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James Clerk Maxwell and modern physics

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Chapter VII.

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CHAPTER VII.

SCIENTIFIC WORK—COLOUR VISION.

FIFTEEN years only have passed since the death of Clerk Maxwell, and it is almost too soon to hope to form a correct estimate of the value of his work and its relation to that of others who have laboured in the same field.

Thus Niven, at the close of his obituary notice in the Proceedings of the Royal Society, says: "It is seldom that the faculties of invention and exposition, the attachment to physical science and capability of developing it mathematically, have been found existing in one mind to the same degree. It would, however, require powers somewhat akin to Maxwell's own to describe the more delicate features of the works resulting from this combination, every one of which is stamped with the subtle but unmistakable impress of genius." And again in the preface to Maxwell's works, issued in 1890, he wrote: "Nor does it appear to the present editor that the time has yet arrived when the quickening influence of Maxwell's mind on modern scientific thought can be duly estimated."

It is, however, the object of the present series to attempt to give some account of the work of men of science of the last hundred years, and to show how each has contributed his share to our present stock of knowledge. This task, then, remains to be done.

While attempting it I wish to express my indebtedness to others who have already written about Maxwell's scientific work, especially to Mr. W. D. Niven, whose preface to the Maxwell papers has been so often referred to; to Mr. Garnett, the author of Part II. of the "Life of Maxwell," which deals with his contributions to science; and to Professor Tait, who in *Nature* for February 5th, 1880, gave an account of Clerk Maxwell's work, "necessarily brief, but sufficient to let even the non-mathematical reader see how very great were his contributions to modern science"—an account all the more interesting because, again to quote from Professor Tait, "I have been intimately acquainted with him since we were schoolboys together."

Maxwell's main contributions to science may be classified under three heads—"Colour Perception," "Molecular Physics," and "Electrical Theories." In addition to these there were other papers of the highest interest and importance, such as the essay on "Saturn's Rings," the paper on the "Equilibrium of Elastic Solids," and various memoirs on pure geometry and questions of mechanics, which would, if they stood alone, have secured for their author a distinguished position as a physicist and mathematician, but which are not the works by which his name will be mostly remembered.

The work on "Colour Perception" was begun at an early date. We have seen Maxwell while still at Edinburgh interested in the discussions about Hay's theories.

His first published paper on the subject was a

letter to Dr. G. Wilson, printed in the Transactions of the Royal Society of Arts for 1855; but he had been mixing colours by means of his top for some little time previously, and the results of these experiments are given in a paper entitled "Experiments on Colour," communicated to the Royal Society of Edinburgh by Dr. Gregory, and printed in their Transactions, vol. xxi.

In the paper on "The Theory of Compound Colours," printed in the Philosophical Transactions for 1860, Maxwell gives a history of the theory as it was known to him.

He points out first the distinction between the *optical* properties and the *chromatic* properties of a beam of light. "The optical properties are those which have reference to its origin and propagation through media until it falls on the sensitive organ of vision;" they depend on the periods and amplitudes of the ether vibrations which compose the beam. "The chromatic properties are those which have reference to its power of exciting certain sensations of colour perceived through the organ of vision." It is possible for two beams to be optically very different and chromatically alike. The converse is not true; two beams which are optically alike are also chromatically alike.

The foundation of the theory of compound colours was laid by Newton. He first shewed that "by the mixture of homogeneal light colours may be produced which are like to the colours of homogeneal light as to the appearance of colour, but not as to the immutability of colour and constitution of light." Two

beams which differ optically may yet be alike chromatically; it is possible by mixing red and yellow to obtain an orange colour chromatically similar to the orange of the spectrum, but optically different to that orange, for the compound orange can be analysed by a prism into its component red and yellow; the spectrum orange is incapable of further resolution.

Newton also solves the following problem:—

In a mixture of primary colours, the quantity and quality of each being given to know the colour of the compound (Optics, Book 1, Part 2, Prop. 6), and his solution is the following:—He arranges the seven colours of the spectrum round the circumference of a circle, the length occupied by each colour being proportional to the musical interval to which, in Newton's views, the colour corresponded. At the centre of gravity of each of these arcs he supposes a weight placed proportional to the number of rays of the corresponding colour which enter into the mixture under consideration. The position of the centre of gravity of these weights indicates the nature of the resultant colour. A radius drawn through this centre of gravity points out the colour of the spectrum which it most resembles; the distance of the centre of gravity from the centre gives the fulness of the colour. The centre itself is white. Newton gives no proof of this rule; he merely says, "This rule I conceive to be accurate enough for practice, though not mathematically accurate."

