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Research Report



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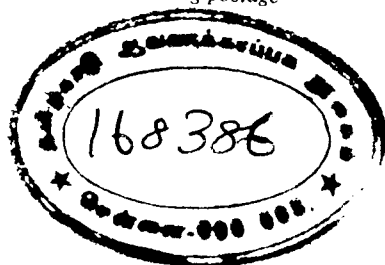
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THE ENERGY OF THE STAR

C. M. BOND I AND H. BOND I

THE shining stars are a familiar and beautiful phenomenon. The amount of light we receive from them is not impressively large, but once their enormous distances are appreciated, it becomes clear that they are radiators of vast power. The nature and constitution of the stars, and particularly the source of their energy, are problems of great interest.

The interest is heightened when it is appreciated that our sun is an ordinary star, distinguished only by its proximity. The radiation of the sun is the most significant feature of our environment, and all life would be impossible without it. The complexity and constant change so characteristic of happenings on the surface of the earth occur only because conditions here are so far from thermal equilibrium. This strong thermal disequilibrium is primarily due to the earth's being embedded in an environment partly extremely hot (the surface of the sun) and partly exceedingly cold (the depths of space). •

The theory of stellar structure is an ambitious attempt to describe the features of the stars in terms of laboratory physics. Though the masses, temperatures, and pressures are vastly in excess of what the physicist can experiment with, the theory is highly successful in correlating astronomical and laboratory data. A particularly gratifying feature is the excellent agreement between the properties of the stellar energy sources as inferred astronomically and the nuclear processes accessible to the physicist. This article will give an outline of the chain of reasoning that leads to this agreement, and will also indicate some of the unresolved questions remaining.

OBSERVED CHARACTERISTICS OF STARS

The number of stars observable in large telescopes is very great indeed, but the characteristics of interest for the theory of stellar

structure are known only for a limited number of these. The apparent brightness of a star (that is the intensity of light received here) can be measured, and a spectroscopic analysis gives the colour composition of the light of the star. The distances of several hundreds of the nearest stars have been measured with fair accuracy. These distances range from a few up to about 50 light years (one light year is about 6 million million miles).

Once the distance of a star and its apparent brightness are known, it becomes possible to infer how much light the star sends out altogether, since the weakening of light with distance is given by the inverse square law of optics. Other causes of weakening such as scattering by interstellar 'fog' are almost certainly quite unimportant for these near stars. The rate at which the star sends out light (energy) is known as its luminosity, L . It is a figure that varies very widely between different stars.

Important inferences can also be made from the colour composition of a star's light. It is fairly obvious that a star is a glowing body, and it is well known experimentally that the colour of a glowing opaque body depends only on its temperature and not on its composition. A red-hot iron poker, a red-hot piece of coal, a red-hot fire brick all look alike and are at the same temperature. At higher temperatures they would all glow yellow, and at still higher temperatures, white and even bluish white. Hence the temperature, T , of a star's glowing surface can be inferred from its colour without any assumptions concerning its composition. The temperature in turn determines the amount of light emitted per unit surface area. If therefore the colour of the star is known as well as its luminosity, L , then its surface temperature, its emission of light per unit area, and the total surface area of the star can be inferred. Making the plausible and well supported assumption that most stars are spherical in shape, the radius, r , of the star follows.

A further quantity that can be determined for some stars is the mass, M . This is due to the circumstance that a large number of stars have companions. These so-called binaries describe orbits about each other that can be observed. The gravitational attractions of the stars towards each other and hence their

masses can be inferred (see *Science News* 24, p. 46). It must be mentioned, however, that the number of stars with known mass is far smaller than the number whose luminosity, surface temperature, and radius are known, and very few of the mass determinations are of high accuracy.

The quantities, L , T , r , M , form the primary data for the theory of stellar structure, but some other characteristics of stars are also observable. Owing to the fact that the light of a star comes from the extensive stellar atmosphere with considerable temperature gradients, a detailed analysis of the spectrum yields some information about the chemical composition of the material of the stellar atmosphere. Spectrum analysis may also reveal information about the rotation and about the magnetic field of the star. Neither of these seems at present to be of much importance for the theory of the interior of the stars, though they probably affect the course of evolution.

Another observable characteristic is the variability of certain stars. Although most stars do not seem to have altered noticeably in historical times, there are some stars whose properties change rapidly. Some increase their luminosity suddenly by a huge factor ('novae' and 'supernovae'), others go through regular fluctuations of brightness, with periods anywhere from a few hours to hundreds of years. The theory of these stars is as yet imperfectly understood and will not be discussed here.

In addition to these 'individual' properties of stars it is possible to investigate their 'social' properties, such as whether stars of certain types tend to occur frequently or rarely, in close company with other stars or far from them, in clouds of interstellar matter or far from such clouds, or to move rapidly or slowly relatively to their neighbours. These properties are of great interest for the theory of stellar evolution.

THE TWO DIAGRAMS

The chief concern of the theory of stellar structure is with the three variables (L , M , r) or the equivalent set (L , M , T). If these three variables were randomly distributed among the stars, the task of any theory would be extremely difficult. It turns out how-

ever that the variables are strongly correlated with each other.

Consider first the richer material, namely all the stars for which L and T_e are known. These may be represented in the diagram first drawn by the Danish astronomer E. Hertzsprung and by H. N. Russell of Princeton. In this Hertzsprung-Russell diagram the horizontal scale shows, in effect, the surface temperature, T_e , and the vertical scale the logarithm of the luminosity, L . (Figure 1.)

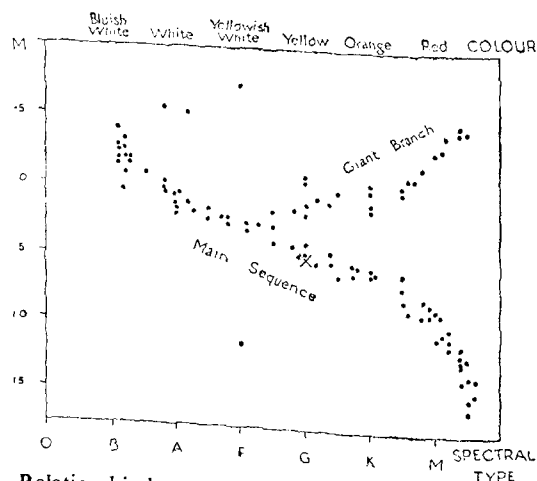


Fig. 1. Relationship between luminosity (vertical scale) and spectral type and colour (horizontal scale); surface temperature, T_e , increases from right to left across the diagram.

Most stars, including our sun (represented by X), fall into the diagonal band known as the main sequence stretching from the right hand bottom corner to the left hand top corner. In this sequence the surface temperature increases slowly with the luminosity. The luminosity at the bottom is about 1/100 of the sun's luminosity (3.8×10^{23} kilowatts) whereas at the top it is about 1,000 times greater than for the sun. But the surface temperature varies only from about 3,000° on the right through 5,700° for the sun to 20,000° towards the left. It is rather difficult

to estimate the distribution of main sequence stars in frequency of occurrence, since bright stars can be observed at large distances and faint stars only in our neighbourhood or not at all. It is probably fair to say that we receive about as much light from stars brighter than the sun as from fainter stars. This involves a huge disparity in numbers. The region marked 'Giant Branch' is filled by several families of stars of which the most common type are known as 'red giants'. They are of the same luminosity as the brightest main sequence stars but of much lower surface temperature and hence much greater radius. The space frequency of these extended stars (of which Capella and Betelgeuse are well-known examples) appears to be somewhat, but not much, lower than that of main sequence stars of the same luminosity.

The dot near the middle of the base represents a type of star of low luminosity and high surface temperature (and hence small radius) known as 'white dwarfs'. Owing to their low luminosity only a few of these objects are known, although they are probably very common. The first and most famous example of this type is the companion of Sirius.*

The second type of diagram that can be drawn using observational data is the so-called mass-luminosity diagram in which the luminosity of the star is plotted against its mass (Figure 2). This diagram shows fewer points than the Hertzsprung-Russell diagram and the observational uncertainties are appreciably greater. Nevertheless certain features are clearly apparent. The representative points of main sequence stars all lie close to a certain curve. This curve expresses a very sensitive dependence of luminosity on mass, L , varying approximately like M^3 for very faint stars and more like M^5 for bright stars. The representative points of the few red giants with known mass are also on or near this curve, but the luminosities of the white dwarfs are far below those of main sequence stars of the same mass (white dwarfs are represented by crosses).

*White dwarfs are an end product of stellar evolution. They do not have internal energy sources, and hence will not be referred to again. There is a satisfactory theory of these stars.

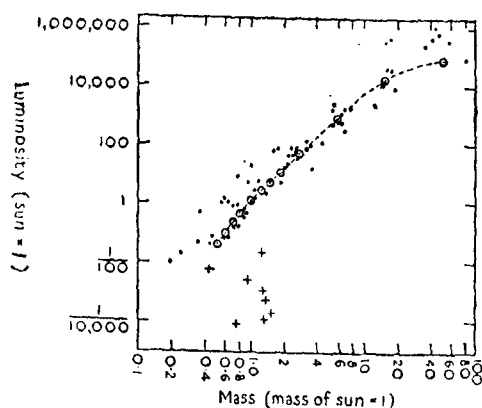


Fig. 2. Mass-luminosity relationship from McCrea, W. H. *Physics of the Sun and Stars*, Hutchinson's University Library (by courtesy of the author and publishers).

The following summary of the observational data characterizes the features that a theory of stellar structure must explain:

(1) For most stars the luminosity and the radius are definite functions of the mass. The luminosity increases very rapidly, the radius rather slowly, with the mass. The sun ($M = 2 \times 10^{33}$ grammes, $r = 7 \times 10^{10}$ centimetres; $L = 3.8 \times 10^{33}$ ergs/sec = 10^{25} kilowatts) belongs to this family, the main sequence stars.

(2) Some bright stars have much larger radii than main sequence stars of the same luminosity, but probably have much the same mass.

(3) Some stars, probably of quite common occurrence if they could be detected, have far lower luminosity and much smaller radii than main sequence stars of the same mass ('White Dwarfs').

STELLAR ENERGY

A star constantly loses energy from its surface at a rate equal to its luminosity. How is the surface kept hot, i.e. what is the source of this energy? The answer to this question will clearly depend on the length of time for which the stars have been

shining. In the case of the sun there is strong evidence from geology that the sun must have radiated with roughly constant luminosity for several hundred million years at least. Evidence for other stars is less direct, but taken together one can be fairly certain that most stars have kept on shining for hundreds of millions of years. What source of energy can have kept up this supply for so long? It is easily worked out that the most powerful chemical reaction (burning) could not have kept the sun going for more than 10,000 years. Even the energy released in the sun's gravitational contraction from a diffuse gas to its present state could keep it shining only for some ten million years. Hence the energy source must be vastly greater than any of these, and our present knowledge shows that the only such possibility is nuclear energy.

Nuclear energy is released in two types of process:

(1) The breaking down of heavy nuclei into nuclei of moderate atomic weight through natural radioactivity or fission.

(2) The building up of nuclei of moderate atomic weight from nuclei of small atomic weight.

Processes of type 1 that are to release sufficient energy for the required periods of time require the presence of uranium or thorium in vastly greater quantities than are permissible from spectroscopic data on the constitution of stellar atmospheres and interstellar matter. Also, the stellar properties following from such a process of energy generation are quite different from the observed ones.

The only process of type 2 that liberates sufficient amounts of energy is the building up of helium from hydrogen. There are two different ways of doing this, both of which seem to be of importance for stars. They are described in detail later on. The rate of energy output of these reactions increases rapidly with temperature and reaches sufficient amounts for stellar purposes near fifteen million degrees. As will be seen later these processes fully account for the general properties of the stars. Also hydrogen, the raw material of these means of energy liberation, is known to be very abundant indeed in the universe, in fact many times more so than all the other elements put together.

The temperature sensitivity of these reactions has two important consequences:

(1) It implies that most of the energy of the star is generated near its centre (where it is hottest) so that the bulk of the star acts merely as a pipeline, transporting energy from the centre to the surface, which radiates it into space.

(2) It implies that the very different rates of energy generation per unit mass in different stars are due to only slight differences of central temperature (between 10 and 20 million degrees).

These two characteristics will be found to be the two chief clues to the theory of stellar structure.

STELLAR STRUCTURE

We have now got some knowledge of the internal temperatures of main sequence stars and this allows us to infer the state of the material there. Although the density in stellar cores may range up to several hundred times the density of water (even the mean density of the sun somewhat exceeds that of water), quantum theory proves that at these temperatures there are no cohesive links between atoms. Accordingly, the material is neither solid nor liquid, but must be *gaseous*. The gaseous nature of the material makes the investigation much easier, since the relations between pressure, density, and temperature are particularly simple in gases.

The stars are, then, enormous balls of gas. The powerful force of gravitation is clearly responsible for holding them together, and great pressures must be present to prevent a total collapse due to the gravitational force. Gravity and the pressure gradients must be accurately balanced throughout the star, for if the pressure gradients remained less than gravity by only 1 per cent, a star like the sun would collapse completely in five hours. The equality of the forces leads one to expect that the total gravitational and pressure energies of the star are at least of the same order of magnitude. The average gravitational energy per unit mass will be a certain appreciable fraction of the value of this quantity at the surface (which is known, if the mass and radius of the star are known), while the average pressure

(thermal) energy will similarly be an appreciable fraction of its value at the centre, which in a gas is just a certain multiple of the central temperature. Hence the order of magnitude of the central temperature may be ascertained from known data, and the fact that the result arrived at by this method is also 10 to 20 million degrees, in agreement with the nuclear physics value, gives great confidence in the theory.

Owing to the temperature sensitivity of nuclear reactions, almost all the energy of a star is generated in the deep interior. It is then transmitted through the bulk of the star to the surface (where it is radiated into space). Since the surface temperature of most stars is only a few thousand degrees, compared with a central temperature of over ten million degrees, there is a temperature gradient of an average value of about 20° per kilometre, to give the value for the sun. A temperature gradient leads in a familiar way to a flow of energy from hot to cold regions by heat conduction. However, this means of energy transport is not of great importance in stars since, at such high temperatures, radiation transports much more energy than conduction. This is chiefly due to the fact that, whereas the energy content of matter increases only like the first power of the temperature, the energy content of radiation is proportional to the *fourth* power of the temperature. Hence the importance of radiation is vastly greater in stars than on the earth.

Energy transport by radiation may be pictured as follows: Consider a small piece of material in the star. It will glow, sending out radiation in all directions. The radiation will travel on until it is absorbed by similar glowing pieces of matter. However, if we consider radiation travelling outwards, it will be absorbed by matter at a slightly lower temperature. Accordingly the absorbing matter will glow slightly more dimly than the original piece. Hence its radiation will carry slightly less energy back to that piece than it received from there. Therefore there is a net flow of energy outwards. This is the method of radiative transfer of energy. It will be realized that the outward flow of heat, that is the luminosity, constitutes only a minor leakage from the hot interior. In other words, the heat content of a star

equals the energy radiated during a considerable period (in the case of the sun over 10 million years).

In addition to radiation and conduction, there is yet another mode of energy transfer, namely convection. In convective transfer (familiar from the motion of water in a saucepan heated from below) the material is not at rest, but circulates, hot currents rising and cold currents flowing down. In this manner, very large amounts of energy can be carried, but convection will not set in unless the temperature gradient exceeds a certain value (as is familiar from the case of water).

Thirty years ago Eddington tackled the problem of the extent to which energy transport considerations determined the structure of a star. Although nuclear physics was then quite unable to say anything about energy generation, Eddington showed that, for a homogeneous* star, the 'pipeline' condition for transferring the energy from the centre to the surface implied a relation between mass, luminosity, and radius. Since the radius enters only in a quite secondary way, Eddington's relation can be directly compared with the mass-luminosity diagram. The agreement, which originally was already good, is now, with improved knowledge, as close as the uncertainties of the observations will allow. The main change has been the recognition, due to F. Hoyle, of the high hydrogen content of the stars.

The central temperature of a homogeneous star can be inferred from its mass and radius by means of the 'pipeline' relation. It turns out that the central temperatures of main sequence stars (if they are supposed to be homogeneous) are very uniform, varying from around 10 million degrees for faint stars to 20 million degrees for bright ones.

Conversely, knowledge of the conditions required for nuclear reactions to produce the required energy determines the central temperature and so leads to a second relation between mass,

Homogeneous means that the chemical composition of the material is the same throughout the star. The assumption of homogeneity is mathematically highly convenient and is plausible for a star freshly condensed from uniform diffuse matter. The range of validity of the assumption will be discussed later.

radius, and luminosity. Two such relations imply that, for a given mass, both the radius and the luminosity of a homogeneous star are determined. Accordingly such stars should follow one curve in the mass-luminosity diagram and one curve in the Hertzsprung-Russell diagram. All stars (other than white dwarfs) appear to follow a line in the mass-luminosity diagram, and this is adequately accounted for by Eddington's relation. Stars in the Hertzsprung-Russell diagram do not *all* lie on one line, but the main sequence stars do. From what has been said it is fairly clear that these will be identified with homogeneous models, and that the exact shape of the main sequence will be determined by the details of nuclear energy-generating reactions. These will now be discussed.

THERMO-NUCLEAR REACTIONS

From the point of view of the nuclear physicist, two facts about the conditions of stellar energy generation are specially significant. First, the rate of energy liberation per unit mass is extraordinarily low by terrestrial standards. The average for the sun is only one watt for every 5 tons, and even the central value turns out to be merely around one watt for every 50 kilograms, which is barely 1 per cent of the value for human metabolism. The brightness of the surface is due to the huge depth of energy-producing matter below each element of surface.

Secondly, at temperatures of around 15 million degrees, the average kinetic energy of the nuclei* is far too low to induce any nuclear reactions.

These two characteristics are of course closely connected. The energy released in any one suitable nuclear reaction is so large that the reaction rates in stars must be exceedingly low. On the other hand, the actual kinetic energy of particles in a gas varies widely about the average. Maxwell's distribution law shows that particles much faster than the average occur at any temperature, though particles of more than, say, ten times the average kinetic

*At temperatures such as exist through most of a star, all light atoms are completely ionized, so that the gas consists essentially of nuclei and electrons.

energy are extremely infrequent. Given any such high speed, the proportion of particles with speeds exceeding it depends, under equilibrium conditions, very critically on the temperature. The great temperature sensitivity of stellar thermo-nuclear reactions is thereby accounted for.

