in a reaction from the earlier custom of representing great men as free from all blemish and weakness, delights in attempting to show that nobody much exceeds the common level. If an earlier painter might have left out Cromwell's warts, the painter of to-day might represent his face as one huge wart. I have read records of Newton's weaknesses and I know of the adumbrations of his discoveries that can be found in forerunners and contemporaries: I acknowledge that his earlier biographer shut his eyes to any incident, writing or action that might seem to detract from his perfection. Nevertheless, all things considered, I think that the contemporary judgment of his greatness can still stand, and that, if the Marquis de l'Hôpital's query as to whether Newton ate, drank or slept like ordinary men ("for I picture him to myself as a celestial genius") seems to our present-day sobriety an affectation, nevertheless we may agree that the line of Lucretius placed on the Trinity statue was well chosen and fitting—

Qui genus humanum ingenio superavit

"who excelled the human race in power of thought".

NEWTON AS AN EXPERIMENTER

By THE RIGHT HON. LORD RAYLEIGH, F.R.S.

THE duty has been assigned to me of telling you something about Newton as an experimentalist. As the result of a study of what is known of his history, it seems to me that among his various intellectual pursuits experiment was his first love and the love to which he was most constant. Strange though it be, he seems in some moods to have doubted whether his theoretical studies were worth while, and I do not recall any case where he expressed himself enthusiastically about them. On the other hand, he speaks of his optical work as "The oddest, if not the most considerable detection which hath hitherto been made in the operation of nature".

Newton loved the mechanical side of experimental work. As a boy he constructed sundials, and, what is more, fixed one of them into the side of the house effectually enough for it to be there a century later. A notebook of his boyhood shows him assiduous in collecting recipes for various kinds of drawing materials, and he notes methods of performing some (rather nasty) conjuring tricks. Later on, when he is making his reflecting telescope, it is obvious that he is a skilled amateur mechanic, at home in furnace operation. He builds his own brick furnace, prepares speculum metal, and is apparently more successful than the professional opticians of the time in grinding and polishing it to a satisfactory spherical figure. (The days of parabolizing were not yet.) It was not until a good many years later that they were able to put such instruments on the market.*

Asked in his old age where he got the tools for his work, he replied that he had made them himself, and could have achieved little progress without doing so.

There are occasional hints to be gleaned that Newton practised other mechanical arts. Thus, when he examines the colour of thin blown glass, it appears that he has the facilities for glass-blowing at hand, and was presumably able to use them.

So much for the base mechanical side. Newton, however, had what may be called the itch of experiment and instinctively examined in this way any natural phenomenon that excited his interest. This instinct is not a common one, and it would be of interest to investigate statistically whether it is more correlated with mathematical aptitude than with, say, an aptitude for literary and historical studies. Newton had all these. Although he experimented in other fields, such as mechanics, heat and electricity, and even in anatomy and physiology, his optical experiments are of much greater importance, and in the short time at our disposal we shall only be able to consider a part even of these. The fundamental researches on the composition of white light were read before the Royal Society in 1672, and afterwards recapitulated in his "Opticks" (1704), and we cannot do better than concentrate our attention on them. Although the results are common property nowadays, yet on an occasion like this we shall do well to go back to Newton's own methods and point of view, and to repeat his experiments as nearly as we can in his own way. We must be content to use the positive crater of the electric arc to represent the sun.

Newton's experiments on the spectrum are sometimes presented as if he had started out with the idea of examining the composition of white light. It is true that his "Opticks" (like his "Principia") introduces the various topics as theorems or problems proposed after the manner of Euclid. It does not seem likely, however, that he set out in the first instance to prove any proposition. He bought a prism at Stourbridge Fair (near Cambridge) in 1666, "to try therewith the celebrated phenomena of colours". It is clear from this that the prismatic colours were quite a well-recognized phenomenon at this time, and this is also shown by the circumstance that the art of cutting diamonds so as to display them was already long known. In Peacham's "Gentlemanly Exercises" (1612) reference is made to "A three square cristal prisme wherein you shall perceive the blew to be outmost next to the red", and Grimaldi and others had already experimented on the subject, though without arriving at clear views. We can readily imagine how Newton, handling the prism, would soon find that the colours were well seen in candle-light, but not in diffused daylight. It would not be a long step from this to try the effect on a beam of direct sunlight admitted through a hole in the shutter.

