INSTRUMENTS IN SCIENCE AND INDUSTRY*

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I FEEL that it is a great honour to be chosen as president of Section A of the British Association, particularly because on looking through the names of my distinguished predecessors I find that I am the first professional maker of scientific instruments to occupy this chair. My immediate predecessor, Dr. C. G. Darwin, who now occupies the important position of director of the National Physical Laboratory, gave us at Cambridge a brilliant dissertation on the use of mathematics in solving physical problems, and the need of the mathematical outlook when facing a series of facts requiring solution. He would, I am sure, be one of the first to insist that the mathematician requires physical facts to enable him to develop a physical theory, and that the probable soundness of the theory will depend largely upon the accuracy of the data discussed. In the majority of cases this accuracy depends on the qualities of the apparatus employed in the observations, assuming that the observer is fully qualified and capable of obtaining the best results from it. I believe that all such observers now demand far more from their apparatus than was formerly possible, but few realize the amount of thought and labour involved in raising the accuracy obtainable from one to one-tenth of one per cent.

The help that instruments have given to the advancement of science is a fascinating theme, and at the same time a wide one. Among the earliest and most striking examples we find that Kepler was able to state his laws of planetary motion as a result of the observations made with Tycho Brahe's carefully constructed instruments. Tycho (1546–1601) first introduced (though he did not discover) the method of transversal division of the arc, which is now familiar to us as the basis of the diagonal scale. It was he who first pointed out the importance of symmetry in an instrument. The ingenious naked-eye sights developed by him were a remarkable improvement on the simple sights previously used. According to Dreyer, his determinations of the right ascensions and declinations of his nine standard stars show a probable error of less than thirty seconds of arc—an almost incredible achievement.

I propose to consider a few well-known instruments and to use them as examples to indicate how the development of a particular subject has grown largely with the perfection of the instruments used to investigate it. It is in every way a reciprocal process. By means of an instrument certain evidence is obtained; this evidence does not go far enough and the instrument must be improved to enable further facts to be found. If, for example, the biologist requires to examine small bodies beyond the range of his microscope, he appeals to the physicist to help him, and the appeal is not in vain. Most probably, as a result of the work on his colleague's problem, the physicist develops a technique which will be of service to him or to a fellow-physicist.

THE MICROSCOPE

The first example I shall take is the microscope, an instrument which is used in every observational science and, in some form or another, in nearly every industry. The early story of the microscope has been often told, and yet it may be of interest to recall the most important stages in its development. The first instruments consisted of single lenses, actually small globules of glass, which, when the surfaces were suitably ground, yielded in the hands of skilled observers surprisingly good results. The outstanding example is the Dutch naturalist Leeuwenhoek, who during the period 1674–1723, using a microscope of this type, discovered the protozoa and bacteria, and made many other biological observations of supreme importance.

Hooke, who was Leeuwenhoek's correspondent, was working in microscopical problems at the same time, and in the "Micrographia" (1665) described his own microscope—the first compound microscope. The optical system of this instrument consisted of a converging lens, called the object-glass, the field lens, and a third lens, the eye lens. Although it has been stated frequently that Hooke first introduced the field lens to enlarge the field of view, there is little doubt that this invention was due to Monconys, who published a short description of a compound microscope made to his design in 1660. This scarcely detracts from the credit due to Hooke, whose publication became so generally known, and whose optical system was universally adopted and remained practically unchanged for more than a hundred years.

Hevelius, in 1673, described in his "Machine Coelestis" a screw-focusing adjustment that he had fitted to an instrument of the Hooke type which was the forerunner of the modern mechanism

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adopted (or invented independently) by John Marshall (1663–1725), one of the great opticians at the close of the seventeenth century. Marshall should be remembered by the fact that he was the first to introduce the method of grinding a number of pieces of glass on to the surface of a large convex spherical block, and working them with a concave spherical tool. This is still the method employed for polishing lenses in quantity. In the modern spectacle lens factory as many as a hundred and fifty are sometimes polished in one block.