The need for high kinetic energies arises principally because of the electrostatic repulsion between nuclei. Unless this 'Coulomb barrier' is penetrated, nuclear forces cannot possibly act. As the nuclei of heavier elements carry higher charges, only light elements are relevant for stellar reactions. Helium does not partake in any reactions except at substantially higher temperatures, and lithium, beryllium, etc. are very rare. Hence only hydrogen makes a suitable nuclear fuel, as H. A. Bethe showed in 1938. He also found that hydrogen was able to participate in two significant nuclear reactions, as has already been mentioned.

The first of these is the so-called proton-proton (*pp*) chain. This starts with two protons uniting to form a deuteron, emitting a positron and a neutrino.* Next, the deuteron absorbs a proton and emits a γ -ray, thereby changing into helium-3. The most common final process in the chain consists of two helium-3 nuclei uniting and emitting two protons, thereby forming a helium-4 nucleus (α -particle). This end result also follows from various other less probable final reactions.

The second series of reactions is the famous Bethe (CN) cycle, in which 4 protons are successively added to a carbon-12 nucleus, the result of the last reaction being an α -particle and a carbon-12 nucleus. Carbon therefore acts purely as a catalyst in this cycle and helps to turn hydrogen into helium without being used up itself. Thus the low abundance of carbon is not reduced by the process, hydrogen being the sole fuel used up.

The Coulomb repulsion that has to be overcome is far greater in the CN cycle than in the *pp* chain, and accordingly the reaction rate of the *pp* chain is not as extremely temperature-sensitive as the rate of the CN cycle. In stellar conditions the first

*An uncharged particle, of small or zero mass, postulated to conserve momentum, energy, and spin in nuclear transformations.

varies like the fourth, the second like the eighteenth power of the temperature.

It will be evident from the figures given earlier that a reproduction of stellar conditions in the laboratory would lead to unobservably low reaction rates with the comparatively low densities used in accelerators. However, the energies attainable in accelerators vastly exceed those occurring in stellar conditions. Using energies corresponding to considerably higher temperatures will lead to observable probabilities for all reactions except the formation of deuterons in the *pp* chain, as the low temperature-dependence implies that even at laboratory energies the probabilities are still impossibly low.

In order to get data of astrophysical relevance, the laboratory figures have to be extrapolated to lower energies. The use of standard scattering formulae allows this extrapolation to be made unambiguously, provided only that there is no nuclear resonance energy level* much below the laboratory range. This possibility introduces a slight uncertainty even in the Bethe cycle, although each of the reactions is independently observable in the laboratory. It is clear that the total reaction rate for the cycle will be determined by the slowest reaction. This is probably the reaction in which nitrogen-14 is turned into oxygen-15—but a low-lying resonance in this reaction has been suspected. If this is present (and the most recent evidence makes it fairly unlikely) then the crucial reaction would be the first one, involving the carbon-12 nucleus. In stellar conditions this change would make a difference of a factor of 20 in the rate of energy generation at a fixed temperature. For a given energy output (which is the true stellar problem, since Eddington's pipeline relation determines the rate of energy leakage to the surface) the effect on the central temperature would be less than 20 per cent owing to the temperature sensitivity of the reaction.

In the case of the *pp* chain, the first reaction has by far the smallest probability. Unfortunately this cannot be measured in

*That is, there is no especially favoured energy for which the probability of the reaction is markedly greater than for neighbouring energies.

the laboratory, but can be inferred from measurements of radioactive processes in which an electron or positron is emitted (β -decay) through the theory of such processes. Though the method is indirect, the uncertainty of the result is only about 20 per cent.

It will be seen that these results, due to W. A. Fowler, the Lauritsens, E. E. Salpeter and others, have given remarkably high accuracy to our knowledge of central conditions in stars. In spite of this, the detailed comparison with astronomical data is not yet in a completely satisfactory state. Before starting on a discussion of this, it should be pointed out (as is clear from what has been said earlier) that homogeneous stellar models constructed on the basis of the laboratory data show good agreement with the observed properties of main sequence stars.

COMPLICATIONS AND OBSERVATIONS

The energy released in the processes which convert hydrogen into helium emerges largely in the form of γ -rays, positrons and kinetic energy of nuclei. All these are immediately absorbed and turned into maintaining the local temperature, but the neutrinos produced escape. The effective result is that about one part in 140 of the rest mass of hydrogen consumed appears as stellar energy. Taking the sun as example, this would imply that the conversion of its entire mass from hydrogen to helium would sustain its present luminosity for 10^{11} years. As the age of the sun is estimated at about 5×10^9 years, only about 5 per cent of its hydrogen can have been converted into helium. Since the luminosity of a star depends so critically on its mass, the proportion will be much lower for faint (i.e. light) stars and much higher in bright (i.e. massive) stars. In fact very bright stars cannot possibly be as old as the sun.

The conversion takes place at a far higher rate in the hot central regions than in the outer parts of a star. Accordingly, unless gaseous motions keep the stellar material mixed, a star will have much more helium near the centre than further out, once its first youth is over. This again will occur much sooner for bright than for faint stars.

It can be shown that if the highly temperature sensitive (and

highly concentrated) Bethe cycle produces most of the energy, then the star has a core in which convection currents transport the energy. Thanks to these convection currents, the stars are highly stable. This means that gravitational contraction acts as a thermostat, ensuring that central energy generation equals surface energy loss. The same adjustment mechanism assures stability for stars supplied by the pp chain even without convection currents. Outside the limited convective region the gas is probably so much at rest that mixing is negligible.

Once the inner part of a star is helium-rich, the theory of homogeneous stars no longer applies. The calculations become more intricate. It appears probable that the first effects of ageing in a star move its representative point slightly to the right in the Hertzsprung-Russell diagram as the radius increases a little. Later developments presumably remove the star from the main sequence and turn it into a red giant (Hoyle and Lyttleton, Schwarzschild and Sandage). This is satisfactory in that it shows that the simplest model, the homogeneous one, corresponds to the most common type of star, the main sequence stars. It also shows that, by dropping the assumption of homogeneity, the theory can account for red giant stars.

However the developments discussed show a difficulty in the detailed comparison of theory and observation. One cannot infer directly from the observations what stars are young enough to be homogeneous. Many main sequence stars are no doubt slightly reddened by having a small helium-excess in the core. Many of the best data (especially those for the sun) must be suspect for this reason. A perfect theory and excellent observational data might indicate the central helium abundance. Interesting as this is, it is no test for the theory to predict an otherwise unobservable quantity. Taking the main sequence stars appearing furthest to the left in the Hertzsprung-Russell diagram would help, but it is doubtful whether the observations are accurate enough to make this selection valid.

A further difficulty arises in the case of the fainter stars. These might be considered specially valuable since they could have produced scarcely any helium in the estimated life of our

Galaxy, and so could be assumed to be homogeneous. However, the surface temperature of these stars is so low that hydrogen is neutral at the surface, though ionized not far below. Since at the same pressure and temperature, neutral hydrogen is twice as heavy as ionized hydrogen, this implies that heavy matter lies on top of light matter. This is clearly an unstable arrangement and, in the intense gravitational field of stars, produces powerful vertical convection currents, penetrating far below the level at which hydrogen becomes ionized. It is almost impossible to calculate just how far these currents will go, as difficult hydrodynamical problems arise. Since the structure of the outer layers is affected by these currents, the theoretical prediction of central conditions is affected by this unsolved question, and again a detailed test of the theory becomes impossible. In order that central conditions in faint stars should be such that nuclear processes produce the known luminosity, the currents must range down to regions where the temperature is 2 million to 3 million degrees. Though the sun is rather brighter than these stars it is satisfactory that a remarkable measurement by J. L. Greenstein indicates that the solar convection currents also reach down to regions at 3 million degrees. The basis for this statement is that a detailed spectroscopic examination of the solar surface shows lithium to be abnormally scarce, while beryllium is there in its usual, though low, abundance. The clue to the interpretation of this observation is that lithium is destroyed in nuclear reactions at as low a temperature as 3 million degrees, whereas beryllium is stable up to 4 million degrees. Accordingly it can be inferred that the outer layers of the sun are mixed through to a depth corresponding to between 3 and 4 million degrees.

One of the interesting questions raised by nuclear physics is that of the switch in the mode of energy generation. Since, by Eddington's mass-luminosity relation, massive stars lose more energy per unit mass than light ones, the central temperatures of massive stars must be higher than those of light ones. The far higher temperature sensitivity of the CN cycle than of the *pp* chain implies that at higher temperatures the CN cycle dominates while at lower temperatures the *pp* chain produces more

energy. Hence massive stars get their energy from the CN cycle, light ones from the *pp* chain. It turns out that the switch occurs somewhere along the populated part of the main sequence. If the lower rate for the CN cycle is the correct one, the switch should occur for stars about 6 times as bright as the sun, while, if the higher rate applies, the switch occurs for stars very little brighter than the sun.

Astrophysically the switch should result in a change of the slope of the main sequence. In the solar region there is almost certainly no such change, and the change of slope occurring at 1/6 solar luminosity is too far from the switch point predicted by theory. At stars 6 times as bright as the sun there is no evidence for a change of slope, but also none against it. Once again, the agreement between theory and observation, while good on the broad outlines, cannot be tested in detail.

An interesting but baffling observation is due to A. McKellar. Carbon exists in two isotopes, carbon-12 and carbon-13. On the earth carbon-12 is 90 times as abundant as carbon-13. In a region where the CN cycle is operating (since both carbon-12 and carbon-13 partake in the cycle) the ratio is determined by the ratio of two reaction rates and is only about 4. By an extreme refinement of spectroscopic technique, McKellar has been able to show that in the surfaces of some extremely red (i.e. very extended) red giants the ratio of isotopic abundances is between 3 and 4, while in others it is much higher. While it might at first sight appear attractive to regard the stars with a ratio of 3 to 4 as well mixed stars with the CN cycle active at the centre, this is plainly impossible. A well mixed star is homogeneous. If such a star is very extended, its central temperature is far too low for the CN cycle to operate. Conversely if the CN cycle is the energy source of such an extended star, it must be inhomogeneous. Hence the excess carbon-13 cannot have come from the centre to the surface, since any mixing leading to this would have destroyed the star's inhomogeneity.

A more recondite explanation of McKellar's observation is called for. It must be remembered that the surfaces of the stars are very exceptional places, with a temperature intermediate

between the cold of space and the heat of the stellar centres, and in these extraordinary circumstances explanations which would otherwise be far-fetched might apply.

Summing up, one may say that the success of the theory of stellar structure in accounting for the observational features in outline shows that the daring extrapolation of nuclear physics, quantum theory, and gravitational theory to these distant and strange objects is justified. However, a detailed test of the theory turns out to be difficult, as complicating factors, hard to take account of theoretically or observationally, blur the finer features on which such a test should rest.

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INTERSTELLAR MATERIAL

F. D. KAHN

It has been known for some thirty years now that the sun belongs to a system of stars, estimated to number 100,000 million in all, which together form the Galaxy. The system has, roughly, the shape of a flat round disk with a spherical bulge at its centre. The radius of the disk is estimated to be 12,000 parsecs, and the sun is about 8,000 parsecs from the centre. (To give some idea of the length of a parsec, the distance from the sun to the earth is 93 million miles = five millionths of a parsec.) The whole system of stars rotates about the axis of the disk, the centrifugal force on each one of its members being balanced by the gravitational attraction of the others. However, the motion is not that of a rigid body, in which the time of revolution is the same for all parts. The further a star is from the galactic centre the longer it takes to complete the circle: the sun, for example, takes some 220 million years to go round once. This type of motion is called differential rotation.

For some time the differential rotation was investigated by statistical methods. The motions of the stars in various parts of the sky were analysed and J. H. Oort, of Leiden, deduced from them some data about their large-scale motion in the neighbourhood of the sun. But a serious obstacle in this study is the interstellar material, which prevents the observation of parts of the Galaxy which are more distant from us. For instance, a picture of the sky taken in the direction of the galactic centre does not show an extremely dense collection of stars like the centre of the Andromeda nebula, a neighbour of the Galaxy and similar to it in many ways. Instead it shows a dark lane bordered by a reasonably luminous region. This might be so because the centre of our Galaxy is hollow, but then one should, at least, see the farther side through the hole. It seems far more plausible that the central

regions are really bright but that there is some material in the space between the stars which absorbs or scatters the light coming from there and prevents it from reaching us. This is one way in which interstellar material makes itself felt.

A closer look at the Andromeda nebula and at other similar objects shows that they also contain obscuring material. It usually lies in a rim round the centre of the nebula and its thickness is, as a rule, smaller than that of the disk filled by the stars. It can be seen in a very striking way on a picture of *M* 104 (the Sombrero nebula, Inset 1).

A connexion has recently been found between the presence of dark material and the population of stars in a nebula, or a given region of a nebula. Thus the outer parts of the Andromeda nebula contain plenty of dark patches, have an irregular appearance, and the most outstanding stars found there are very bright and very hot. There is reason to believe that such stars cannot be more than a few million years old. For comparison, the oldest exposed rocks on the earth are more than 2,000 million years of age and therefore must be much older than these young stars. Similar stars also exist in our region of the Galaxy, e.g. the Trapezium group in Orion, and here again there is plenty of dark material nearby. The picture of the so-called Horsehead nebula shows some of the dark matter in Orion (Inset 2). Further evidence of the youth of such stars is that they occur in groups, which were discovered and called associations by V. A. Ambartsumian, of Erevan. The motion of an association in Perseus has been analysed by A. Blaauw, of Leiden (now at Yerkes), who found that 1,300,000 years ago it was all contained in a much smaller volume and probably originated there. A great deal of obscuring material is still found near the association.

On the other hand if a system of stars does not contain any dark patches, then it usually has a very regular structure and the most prominent stars in it are far less hot and bright. There is no reason to believe that any star in such a system is particularly young. The contrast between the two types of system is shown by the picture of *NGC* 4647 and *NGC* 4649, a spiral and a globular nebula in Virgo (Inset 3).

THE OBSCURING MATERIAL

The interstellar obscuring material (which we shall from now on call dust) turns up not only in such striking dark patches as in the Ophiuchus nebula, which hides the centre of the Galaxy. It also appears in smaller clouds, none of them opaque. If a star is far away from the earth and is seen through a number of these clouds it will look rather dimmer than it really is. But how can one decide whether a star looks dim because there is dust in front of it? It might just be naturally less bright than some other stars. This question can be answered. One can investigate galactic star clusters – these are compact groups of stars found in the rim of the Galaxy. They all have about the same linear diameter and total brightness. The distance of a given cluster can be judged by its angular diameter. If there were no interstellar dust between us and a given set of clusters then the apparent brightness of its members, as seen on the earth, should fall off as the inverse square of their distance from the earth. In fact, the apparent brightness falls off more quickly than this; the difference is due to the extinction of light by the dust grains.

The grains do not extinguish the light uniformly, but blue light is removed more easily than red. One can compare, for instance, two stars of a certain type, one near the sun and the other far away. The type of the star can be found by splitting up its light into a spectrum and finding the most noticeable absorption lines in it. In this way almost all stars can be assigned to one of ten classes (O B A F G K M R N S, in order of decreasing brightness) and each of these can again be subdivided into a number of subclasses. One can then speak of a B4 star, and mean by this a star, in the spectrum of which the most prominent lines are those of neutral helium, neutral hydrogen, ionized oxygen, and doubly ionized silicon.

On observation, one finds in general that in a bright B₄ star (or a star of any other type) the blue end of the spectrum contains more energy relative to the red end than it does in a dim B₄ star. This is interpreted as follows. The light from the dim star has passed through more interstellar dust clouds than the

light from the bright star. The dust removes blue light more easily than red light and so the star which has been dimmed has apparently become redder as well. A similar effect is noticeable when the sun is seen through mist. The water droplets in the mist scatter blue light more easily and so the sun appears to be redder than usual, as well as dimmer.

We may define $E(\lambda)$ as the efficiency of a grain in removing light of wavelength λ . Then observation shows that, approximately,

$$E(\lambda) = \text{constant} \times (17,000/\lambda - 1) \quad (\text{Eqn 1})$$

when λ is expressed in ångström units ($1 \text{ Å} = 10^{-8} \text{ cm.}$). The formula holds quite well for visible radiation, i.e. when λ lies between 4,000 Å (violet light) and 8,000 Å (red light). The efficiency of the grains in extinguishing starlight is then almost three times greater in the violet than in the red region of the spectrum. Equation 1 gives a clue to the size of the grains.

A second clue is the following. The grains cannot absorb an appreciable fraction of the stellar radiation incident on them; they must, rather, scatter it out of its original path, for there is much diffuse light visible in the Milky Way whose presence cannot be explained otherwise. If the grains were small particles of an electrically conducting substance, such as iron, they would absorb too much of the light. It is more probable that they are made of some non-conducting (dielectric) substance, such as ice, which has a refractive index $n=1.3$, or glass with $n=1.5$. Optical theory indicates that spherical dielectric particles with $n=1.4$ have the extinction efficiency $E(\lambda)$, given by equation 1, if they have a radius of about 0.4μ ($10,000\mu = 1 \text{ centimetre.}$) With much smaller particles one would have an efficiency $E(\lambda) = \text{constant}/\lambda^4$; with much larger particles the efficiency is independent of the wavelength.

We can now make a very rough estimate of the number and mass of the grains per unit volume of interstellar space. Though not everybody would agree with his estimate, H. C. van de Hulst, of Leiden, has recently stated* that the extinction of star-

*At the Liège Symposium on Solid Particles in Astronomical Objects, July 1954.

light in the Galaxy amounts to about two magnitudes per 1,000 parsecs. This means that on passing through 500 parsecs of interstellar space the light of a star is diminished by one magnitude (i.e. its intensity is cut down by a factor 2.5), in addition to the diminution caused by the inverse square law. This will happen if the grains contained in a column 500 parsecs long have approximately sufficient cross-sectional area to cover the base of the column. By arranging the grains properly one could make them cut off all the light, but they are, in reality, less efficient than this because they distribute themselves at random.