There is no reason to think that he did this with a very clear anticipation of what the effect would be. He was exploring a nearly virgin territory. His beam of sunlight passing through the hole produced an image of the sun. It was what we now call a pinhole image, though the hole need not be very small. Newton's hole was $\frac{1}{3}$ in. diameter. Then he interposed the prism (Fig. 1).

To most people the colours would seem the main

* Among the first successful commercial makers of reflecting telescopes was James Short (1710–1768), whose instruments were of the Gregorian type. He is said to have made a considerable number of concave and convex mirrors, and to have 'married' them by trial of what pairs gave the best result.

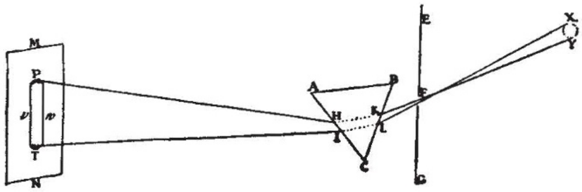

Fig. 1.

feature of this experiment, but Newton was more surprised and impressed with the fact that the sun's image was no longer round, but was spread out into a band of which the length was some five times the breadth. The breadth of the image as projected through the prism still answered to the sun's diameter, that is to say, it was equal to the diameter of the original round image of the sun at the same distance with the prism away.

"If," he says, "the refraction were done regularly according to one certain proportion of the sines of incidence and refraction, as is vulgarly supposed, the refracted image ought to have appeared round."

At the same time the colours had to be taken into account. Were the colours definitely related to the differences of refraction, or was the apparent relation only incidental? In Newton's words:

"Wherever this inequality arises, whether it be that some of the incident rays are refracted more, and others less, constantly or by chance, or that one and the same ray is by refraction disturbed, shattered, dilated and as it were split and spread into many diverging rays, as Grimaldi supposes, does not yet appear by these experiments, but will appear by those that follow."

The next experiment was accordingly designed to throw light on this point. It is known as the experiment of crossed spectra (Fig. 2), the idea being to refract each of the coloured rays a second time, in a direction at right angles to the former, and to see whether the blue rays, which were more refracted than the red, would be so again. Also to see whether they would retain their original colour, or whether they would undergo further analysis.

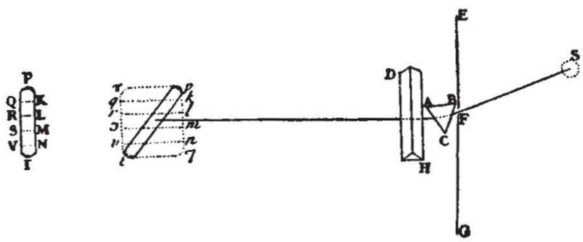

Fig. 2.

Newton made several more elaborate variants of this experiment. In one of them, two holes were used with a prism in front of each, and two spectra were then projected on the screen in line, the red of one following on the blue of the other. Refracting them upwards with a third prism, this line is dislocated, and that blue and red which were before adjacent are now widely separated (Fig. 3).

Newton in this way arrived at the view that the original white light of the sun consisted of coloured components, red, yellow, green, blue and violet. Each of these had a characteristic index of refraction and was bent to a perceptibly different extent by the prism. The result was that the original round white image of the sun was replaced by a series of coloured images side by side, overlapping and blending one with another. On introducing a second prism at right angles, each of these coloured images was again refracted to its characteristic extent and each retained its colour without further analysis.

Newton, however, soon saw the crudeness of his first arrangements, and we will now consider the methods he used to improve them. As he pointed out, the individual coloured images of the sun overlap at the middle, but not at the edges. Images of the sun are not in fact very suitable, because the angular width of the sun is about half a degree, and this is a considerable fraction of the angle between the red and violet rays. We want to make the sun in effect smaller, by blocking out part of its disk, which might be done in imagination by a distant diaphragm supported in mid-air. At the same time the hole in the shutter might with advantage be replaced by a lens, which would render the images sharper. When we have got so far in imagination, we notice that the long distance between the diaphragm in mid-air and the lens is not essential; with a suitable lens a moderate distance will do. We bring the diaphragm nearer, and fix it in the shutter, and bring the lens forward into the room, placing it so as to form a distinct picture of the diaphragm on the wall (Fig. 4).