Although many variations in the design and mechanical construction of the microscope were made during the eighteenth century and the early years of the nineteenth, yet there is no invention of fundamental importance to record until the construction of the achromatic objective. This was first successfully completed by the French optician Chevalier about 1825, and in England by Tulley working about the same time to the designs of Joseph J. Lister, nearly sixty years after the construction of a successful achromatic telescope objective.

Abbe carried the corrections of the aberrations to a far higher degree of perfection, notably by using glasses of new types which at his suggestion had been worked out by Schott, to produce, about 1886, the so-called apochromatic objective in which the colour correction was greatly improved.

It is difficult to see how the resolving power of the microscope is to be further increased using light from the visible region of the spectrum. The biologist, and particularly the medical man, is anxious to study organisms the structure of which is too fine to be resolved by any object glass when using ordinary white light, the alternative to which is the employment of rays of shorter wavelength, namely, the ultra-violet. Glass lenses are opaque to these short wave-lengths, and therefore lenses made of fused quartz must be used. J. E. Barnard, who has developed a very successful technique in connexion with ultra-violet microscopy, has shown that it is possible to study and photograph living bacteria, which are normally transparent to light from the visible region of the spectrum, without staining and therefore killing them. The use of such short wave-lengths has necessitated the construction of extremely rigid mountings in the microscope body and complete absence of play in the moving parts of the instrument. As showing the perfection of the technique obtained with ultra-violet microscopy, it may be mentioned that it is possible to take a series of photographs of an object in successive parallel planes separated by distances of the order of 0·0002 mm.

The use of short-wave radiations has proved so successful in the case of the ultra-violet microscope that a technique has been developed which offers great possibilities for the use of still shorter radiations. As is well known, a beam of cathode rays can be brought to a focus by passing the beam through a magnetic or electrostatic field, in a manner very similar to that in which light is brought to a focus by a convex lens. In the same way, an electron image of a surface may be formed owing to the fact that the electrons will be scattered by an amount depending on the density (or mass concentration) of the surface on which they impinge. By forming the image on a fluorescent screen it can be rendered visible, or if projected on to a sensitized plate, photographically recorded.

In an instrument designed by Von Borries and Ruska, an electron stream is passed through two specially designed electromagnets (or magnetic lenses), mounted one above the other, which act as equivalents to the objective and eye-piece of an optical microscope. If an object is placed between the poles of the lower magnet, some of the electrons will be scattered by the material of the object and others will be diverted by the magnetic flux so as to form an image of the object in a plane below the magnet. That an image can be formed in this way depends upon the fact that the scattering is proportional to the mass concentration at different parts of the object. The scattering will be greater from the thicker parts than from the thinner ones, and thus the dark parts of the image will correspond to the thick parts of the object, and *vice versa*. Magnifications of about twenty times those obtained with the optical microscope can be obtained. Excellent photographs have been taken of bacteria and bacilli at magnifications of 10,000 and 20,000 diameters.

Sorby, in 1864, was the first to investigate the structure of metals and alloys by the microscope, and although it was a considerable time before his work was appreciated, there is now no metallurgical laboratory worthy of the name that does not possess a microscope by means of which the molecular structure of an alloy can be examined and photographically recorded.

THE TELESCOPE

Although the discovery of the telescope antedated that of the microscope, in its service to mankind it ranks as second to it. The credit of the invention of the telescope must go to a Dutchman, Lippershey; yet it was Galileo who first produced an instrument worthy of the name. He ground and polished his own lenses, and in 1610, with a telescope magnifying thirty-three diameters, discovered the satellites of Jupiter. Amongst his many astronomical observations he discovered the phases of Venus, and estimated the height of the lunar mountains from the length of their shadows.

Newton pointed out that the focal length of the refracting telescope could not be reduced owing to the refrangibility of light of different colours, and that it was not possible to focus for all the colours simultaneously and thus obtain a sharp image. He measured and calculated the distance between the foci of the red and violet and showed that it was about 1-50th the diameter of the lens. It was to overcome this difficulty that the glasses were made small and of long focal length. It is almost unbelievable that James Bradley, in 1722, measured the diameter of Venus with a telescope having a focal length of 212 ft., the supporting mast being about 45 ft. long.