Taking the grains, as before, to be of radius about 0.4μ , van de Hulst's estimate leads to an average abundance of one grain in about 7.5×10^{13} cubic centimetres—or in round figures, say a cube of sides 200 yards. If the grains consist of a substance with the density of water, they would contribute to the mass of the Galaxy about 3.5×10^{-26} gramme per cubic centimetre; this is about one hundredth of the contribution made by the known stars near the sun. The dust is only a minor constituent of the stellar system and yet it seems to have an important influence on its nature.

The temperature of the grains can be estimated to lie between 10°K and 40°K (i.e. between -263°C and -233°C).

INTERSTELLAR GAS

Interstellar space also contains gas, which can be detected in a number of ways. It becomes luminous near hot stars. In these regions of space, the hydrogen, which is the main constituent of the gas, is almost completely ionized, and they are known therefore as H II regions; an example is the diffuse bright area in Inset 2. The remainder of space, where the hydrogen is neutral, is called an H I region.

The gas in an H I region can be observed by means of the absorption lines of neutral sodium (Na I) and ionized calcium (Ca II) which it superposes on the light of distant stars. One can infer from the appearance of the lines that the gas is present in separate clouds, just like the grains, and that there is a fair correlation between the strengths of the lines on a given star

and the degree of reddening of that star by the grains. Lately the properties of the gas have also been studied by means of a radio telescope working at a wavelength of 21 centimetres, where there is a very long-wave spectral line of the hydrogen atom. This method has proved very powerful and has shown that the gas has a temperature of about 125° K (– 148° C); that, by and large, it moves round the centre of the Galaxy with the majority of the stars, and that individual clouds of it have, in addition, random velocities of about 10 kilometres a second. The average density of the gas is estimated to be 2×10^{-24} gramme per cubic centimetre, but much of it is concentrated into clouds with a mass density twenty times as high. The gas is then about sixty times more abundant, by mass, than the dust, and its contribution to the mass of the Galaxy is about half that of the known stars near the sun.

THE INTERSTELLAR MATERIAL AS A WHOLE

The relative abundances of the more important elements in the interstellar material are at present thought to be as set out in Table I: the data are taken from L. H. Aller, *The Atmospheres of the Sun and Stars*.

TABLE I: *Relative abundances by mass of the more important elements in interstellar material (Hydrogen = 1)*

Element	Relative abundance	Element	Relative abundance
Hydrogen	1	Carbon	0.001
Helium	0.54	Magnesium	0.001
Neon	0.01	Iron	0.001
Oxygen	0.01	Silicon	0.0005
Nitrogen	0.004	Sulphur	0.0005
Arsenic	0.002	Total	1.57

The grains are probably too warm to contain hydrogen, helium, or neon in solid form. Even if all the other elements in the list occur in the grains it will still be hard to concentrate a sixtieth

part, by mass, of the interstellar material in them. The difficulty is only slightly eased when we consider that oxygen, carbon, and nitrogen probably turn up in the grains as the hydrogen compounds H_2O , CH_4 , and NH_3 , and will therefore contribute more than their own weight. However, we may have overestimated the amount of interstellar extinction and underestimated the efficiency of the grains in causing it.

Clearly the interstellar material is an important part of our galactic system and astronomers are making a serious attempt to understand it better. In the last twelve months there have been two important conferences to discuss the subject. The first was the Symposium on Cosmical Aerodynamics, held at Cambridge in July 1953, the second the Symposium on Solid Particles in Astronomical Objects, held at Liège in July this year (1954).

Both gas and grains were considered at Cambridge. The general feeling of the conference was that the problems of the interstellar material were a lot harder than one had thought.* One notable new idea, however, was described by J. H. Oort in a paper outlining a theory to explain the formation of stars, and the random motion of the interstellar material. The clouds of gas in the Galaxy collide with one another from time to time and tend to lose their kinetic energy of motion. The whole system therefore gradually slows down and its separate parts gather together into one large cloud, which eventually becomes unstable under its gravitational self-attraction. Its central part collapses first and forms a new star, the radiation from which ionizes the gas around it and transfers heat to it. When conditions are suitable, this produces a kind of explosion and then the gas around the new star is both compressed and pushed away. The interstellar material regains kinetic energy in this way. At the same time the compression in the gas may be high enough for it to become gravitationally unstable and to condense into an expanding association of stars. The theory may

*An account of the conference was given by B. J. Bok in the issue of *Sky and Telescope* for December 1953. The full proceedings will be published in Holland later this year.

also explain the formation of the small dark globules of interstellar dust, which can be seen superposed on many bright H II regions, and in which the concentration of grains must have many thousand times the value which is normal in interstellar space.

Further study of this new idea shows two results. Firstly, one finds, even with quite plausible assumptions, that the explosion cannot give a speed much above seven kilometres a second to large gas masses. One would really like the speed to be twice as high, and there is some hope that an improvement in the assumptions will lead to higher speeds. But then A. Blaauw and W. W. Morgan, of Yerkes, have recently found a pair of stars which both appear to be members of an expanding association centred on the Orion nebula and to be receding from it in diametrically opposed directions at about 130 kilometres a second. This is far above the limiting speed one can hope to reach by means of Oort's mechanism. There is evidently some other process at work which helps also to make the associations expand.

Secondly, the gas must be able to radiate away its heat even at quite low temperatures, i.e. between 100°K and 200°K, if it is to be sufficiently compressible during the explosion. One also needs such a cooling mechanism to explain the thermal equilibrium of the interstellar gas in general, for a good deal of heat is generated during collisions between different clouds and yet the matter in them is relatively cool, according to the measurements on 21-centimetre wavelength quoted above.

At the Symposium in Liège the emphasis was placed almost entirely on the nature, role, and observable effects of solid particles in various astronomical fields. Only half the symposium dealt with interstellar dust, and some thirty papers were submitted here. The role of the dust grains in the formation of new stars was discussed during one session, introduced by B. Strömgren, of Yerkes, in which he pronounced the death sentence on what once was one of the most promising theories in astrophysics. The theory, put forward in 1940 by L. Spitzer, Jr., of Princeton, and F. L. Whipple, of Harvard, suggested that

interstellar dust clouds are liable to collapse because the radiation pressure of the light from outside them eventually drives the dust grains together towards the centre. After a while the grains will begin to drag the gas with them and eventually the density of the whole mass becomes so large that it can no longer resist its own gravitational attraction and it contracts to form a new star. The theory was especially pleasing because it predicted that the new stars would contain an abnormally large amount of material derived from the dust grains, and would therefore be exceptionally rich in metals.

Since then it has turned out that such a process of star formation would take at least 100 million years and would require particularly quiet conditions in interstellar space. This is just what one does not find. Dr Strömgren also pointed out that even if new stars are richer in metals than old stars they have about the same composition as the interstellar gas, and this removes the *raison d'être* of the theory.

In fact the dust grains must have a less direct role in the birth of new stars. Few people were willing to commit themselves by sending in papers to this section of the symposium. Most of the contributions dealt, instead, with the observable properties of the dust particles, and some interesting new results were reported.

A. D. Thackeray, of the Radcliffe Observatory, described a star which has become $2\frac{1}{2}$ magnitudes fainter in the last four years, that is, its light intensity now is only one-tenth of what it was then. This is due to the obscuration of the star by a small dense cloud of dust which has drifted in front of it – or, perhaps, behind which the star has hidden itself. The diameter of the cloud is estimated to be 1,000 astronomical units, otherwise 93,000 million miles, very small by interstellar standards. If the grains in the cloud are of the same type as those in interstellar space, they must be 250,000 times as abundant here in order to produce the observed darkening of the star. With a correspondingly large gas density, the cloud will contain about 5×10^{-19} gramme of matter per cubic centimetre, and will have a total mass of about one thousandth part of that of the sun. This is a little

disappointing because the cloud turns out to be too light to be a new star in the course of formation.

B. J. Bok and his colleagues, of Harvard, described some measurements made to find the degree of correlation of the interstellar extinction with the intensity of the 21-centimetre line, for particular regions of the sky. The two seem to go hand in hand in the dark nebulae of Orion and Taurus but not in those of Ophiuchus. This paper added some new fuel to an argument, started at Cambridge last year, as to whether the gas and the grains are always present in space in the same relative proportions or not. But the question was not settled; the data obtained with the 21-centimetre line can be interpreted in a number of ways and, even worse, some measurements made in Holland have suggested that there is no simple relation between the extent of interstellar absorption and the intensity of the 21-centimetre line, even in small regions of the sky, i.e. within the Taurus nebula. The problem needs a really systematic study.

Many of the papers discussed interstellar polarization. This effect was discovered and reported about five years ago by W. A. Hiltner, of Yerkes, and can be detected in various regions of the sky. It is associated with interstellar extinction, for a star whose light appears polarized is always reddened as well. Perhaps a word should be said about its nature.

At any point illuminated by a source of light there is a rapidly varying electromagnetic field. Both the electric and the magnetic fields always lie in a plane which is perpendicular to the line joining the source to the point. In ordinary light, say direct sunlight, the electric field shows no preferential direction in the plane. But when the light is partially polarized the average electric field tends to be strongest along one line in the plane, which gives the direction of polarization,* and to be weakest along the line perpendicular to it. The ratio of the average strengths gives the degree of polarization.

The existence of the effect has two consequences. The light leaving the stars is not polarized, and so the interstellar material

*According to the definition agreed to at Liège.

must be responsible. This means that the grains scatter more efficiently that component of the starlight whose electric field lies perpendicular to the eventual direction of polarization, so that this component is weakened relative to the other. Therefore the grains are not all spherically symmetrical, and some at least of them have an optical axis; further, some physical agency keeps them so aligned that their optical axes have a certain preferential direction when seen from us.

Needle-like grains might produce this effect. Some calculations made by H. C. van de Hulst showed, however, that such particles can, at best, have an absorption ratio 11:10 for the two directions of polarization. The required average ratio is about 107:100 if observations are to be explained, and so the needles would have to be rather well aligned. This might be very difficult. It was interesting, for this reason, to hear E. Schatzman and R. Cayrel, of Paris, describe a new model grain of graphite, which they had made in the laboratory. A cloud of such grains, all held parallel to one another, produces very strong polarization in light passing through it. Perhaps interstellar space contains many such particles, but probably there are grains of other types as well.

A magnetic field in space will line up the grains, according to a theory of L. Davis and J. L. Greenstein, of Pasadena, which the majority of astrophysicists believe to be correct. (There are other theories as well, notably one by T. Gold, of Herstmonceux, who dispenses with magnetic fields and only requires an interstellar wind.) The direction of the field is the same as that of the direction of polarization.

J. S. Hall and A. Behr separately described the polarization of stars shining through certain filamentary nebulae, and found that the magnetic fields here lie parallel to the filaments. This may help, one day, to explain the mechanics of these structures. Interstellar polarization will also help in mapping and measuring the general magnetic field in the Galaxy. We need a better knowledge of this to understand the structure of our stellar system and, possibly, the origin of cosmic rays.

Professor van de Hulst summed up everybody's feelings when

he said that the grains now seem to be just tracers in the interstellar gas, like smoke in the wind. They are abundant in the spiral nebulae and near new stars only because the gas is abundant there. A magnetic field sets them in a certain direction but they have no back action on the field. Possibly their only physical importance is that their surfaces act as catalysts in the formation of interstellar molecules, such as H_2 , H_2O , and so on. Even this was disputed by one author, but on seemingly insufficient experimental evidence. The H_2 molecules themselves are important because they can radiate away the heat of the interstellar gas even at quite low temperatures. They can be destroyed again by stellar radiation; the grains are therefore needed to maintain the balance, and resume a little significance in interstellar physics. But they have lost the glory they had in the heyday of Spitzer and Whipple's theory.

FURTHER READING

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These publications are not too technical. A good account of what one can do with 21-centimetre line observations is given by H. C. van de Hulst, C. A. Muller, and J. H. Oort in *Bulletin of the Astronomical Institutes of the Netherlands*, No. 452, 1954, but this is probably too hard going for the non-specialist.

THE BOILING OF LIQUIDS

J. W. WESTWATER

IT is a curious fact that some of the most familiar phenomena in nature are among the least understood. Consider the boiling of water. Man's acquaintance with this phenomenon is at least as old as his discovery of fire, yet until very recent years no one had ever made a serious study of how and why liquids boil. It has turned out that boiling is far more complex than anyone had imagined.

In 1934 Shiro Nukiyama, a Japanese, carried out a simple experiment. He submerged a fine platinum wire in water and heated the wire with an electric current to produce boiling. He discovered that the rate of heat flow from the wire to the liquid increased steadily as he raised the temperature of the wire until its temperature reached 150°C . Then a totally unexpected thing happened. When he increased the current slightly at that point, the wire temperature (calculated from its electrical resistance) jumped suddenly to about $1,000^\circ\text{C}$. Either at 150° or at $1,000^\circ\text{C}$ the wire made the water boil. But it was simply impossible to raise the wire temperature to just a few degrees beyond 150°C . Nukiyama now tried wires of nickel and of a nickel-chromium alloy. When their temperature made the jump beyond 150°C , the wires melted, these metals having lower melting points than platinum. The boiling, of course, then came to a halt. This temperature jump was puzzling. Why should it be easy to boil water with a wire at 150°C , but apparently impossible to boil water with the same wire at 160°C ? Nukiyama went back to the platinum wire to look more closely into the boiling at high temperature. He was able to reduce the temperature of the wire gradually down to 300°C . Above that level any rise in the temperature caused an increase in heat flow, and vice versa. This is the situation represented by the right-hand part of Figure 1, which shows how heat flow varies with temperature. Here the

experimental results seemed to be normal and in agreement with intuition. But any attempt to reduce the wire temperature slightly below 300° C met with failure. It then dropped suddenly below 150° C, that is to the left-hand part of the curve.

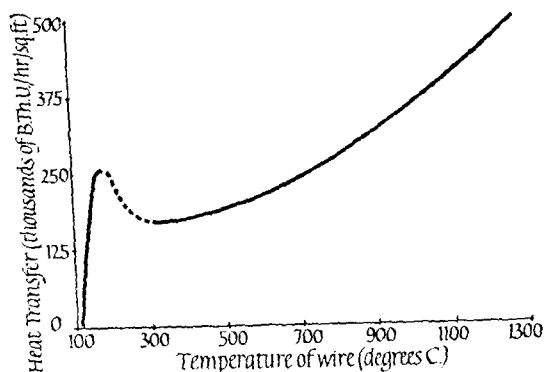


Fig. 1. Experimental curve showing the rate of transfer of heat from an electrically heated wire to boiling water. The left-hand part of the curve was obtained by gradually increasing the current in the wire; but above 150° C the wire temperature jumped suddenly to about 1,000° C. The right-hand part of the curve was obtained by reducing the wire temperature. (After Shiro Nukiyama.)

Nukiyama concluded that one type of boiling occurred below 150° C and another above 300° C, and he guessed that a third, abnormal type of boiling might take place in the region between 150° and 300° C. It was clear that, if a middle type did exist, it would have a peculiar characteristic: any increase in the metal temperature would cause a *decrease* in the heat released, as in the part of the curve shown dotted in Figure 1. This, certainly, is contrary to intuition.

RECENT EXPERIMENTS

The problem has recently been pursued further in our laboratory at the University of Illinois with support from the National Science Foundation. It has attracted a lively practical interest

with the advent of nuclear reactors, jet engines, and rocket motors. A nuclear reactor, for example, requires the removal of large amounts of heat from a relatively small reaction zone. The use of boiling liquids as coolants appeals to engineers because of the rapid rate at which such a liquid can absorb heat. One square foot of a hot solid at 145° C can transfer to boiling water as much as 400,000 British thermal units per hour, enough to generate about five tons of steam per day. This is about 10 times the rate at which heat can be transferred to non-boiling water and about 100 times the rate to circulating air. Progress in the study of boiling has been stimulated greatly by the promise of quick application of new information.

Nukiyama was quite correct: there are indeed three types of boiling. They are usually called nuclear, transition, and film boiling. To the eye they are distinctly different. An experienced worker can even distinguish them by ear. In a typical test the noise rises from 2 to 18 and then to 26 decibels as the boiling progresses from nuclear to transition to film boiling. The appearance of these boiling phenomena is shown in the photographs reproduced as Inset 20 to 22; they were taken by J. G. Santangelo at the University of Illinois. The exposures were at one millionth of a second and were obtained by the flash-tube technique. Methyl alcohol was selected as the boiling liquid so that all three types of boiling could be obtained within the range of temperatures available with laboratory steam heat (100° to 170° C). The heating element was a copper steam tube three-eighths of an inch in diameter. The choice of steam heat was important, because transition boiling happens to be quite stable with a steam tube, but is very unstable with an electrically heated element. The copper tube was 3½ in. long and was of bayonet construction. It was placed horizontally in a flat-sided glass boiler containing about one gallon of methyl alcohol. As the alcohol boiled, the vapour passed to a water-cooled condenser; from there the condensed liquid returned continuously to the boiler. The amount of heat transferred was calculated from measurements of the rate of steam condensation in the boiler tube, and there were check measurements of the heat absorbed by water

in the condenser and of the temperature of the alcohol leaving the condenser. The steam temperature was calculated easily from the measured steam pressure. The alcohol boiled at its normal boiling point, 64.7°C .

Nuclear boiling is the usual boiling that occurs in a tea-kettle. Bubbles form on the hot surface of the kettle bottom with great speed. As soon as one bubble breaks loose, a new one grows at precisely the same point on the hot solid. The solid seems to be peppered with active points. Bubbles keep forming repeatedly at these points, even though near-by areas of the solid may be clean and free of bubbles. The amount of heat transferred to the liquid depends on the number of active points. An increase in the metal temperature activates new ones. A decrease causes some of the old points to cease functioning. No one knows just what an active point is. Suggestions have been made that it may be a tiny impurity on the solid or a microscopic sharp-point roughness of the surface or perhaps a tiny cavity (containing adsorbed inert gas) in the solid. In the case of methyl alcohol, when the temperature difference between the solid and the liquid is 39°C each active point emits bubbles at the rate of about 17 per second. This, of course, is not evident to the unaided eye. The fact was discovered from close-up motion pictures taken at 4,000 frames per second and projected at 16 frames per second. This technique gives a slow-down in the action by a factor of 250 to 1. The fast emission of bubbles results in violent agitation of the liquid. Undoubtedly the agitation assists the heat transfer and is the principal reason why nuclear boiling is such an efficient way of transferring heat. When the transfer is at a maximum rate, practically the whole surface of the hot solid is covered with active points and bubbles (Inset 20). The active points are so close together that occasionally the bubbles interfere with one another. The critical temperature difference at which the maximum heat flow occurs is 57°C for methyl alcohol boiling on hot copper: for other liquids and other hot solids the value varies from about 10° to 60°C . The value depends on the liquid, the metal, the surface smoothness of the metal, the pressure and other factors.

