ten-thousandths of an inch apart, and think of these almost countless elements as destined to convey the impressions of the almost countless points which we can distinguish as separate in the field of view; still more when we think of the correspondence of the two eyes and of all that that involves—that the mosaics should be of the same pattern and very approximately at least of the same size; that their elements should be brought into correspondence two and two in a perfectly methodical manner, those elements in the two eyes corresponding which agree in distance from the centre and angle of position; when we consider the number and fineness of the fibres leading from the elements and into the brain—when I say we contemplate all this, it seems difficult to understand how we can fail to be impressed with the evidence of Design thus imparted to us.

I am aware that some see in all this only the operation of the law of the survival of the fittest, through which it is supposed, if we grant the postulates which the theory requires, the whole structure, complex and elaborate as it is, arose from some excessively simple beginning, from some lowly organism in which nothing of the kind existed, merely through the consequences of casual variations from the original type. Even if this were granted, it would not follow that no evidence of design was left; but can we grant it as even a probable hypothesis, for no one I suppose would hold it to be proved? The process supposed in the theory may be one real feature in a very complex whole; namely in the existence of the various forms of living things, both vegetable and animal, that we behold; but that we want nothing more to account for the existence of structures so exquisite, so admirably adapted to their functions, is to my mind incredible. I cannot help regarding them as evidences of design operating in some far more direct manner, I know not what;

and such I think would be the conclusion of most persons.

But design is altogether unmeaning without a designing mind. The study then of the phenomena of nature leads us to the contemplation of a Being from whom proceeded the orderly arrangement of natural things that we behold. Thus we are led to place in a Being this attribute of self-existence which we failed to find in the races of living creatures, or even in the majestic march of the planetary bodies, though ages may elapse before any deviation can be observed from the periodic motions which they execute in accordance with the law of gravitation. And in the present connexion it is noteworthy that it is precisely this attribute of self-existence that God himself chose for his own designation. When Moses was commissioned to go to his countrymen the Israelites and announce their coming deliverance from Egyptian bondage, and enquired by what name he was to call Him who sent him, the reply is, "Thus shalt thou say unto the children of Israel, I AM hath sent me unto you."

At the beginning of this lecture I asked you in imagination to ignore your own existence, while applying your minds to the contemplation of inanimate nature. From thence we passed on to the consideration of races of living things, which led us on to their structure, and in particular to the structure of a very marvellous organ of our own bodies. So far however we have merely contemplated our bodies as we might have done the planets, as something external to ourselves. But let us now pass on to consider our minds—the human mind. Here we can no longer contemplate something external to us, for we touch our inmost selves. There is some very intimate connexion between thinking, as we know it in ourselves, and the condition of the brain. So close is the connexion, that some have supposed that thinking is a mere function of the material organism, conditioned by nothing more than the motions of the molecules of which that organism consists. But surely this is going far beyond a legitimate inference from the observed facts. The body of a living animal is obedient to the laws of motion, the law of gravitation, and similar laws of the kind which belong to dead matter. But that does not prove that life is nothing more than a process depending on such laws. So if thinking be accompanied, as we know it in ourselves to be accompanied, by a state of activity of the material organism of which the body consists, that does not prove that thinking is nothing more than an action of the material organism. We have seen that life can only proceed from the living; may it not be in a similar manner that mind can only proceed from that which has mind? See what the contrary supposition leads us to. Here is man, in a geological sense a creature but of yesterday, utterly incapable of accounting for his own existence by any play of mere natural forces, and yet ignoring the existence of any mind higher than his own mind, though ready enough to admit the existence of unintelligent law, and that, without limitations of time or space.

As then the indications of design in the material construction of our own bodies lead us to the contemplation of mind in that from whence they originated, so the consideration of mind as it exists in ourselves points in the same direction. We are led therefore to attribute personality to that in which alone we can rest as the first cause of all.

But I would not for a moment be understood as if it were through science only, or even through science mainly, that we are led to a conclusion so important. Man's intellect does not form the sum total of his mental powers. He is endowed with feelings and aspirations, and has a sense of right and wrong too universal to be attributed to the result of education, though of course capable of cultivation. This points to a power above him; and it may be doubted whether a nation ever existed so rude and barbarous as to be destitute of the idea of a power higher than man. Thus considerations derived from totally different sources converge towards a common conclusion.

But when we speak of the First Cause as personal, it must be remembered that human language fails us in attempting to describe the infinite. When we think of a law of nature, the limitations of space and time do not enter into the conception. Take for example the law of gravitation. We speak of it as universal gravitation; we think of it as operative in the past ages to the contemplation of which we are led in our geological speculations as well as at the present day; we regard it as holding together the components of the most distant double star as well as maintaining in their orbits the planets of our own system; but we do not think of gravitation as a power endowed with mind. On the other hand when we speak of a person we can hardly avoid thinking of our own personality, and of the limitations of time and space to which we are subject. We find it hard to put the two ideas together—that of personality, and that of exemption from the limitations of time and space. Yet each mode of conception helps to supplement that which is lacking in the other. If we shut our eyes to the grandeur of nature, and do not attempt through the things that are made to acquire higher conceptions of the eternal power and Godhead of the Maker, our conceptions of the Divine Being are apt to become too anthropomorphic. If on the other hand we confine our attention to the study of nature in all its immensity, our conceptions of its Author are in danger of merging in a sort of pantheistic abstraction, in which the idea of personality is lost.

Are we then left to lose ourselves in an ocean of immensity, and driven to the conclusion that God is unknowable? Nay, as Christians we believe that the character of God has been revealed to us as it never had been before through that Divine Being who took our nature upon him and dwelt among us full of grace and truth. The greatness of the universe displays to us something of the greatness of its Author; but when we study the character of the Son, who is the image of the invisible God, we learn as never had been learnt before the lesson that God is Love.

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[N.B. The Roman numerals refer to the first, second and third courses, which are published separately.]

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