In 1663, James Gregory suggested the construction of a reflecting telescope, and in 1668 Newton constructed the first practical instrument, having made his own alloy for the mirror and having devised methods for grinding and polishing it. A sentence in his "Optiks" (Bk. I, Pt. 1, Prop. VI, p. 75) shows how serious the position had become: "Seeing therefore the improvement of Telescopes of given length by Refractions is desperate; I contrived heretofore a Perspective by reflexion, using instead of an Object Glass a concave Metal."

The manufacture of satisfactory reflectors was very difficult, and it was not until an instrument maker, James Short of Edinburgh, about 1730, produced instruments with parabolic figuring, that the reflector came into general use. His instruments, even now, may be regarded as examples of first-class workmanship.

Sir William Herschel began making specula in 1774 and constructed a large number of reflecting telescopes, the most famous being his instrument at Slough of 4 ft. aperture and 40 ft. focal length; this was completed in 1789. Unfortunately, the weight (25 cwt.) of the large speculum rendered it liable to distortion, and it is of interest to note that all Herschel's discoveries were made with smaller instruments. More than fifty years later a reflector of 6 ft. aperture and 54 ft. focal length was erected by Lord Rosse at Parsonstown. All these instruments were fitted with metal mirrors which had an unfortunate tendency to tarnish, and re-polishing was apt to spoil the figuring of the mirror. In the modern instrument the metal mirror is replaced by glass which can be re-silvered at intervals. During the last few years aluminium has taken the place of silver as the reflecting surface, the aluminium being deposited on the glass surface under vacuum. The aluminium film does not tarnish, is more robust than silver and has a higher coefficient of reflection for short wave-lengths, and is thus more efficient photographically.

Owing to the increasing demand for telescopes of higher magnification, and of increased light-gathering power, the size of the mirrors used in the modern instruments is steadily increasing. The Mount Wilson Observatory has a telescope with a mirror 100 in. in diameter, and it is a matter of common knowledge that magnificent photographs of nebulæ, etc., have been obtained with it. At the present time an instrument having a mirror 200 in. in diameter is being constructed for the Mount Palomar Observatory. The manufacture of the borosilicate glass (pyrex) block for this mirror, which weighs twenty tons, has been a feat of considerable skill, and if it is successfully ground and polished, as appears likely, it will be a great engineering triumph. We have become so accustomed to success in mounting and operating these large telescopes, that we are apt to forget that this is the heaviest and certainly the most impressive side of instrument construction work.

For the large telescope the reflector has established itself as the most satisfactory instrument, whereas for the smaller telescope, and for the everyday purposes of life, the refractor is still the more efficient. In 1733, Chester Moor Hall found that by combining lenses made from glasses having different refractive indexes he was able to correct for the unequal refrangibility of light of different wave-lengths, and succeeded in making lenses which produced images free from colour. The same discovery was made independently by John Dolland, who, in 1758, produced an achromatic telescope in which the object glass consisted of a convex lens of crown glass combined with a concave lens of flint glass. The invention of the achromatic lens must be considered as one of the milestones in the development of scientific instruments.

The Spectroscope

Perhaps there is no instrument which in recent times has aided pure science so much, and is now beginning to help industry, as the spectroscope. Fraunhofer constructed the first spectroscope in 1817, and made the first measurements of the lines of the solar spectrum. He was also the first to observe the spectrum of the electric spark. In 1842, Becquerel and Draper independently photographed the solar spectrum on daguerreotype plates, thus laying the foundation for the modern science of spectroscopy.