When the temperature difference is increased slightly beyond the critical value, a dramatic change occurs. The rate of heat transfer drops considerably (Figure 2), and the boiling becomes noticeably louder. High-speed motion pictures show a series of small explosions occurring along the solid surface. In methyl alcohol at a temperature difference of 74°C the bursts occur 84 times per second per inch of length of tube (along the visible, photographed side of the tube). The bursts are at random locations; active centres no longer exist. The hot solid is now entirely blanketed with vapour, and the liquid no longer touches the solid at any place (Inset 21). The miniature explosions of newly created vapour keep blasting the surging liquid away from the metal. Each slug of vapour grows to its full size in about three thousandths of a second; in that time it pushes the liquid about four millimetres away from the solid. Then, after the velocity of the moving vapour has been slowed down by friction with the surrounding liquid, the vapour slug ruptures, and bubbles

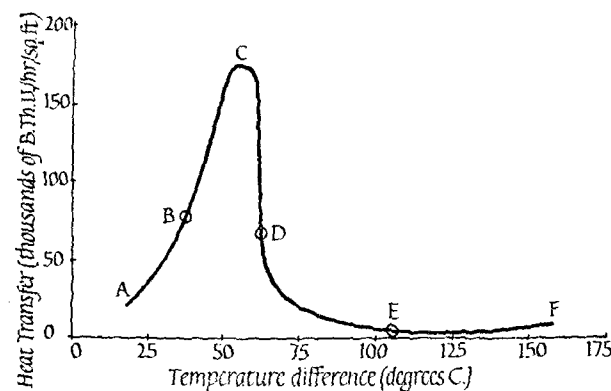


Fig. 2. Heat-transfer curve for methyl alcohol plotted by the copper-tube technique. Nuclear boiling occurs from A to C; transition boiling from C to E; and film boiling from E to F. The photographs reproduced as Inset 20, 21, and 22 were taken at B, D, and E respectively. The temperature difference is that between the tube and the boiling liquid.

rise from it to the liquid surface. This is the transition type of boiling.

The great difference between nuclear boiling and transition boiling is that the former rapidly generates uniform bubbles from specific nuclei, while the latter exhibits a random generation of bubbles by sudden bursts. The reason that the rate of heat transfer drops as boiling enters the transition region is because of the insulating blanket of vapour on the hot solid. The blanket begins to form when the temperature difference rises slightly above the critical point and grows thicker as the temperature is increased.

Eventually the blanket becomes so thick that it smothers all vapour bursts. Now begins the final phase, that of stable film boiling. Heat transfer and vapour generation fall to their lowest values. For methyl alcohol the minimum rate of heat transfer is only 3 per cent of that at the peak of ordinary (nuclear) boiling. In other words, the heat given off from the solid at 122°C is more than 30 times as great as that at 165°C . It is clear now why an electrically heated wire submerged in a boiling liquid may suddenly burn out. When the critical temperature difference is passed, the heat absorption by the liquid drops swiftly to a small percentage of its prior value. Meanwhile the electric current continues to generate heat in the wire at the same rate as before. High heat input and low heat output result in an accumulation of heat in the wire.

In film boiling no explosive bursts can be seen. A loud, drum-like noise rumbles from the liquid. Its dominant tone is from 25 to 30 beats per second. Through the stable layer of vapour, which completely blankets the solid surface, heat passes to the liquid by conduction and radiation. Convection probably is negligible. New vapour is formed only at the vapour-liquid interface, not on the surface of the solid. It flows to the top of the boiler with a gentle wave motion — a steady series of ripples passing at a rate as high as 74 per second. If the vapour is allowed to accumulate, eventually a rod-like mass of vapour is formed along the top of the tube. The rod is smooth at first, but gradually a series of peaks, about equally spaced, appears in it (Inset 22). These nodes

break off simultaneously along the entire tube, and large bubbles rise side by side in a row. In methyl alcohol at a temperature difference of 102°C , a vapour rod forms and breaks at intervals of about six hundredths of a second. The bubble sizes (about a third of an inch) and spacings (half an inch apart) are surprisingly uniform. Oddly enough, in every second rank the bubbles arise at what were spaces in the rank before; the effect is that of a parade in which the even-numbered rows of marchers are displaced sideways by a half-space. Film boiling is the type that occurs when a drop of water falls on a red-hot stove. The drop rolls about noisily, but it evaporates slowly. A drop on a moderately warm stove boils in nuclear fashion and evaporates much more rapidly.

All three types of boiling occur when a red-hot metal is quenched in water (Figure 3). The metal first cools slowly, then rapidly, then slowly again. The boiling goes through the three stages in the reverse of the usual order: film boiling comes first, then transition boiling, and finally nuclear boiling, when the solid has been cooled to below the critical temperature difference and proceeds to lose heat most rapidly. After boiling ceases, the last cooling is by natural convection.

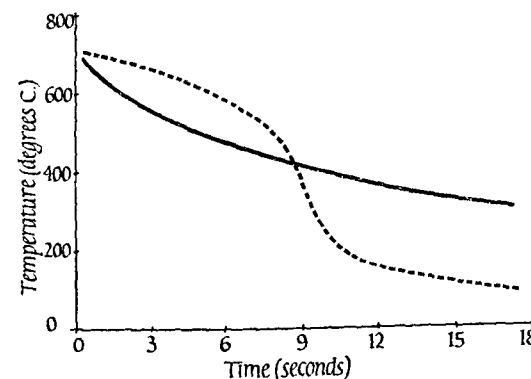


Fig. 3. Cooling curve of 1-in. steel bar quenched in a non-boiling liquid (solid curve) and in a boiling liquid (dotted curve).

CONCLUSION

To sum up, nuclear boiling is marked by large rates of heat transfer and the rapid formation of bubbles from fixed points. Transition boiling exhibits a poorer heat transfer and random bursts of vapour. Film boiling shows the poorest heat transfer and a complete blanketing of the hot solid with a film of vapour. The best heat transfer is obtained at the critical temperature difference, which is the dividing line between nuclear and transition boiling. At an extremely high temperature difference a solid can transfer a great deal of heat to a liquid by means of radiation, but that is another story.

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USES OF MASS SPECTROMETERS

M. P. BARNETT

EARLY in the present century, the masses of individual atoms were first determined. To do this, the atoms were given an electric charge, usually by removing an electron from them, and the ratio of charge to mass in the residual particle was then obtained by measuring its deflexion in magnetic and electric fields of known strength. The development of this method into an accurate technique of measurement was due almost entirely to one man, F. W. Aston; and the immediate consequence was the discovery, surprising at the time, that all atomic masses are close to integral multiples of the same basic unit, the mass of the hydrogen atom. Aston's instrument was known as a 'mass spectrograph' because the atoms were separated and spread out according to their masses, much as in an optical spectrograph light waves are separated and spread out according to their wavelengths. The object at this stage was to measure the masses of the atoms as accurately as possible, as is still of interest in nuclear physics. The numbers of atoms of different masses were not counted. In a more recent application, the mass spectrograph has been used to compare the ratios of mass to charge in the electron and positron. It has been shown to a higher accuracy than before that these two particles are, in fact, equal in mass, and equal but opposite in charge.

Aston's mass spectrograph has given rise to two further types of instrument – the uses of one of which, the 'mass spectrometer', is the main subject of this article. The other, the 'mass separator', was used during the war for the separation of uranium atoms on the basis of their masses, and is still used today for the separation of pure isotopes of many of the elements. Here there is no kind of measurement; it is essentially a sorting-out device. The 'mass spectrometer', on the other

hand, like the mass spectrograph, is an instrument of measurement. But instead of measuring the masses of particles, it takes these for granted and measures the quantities of each type of particle present. It is primarily an instrument of analysis, though there are other uses to which it can be put. Its development has been linked inseparably with the needs of industry.

Individual applications of the mass spectrometer affect fundamental research on chemical reactions in solution and in gases, including those that take place in flames; technological research in the petroleum industry and control of the routine operation of oil refineries; the elucidation of metabolic processes; the determination of the age of minerals and of the nature of the upper atmosphere; diagnostic procedures in medicine; the understanding of the nature of chemicals present in surface layers and of the forces between molecules in gases; and the preparation of materials for electronic valves and transistors. Questions can crop up in almost any branch of science to which the direct measurement of the relative amounts of particles of different masses provides the answer; and, by varying degrees of subtlety, many other problems can be thrown into a form in which the mass spectrometer can help.

As in the mass spectrograph, the atoms or molecules produced in one vessel are first given an electric charge. They are then projected into another vessel, in which their paths are controlled by electric and magnetic fields that can be set by the experimenter. These fields make the paths of all particles of one particular mass intersect at a single point, where they may be collected free from particles of all other masses. The processes that occur are summarized in Figure 1. In the vessel *A*, the particles to be separated are produced and ionized, that is, given their electric charge. When the substance to be treated in the mass spectrometer is already a gas, a small sample is simply allowed to flow into the vessel *A*, through a capillary tube. A beam of electrons is then fired into the vessel to tear out other electrons from the gas molecules. Even when the substance to be analysed is a solid, it may still be possible to boil a sample in a furnace and to convey its vapour into *A* via a metal tube. With

very involatile materials, such as high boiling metals, the specimen can be attached to an electrode inside *A*, and an electric discharge passed between this electrode and another. Ions become detached from the surface of the metal, and can then be passed directly into the vessel *B*, where they are separated from each other. The mass spectrometer is operated at very low pressures. Only a minute amount of material is therefore needed, and, if required, the vessel *A* can be connected to another vessel in which a reaction is occurring in such a way that the contents of this may be sampled periodically. But to ensure that the samples are typical is not easy – as will become apparent later when uses are being discussed.

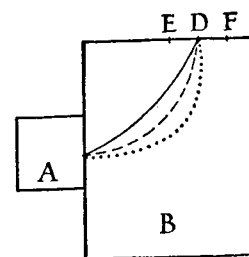


Fig. 1. Simplified diagram of mass spectrometer. *A* represents the vessel in which the vapour of the substance being analysed is first bombarded with electrons, so producing ions that then travel through the focusing vessel *B* under the influence of a magnetic field. The paths of three ions of identical mass, that are all collected at point *D*, are sketched. *E* and *F* are points at which ions of other mass may collect.

The rectangle *B* is the simplest possible representation of this separating vessel, usually of complicated design which differs in different types of instrument. Part of the vessel is between the poles of a powerful electromagnet – which it is important should provide a steady field – and in part of it electric fields are produced between pairs of condenser plates. *D* denotes the point at which particles of a particular mass accumulate; paths for three such particles are indicated. They converge to a focus, just as

light rays starting from a point but proceeding in different directions are all brought to a focus at another single point by a lens. Some mass spectrometers are designed so that particles of different masses are brought to a focus at different points simultaneously. Thus *D*, *E*, and *F* might be foci for particles of three different masses. Other instruments are designed so that particles of just one mass are brought to a focus at a time, particles of other masses executing paths that bring them into ultimate collisions with the walls of the vessel, where they are lost from the experiment.

Originally, the ions were allowed to impinge on a strip of photographic material, which they fogged. The extent of the fogging at a particular point is then an indication of the number of particles that have arrived there. With equipment that focuses a whole range of ions simultaneously onto the photographic plate, the regions of fogging are very narrow, corresponding to masses that are practically integral multiples of the weight of the hydrogen atom, as mentioned earlier. If the intensity of fogging on such a plate is plotted against the mass corresponding to the position on the plate, a 'spectrum', consisting of very sharp peaks, separated by nearly horizontal lines, results.

Since the particles collected are necessarily charged, their arrival constitutes an electric current which can be amplified — the ion current. With spectrometers that focus particles of just one mass at a time, the number passing through the focal point per second is measured by placing a metal plate at the focus, at which the ions collect, and incorporating this plate in an amplifying circuit. Now the mass of the particles which are focused at any one time depends on the electric and magnetic fields in the separation vessel. Alteration of these by a suitable amount causes particles of a second mass to be focused onto the collector, and further alterations focus particles of other masses in turn. By allowing the values of the electric and magnetic fields to pass through a range of values, particles whose masses lie between any desired limits may be focused and collected, one after the other. Plotting the ion current against the focusing field gives a graph similar to Figure 2; the peaks correspond with

fields that focus particles whose masses are approximately multiples of the mass of the hydrogen atom, and the troughs with fields that would focus particles of intermediate masses, if any such existed.



Fig. 2. Portion of a typical mass spectrum, as it might be traced on a rotating drum recorder. The mass/charge ratio of the ions is measured along the horizontal axis, and the peak ion current vertically.

Such a graph is usually recorded by a pen on a moving drum, at the same time as the information from the analysis is obtained. But where quick changes are being studied, it can be arranged that the graph is traced at high speed on the face of a cathode-ray tube, and recorded photographically at whatever intervals are thought suitable for the job. This is a relatively recent development.

There is also a special type of mass spectrometer that focuses just two ion beams simultaneously, letting other particles hit the vessel walls. These machines are used to compare the relative amounts of two isotopes in a mixture, or the relative amounts of two molecules which are identical except that one contains one isotope of a particular element and the other contains another isotope. The difference in mass can be adjusted to be one or two units, and the actual masses to be anywhere within a fairly wide range.

The earliest mass spectrometers represented an adventure, both in ideas and in laboratory manipulation; their successors are produced commercially, housed elegantly in pastel, dial-strewn cases that mask their structural individuality behind the stylized uniform of modern instrumentation. (See, for example, Inset 14.) Some are robustly designed for mobility in factory

use. They do not in general provide their owners with the same diversions that the prototype equipment did, or so the mass spectrometer builders would prefer us to believe. But their use is closely related to the development of several new ideas, each of which, within its own particular field, constitutes quite an adventure in extending the range of what it is possible or practicable to accomplish and unravel. An essentially simple application will be given first.

LEAK DETECTION

The simplest of all uses of the mass spectrometer is to detect the presence of particles of a single specified mass. A good example is the use of helium for the location of leaks in high-vacuum equipment, which is now sometimes of surprisingly large volume. The concentration of helium in the atmosphere is very low, and only minute amounts are present normally in the gases pumped out of equipment that is being evacuated. Now if a piece of equipment leaks and if some helium is introduced into it, the gas outside soon contains more helium than usual. Conversely, if the equipment is pumped out, placed in a vessel containing helium and pumping continued, helium appears in the gases that are being removed. In either case detection of a small amount of helium in excess of the negligible quantity usually present establishes the presence of a leak. All that is necessary is to test for the presence of particles of mass 4. Only small amounts of material are needed, one part in 200,000 of helium can be detected, and the test can be made quickly. The mass spectrometer can even be set to ring an alarm bell when a leak has been found.

The early requirements of atomic energy contributed largely to the development of the mass spectrometer as a leak detector, a use that it now finds in many industrial processes where vacuum or hermetically sealed equipment is employed. Examples are the preservation of penicillin and of blood plasma by dehydration at very low pressures; the drying of many foods, also at low pressure; the testing of refrigerator trucks for gas tightness; and the making of the relatively new element, titan-

ium. Not only are leaks detected, their precise location may also be found by spraying each part of the surface in turn with a fine jet of helium gas. The gases pumped from within the system are passed into the mass spectrometer until it signals the detection of helium.

Sometimes an escape of gas is suspected in the neighbourhood of buried pipes. If there are several pipes near each other, it is important to know which is leaking. Helium may be introduced into each in turn at the pumping station, and the gases emerging from the ground in the region of the leak sampled in a mass spectrometer. As soon as helium is detected the leaky pipe may be identified, and sealed off.

In all applications of the type just described the element detected, helium, is used for the special purpose of testing for leaks. The same principle can be applied also to keep a continuous watch for the presence of any element that is dangerous or unwanted in any particular plant. An example is the monitoring of annealing furnaces for the presence of oxygen, which in the treatment of some metals must be kept within very low limits.

ISOTOPIC RATIOS

The next simplest use of the mass spectrometer is to measure the quantity of one isotope of an element compared with another — the isotopic ratio as it is called.

Age of Minerals

One such use has been in the determination of the time that has elapsed since different minerals were segregated in the crust of the earth. This method can be applied to rocks that contain a radioactive element. Suppose that a specimen of the U^{238} isotope of uranium was entrapped in a rock when this was laid down at a certain point in the earth's history. This uranium will ever since have been breaking down slowly and through successive stages into the lead isotope Pb^{206} . Provided that water has not seeped through the rock and dissolved out the minerals present, the total number of uranium atoms, plus lead atoms, will have remained constant after an initial period of around a

hundred thousand years. Provided that no lead was introduced into the rock along with the uranium when it was deposited, measuring the amount of uranium and lead present today will give a measure of the amount of uranium originally present. Knowing this, the amount of lead produced, and the rate of decay of U^{238} , the length of time can be calculated during which the uranium has been decaying, and hence the age of the mineral. It is possible, however, to do better than this. The uranium isotope U^{238} always occurs together with a smaller amount of the isotope U^{235} , which also decays to form a different lead isotope, Pb^{207} . These two lead isotopes are formed at different rates from their parent uranium isotopes, and by measuring with a mass spectrometer both the ratio of Pb^{206} to Pb^{207} and that of U^{238} to U^{235} , the age of the rock can be estimated with greater precision. There is also a further check from the existence of yet another lead isotope, Pb^{204} , which cannot be formed from the radioactive decay of any substance that could have been present in the rock. Hence, if Pb^{204} is looked for and found, the amount of lead that has always been present can be independently estimated. This is a necessary precaution if only the ratio of U^{238} to Pb^{206} has been measured – and serves in any case as a check.