Maxwell proved that Newton's method of finding the centre of gravity of the component colours was confirmed by his observations, and that it involves

mathematically the theory of three elements of colour; but the disposition of the colours on the circle was only a provisional arrangement; the true relations of the colours could only be determined by direct experiment.

Thomas Young appears to have been the next, after Newton, to work at the theory of colour sensation. He made observations by spinning coloured discs much in the same way as that which was afterwards adopted by Maxwell, and he developed the theory that three different primary sensations may be excited in the eye by light, while the colour of any beam depends on the proportions in which these three sensations are excited. He supposes the three primary sensations to correspond to red, green, and violet. A blue ray is capable of exciting both the green and the violet; a yellow ray excites the red and the green. Any colour, according to Young's theory, may be matched by a mixture of these three primary colours taken in proper proportion; the quality of the colour depends on the proportion of the intensities of the components; its brightness depends on the sum of these intensities.

Maxwell's experiments were undertaken with the object of proving or disproving the physical part of Young's theory. He does not consider the question whether there are three distinct sensations corresponding to the three primary colours; that is a physiological inquiry, and one to which no completely satisfactory answer has yet been given. He does show that by a proper mixture of any three arbitrarily chosen standard colours it is possible to match any

other colour; the words "proper mixture," however, need, as will appear shortly, some development.

We may with advantage compare the problem with one in acoustics.

When a compound musical note consisting of a pure tone and its overtones is sounded, the trained ear can distinguish the various overtones and analyse the sound into its simple components. The same sensation cannot be excited in two different ways. The eye has no such corresponding power. A given yellow may be a pure spectral yellow, corresponding to a pure tone in music, or it may be a mixture of a number of other pure tones; in either case it can be matched by a proper combination of three standard colours — this Maxwell proved. It may be, as Young supposed, that if the three standard colours be properly selected they correspond exactly to three primary sensations of the brain. Maxwell's experiments do not afford any light on this point, which still remains more than doubtful.

When Maxwell began his work the theory of colours was exciting considerable interest. Sir David Brewster had recently developed a new theory of colour sensation which had formed the basis of some discussions, and in 1852 von Helmholtz published his first paper on the subject. According to Brewster, the three primitive colours were red, yellow and blue, and he supposed that they corresponded to three different kinds of objective light. Helmholtz pointed out that experiments up to that date had been conducted by mixing pigments, with the exception of those in which the rotating disc was used, and that it is

necessary to make them on the rays of the spectrum itself. He then describes a method of mixing the light from two spectra so as to obtain the combination of every two of the simple prismatic rays in all degrees of relative strength.

From these experiments results, which at the time were unexpected, but some of which must have been known to Young, were obtained. Among them it was shown that a mixture of red and green made yellow, while one of green and violet produced blue.

In a later paper (*Philosophical Magazine*, 1854) Helmholtz described a method for ascertaining the various pairs of complementary colours—colours, that is, which when mixed will give white—which had been shown by Grassman to exist if Newton's theory were true. He also gave a provisional diagram of the curve formed by the spectrum, which ought to take the place of the circle in Newton's diagram; for this, however, his experiments did not give the complete data.

Such was the state of the question when Maxwell began. His first colour-box was made in 1852. Others were designed in 1855 and 1856, and the final paper appeared in 1860. But before that time he had established important results by means of his rotatory discs and colour top. In his own description of this he says: "The coloured paper is cut into the form of disc, each with a hole in the centre and divided along a radius so as to admit of several of them being placed on the same axis, so that part of each is exposed. By slipping one disc over another we can expose any given portion of each colour.