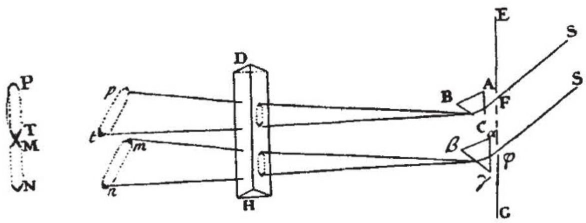

Fig. 3.

We have now the diaphragm fixed in the shutter, and backed by the sun, as our effective source of light. In this respect it differs altogether from the original diaphragm, which acted not as a source, but as an image-forming pinhole. We now have a picture of the diaphragm and not of the sun, and it will be advantageous to substitute a slit, which would not previously have been any use, because the size of the image was then defined by the angular diameter of the sun. With the slit *and the lens* we shall get narrow well-defined images in each colour, and the colours will be pure and not overlapping. (Needless to say, modern refinements carry the matter much further.)

The explanation I have just given is in substance Newton's own.

Let us now project the spectrum on to a small

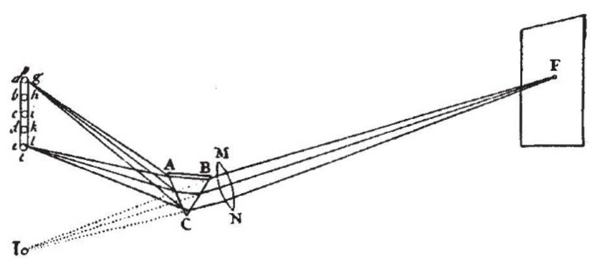

Fig. 4.

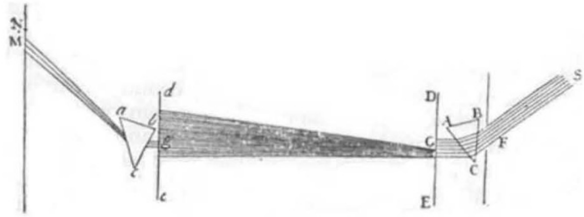

Fig. 5.

screen with a slit (Fig. 5) in it, which to avoid confusion I will call the screen-aperture. A colour passing through the screen-aperture is isolated, and if I rotate the prism, I can throw the various colours in succession on the slit in the screen-aperture, so that the image on a second screen is taken through the succession of spectrum colours from red to violet. Starting with it at the red, and placing a second prism in position behind the screen-aperture, the rays are deviated, as we should expect; but there is no elongation of the image this time, nor is there any diversity of colour. The red image remains red. The same applies to any other colour of the spectrum that is passed through the screen-aperture. But as the successive colours are passed, from red to violet, the deviation on the second screen continually increases, the red being the least deviated and the violet the most.

This experiment shows essentially the same thing as the experiment of crossed spectra, but more perfectly.

The important point is that having once analysed white light into its prismatic constituent colours, this analysis is final, and further prismatic analyses can do no more. Further, each colour has its characteristic refrangibility, which will show itself at every refraction. Newton attached the greatest importance to this experiment, which he called, in Baconian phrase, the "experimentum crucis".

Having effected the analysis of white light into its constituent colours, he proceeded to reverse the process, and to show how the colours of the spectrum could be recompounded into white light. This he did by projecting the spectrum upon a large lens (Fig. 6), when the various rays were all converged to the same place and produced a patch of white light at the focus.