Measurements of isotopic ratios have also been used to estimate the time at which the earth's crust solidified. It is assumed that when the surface was completely molten, constant mixing and diffusion produced a uniform distribution of the isotopes for every element. The lead that was deposited in minerals at the time when solidification occurred contained the isotopes Pb^{206} and Pb^{207} in a constant ratio, and the isotopes U^{238} and U^{235} in another definite ratio. The present-day relative proportions of U^{235} and U^{238} , which are more or less constant over the earth's surface, are related in a simple way to the original ratio of these species and their respective rates of decay. Many minerals were formed subsequently containing lead that had originated in part from these original lead deposits and in part produced by the radioactive decay of uranium and thorium in the locality. The time that had elapsed between the solidification

of the crust and the deposition of these later minerals determines the extent to which their isotopic composition differs from that of the original lead. By determining isotopic ratios with a mass spectrometer for a number of different minerals, this 'original' composition can be calculated, providing an estimate of the time between the solidification of the crust and the deposition of particular rocks. Independent estimates of the age of these minerals relative to the present day, based partly on the arguments of the previous paragraph, permit the time that has elapsed between solidification of the crust and the present to be calculated.

A further method of estimating age is based on the radioactive breakdown of the K^{40} isotope of potassium. This breaks down by two independent processes of decay, one leading to the Ca^{40} isotope of calcium, and the other to the A^{40} isotope of argon. Assuming the A^{40} of the atmosphere to have been derived solely from the decay of K^{40} , rough estimates have been made of the age of the present atmosphere of the earth.

Natural Enrichment

In all these examples, the isotopes measured have been formed as the result of radioactive decay. Differences have been found also in the isotopic ratios of certain elements – for example, oxygen, carbon, boron, and sulphur – according to the conditions of their occurrence. Such variations are unconnected with radioactivity. They can be explained in part as the result of physico-chemical processes which lead to a slight enrichment in one isotope compared with another, but in few cases, if any, are the causes of these natural variations yet completely understood. One of them offers a new indication of the course of climatic changes in past ages; there is a correlation between the temperature of sea-water and the ratio of oxygen isotopes found in carbonate deposited in shells at that temperature. Again, the proportion of the lighter isotopes of both carbon and sulphur appears to be higher in material of biological origin. It has been said that native sulphur formed by bacterial action can be distinguished in this way from deposits the origin of

which is volcanic; and that the earliest evidence of life on the earth may come from the isotopic ratios of carbon in rocks. Several new lines of research have thus been opened up by the mass spectrometer which are already of interest to geologists.

Forces between Molecules

A quite different application of isotope measurements is in connexion with the diffusion properties of gases. If two vessels of the same gas, say oxygen, are joined together, their contents will in time mix completely, part of the gas present originally in each vessel having diffused into the other. To distinguish between molecules originating from the two vessels, different isotopes may be used. Thus one vessel might be filled with oxygen gas the molecules of which contained equal numbers of normal oxygen atoms, O^{16} , and of O^{18} atoms, and the other with normal oxygen gas (O^{16}_2). Then, after the vessels are connected, the proportion in which the two isotopes are present can be measured at intervals, and the diffusion rate determined.

Now this rate is related to the forces between the molecules. As such, it is not only important in principle but has gained a special significance for the theoretical investigator from the greater facility of calculation provided by the advent of high-speed computers. These machines have brought the prediction of the mechanical properties of gases, using the equations of statistical mechanics, into the realms of possibility. Essentially, if the force between two molecules in a gas is known as a function of the distance between the molecules, all the static properties of the gas – that is, the law relating pressure, volume, and temperature (which for a perfect gas would be Boyle's law) – can be predicted, and the dynamic properties such as viscosity and diffusion rates calculated. It is possible to suggest a number of different forms for the equation describing the intermolecular force. Taking each of these in turn, the corresponding behaviour that might be expected for the gas may be calculated, and the equation corresponding most closely with experimental results assumed to be the best. Once a really good equation has been found, and checked for a number of gases, it will presumably be

safe to apply it to others for which the corresponding experiments have not been carried out. The information that such an equation could provide is needed, for example, in analysing the processes that occur in flames, some of which may never be amenable to direct experimental observation, although they are clearly of practical importance.

TRACER APPLICATIONS

As in these other applications, the use of stable isotopes as 'tracers' in biochemical research involves the measurement of an isotopic ratio. The ratio to be measured is here no longer a natural one, varied in whatever way by past conditions, but one deliberately altered for and during the experiment. The underlying principle is similar to that involved in labelling molecules with radioactive atoms. For example, if the fate of a particular ingredient of food in the body is to be found, a sample is prepared in which one of the atoms is replaced by an isotope that normally occurs in negligible amount. Then after feeding the ingredient to an animal, its tissues are examined in a mass spectrometer, to detect an abnormal concentration of this isotope. It is assumed that the tissue in which this is found represents the destination of the molecule in which it was incorporated originally. Radioactive isotopes can be detected simply by their activity using a Geiger counter. But non-radioactive isotopes, requiring the use of a mass spectrometer, are an extremely useful supplement or alternative. For one thing, there are no suitable radioactive isotopes of several important elements, notably nitrogen; for another, it is convenient at times to dispense with all the practical problems associated with the manipulation of radioactive material.

The most important outcome of this type of work has been in connexion with the dynamic equilibrium of the body. Materials which are present in the body in an amount that does not change from day to day are nevertheless constantly undergoing breakdown and reconstruction. This is true, in general, of proteins, of which the component units are amino-acids, as it is also of other substances in the body. In one experiment, an amino-acid

labelled with a particular nitrogen isotope was fed to rats. The rate at which it accumulated in the liver, and then disappeared when feeding was stopped, suggested that as much as ten per cent of the proteins there were rebuilt every day. The general impression from a very large number of experiments using tracer methods is of the widespread fluidity of the body's chemistry. There was talk at one time of a 'metabolic pool' of relatively simple components from which the more complex molecules were continually being built up, and to which their breakdown products were returned for use elsewhere in the body. The concept of a pool of materials common to the whole body, and equivalent in all types of use, has proved to be an over-simplification; but it remains a partial truth, and its critical examination and reappraisal is still in progress. In all this work, the ability to label nitrogen atoms and to follow their distribution is of key importance.

It is also important at times to know which part of a molecule breaks off during a metabolic process, or even in a test tube reaction. For example, if a molecule containing three carbon atoms in a row gives rise to another molecule in which just two carbon atoms are left, the question arises as to which terminal atom was detached. By replacing the atom at one end by the C^{13} isotope not normally present, and testing the product for C^{13} content in a mass spectrometer, an immediate answer is possible. Sometimes the situation becomes a little more complicated, the product of the isotopically labelled molecule becoming diluted with material from other sources in the body. Even then, track can be kept of the molecules whose precursors were introduced specially, by labelling isotopically a second atom, which is not affected by the metabolic cycle. Thus the molecule of the amino-acid serine $CH_2OH.NH_2.CH.COOH$ is converted in the rat into $CH_2NH_2.COOH$, which is glycine. The question arose whether the $COOH$ group of the glycine was the $COOH$ group of the serine, or whether it was derived from the CH_2OH group, as conceivably it might be. The answer was obtained by feeding a rat with serine in which both the $CHNH_2$ group and the $COOH$ group were separately labelled. The

nitrogen of the $CHNH_2$ group was N^{15} , and the carbon of the $COOH$ group was C^{13} , whereas the carbon of the CH_2OH group was the common C^{12} isotope. Strictly speaking, the nitrogen and the carbon used for labelling was 'enriched' in the isotopes mentioned, while the unlabelled carbon consisted of the natural mixture of isotopes; but this does not affect the principle of the experiment. Both the N^{14}/N^{15} ratio and the C^{13}/C^{12} ratio in the glycine were analysed in a mass spectrometer. The fraction of the molecules containing C^{13} was found to equal the fraction containing N^{15} . It was therefore inferred that these C^{13} atoms were in the same molecules as the N^{15} atoms, and therefore that it was the CH_2OH group which had been 'lost' during the metabolic reactions.

ISOTOPIC DILUTION

A rather spectacular application of isotope-ratio determinations is in the 'isotopic dilution' method for measuring minute concentrations of impurities in metals. The impurity – which for illustration may be magnesium – is assumed to have the same isotopic composition as has magnesium found in nature, that is to say, it consists predominantly of Mg^{24} . The principle of 'isotopic dilution' is then as follows. The original material, containing only a very small quantity of magnesium, is dissolved in solution, and to this the corresponding salt of the pure isotope Mg^{26} is added in fair concentration. The magnesium atoms of this salt will mix with those present as impurities, and they will travel together in whatever process of chemical separation may now be used. Finally their combined isotopic composition is found in a mass spectrometer. Very slight traces of one isotope can be measured in the presence of the other, and the amount of the original 'impurity magnesium' can then be calculated.

A case for the application of this method arose in connexion with the development of the transistor as an electronic device, roughly equivalent to a valve. For this purpose, it became necessary to prepare specimens of germanium in which the concentration of certain other metals was less than one part in ten million. Certain impurities can have a profound effect

on the electrical properties of the material when present in greater concentrations. In many cases the amount of impurity left in a sample is estimated from a comparison of the measured electrical properties with a theoretical limit derived from other experiments. The isotopic dilution method may provide a means not only for detecting such impurities but also for estimating their concentration.

A similar procedure has been usefully employed in protein analysis, and may find many further uses in organic chemistry. One important problem, with both practical and theoretical implications, is that of measuring the relative rates at which a molecule is attacked in different positions simultaneously by the same reagent, or the rates at which a reagent reacts with two different chemicals at the same time. Considerable difficulty is experienced in isolating the reaction products for analysis, and the method of isotope dilution might be used here to good advantage.

MOLECULAR FRAGMENTS

The mass spectrometer can also be used in purely chemical research to recognize the presence of a particular fragment of a molecule that is being disrupted, and hence can be employed further to determine the rate of disruption and even the work done in effecting it. Most experiments of this type have been done with organic-free radicals,* that is with uncharged fragments of organic molecules in which one atom has one of its valencies unsatisfied; they are therefore highly reactive groups. Such radicals may be produced by the high-temperature decomposition of hydrocarbons such as methane, CH_4 , which forms the methyl radical, CH_3 , or by the decomposition of organo-metallic compounds, such as lead tetraethyl (the original anti-knock material added to car fuel) which also produces methyl radicals. The material is decomposed in a furnace and part of it is allowed to enter the vessel *A* (referring back now to Figure

*These were discussed by George Porter in *Science News* 19 under the title 'Elusive Chemicals'.

1) via a small perforation in a metal diaphragm. Once in *A*, the radicals, say CH_3 , are bombarded with electrons, which tear out other electrons to form the corresponding radical ions, such as CH_3^+ , detectable as a particle of mass 15.

It is also possible, as already mentioned, to measure the work done in removing the electrons, that is, the ionization potential of the radicals.

The electrons used to bombard the particles in the vessel *A* derive their energy from an electric field through which they are first accelerated. When this field is very small, the bombarding electrons do not travel with sufficient momentum to remove other electrons from the radicals with which they collide. Ions corresponding in mass to these radicals are not then detected by the mass spectrometer. But when a particular accelerating potential is applied to the bombarding electrons, their momentum becomes just sufficient to ionize the radicals and a current is detected by the collector plate in the spectrometer.

A third type of experiment may be conducted in which entire molecules are fed into the vessel *A*, and are then bombarded with electrons that are travelling so rapidly that they can both tear out electrons and also break bonds joining carbon atoms to hydrogen atoms and to other carbon atoms. The hydrogen atom which is removed from a molecule of methane, when a CH_3 radical is formed from it, was previously held by a C-H bond to the carbon atom. So by measuring the 'appearance potential', that is the potential that must be applied to the bombarding electrons to make say the CH_3^+ radical ion appear in the mass spectrometer when methane is in *A*, the energy needed to break the C-H bond may be calculated.

Measurements such as these of the bond energies and ionization potentials of molecules are important in many directions. Examples are the 'cracking' of hydrocarbons, as is done in oil refineries to obtain increased yields of petrol, and in the study of flames and combustion, in which the formation of free radicals is involved. A recent variant is important in studying the breakdown of the gaseous insulators used in electrical engineering. Here the molecule ionized gains an extra electron instead

of losing one – that is a negative ion is formed. The gas commonly used as an insulator is sulphur hexafluoride, and the ion is accordingly SF_6^- .

The results of this type of experiment are also of considerable interest to the theoretical chemist, whose goal is the prediction of the properties of chemical systems simply from a specification of the numbers and types of their constituent atoms. This may sound rather a tall order, and in fact it is. An approach from first principles is, however, possible to this extent: that quantum mechanics provides a set of equations, which, if they could be solved, would permit of such predictions. Unfortunately, the equations are far too complicated for an exact solution to be possible. Instead, approximations must be used, and even with these it is necessary to use high-speed computers to get results of any real significance. In practice there are a host of different approximations that might be tried. To decide which is the best, a comparison with experimental results is necessary. It is not advisable to waste too much effort on test calculations, so that the comparison between theory and experiment is most profitably sought with the systems that are the least difficult to handle mathematically. It so happens that hydrocarbons and their radicals are especially suited to this purpose. One reason for this is the fact that many different fragments can be constructed out of just a few carbon and hydrogen atoms. These could all be handled on the computer with the same basic instructions and procedures. Since the 'programming' of calculations to be done by computers is lengthy and tedious, this is a very practical advantage.

FULL SPECTRUM ANALYSIS

In the applications of the mass spectrometer which have so far been described the actual measurements have been concerned with just one or two lines in the spectrum, and it has also been quite obvious which element or compound was producing the particles that were observed, and what these particles were. In some cases interest has been centred just on the amounts that were present of the substances producing these particles. At

times the problem has been explaining why these amounts were in fact present.

In the present section we are concerned with some problems that are rather more complicated, namely the observation and interpretation of a complete mass spectrum, usually derived from a mixture of substances. The spectrum of any single substance is quite characteristic, serving in effect as a finger-print that may be recognized. This is true not only of elements and simple molecules that give rise to spectra consisting of just a few lines, but also of larger molecules that break down into a dozen or more different fragments, and even of samples of paper or plastic or photographic film in which the nature of the fragments and their mode of origin is uncertain.

In dealing with the spectrum of a mixture there is a further difficulty that sometimes must be met. Suppose, for example, that we are dealing with half a dozen neighbouring elements, each with its own spectrum of isotopes; and, as is commonly the case, that there are overlaps between the mass-numbers of isotopes of one element and those of the next. Merely by looking at the results of measurement, we shall then be unable to distinguish by eye the spectrum corresponding with any one element. We shall find only a single composite spectrum. We must assume therefore that the spectra of the individual elements, if we could see them, would be as they usually are – that the isotopic ratios of each are normal. And the object will be to arrive, by trial and error or analysis, at the proportions in which each individual spectrum contributes to the whole. It is not a very serious problem in practice if dealing only with ions formed from atoms. For most of the elements there are only one or two isotopes that matter. It is more of a problem when dealing with ions formed from molecules which contain several atoms and which can break up in many ways into particles of different masses. But the problem can always be solved, and, while it was at one time a nuisance to deal with mixtures of a large number of constituents, the difficulty of interpreting such results has been removed by modern computing machines.

Equipments in which the full mass spectrum is recorded

simultaneously are not now very common. One was used recently, however, to analyse a mixture of rare earth atoms that had just been irradiated with neutrons. The different isotopes in the mixture were focused on to different positions of a photographic plate, where they stuck. This plate was then removed and another placed on top of it. Under the influence of the irradiation some of the isotopes had become radioactive and fogging occurred on the second plate immediately above the deposits of these isotopes. In this way it was possible to decide which rare earth atoms had become radioactive. The actual rate of decay of an isotope could also be measured by leaving the two plates in contact until a certain amount of fogging had occurred on the second, then replacing this by a third plate, and noting the time needed for this to fog to the same extent.

Full spectral analyses, however, are effected more usually with a scanning technique, sweeping through an appropriate range of strengths of the focusing magnetic or electric fields. The interpretation of this type of spectrum is simplest for alloys, since the mixture then is one of elements.

Simple molecules, too, such as occur in the atmosphere merely give rise to particles of just one or two different masses when they are bombarded in the ionizing vessel, and the amount of each ion usually can be related directly to the amount of one or other component of the gas mixture. For these simple gas mixtures, a fairly narrow range of masses is covered. The speed of analysis is often of importance. For routine work, analysing the gases in valves, the spectrum can be displayed on the screen of an oscilloscope. For use in sampling the gases of the upper atmosphere, compact mass spectrometers that can be packed into rockets, and which sweep the entire spectrum necessary in a second, have been described.

The gases expelled in human breath are also analysed rapidly by a mass spectrometer. With the advent of more and more instruments for the rapid measurement of physicochemical properties, medical diagnosis may soon involve the reading of many more dials and gauges than just the level of mercury in a thermometer.

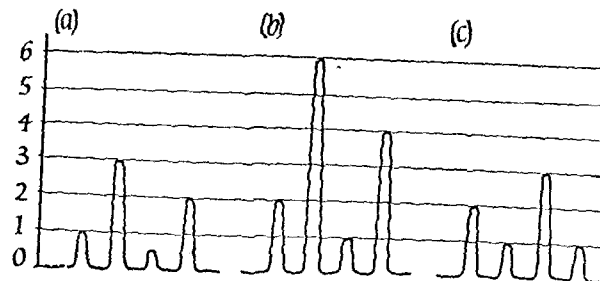


Fig. 3. (a) represents a portion of the mass spectrum of a substance *A* (which might be ethane) measured under standard experimental conditions, when .0001 gramme has been introduced into the mass spectrometer. (b) represents the same portion of the mass spectrum of the same substance *A*, measured under identical conditions, when .0002 gramme has been introduced. (c) represents the same portion of the mass spectrum of a second substance *B*, when .0001 gramme has been introduced.

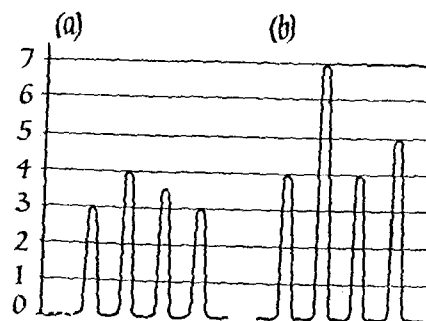


Fig. 4. (a) represents the mass spectrum of a mixture of .0001 gramme of substance *A* and .0001 gramme of substance *B*; the height of each peak is the sum of the heights of the corresponding peaks in Figures 4 (a) and (c). The curve on the right (b) represents the mass spectrum of a mixture of .0002 gramme of substance *A* and .0001 gramme of substance *B*; the heights of peaks are in this case the sum of those shown in Figure 4 (b) and (c).