These discs are placed on a top or teetotum, which is spun rapidly. The axis of the top passes through the centre of the discs, and the quantity of each colour exposed is measured by graduations on the rim of the top, which is divided into 100 parts. When the top is spun sufficiently rapidly, the impressions due to each colour separately follow each other in quick succession at each point of the retina, and are blended together; the strength of the impression due to each colour is, as can be shown experimentally, the same as when the three kinds of light in the same relative proportions enter the eye simultaneously. These relative proportions are measured by the areas of the various discs which are exposed. Two sets of discs of different radius are used; the largest discs are put on first, then the smaller, so that the centre portion of the top shows the colour arising from the mixture of those of the smaller discs; the outer portion, that of the larger discs."

In experimenting, six discs of each size are used, black, white, red, green, yellow and blue. It is found by experiment that a match can be arranged between any five of these. Thus three of the larger discs are placed on the top—say black, yellow and blue—and two of the smaller discs, red and green, are placed above these. Then it is found that it is possible so to adjust the amount exposed of each disc that the two parts of the top appear when it is spun to be of the same tint. In one series of experiments the chromatic effect of 46·8 parts of black, 29·1 of yellow, and 24·1 of blue was found to be the same as that of 66·6 of

red and 33.4 of green ; each set of discs has a dirty yellow tinge.

Now, in this experiment, black is not a colour ; practically no light reaches the eye from a dead black. We have, however, to fill up the circumference of the top in some way which will not affect the impression on the retina arising from the mixture of the blue and yellow ; this we can do by using the black disc.

Thus we have shown that 66.6 parts of red and 33.4 parts of green produce the same chromatic effect as 29.1 of yellow and 24.1 of blue. Similarly in this manner a match can be arranged between any four colours and black, the black being necessary to complete the circumference of the discs.

Thus using A, B, C, D to denote the various colours, a, b, c, d the amounts of each colour taken, we can get a series of results expressed as follows: a parts of A together with b parts of B match c parts of C together with d parts of D ; or we may write this as an equation thus:—

$$a A + b B = c C + d D,$$

where the + stands for "combined with," and the = for "matches in tint."

We may also write the above—

$$d D = a A + b B - c C,$$

or d parts of D can be matched by a *proper* combination of colours A, B, C. The sign - shows that in order to make the match we have to combine the colour C with D ; the combination then matches a mixture of A and B.

In this way we can form a number of equations for all possible colours, and if we like to take any three colours A, B, C as standards, we obtain a result which may be written generally—

$$x X = a A + b B + c C,$$

or x parts of X can be matched by a parts of A, combined with b parts of B and c parts of C. If the sign of one of the quantities a , b , or c is negative, it indicates that that colour must be combined with X to match the other two.

Now Maxwell was able to show that, if A, B, C be properly selected, nearly every other colour can be matched by positive combinations of these three. These three colours, then, are primary colours, and nearly every other colour can be matched by a combination of the three primary colours.

Experiments, however, with coloured discs, such as were undertaken by Young, Forbes and Maxwell, were not capable of giving satisfactory results. The colours of the discs were not pure spectrum colours, and varied to some extent with the nature of the incident light. It was for this reason that Helmholtz in 1852 experimented with the spectrum, and that Maxwell about the same time invented his colour box.

The principle of the latter was very simple. Suppose we have a slit S, and some arrangement for forming a pure spectrum on a screen. Let there now be a slit R placed in the red part of the spectrum on the screen. When light falls on the slit S, only the red rays can reach R, and hence conversely, if the

white source be placed at the other end of the apparatus, so that R is illuminated with white light, only red rays will reach S. Similarly, if another slit be placed in the green at G, and this be illuminated by white light, only the green rays will reach S, while from a third slit V in the violet, violet light only can arrive at S. Thus by opening the three slits at V, G and R simultaneously, and looking through S, the retina receives the impression of the three different colours. The amount of light of each colour will depend on the breadth to which the corresponding slit is opened, and the relative intensities of the three different components can be compared by comparing the breadths of the three slits. Any other colour which is allowed by some suitable contrivance to enter the eye simultaneously can now be matched, provided the red, green and violet are primary colours.

By means of experiments with the colour box Maxwell showed conclusively that a match could be obtained between any four colours; the experiments could not be carried out in quite the simple manner suggested by the above description of the principle of the box. An account of the method will be found in Maxwell's own paper. It consisted in matching a standard white by various combinations of other colours.

The main object of his research, however, was to examine the chromatic properties of the different parts of the spectrum, and to determine the form of the curve which ought to replace the circle in Newton's diagram of colour.