In 1859, Kirchhoff showed that the luminous vapour of a metal has the property of absorbing the same kind of light as it emits at the same temperature. Kirchhoff recognized the fundamental importance of his discovery, entitling it "spectrum analysis"; but it is largely due to Hartley (1882) and later to Twyman, who designed simple and efficient instruments, that spectroscopic analysis has become a quantitative method of chemical analysis. The spectrograph is now one of the most important tools in the metallurgical and chemical laboratory. In the manufacture of steel it is proving an invaluable check on the quality of the materials, the spectrogram obtained from the sample under test being compared with that taken from a standard. The speed of analysis may be judged from the statement that it is possible for one man to analyse twelve samples of nickel-chromium-molybdenum steel spectrochemically for the elements silicon, manganese, nickel, chromium, molybdenum, vanadium, aluminium and copper in less than one day. The spectroscope has also become a tool in common use in the steel warehouse, the storekeeper being able by its means to detect any mixing of the batches of steels.

In the laboratories of the works producing non-ferrous materials the spectroscope is proving equally efficient. For example, the failure of lead pipes from causes other than frost has been considerable, and has been traced to impurities in the lead. A spectroscopic examination of the pipe that has failed shows in a few minutes the undesirable impurities present, and, if the examination is carried further, the quantities of those impurities.

Our knowledge of the constitution of the celestial bodies is almost entirely due to the spectroscope. By its means it has been possible to discover what elements are present in the vapour surrounding them. This was strikingly shown by the discovery by Lockyer, in 1868, of an unknown gas (helium) in the bright-line spectrum of the sun's atmosphere, which was identified by Ramsay twenty-seven years later in the terrestrial atmosphere. The photographing of the sun's disk in a limited band of wave-lengths has led to the development of a special form of recording spectroscope, the photo-spectro-heliograph. In this instrument the slit of a spectroscope is slowly traversed across the sun's image, the selected radiation falling upon a photographic plate. Thus a picture of the sun is built up from a series of photographs taken in the selected wave-lengths. For example, if the wave-length selected is one of calcium, a picture of the disk is obtained showing the distribution of calcium over the sun's surface. The major part of the knowledge obtained about the double stars and also the determination of the velocity of stars in the line of sight has been obtained from spectroscopic observations. The theory of the expanding universe may be said to rest on spectroscopic observations.

SURVEYING INSTRUMENTS

The distinction between the telescope suitably mounted to survey the heavens and that used to measure distances upon the earth's surface is a faint one. The transit instrument is in general only a larger form of theodolite. The early surveyors (and here we may go back to early Egyptian times) made plans by means of rods and plummets; but it was not until the invention of the astrolabe and the use of a divided circle fitted with sights that accurate surveying was attempted. The first mention of the word 'theodolite' occurs in a book "Pantometria" (1571) by an Englishman, Thomas Digges. (It is a matter of interest that Digges has some claim to be called the inventor of the telescope). The early the odolites, like the astronomical instruments, were fitted with pin-hole sights: in the case of the latter instruments, an important controversy arose between Hooke and Hevelius (1679) concerning the relative advantages of telescopic and open sights. Although Hevelius was not convinced, the telescopic sight was almost invariably used after that date. Mention should be made that William Gascoigne invented the filar micrometer and fitted it to a telescope in 1640: this invention greatly increased the accuracy of instruments to which it was attached. Bradley's observation in 1722 shows that he used a form of filar micrometer with considerable success.

As the demands of the astronomer (and later of the surveyor) increased, so the need for improved divided circles became more urgent. The accurate dividing of circles has always been one of the more difficult tasks of the instrument maker, and it is almost entirely due to the English manufacturer that the art of dividing has reached its present high position.

In 1766 Jesse Ramsden made his first circular dividing engine, but as it was not sufficiently accurate for dividing the scales of nautical instruments, he completed a second machine nine years later. It was with this machine that he divided the circles of the 3-ft. theodolites used in the principal triangulation of Great Britain and Ireland, 1792–1862. They were divided to 10 minutes and read to one second of arc by three micrometer microscopes.