But whilst there are almost limitless possibilities for the rapid and accurate analysis of gas mixtures, it is the analysis of hydrocarbons that has provided the mass spectrometer with one of its most widespread uses, and from the users' viewpoint one of the most remunerative. And just as the mass spectrometer has appeared at an opportune time for the theoretical chemist who wishes to avail himself of the modern computer, so calculating machines have been very welcome to the petroleum engineer using the mass spectrometer to control a refinery.

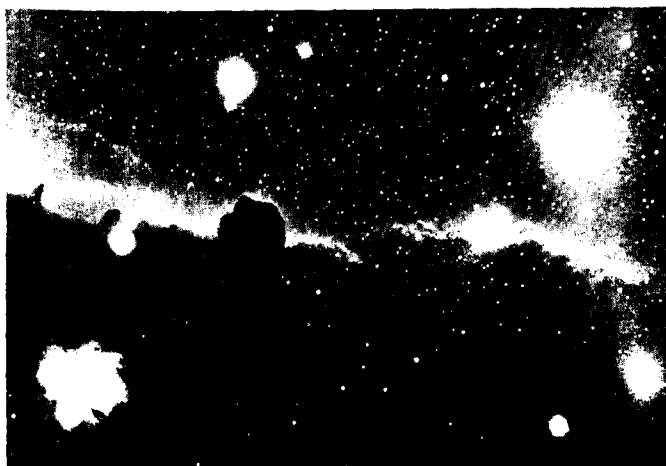
If a sample of a single hydrocarbon, say ethane, is introduced into the ionization chamber of a mass spectrometer, and bombarded with electrons, these will remove further electrons from the molecules, and will also break a number of bonds. A whole mixture of fragments will be formed, ethane, $C_2H_6^+$, for example giving different amounts of $C_2H_6^+$, $C_2H_5^+$, CH_3^+ , CH_2^{++} and so on. The relative amounts of these ions depend on the exact conditions of operation, and on the exact shape of the mass spectrometer. But if these are kept constant, the relative amounts of the products will remain constant, and so therefore will the shape of the spectrum. Its use as a finger-print has already been mentioned. Further, while the shape of the spectrum depends on the nature of the hydrocarbon, its exact height depends on the amount of the hydrocarbon that is present. For example, if .0001 gramme of ethane is introduced into the mass spectrometer, part of the spectrum recorded might look like Figure 3 (a), whilst if .0002 gramme of ethane were used, every peak would be doubled in height, as in Figure 3 (b).

If two hydrocarbons are present together in the mass spectrometer, the spectrum that is observed is simply the sum of the spectra that each would produce if present by itself. The shape of this spectrum depends, therefore, on the shapes of the spectra of the two hydrocarbons, and also on the amounts of each present. Suppose, for the sake of argument, that .0001 gramme of propane would produce the spectrum sketched in Figure 3 (c). Then the spectrum produced by a mixture of .0001 gramme of ethane and .0001 gramme of propane would be obtained by adding together the peak heights of Figures 3 (a) and 3 (c).

INTERSTELLAR MATERIAL



1. An extragalactic object: the Sombrero Nebula. The obscuring material is concentrated in a thin disk surrounding the central mass of stars.

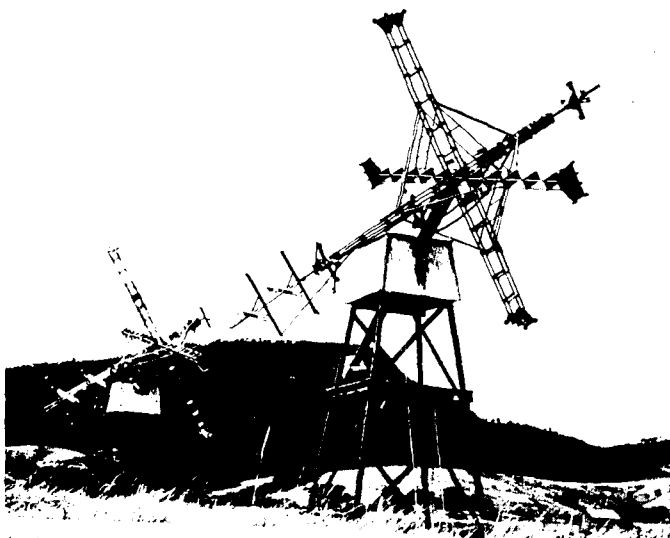


2. The Horsehead Nebula in Orion, a well-known dark cloud in interstellar space. (Photographs from Mount Wilson Observatory.)



3. A spiral and a globular nebula in Virgo. The spiral nebula contains much interstellar dust, has an irregular structure, and some very bright stars are found in it. (Mount Wilson Observatory.)

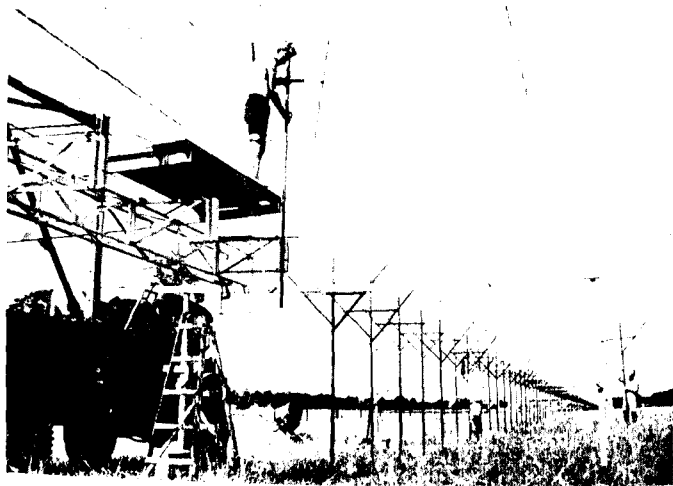
RESEARCH REPORT



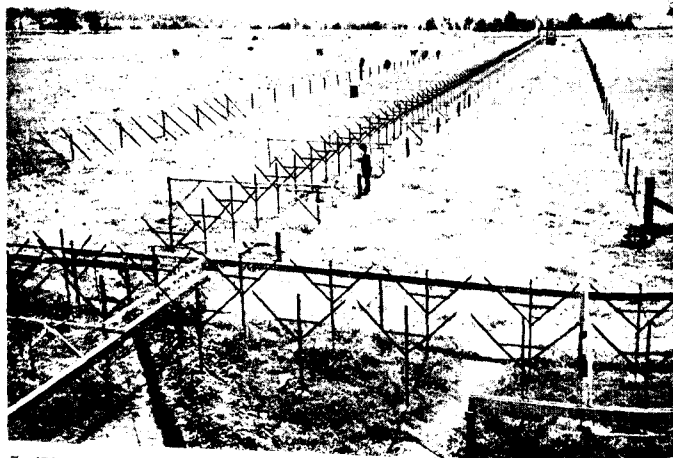
4. Aerial system of the ultra-short-wave radio spectrometer used at Dapto, New South Wales, to record the changing wavelengths of solar radio-emission during various types of outburst.



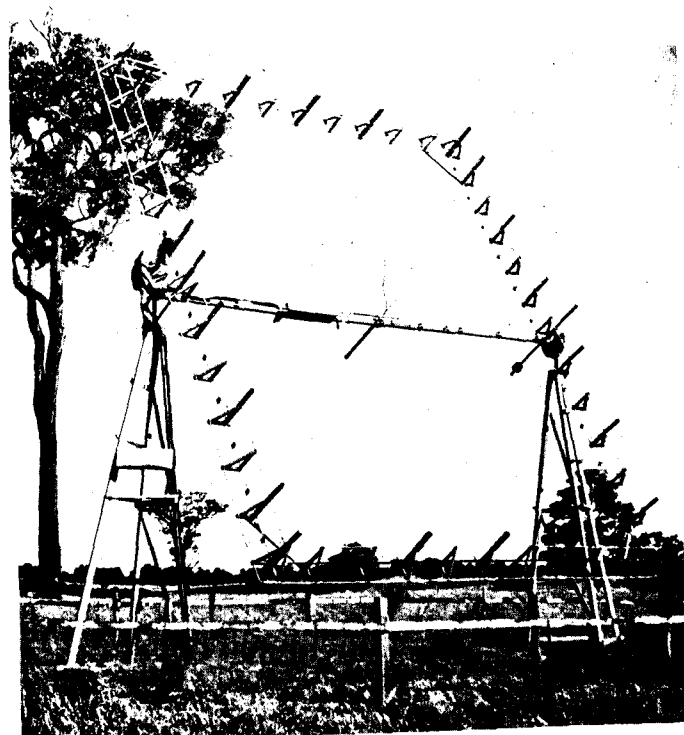
5. Detail of a new type of 'radio telescope' during installation at St Mary's, 30 miles from Sydney, New South Wales, for the Commonwealth Scientific and Industrial Research Organization. Two long thin arrays are arranged in the form of a cross (N-S and E-W). Either array separately has a fan-shaped beam of reception; from the two together an effectively pencil beam is obtained ($\frac{1}{4}$ beam width). The arrangement was designed by Mr B. Y. Mills.



6. One arm of the crossed aerial array shown in detail in Inset 5. The sides of each 'Y' are two dipoles (wavelength 3.5 metres); the length of the arrays is 1500 feet.



7. The centre of the crossed arrays; the direction of 'viewing' (in declination) is controlled by phase adjustment in the north-south arm.



8. Radio interferometer used in a survey of celestial radio-sources 'visible' from the southern hemisphere. (This and the preceding four photographs are by courtesy of the Australian News and Information Bureau.)

MILK OUT OF AFRICA



9. A bull of a dwarf tropical breed (the Muturu) of the coastal regions of Nigeria.



10. Tropical dry-zone cattle (White Fulani breed), Northern Rhodesia. (Author's photographs.)

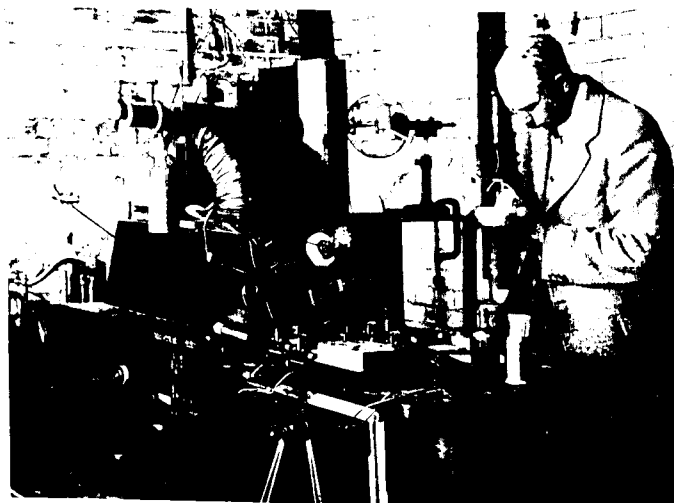


11. A cow of one of the most productive African breeds (Nandi) from Kenya. This cow has had 13 calves and has averaged 300 gallons of milk per lactation. (Kenya Information Office.)

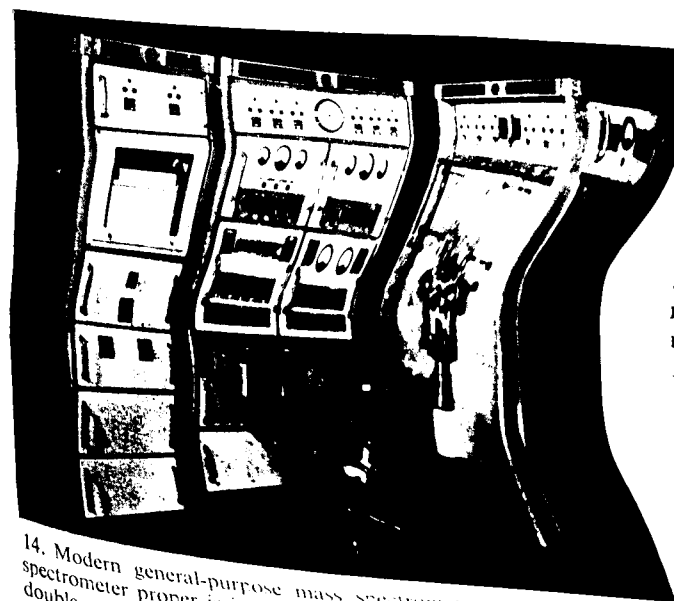


12. Contrast in size between a dry-zone white Fulani cow and a cow from the wetter coastal plains. (Crown copyright.)

USES OF MASS SPECTROMETERS



13. F. W. Aston with his second mass spectrograph (1927) and associated equipment. (By courtesy of the Department of Physics, University of Cambridge.)



14. Modern general-purpose mass spectrometer (Type MS2). The spectrometer proper is in the unit on the right. In front of this is a double gas-inlet system, which can be used in the accurate comparison of a given sample and standard. The control unit is in the middle, and the recorder on the left. (By courtesy of the Metropolitan-Vickers Electrical Company, Ltd.)



15. Apparatus used at the U.S. National Bureau of Standards in preparing vacuum-sealed, gas-free samples of 169 hydrocarbons of known high purity. Such samples are needed, among other purposes, in mass spectrometry to establish the spectra of individual compounds in isolation.

AUSTRALIAN PROTON SYNCHROTRON



16. A proton synchrotron, designed to accelerate protons to 10,000 million electron-volts energy, is being built in the Research School of Physical Sciences, the Australian National University, Canberra. The photograph shows a 136-inch magnet coil winding being lowered into position. (*Australian News and Information Bureau.*)

THE BOILING OF LIQUIDS



20. Nuclear boiling photographed in a glass tank filled with methyl alcohol; exposure-time, 1 microsecond. Running across the tank is a copper tube heated with steam. Bubbles of alcohol vapour form repeatedly at the same points on the surface of the tube.



21. Transition boiling occurs at temperatures higher than those which cause nuclear boiling. Slugs of alcohol vapour form explosively, and the surface of the tube is entirely blanketed with vapour. One slug of vapour surges away from the tube at lower right.



22. Film boiling occurs at temperatures higher again than those which cause transition boiling. The tube is surrounded by a transparent film of alcohol vapour. At the top of the tube the vapour has formed into a wavy 'rod', which is about to break into a row of bubbles.

That produced by a mixture of .0002 gramme of ethane and .0001 gramme of propane would, however, be obtained by adding together the peak heights of Figures 3 (b) and 3 (c). The spectra for these two mixtures are drawn in Figures 4 (a) and 4 (b) respectively.

The relative amounts of two hydrocarbons in a mixture can be calculated simply from the heights of two peaks in the spectrum. In fact the amount of each hydrocarbon is the sum of two terms, each term being the product of a peak height in the spectrum of the mixture with a number that is constant for the hydrocarbon and the apparatus. How these constants are found in detail does not matter here; both calibration experiments and calculations are needed to get them. But they need not be often determined.

The same principle can be used in the analysis of a mixture of twenty hydrocarbons. The observed spectrum is simply the result of superimposing twenty individual spectra each scaled according to the amount of the corresponding hydrocarbon present. The amount of each constituent is now found as the sum of twenty terms, each term being the product of an observed peak height with a suitable constant. (The same procedure can be used also for the analysis of composite spectra of other kinds, e.g. infra-red spectra, provided that the individual spectra of the pure components differ sufficiently; but it does not seem to have been adopted as extensively as it might.)

Developments in petroleum engineering necessitated the introduction of a rapid method of analysis for mixtures of hydrocarbons that were very similar chemically and physically, difficult and tedious to separate, and fairly inert as regards reactions. The mass spectrometer met this need, and used only small amounts of material, which is an added advantage. Its popularity in this field spread rapidly, despite the bulk of the associated computational work, and the apparatus was improved until a full spectrum could be recorded in twenty minutes. But the corresponding calculations became increasingly lengthy, as the number of components in the mixtures was increased. Calculating staffs began to swell, the time required

for computation becoming the factor determining the rate and cost of the operation as a whole. But then in the United States, and now in Great Britain, small digital computers, designed primarily for accounting work, were introduced to the field. These machines have altered completely the speed and economics of the process. For example, the entire calculation for a twelve component mixture can be effected on the most recent small computer in less than a minute. These calculating machines, some as small as a radiogram, are provided with the results of the mass spectrometer experiment, and the constants of the calculation, as patterns of holes on pieces of card that are sucked through electrical circuits. The results of the calculation are punched out as patterns of holes on other cards, from which printed reports may be prepared in a second small machine. Originally, the calculations were performed at odd intervals during the day on equipment used mainly for refinery accounts. The versatility of the machines is such that they can be switched from one type of problem to another in a matter of seconds. Since computing has been brought to the attention of the petroleum engineer, many other arithmetical problems have been found, for example in connexion with distillation practice. Now that the speed of calculation has been increased, the operation of the mass spectrometer itself is being speeded up, by improving the electronics associated with the measurement of the ion current.

To facilitate this type of work still further, special equipment has been designed and marketed that records the peak heights as a printed table on a sheet of paper, eliminating the operator needed previously to measure the peaks recorded graphically on the moving drum. This digitizing equipment that turns graph peaks into numbers could find many further uses in laboratories and industry. Still greater efficiency has been achieved by making the digitizer punch cards that can be fed straight to the computer which performs the mass spectrometric calculations.

The need for such speed in petroleum calculations springs partly from the manner of operation of refineries, with several streams of material of changing composition having constantly

to be blended according to complicated requirements that also fluctuate. Much has been achieved in streamlining these processes of analysis and computation and plant design, and the day of the fully automatic operation of a refinery seems to be drawing nearer and nearer.