If a kind of large-scale model of a comb as used by Newton (Fig. 7) be placed in front of the lens, some part of the spectrum will be intercepted by the comb, and the white patch produced at the focus of the lens by recombination of the entire spectrum loses its whiteness, and becomes tinged with colour. The colours produced in this way are not pure spectrum colours, because any tooth of the comb permits colour from parts of the spectrum on either side of it to pass. The colours therefore are composite, but the complete spectrum is necessary to produce white. If the comb is moved slowly to and fro, the coloured patch varies, being now reddish, now

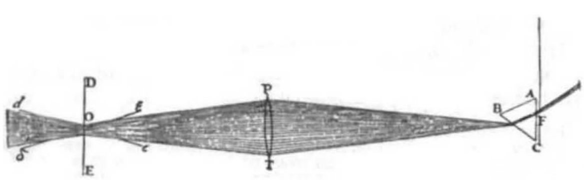

Fig. 6.

yellowish, now bluish, but never white. If, however, it is moved to and fro as rapidly as may be, all the spectrum colours are present in succession. They blend by persistence of vision, and the patch becomes white again.

Newton devoted considerable attention to the colours of natural bodies, and he came to the conclusion that a coloured body is only coloured in virtue of its power of reflecting some of the components of white light more than others. When a spectrum is projected on a red screen, we see red light where we saw it before, and nowhere else. The colours are not altered, though red is the only one which is strongly reflected by the red screen. The others are mostly absorbed, and their place in the spectrum is comparatively dark. Red is advantageous for such experiments, as red pigments are much the purest in colour.

In another of Newton's experiments the spectrum is projected on a large lens as before. If a white card is held at the focus, it appears white, for all the colours are converged upon it. If a card painted with cinnabar (vermilion) is placed there, it appears red as usual. If we block out the red part of the spectrum at the lens, the card shows no trace of red, becoming comparatively dark. If we block out everything but red, the card shows up with a purer red than at first.

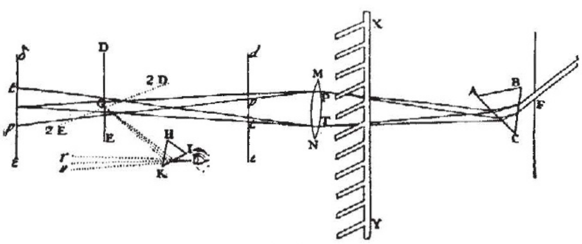

Fig. 7.

We have now been through most of the experiments by which Newton supported his main proposition "The light of the sun consists of rays differently Refrangible", following his own methods as closely as might be. They are a model for all time of how experimental research should be conducted, and it is difficult to our generation to see how any intelligent person could refuse his assent. This was by no means the unanimous opinion of his own contemporaries. One critic, Linus by name, maintained that the spectrum could only be seen when the sun was shining through cloud, and it is strange, but true, that Newton was seriously discomposed by this ridiculous mare's nest. Goethe bitterly attacked Newton, using abusive expressions, and apparently thinking that to use isolated beams of sunlight admitted into a dark room was treating Nature in an unfair manner, and compelling her under torture to say what she did not really mean!

The opposition to Newton's views did not finally die down until within measurable distance of our own time. In a book dated 1853, and dedicated to a man whom I as a boy personally knew, Sir David Brewster says: "The conclusion deduced by Newton is no longer admissible as a general truth 'That to the same degree of refrangibility ever belongs the same colour and to the same colour ever belongs the same degree of refrangibility'."*

* It is not intended to criticize Brewster adversely. The appearances by which he was misled are extremely deceptive.

Let us not make the mistake of thinking that Newton in his optical researches, exploring virgin ground, had easy triumphs. He did not escape the usual fate of discoverers. His jealous contemporary Hooke said his conclusions were not new ; his admiring biographer, Brewster, concluded that they were not true !

Exhibits Illustrating some of Newton's Experiments

Arranged by Lord Rayleigh, as a supplement to those shown in his lecture.

"OPTICKS." BOOK I. EXPERIMENT I.

To show that lights which differ in colour differ also in refrangibility.

Newton's account abbreviated :

"I took a black oblong stiff paper. One part I painted into a red Colour, the other into a blew. This paper I viewed through a Prism of Solid Glass. I found that if the refracting Angle of the Prism be turned upwards so that the paper may seem to be lifted upwards by the Refraction, its blew half will be lifted higher by the Refraction than its red half. But if the refracting Angle of the Prism be turned downwards, so that the Paper may seem to be carried lower by the Refraction, its blew half will be carried something lower than its red half."

A.—"OPTICKS." BOOK I. PART II. EXPERIMENT XVI.