Maxwell adopted as his three standard colours: red, of about wave length 6,302; green, wave length 5,281; and violet, 4,569 tenth metres. On the scale of Maxwell's instrument these are represented by the numbers 24, 44 and 68.

Let us take three points A, B, C at the corners of an equilateral triangle to represent on a diagram these three colours. The position of any other colour on the diagram will be found by taking weights proportional to the amounts of the colours A, B, C required to make the match between A, B, C and the given colour; these weights are placed at A, B, C respectively; the position of their centre of gravity is the point required. Thus the position of white is given by the equation—

$$W = 18.6 (24) + 31.4 (44) + 30.5 (68)$$

which means that weights proportional to 18.6, 31.4 and 30.5 are to be placed at A, B, C respectively, and their centre of gravity is to be found. The point so found is the position of white. Any other colour is given by the equation—

$$X = a (24) + b (44) + c (68).$$

Again, the position on the diagram for all colours for which a , b , c are all positive lies within the triangle A B C. If one of the co-efficients, say c , is negative the same construction applies, but the weight applied at C must be treated as acting in the opposite direction to those at A and B. A mixture of the given colour and C matches a mixture of A and B. It is clear that the point corresponding to X will then lie outside the triangle

A B C. Maxwell showed that, with his standards, nearly all colours could be represented by points inside the triangle. The colours he had selected as standards were very close to primary colours.

Again, he proved that any spectrum colour between red and green, when combined with a very slight admixture of violet, could be matched, in the case of either Mrs. Maxwell or himself, by a proper mixture of the red and green. The positions, therefore, of the spectrum colours between red and green lie just outside the triangle A B C, being very close to the line A B, while for the colours between green and violet Maxwell obtained a curve lying rather further outside the side B C. Any spectrum colour between green and violet, together with a slight admixture of red, can be matched by a proper mixture of green and violet.

Thus the circle of Newton's diagram should be replaced by a curve, which coincides very nearly with the two sides A B and B C of Maxwell's figure. Strictly, according to his observations, the curve lies just outside these two sides. The purples of the spectrum lie nearly along the third side, C A, of the triangle, being obtained approximately by mixing the violet and the red.

To find the point on the diagram corresponding to the colour obtained by mixing any two or more spectrum colours we must, in accordance with Newton's rule, place weights at the points corresponding to the selected colours, and find the centre of gravity of these weights.

This, then, was the outcome of Maxwell's work on

colour. It verified the essential part of Newton's construction, and obtained for the first time the true form of the spectrum curve on the diagram.

The form of this curve will of course depend on the eye of the individual observer. Thus Maxwell and Mrs. Maxwell both made observations, and distinct differences were found in their eyes. It appears, however, that a large majority of persons have normal vision, and that matches made by one such person are accepted by most others as satisfactory. Some people, however, are colour blind, and Maxwell examined a few such. In the case of those whom he examined it appeared as though vision was dichromatic, the red sensation seemed to be absent; nearly all colours could be matched by combinations of green and violet. The colour diagram was reduced to the straight line B C. Other forms of colour blindness have since been investigated.

In awarding to Maxwell the Rumford medal in 1860, Major-General Sabine, vice-president of the Royal Society, after explaining the theory of colour vision and the possible method of verifying it, said: "Professor Maxwell has subjected the theory to this verification, and thereby raised the composition of colours to the rank of a branch of mathematical physics," and he continues: "The researches for which the Rumford medal is awarded lead to the remarkable result that to a very near degree of approximation all the colours of the spectrum, and therefore all colours in nature which are only mixtures of these, can be perfectly imitated by mixtures of three actually attainable colours, which are the red, green

and blue belonging respectively to three particular parts of the spectrum.

It should be noticed in concluding our remarks on this part of Maxwell's work that his results are purely physical. They are not inconsistent with the physiological part of Young's theory, viz., that there are three primary sensations of colour which can be transmitted to the brain, and that the colour of any object depends on the relative proportions in which these sensations are excited, but they do not prove that theory. Any physiological theory which can be accepted as true must explain Maxwell's observations, and Young's theory does this; but it is, of course, possible that other theories may explain them equally well, and be more in accordance with physiological observations than Young's. Maxwell has given us the physical facts which have to be explained; it is for the physiologists to do the rest.