CONCLUSION

In the story of the mass spectrometer there can be seen one of the sources of excitement in contemporary scientific research and also one of the major problems of science. Both are associated with the question of relevance. It is probably no exaggeration to say that developments in any one field of scientific activity may have repercussions on virtually any other branch of science. One development may provide a technique useful elsewhere, or it may be constructed by a subtle manoeuvre on the part of the experimentalist seeking to circumvent the technical obstacles that hinder progress in a particular practical problem. Whenever some elaborate cross linking of subjects is announced, one is left wondering how many other problems baffling workers at the time might not be resolved similarly. There is no way of knowing. The scientist developing an experimental technique cannot anticipate all its possible applications; its utility in some particular situation may be apparent only to someone familiar with all the intricate technical details of the latter. The review article that presents a picture of what a technique can do assists; but the sheer bulk of current research, the bulk of the review literature itself, leave the possibility of serious oversights by experimentalists snowed under by immediate practical problems. And the unexpected gambit is still dependent on the individual with insight and a particular turn of mind being involved in the situation at the appropriate time.

The story has been presented, with several necessary omissions, in an effort to demonstrate the versatility of the mass spectrometer, a versatility that may be enhanced by the production of equipment to be used interchangeably for experiments of different types within the same laboratory. By presenting the different

applications with equal weight the historical development of the equipment's use has perhaps been lost, a history linked inseparably with the needs of commerce and industry.

In fact the tale of the mass spectrometer follows a cycle that is being repeated over and over again, a theme resurgent in the physico-chemical sciences today. First an apparatus is constructed to confirm that matter really does behave in a manner corresponding to some particular implication of the model that has been constructed for it. Then, at a certain juncture, the same basic principle is incorporated into an equipment needed to meet a pressing technical requirement. The relevance to the problem may have been known for a long time but never exploited owing to inertia and concern for its economic practicability. Then the exigencies of a particular situation make cost irrelevant, the development of a working tool to do a particular job being all that matters. Science finds itself with an equipment being produced in numbers that permit of economical manufacture. Availability breeds applications. The concentration of effort on further development becomes advantageous to the companies producing the apparatus, improvements ensue, specialized variants for particular uses are created. The machine becomes topical, its use more widespread, perhaps it even reaches that mysterious point at which its presence is a necessity in any laboratory with a claim to being up to date. Topicality brings with it the backwash of associated academic problems, most of which have been gathering dust on university shelves and apparatus for many years owing to a lack of external interest and support. Then, to make use of the results that the equipment provides, further auxiliary apparatus is designed. This in turn finds other uses. Viewed in retrospect, it can be seen that the basic equipment merely provided the situation justifying development of auxiliary equipment of much more general use, overcoming the next generation of inertia. As time goes on the basic equipment, perhaps our mass spectrometer, becomes embedded deeper and deeper in a network of apparatus and operational procedures. The final stage may well be the discovery of a new principle, its development and incorporation

into an apparatus displacing the mass spectrometer from some of its applications, doing jobs that would not have been thought of if the mass spectrometer had not been there to do them first. Perspective in design and development will gradually change, a new research medium will develop, and the cycle repeated.

FURTHER READING

An excellent monograph, of which considerable use has been made in the earlier sections of this article, is:

Barnard, G. P. *Modern Mass Spectroscopy*. London, The Institute of Physics, 1953.

Other general references are:

Robertson, A. J. B. *Mass Spectroscopy*. London, Methuen, 1954.
Mayne, K. I. 'Mass Spectroscopy'. *Reports on Progress in Physics*, **15**, 24 (1952).

Hipple, J. A. 'Applications of the Mass Spectrometer'. *Frontiers in Chemistry*, **7**, 183. New York, Interscience Publishers, Inc., 1953.

Wilson, D. Wright and others. *Preparation and Measurement of Isotopic Tracers*. Ann Arbor, Michigan, J. W. Edwards, 1947.

Reviews of mass spectrometry by Hipple and others are published yearly in *Analytical Chemistry*. A conference on applied mass spectrometry was organized by the Institute of Petroleum in October 1953, and its proceedings are due for publication towards the end of the present year.

BIOLOGICAL INDIVIDUALITY

G. M. WYBURN

THE beginner in biology might well be surprised to find there is no diversity of size and structure of the germ cells to parallel the manifold patterns of the adult animal form. The qualitative and quantitative differences between the germ cells of different individuals which must exist and be responsible for the direction of growth and development do not confer on the germ cells any specific structural identity which can be made directly visible by the methods at present available. There are, of course, certain variations in the size and form of the germ cells of animal species, but there is no overt manifestation of the individuality of any one germ cell.

Size, shape and external form, i.e. macroscopic features, give individuality and identity to the adult animal, but the separate parts of the organism have the characteristic (microscopic) structure common to similar functional units in other organisms; for example, the periodic banding of the muscle fibre, the typical appearance of a mucous secreting gland, a kidney tubule, or nerve cell (Figure 1). These cannot by observation alone be identified with any one individual or even species. The organs and tissues have acquired by differentiation a structural and functional individuality, but this is superimposed on the individuality of the organism as a whole and they carry the stamp of the organism of which they form a part. Most mammalian tissues and organs can only survive and be physiologically active within the parent organism.

Biologically, individuality is thus not a simple quality but a mosaic of qualities which indicate the species, the single organism of that species, and marks the differentiated functional components of that organism. The problem is to define the structural basis of this complex.

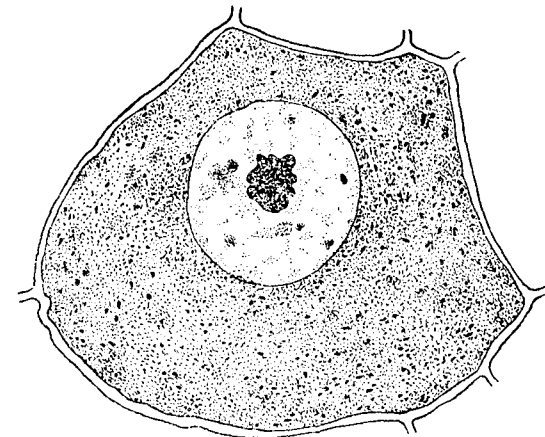


Fig. 1. Typical nerve cell from the spinal ganglion of any vertebrate animal, showing granular cytoplasm, central nucleus with well-marked nuclear membrane, nucleolus and flakes of heterochromatin, but no visible evidence of chromosomes. (Magnification $\times$ about 2,500.)

Orthodox biology accepts the chromatin of the cell nucleus as the substance which determines individuality. The male and female germ cells contribute equal amounts of chromatin to the nucleus of the fertilized egg, and this chromatin serves as a model or template for the synthesis of the further quantities of identical chromatin substance necessary for growth and development. Typically, chromatin is present in dividing cells (normal or mitotic division) as minute paired, rod-like structures – the chromosomes. The number and form of the chromosomes, that is, the amount of chromatin in the cells, is constant for the individuals of any one species. (There are exceptions.) Structurally, chromosomes consist of a number of tightly coiled threads – chromonemata – embedded in a matrix. There is a transverse banding along the length of the chromosome. These transverse bands are the chromomeres – the locus of the hereditary units, the genes, which are regarded as the self-replicating particles responsible for the transmission of inherited characteristics.

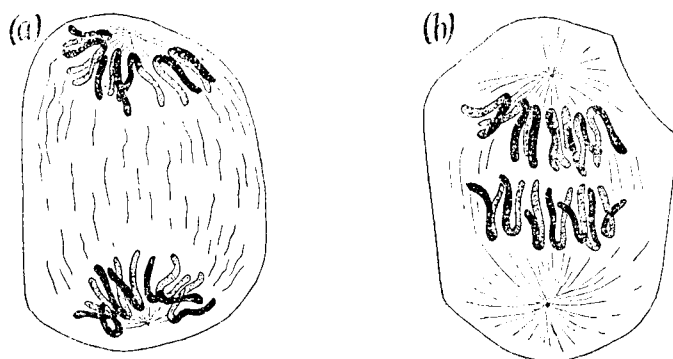


Fig. 2 (a) and (b). Stages in the mitotic division of a cell. The nucleus has resolved into paired chromosomes.

Genetically the chromosome is considered as an orderly linear array of these genes, and each gene or group of genes is believed to control a particular set of characters, for example, height, colour of hair, eyes, etc., and thus collectively confer individuality.

During mitotic division of a cell, each chromosome splits longitudinally, and presumably the genes also split so that each daughter cell receives half the hereditary substance quantitatively and qualitatively (Figure 2). The daughter chromosomes, therefore, bring to the new cell only half the chromatin material of the parent cell, and it will be the task of the new nucleus to restore the amount of chromatin to normal. This would imply that each genetic unit would be responsible for the synthesis of its own specific substance, and a corollary of the concept of the gene is self-replication, each gene acting as a template for the synthesis and reproduction of its own substance and thus able to perpetuate hereditary material.

When the cell is not dividing – the interphase – which is the condition of the cell during most of its life, the substance of the chromosomes form the nucleus of the cell and they themselves persist as uncoiled threads or chromonemata, not normally

visible in the 'fixed' cell, but presumably still carrying the genes.*

Certain parts of the chromosomes remain 'undissolved' and are present in the nucleus as dark granules of heterochromatin.

Of particular interest in this connexion is the heterochromatin of the sex chromosomes. This pair of chromosomes is concerned with the determination of the sex of the individual and it has recently been shown that there is a small circular heterochromatic body in the nucleus of the female somatic cell which is absent from the male somatic cell.

THE CONCEPT OF THE GENE

It is established that the substance of the chromosomes determines the properties which give biological individuality, and that there are specific areas in the chromosomes correlated with specific characteristics. The question arises, are these areas functionally independent, self-replicating units? The evidence for the existence of such units or genes is mainly the result of genetical experiments or observations with regard to the correlation between a change in the structure or function of an organism on the one hand and, on the other, some alteration in a particular region of a chromosome.

The gene is a genetical concept, and although it is customary to refer to the chromomeres as the locus of the gene (Figure 3), there is no direct cytological evidence which would justify a statement of the precise physical relationship between them. The identity of the gene in the 'interphase' chromosome is even more ambiguous. Whether the nucleus is regarded as distended chromosomes, as has been suggested, or it is accepted that the chromosomes are represented in the non-dividing nucleus by the chromonemata, there has been a quantitative change from the chromosomes at division, involving some dispersal of their substance. It is known, for example, that the actual protein mass of the nucleus is much greater than the total amount in the chromosomes. The nucleus, therefore, is something more in terms of volume and mass than the fused chromosomes. If the

*The exception is, of course, the giant salivary gland chromosomes of *Drosophila*, visible throughout the interphase.

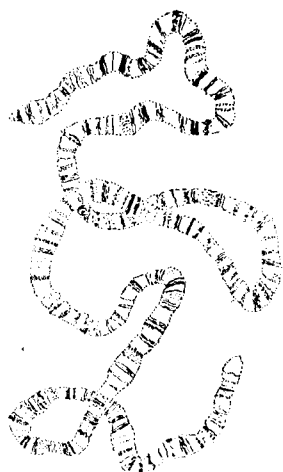


Fig. 3. A chromosome showing characteristic banding. The bands or chromomeres are said to be the loci of the genes. Although the size of a gene has been determined indirectly by experiment, it cannot be shown on the chromosome as a structural entity.

genes are material in nature, and occupy space, then any change in the chromosomes of which they form a part must also affect both their substance and their immediate environment. The gene, therefore, still awaits the final award of full status as a morphological entity.

Functionally, the claim of the genes to act as independent units is not altogether beyond dispute. There is the argument for an integrated condition of the chromosomes in function, that the areas on the chromosome correlated with specific activities owe their effect in part to their position on the chromosome – the so-called position effect. There are, for example, certain regions of the chromosomes that are distinctive chemically – the heterochromatic regions, which seem to influence adjacent areas, and so exert an integrative function. The position effect does not, of course, invalidate the concept of the gene, but suggests there is some mechanism for controlling and organizing its activities.

CHEMISTRY OF THE CHROMOSOMES

The chromosomes are largely made up of nucleoprotein, one of the protein carbohydrate complexes found in biological systems. Nucleoproteins are formed by a salt-like union of a nucleic acid and a basic protein such as protamine or histone.* The nucleic acids are built up from nucleotides – units which yield on analysis nitrogenous bases (pyrimidines or purines), a pentose sugar and a phosphate radical. The two chief types of nucleic acid are ribonucleic acid (RNA) and deoxyribonucleic acid (DNA), which differ in the nature of the sugar radical. DNA is the chief nucleic acid of the chromosomes and, as such, can advance a claim to be the chemical basis of hereditary substance. The number and form of the chromosomes is the same in the individuals of any one species. If, however, the genes are responsible not only for species characters, but also for the specific characters of individual members of the species, there must be differences in the nature of the hereditary substance, which, if they cannot be observed cytologically, exist at molecular level. To satisfy the concept of gene specificity, DNA would therefore require to have an infinite range of possible molecular arrangements, not only with respect to the various species, but also with respect to the different chromosomes and genes of each individual. The large molecular weight (10^6) makes it possible to have innumerable molecular configurations, more than sufficient to provide one for each gene or group of genes. Recent work suggests that the DNA molecule is made up of two backbone chains, coiled round a common axis, each chain consisting of alternating sugar and phosphate groups.† The two chains in this construction are held together by connecting horizontal rods, representing pairs of bases, one from each chain (a purine and a pyrimidine), united by a hydrogen bond. (Figure 4.) There are four bases and innumerable possible sequences of base linkages

*See article, 'The Chemistry of Cells and Chromosomes', by D. L. Woodhouse and H. S. A. Sherratt in *Science News* 24.

†A note on this work was given in *Science News* 29, 109-12.

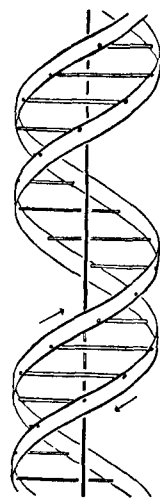


Fig. 4. Model of the structure of a DNA molecule as suggested by Watson and Crick. The horizontal connecting rods represent nucleotide bases joined together by hydrogen bonds. In theory, the nature of the base linkages can vary in the different connecting rods and the possible sequences, that is the relative position of these different types of base linkages throughout the structure provides a potentially infinite number of isomers.

provide an infinite number of permutations and thus the range of isomers necessary for gene specificity. It is contended that such a structure would also be a 'model' mechanism for self-duplication of the genes, for example, prior to duplication the chains would separate, and the pattern of bases in each chain would act as a template for the formation of the complementary chain necessary to restore pairing.

In this connexion, an impressive demonstration of the specificity of DNA in cell types is given by the differential deposition of carbon from Formate, labelled with carbon-14 and administered by injection. Not only is there a different distribution of tracer in the DNA of different organs, but there is

also a characteristic up-take pattern for any one tissue. The possibility of the existence of specific building-up patterns for nucleic acid by particular cell types has suggested the idea that a change in cell individuality, for example, from a healthy cell to a cancer cell, may involve different requirements for the building blocks of its nucleic acid. This might be a profitable approach to the chemotherapeutic treatment of malignant disease.

The relative stability of the gene would be difficult to account for in any multimolecular system, but if each genetic unit is regarded as a single molecule, say of DNA, then the intramolecular forces would be sufficient to maintain structural integrity.

Recent work all converges on DNA as the principal constituent of other known particles which wholly or in part act as genetic determinants, e.g. viruses and cytoplasmic plasmagones. Moreover, it is now well established that a more or less pure extract of DNA prepared from one strain of bacteria (say a type A pneumococcus) can transform another strain (say a type B pneumococcus) into the type A pneumococcus with regard to immunological reactions. This is a pragmatic classification, based on the degree of relationship found in respect of experimentally developed resistance, that is, in interaction between the surface of the bacterium and antibodies developed by the animal in response to another strain of bacteria. There has been a change at least in the surface of the bacterium – beyond this we cannot say – and this change is transmitted to subsequent generations of the treated type B pneumococcus. These so-called bacterial transforming agents, i.e. DNA, thus act as genetic determinants.

Although the idea that single molecules of DNA function as self-replicating units, each responsible for a block of characters, is intriguing and has considerable indirect evidence to support it, there is always the temptation, inspired by the symbolic terms of the geneticist, to construct models as an aid to imagination and to create a picture of molecules of DNA strung out along the chromosomes, each independent unit coming forth

like a metabolic marionette to preside over a circumscribed phase of cell activity; such a model is probably quite remote from what actually happens.

There is as yet but an imperfect understanding of the manner of functioning of the genes in time and space, and a number of very obvious questions have not even acquired an apocalyptic answer. For example, what is the significance of the organization of hereditary substance into the characteristic chromosomes of mitotic division – a phenomenon which is widespread throughout the animal kingdom, and is known to occur even in the reproduction of bacteria. Quite obviously it is a fundamental process representing something more than a mere mechanical device to ensure equal partition of genetic substance.

The development of five-fingered and five-toed appendages in the individual human being is perpetuated by the hereditary mechanism inherent in the chromosomes, and presumably present in all body cells. Only certain cells, e.g. those of the tissues of the limb bud, can be directly interested in the formation of fingers and toes, and it is difficult to conceive that a liver cell, although it possesses the necessary genes, would be concerned in any way in the establishment of the digital formula. Again, the genes which determine the blood group of an individual some time before birth, are also present in the nuclei of the nerve cells of the brain, cells which have specialized in the reception and transmission of stimuli.

If there are specific units for specific tasks, then it must be concluded that of the many thousands of genes in each cell nucleus of an organism, only a select group are active at any one time or place. For instance, in some insects certain embryonic tissues – the 'imaginal discs' – are set aside, i.e. are genetically determined to form part of the adult insect. They lie dormant, i.e. the genes remain inactive, until triggered off by hormones at the pupal stage.

The immediate activity of the hereditary units is probably conditioned by molecular and intramolecular organization and, as a result of this conditioning, the genes directly or indirectly control enzyme production within the cell and, therefore,

cellular metabolism as a whole. There must in addition, however, be some integration of the total genetic activity of an organism directed towards the common purpose of achieving its final form and size and the relative proportion of its several parts.

At present it can be stated with regard to nuclear chromatin that its chemical basis – the nucleoproteins – particularly those containing DNA, are entitled to consideration in any discussion of the 'stuff of inheritance', and genetical experiments favour the conception of hereditary material parcelled out in discrete units, each capable of a measure of independent action. The total endowment of these discrete units or genes confers identity on the organism as an individual member of a particular species.

Preoccupation with established genetical theory has focused attention on the nucleus as the arbiter of biological individuality and there has been a tendency to hand over to the genes complete responsibility for heredity and specificity. However, there is more in a cell than the nucleus, and recently it has become increasingly clear that the remaining cell content, the cytoplasm, has some claim to consideration in this respect, and should not be regarded as subservient to the nucleus at all times and in all places.