In 1826, William Simms invented the self-acting mechanism by means of which the dividing machine became completely automatic, thus saving an immense amount of time, and reducing the risk of error in the dividing of a circle. A similar but larger machine, built by G. W. Watts in 1905, is capable of dividing a circle 4 ft. 6 in. in diameter to 30 seconds of arc with an error not exceeding $\pm$ 1 second.

Linear scales are automatically divided by somewhat similar machines in which are fitted a temperature compensation device for variation in the temperature of the machine and a compensation device for correcting for any variations in the pitch of the master screw. In this connexion the scientific man and the instrument maker are alike indebted to the late Dr. C. Guillaume for the invention of 'invar', a nickel-steel alloy having a remarkably small temperature coefficient of expansion, and hence an almost ideal material from which to manufacture standard scale and measuring tapes. In the case of linear scales, the position of the lines in a good metre scale can be guaranteed to an accuracy of 0·002 mm.

THE THERMIONIC VALVE

An address of this nature would be incomplete if no mention were made of the thermionic valve. Its advent has led not only to the birth of a wide range of new instruments otherwise impracticable, but also to the simplification of many measuring techniques. The thermionic voltmeter was one of the first, if not the first, measuring instrument employing directly a valve, and uses to the full its most valuable characteristics as a measuring device. These characteristics may be briefly summed up as rectification, amplification, rapidity of response, and high impedance. Although these are the prime considerations, others, such as high overload capacity, are advantageous. The rectifying action combined with amplification enables alternating currents and voltages as small as 10^{-4} ampere and 10^{-4} volt to be measured, using a robust moving-coil instrument as a direct reading indicator. The low electrical inertia and high input impedance have, when using suitable diode valves, enabled voltages and frequencies up to 100 megacycles to be measured with reasonable accuracy by robust commercial instruments.

MANUFACTURE OF SCIENTIFIC INSTRUMENTS

Looking back over forty years' experience in the use of scientific instruments, many of those years being spent in their manufacture and development, I am much impressed with the steadily growing demands for higher accuracy. The development of the high-speed steam engine, and later the motor-car, brought about an insistent demand for accurate tools and gauges. This in its turn necessitated better design in the tools and more accurate measuring instruments. The manufacture of interchangeable components in large quantities has still further increased the demand for accuracy. The introduction of the new alloy steels with the special technique required in their heat treatment created a demand for precision thermometry.

The attitude of the manufacturer towards the scientific instrument has completely altered. He was once sceptical as to its usefulness ; he is rarely so nowadays. In the majority of large works the general control over the instruments is now in the hands of a technically trained man, and that in itself relieves the instrument maker of much anxiety. Another fact that impresses one is the great difference between the methods of manufacture during the same period. Forty or fifty years ago, instruments were made in small batches, often by individual workmen. In London they were frequently made for some well-known firm by small chamber men who put the name of that firm upon them. As a result of this procedure, the so-called manufacturer very often had not an adequate knowledge of his products : this practice has almost entirely disappeared, to the benefit of customer and maker.

The increased demand for instruments has led to manufacture in the modern sense of the word. An instrument is carefully designed in the drawing office in consultation with the technical expert. The methods by which the instrument is to be made are considered. If the quantities are large, and if a preliminary model has been approved, then the possibility of the use of die castings, hot pressings or plastic mouldings must be considered, and the importance of interchangeability of components emphasized.

In preparing the design of an instrument it must never be forgotten that a good design helps production. It always pays to spend time in the drawing office rather than in the workshop. The application of geometric design, the early exponents of which were Maxwell and Horace Darwin, often reduces the cost of manufacture and makes a better instrument. I think that the experimentalist, in making up his own instrument, should consider whether he can obtain the same result by a simply designed geometric piece of apparatus, rather than the more elaborate design to which he may be attracted.

The demand for instruments is ever growing. As new problems arise, both in science and in industry, the requirements become more stringent. The instrument maker constantly receives incentives to progress from the scientific worker, to whom he owes not only suggestions but also many of his new materials. It is, I suppose, a truism that if knowledge is to progress it is essential that theory and practice advance together. Nowhere is this more true than in the development of scientific instruments.