In this experiment a uniform field of light is viewed through a reflecting prism. Newton used the cloudy sky. An illuminated opal glass is substituted. The bright part of the field is the region of total reflexion. The relatively dark part of the field, corresponding to steeper angles of incidence, is the region of partial transmission and partial reflexion. A blue arc marks the limit of total reflexion. This shows that white light contains a constituent (blue) which begins to be totally reflected at angles of incidence less steep than are necessary for the other components.

"This blue colour being made by nothing else than by reflexion of a specular superficies seems so odd a Phenomenon, and so unaccountable for by the vulgar Hypothesis of Philosophers that I could not but think it deserved to be taken notice of."

B.—A supplement was arranged to this exhibit, allowing the transmitted light to be examined. A pair of right-angled prisms is used, forming a cube after the manner of Newton, reflexion occurring at the diagonal interface. The field is divided into a bright and a dark part as before, the dark part (no transmission) being the area of total reflexion. A reddish-yellow arc marks the limit of transmission, which is complementary to the blue arc seen by reflexion.

This experiment was performed by Newton in a more elaborate way, using the sun's light and projecting a spectrum of the beam transmitted by the cube.

"OPTICKS". BOOK II. PART I. OBSERVATION xiii.

An experiment showing that Newton's rings, formed between a spherical surface of large radius and a flat plate, are larger in red light than in blue. The observer can rotate the spectrum-forming prism and see the rings dilating as the colour is changed from blue or blue-green towards red.

"Appointing an assistant to move the Prism to and fro about its Axis, that all the Colours might successively fall on that part of the Paper which I saw by reflexion from that part of the Glasses where the Circles appeared, so that all the Colours might be successively reflected from the Circles to my Eye whilst I held it immoveable, I found the Circles which the red light made to be manifestly bigger than those which were made by the blue and violet. And it was very pleasant to see them gradually swell or contract according as the Colour of the Light was changed."

Newton recognized that this proved that there was a coarser structure associated with red light than with blue. In Query 13 at the end he says :

"Do not several sorts of rays make vibrations of several bignesses, which according to their bignesses excite sensations of several colours ?"

AN EXPERIMENT ON FRICTIONAL ELECTRIFICATION.

From the Minutes of the Royal Society. 9 *December* 1675.

"That [Newton] having laid upon a table a round piece of glass about two inches broad, in a brass ring, so that the glass might be about one-third of an inch from the table, and the air between them inclosed upon all sides after the manner as if he had whelved a little sieve upon the table : and then rubbing the glass briskly, till some little fragments of paper, laid on the table under the glass, began to be attracted and move nimbly to and fro ; after he had done rubbing the glass, the papers would continue a pretty while in various motions ; sometimes leaping up to the glass and resting there awhile ; then leaping down and resting there, and then leaping up and down again ; and this sometimes in lines perpendicular to the table sometimes in oblique ones ; sometimes also leaping up in one arch and down in another divers times together, without sensible resting between ; sometimes skip in a bow from one part of the glass to another, without touching the table ; and sometimes hang by a corner and turn often about very nimbly, as if they had been carried about in the midst of a whirlwind ; and he otherwise variously moved every paper with a diverse motion. And upon sliding his finger on the upper side of the glass, though neither the glass nor inclosed air below were moved thereby, yet would the papers, as they hung under the glass receive some new motion inclining this or that way, according as he moved his finger.

The experiment he proposes to be varied with a larger glass placed farther from the table, and to make use of bits of leaf gold instead of papers, esteeming that this will succeed much better, so as perhaps to make the gold rise and fall in spiral lines or whirl for a time in the air, without touching the table or glass.

Ordered that this experiment be tried the next meeting."

A.—An apparatus with flint glass as used by Newton. Its action is uncertain, depending on the hygroscopic condition of the glass. It may fail, as it did when first tried at the Royal Society. Application had to be made to Newton for further directions. In dry weather and with vigorous rubbing it works admirably.

B.—An apparatus with silica glass. This can be taken out and warmed over a spirit lamp ; it will then work without fail.

C.—An apparatus with a sheet of celluloid replacing the glass. This will work at any time without fail, if lightly stroked with the dry hand.