Experimental work on unicellular organisms, where reproduction in its simplest form is a binary fission of parent cell into two daughter cells without the segregation of a germ cell, has disclosed a number of examples of the influence of the cytoplasm on inherited characteristics.

When, for instance, baker's yeast is cultured or 'plated' in a nutrient medium, each yeast cell in the course of a few days forms a colony by a process of budding, whereby the bud receives half of the genetic substance of the nucleus, but only a small segment of cytoplasm. The majority of the colonies are of the same size but amongst them are always a few small colonies. The small colonies are a result of a decreased rate of budding, due to the loss of two respiratory enzymes. It is known that the synthesis of these enzymes requires the presence of a cytoplasmic factor in the form of self-replicating particles or

'plasmagenes'. These particles have a random distribution throughout the cytoplasm, and obviously may now and then be absent from the small cytoplasmic contribution to a bud. On such occasions small colonies are formed.

Another example of cytoplasmic influence on cell 'individuality' is found in the unicellular organism – paramecium. One strain of *Paramecium* – the 'killer' strain – can produce a toxin which destroys another strain – the 'sensitive' strain. The 'killer' character requires the presence of self-replicating Kappa particles in the cytoplasm as well as a special gene in the nucleus. The gene itself cannot initiate the production of the Kappa particles, but is necessary for their maintenance.

There are numerous other examples of the so-called 'cytoplasmic inheritance', and probably as more knowledge accumulates about the inter-relationship of nucleus and cytoplasm, and the manner in which replicating particles such as genes and plasmagenes determine the characteristics of the cell as an integrated unit, the geneticist will come to regard the cell as something more than the playground of the genes.

The problem of nucleo-cytoplasmic relations is again prominent in any consideration of development and cell differentiation in multicellular organisms. The single fertilized cell divides to form cell groups which differentiate and specialize in structure and function to produce the various tissues and organs. Thereafter, the differentiated cell reproduces only its own cell type and thus establishes a cell lineage. The problem of cell differentiation is not a simple one and involves consideration of variations in the structure of the nuclei, changes in the cytoplasm and temporal and spatial factors acting on both nucleus and cytoplasm.

The early developmental processes common to most animals are not concerned with the formation of organs and tissues, but their purpose is to produce the basic plan which defines the form of the embryo and therefore the type of adult organism. These early changes and arrangements would seem to be determined by the organization within the cytoplasm of the fertilized egg to which the male makes a relatively insignificant contribution.

The cytoplasm of the egg is, in the first place, of course, conditioned by the maternal genes, and already before it is fertilized there is cytoplasmic polarity and an inherent molecular organization. For example, there is a graded distribution within the cytoplasm of RNA granules; proteins with SH groups, which make for fibre-like structures; and an enzyme, alkaline phosphatase, which may be associated with the phosphate component of RNA. That the nucleus has little or no influence on the course of events at this stage is confirmed by the results of experimental transplantation of nuclei. In the earlier phases of embryonic development, up to and including the appearance of a two-layered arrangement of cells, the nuclei are still undifferentiated and, if transferred to enucleated eggs, a high proportion of these eggs will segment and develop normally.

Cellular differentiation with the formation of specialized tissues and organs follows this early planning phase and, at this time, there is evidence of commencing nuclear activity indicated by an increase in volume and the appearance of nucleoli denoting nuclear protein synthesis. Cells without a nucleus do not differentiate.

Solely on the basis of quantitative estimations of DNA it is often maintained that nuclei are genetically equivalent, and hence that the more specialized cells, which do not divide, are identical genetically, although they clearly differ in function. Until, however, chemical methods are developed which can detect qualitative differences in the hereditary fraction of nuclear substance within the same organism, and it is possible to correlate the physiological activity with the biological properties of the nucleoproteins, it is reasonable to assume that there cannot be equal activity all the time of all the genes in every cell nucleus of an embryo, and to postulate a selective action of the genes conditioned during the early stages by cytoplasmic differences. There is cytological evidence of nuclear differentiation during the differentiation of organs. There is, for example, the large vesicular nucleus, rich in protein, of such synthetically active tissues as glandular cells and the cells from which ova will later be produced; and, in contrast, the small

nuclei, poor in protein, of cells with a low metabolism. Again in the developing nerve cell, growth of nerve processes, accumulation of cytoplasmic RNA (Nissl's substance) and evidence of function in the form of spontaneous electrical activity coincides with an increase in nuclear volume and, in one part of the nucleus, an appearance associated with a rapid turn-over of RNA.

Throughout cell differentiation, there is always the 'critical' mitotic division when the two daughter cells separate and go their several ways, e.g. the embryonic cells that line the primitive neural tube have a critical mitosis when one daughter cell develops into a nerve cell capable of the reception and transmission of stimuli and the other becomes a supporting cell. Similarly a critical mitosis produces on the one hand the female germ cell, and on the other its attendant nurse cells. Cytologically, a critical mitosis may be indicated by an unequal division of the cytoplasm with subsequent effect on nuclear activity, or there may be an asymmetry of the mitotic mechanism itself, or perhaps differentiation is influenced by the relative orientation of the daughter cells. Duplication of chromosomes without separation of the daughter chromosomes is known to occur in certain tissues. More subtle changes within the chromosomes which escape detection by present techniques may also occur, such as an unequal multiplication rate of various chromosome regions, or rearrangements which will be reflected in position effects. Cytological and cytochemical evidence, for example, points to the importance of the heterochromatic regions in the general metabolism of chromosomes, and the transposition of any part of a chromosome to a 'heterochromatic' region might well impose some modifications on the specific activity of the part transposed.

Cellular diversity in multicellular organisms is thus not the prerogative of nucleus or cytoplasm but the result of inter-relations between them. All parts of the cell contribute to the development of its individuality.

An elegant and convincing demonstration of the individuality of tissues and organs has been given by the use of radioactive

tracers. If an animal of species *A* is injected with homogenates of organs, for example kidney, from an animal of species *B*, the serum of the host animal (anti-sera *A*) will, after an interval, contain an antibody capable of destroying the kidney tissue of animal *B*. This antibody can be separated and labelled with radioactive iodine. When injected into animal *B*, the labelled antibody can be localized and is found in greatest concentration in the tissue against which it has been prepared, in this case, the kidney. This type of reaction broadly resembles the immune response to infection where the causal bacteria act as 'antigens' and elicit specific 'antibody' formation by the host. Here the antigens may be bacterial toxins or some particular structure, such as the capsular polysaccharides of the pneumococcus.

With tissues and organs the precise nature of the antigen, or individuality factor, is less easy to define. The specificity of antigens resides in the chemical structure of the molecules, and most good antigens are proteins. The specificity of protein depends on the combination and arrangement of amino-acids in the polypeptide chains. Other chemical groupings, such as side chains or conjugate combines, may also provide specific determinants. While it is unlikely that all the varieties of protein found in any one tissue or organ act as separate antigens and produce their own specific antibodies, the individuality of a tissue is not a single factor based on any one particular chemical pattern. It is known that radioactive antibodies are not rigidly specific for the tissue or organ against which they have been prepared, and small amounts of the anti-kidney antibodies may, on injection, be localized in other tissues such as liver or lung, although less concentrated there than in the kidney. This is probably due to the formation of antibodies of different specificity from several different antigens in the injected homogenates, some of which are presumably common to other tissues, hence the cross reaction. There is also evidence that single antigens may produce a number of antibodies so that some substance in another organ similar to, but not identical in structure with, the homologous antigen, may combine strongly with some of the antibodies and not with others. Animal tissue has

probably a 'mosaic' of antigens which produce a complex of antibodies representing a type of tissue or organ, the individual organism of which it forms a part, and the species to which the organism belongs.

It is now recognized that a number of diseases (for example, certain types of nephritis, vascular disease and rheumatism) may be due to the evoking of the same defence mechanism by the tissues themselves. In such cases, following infection or other abnormal conditions, a tissue becomes antigenic and provokes specific antibody formation for its own destruction. It is of interest that the antigenic pattern of tissue is not present in foetal mammals or chick embryos, and only develops strongly after birth.

Considered from the view-point of heredity, differentiation, and serological reaction, the physical basis of biological individuality would appear to reside in the cell as a unit, not as a special assignment of a particular cell component, but in the summation and interaction of the activity of its several parts. It is, in other words, a property of what has been called the molecular ecology of the cell. Doubtless in the distant future the physical chemists will be able to provide molecular maps of different cell types and give a visual demonstration of individuality differences in terms of chemical structure. To approach reality, this would require to be a shifting scene and not a static pattern. Even so, there will remain the major problem, the control and integration of cellular activity to achieve the individuality of the organism as a whole, and the still more formidable difficulty, the anthropomorphic interpretation – in what way can geometrical arrangements of molecules and atoms be translated into those abstract qualities which give the individual flavour to human personality?

INSECT PIGMENTS AND COLORATION

B. NICKERSON

THE appeal of colour to man is well known and was probably a major stimulus for the development of his aesthetic tastes. Primitive man, having an economic interest in insects, could hardly fail to be aware of the diversity of colour and pattern in the insect world. Some of the earliest scientific literature is devoted to descriptions of insect colour patterns, and similar articles continue to appear in the various journals of today. An understanding of the significance of colour attracted many early workers to this field of research: Redi, in the seventeenth century, suggested that colour as well as behaviour could affect the survival of an insect species. The advent of the Darwinian theory of natural selection added further impetus to such descriptive work, for so many examples of adaptation to the fight for survival could be found among insects. Wallace described the brilliant colours displayed by many distasteful insects which he believed acted as a warning to potential predators (aposematic coloration), and the camouflage colours which allowed the insect to merge with its background, and were hence described as cryptic coloration, provided further examples of the utility of colour to insects. Extensions of these terms were introduced by Bates in his theory of mimetic coloration. He supposed that an unprotected insect mimics the coloration of a well-protected species, thus developing false warning colours or pseudoaposematic coloration. Müller showed that a number of butterfly species, all possessing aposematic coloration, often tend to resemble one another, thus making their warning, or synaposematic coloration, more easily recognized.

From interest in the value of colour for survival it was natural

to pass to the origin of the colours themselves. The most obvious case, and the one first recognized, is that of colour caused by pigments or biochromes. The pigment extracted from female cochineal insects was already an article of commerce in Mexico when the Spanish arrived there, but it was not until 1920 that its chemical formula was established. It is not, in fact, a very typical insect pigment; however, the delay which took place is a fair indication of the dependence of research in this field on progress in chemical knowledge. In the same way the recognition of colour caused by the physical structure of the cuticle depended on recognition of the wave nature of light and, in particular, on the phenomenon of interference between waves reflected or scattered from closely separated surfaces. Thomas Young, who first established the principle of interference, included in his account, given in 1802, a corollary which he headed 'Of the Colours of Striated Surfaces'. Both systems of coloration play some part in the final colour scheme of many insects, and some of the most beautiful effects are due to their occurrence in combination; but it is with coloration caused by pigments that this article is primarily concerned.

Studies of the chemical constitution of insect pigments have shown that they belong to widely divergent groups, but on the whole are highly complex molecules. There is to some extent a divergence of interest between chemist and biologist. The interest of the chemist is in the structure of the molecules as such, in their relation to other known substances, and in his ability to make them from simpler materials. Work of this kind is laborious and time-consuming, though now less so than formerly because of the greater ease with which small quantities of unknown substances can be separated and distinguished. Also, an insect is not an ideally convenient source of material, and the interest of the chemist is necessarily centred on the most productive source of the substance he wishes to study. Only a minority of insect pigments have been fully examined; many are still at the stage when only such simple properties as solubility and general stability have been used in classification.

Biologists, on the other hand, are more interested in the origin

of the pigments and their integration to give the final coloration. When confronted with the origin of the pigments the biologist is faced with two alternatives: are they ingested with the food and little changed within the body, or are they synthesized from simple substances within the metabolic cycle of the insect? Those in the first category, the exogenous pigments, are on the whole of less interest biologically, apart from identifying the source of the material in the food eaten by the insect. The second group, the endogenous pigments, are of very great interest; they are, as it were, in the main stream of insect metabolism.

PIGMENTS SYNTHESIZED BY THE INSECT

When considering the origin of pigments in this, the endogenous group, it has to be remembered that, as with other 'living' syntheses, many successive steps are involved, each one brought about by an individual enzyme system. The route followed is seldom the same as would be suggested by purely chemical research. All of these pigments contain nitrogen, and all of them also are related to chemical groups which are of widespread importance in animal biochemistry.

Amongst the endogenous pigments the melanins have received most attention, for the black coloration conferred by them is found in practically all groups of animals. In man it is responsible, to some degree, for hair coloration and skin pigmentation. They are extremely stable molecules and the intensity of the colour which they impart to a tissue is thought to be due, in part, to their degree of polymerization. It is also probably determined by their chemical state, for the molecule can be either oxidized, giving the jet black colour seen on gregarious locusts, or reduced, forming a tan pigmentation. In either case the final criteria of colour will be determined by the intensity of the pigment deposit. Research on the nature of the melanins present in black wool has shown that they may combine with protein and the possibility that the insect melanins may combine with the proteins of the cuticle in the hardening and darkening of the cuticle cannot be overlooked. The synthesis of melanin from

the essential amino-acid tyrosine has been known for a long time and some insect melanins can be synthesized with better yield in laboratory experiments by incubating small pieces of the integument with compounds such as di-hydroxy-phenyl-alanine, commonly abbreviated to 'Dopa' or di-hydroxy-benzoic acid. The reaction proceeds under the same conditions using tyrosine, but more slowly. Figure 1 shows the structural relationship between 'Dopa', tyrosine, and melanin. Tyrosine may be the starting point under natural conditions, but this is not certain.

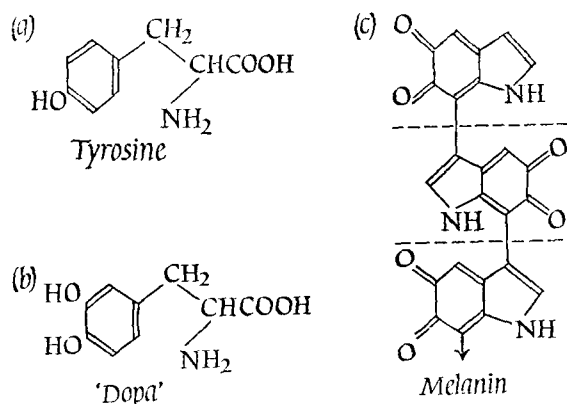


Fig. 1. Melanin (c) can be built up in laboratory experiments from either tyrosine (a) or 'Dopa' (b); 'Dopa' gives the best results. Melanin is formed by the combination of smaller units (three of which are shown separated by dashed lines), and the degree of polymerization is thought to be partly responsible for the final coloration.

Many workers believe that melanins are deposited in the cuticle of the insect as waste products which are excreted when the skin is shed during the growth of certain insects. It is difficult to reconcile this view with the complexity of the mechanism concerned in the melanin pattern-formation of many butterflies and wasps, where a response of the hypodermal tissue seems to

be necessary if the enzyme reaction is to proceed. In stick insects a hormone system influences the degree of pigment deposition, whilst in certain moths the increased melanization of individuals found in industrial areas suggests that a possible genetical factor is concerned in the pigmentation process.

There can be little doubt that the melanin pattern of the Madagascar weevil, *Lithinus nigrocristatus*, provides a protective coloration amidst the black and white lichen which it habitually frequents and, similarly, the brown melanins of many moths render them invisible when resting on tree bark. Apart from survival value, experimental work has shown that consideration of melanin solely as a waste product is not tenable in the case of the Desert Locust. In this species the pigmentation is reduced when the insect is reared at high temperature. If the pigment is purely a waste product of protein metabolism an increase in production would be expected at say 40° C compared with that at 30° C, for in animals whose internal temperature is affected by their environment the basal metabolic rate increases with an increase of environmental temperature. Similarly localized temperature gradients induced on the wing of the butterfly *Samia* do not affect the rate of development or form of the melanin pattern. It would seem that some deeper significance must be attached to these pigment deposits than simply the removal of waste products from the metabolic system. The effect of the black coloration on absorption of heat could profoundly influence the metabolic rate of the insect. Such a difference has already been studied in locusts where the gregarious insects are highly melanized and have a greater metabolic rate than the non-pigmented solitary forms.

The insectorubins are a group of endogenous pigments very similar in chemical properties to the melanins but lacking their extreme inert nature. As in the former group of pigments they contain nitrogen, are thought to polymerize and the colour that they impart to the insects is influenced by their chemical state and association with proteins. Unlike the melanins their distribution, as far as is known at present, is more limited. The yellow coloration seen in some dragonflies is due to the presence of

oxidized insectorubin and the reduced form is responsible for the red pigmentation of immature adult desert locusts. The pigment-protein complexes are thought to modify the visual coloration to a great extent; indeed the brown and buff pigmentation of several species of Orthoptera are thought to be due to such compounds.

Just as the most likely metabolic precursor of melanin is the amino-acid tyrosine, so the metabolic precursor of insectorubin is the amino-acid tryptophan. When one of its oxidation products, kynurenine, is injected into unpigmented *Ephesia* a red insectorubin is deposited in the integument and ommatidia in direct proportion to the amount of the amino-acid injected. The biological significance of the pigment, other than as a breakdown product of tryptophan metabolism, has never been considered in any detail. The presence of the pigment in the eyes of *Ephesia*, *Drosophila*, and *Locusta* together with its strong light absorption properties, especially in the 490 m μ region, tend to suggest that it may play some part in insect vision as well as coloration.

The porphyrins and their breakdown products, the bile pigments, are another group of nitrogen-containing endogenous pigments found in insects, but differ from the melanins and insectorubins in that they are soluble or dispersible in aqueous media. They are the sources of red, yellow, green, and brown pigments in the integument and blood of dragonflies, butterflies, bugs, beetles, and wasps by virtue of their individual chromatic properties or by combination with other pigments. Pterobilin, a green pigment closely related to the bile pigment biliverdin, has been extracted in small quantities from the wing scales of Pierid butterflies, though its metabolic source is unknown. In this work 6,000 individuals were used in the extraction of 8 milligrammes of pterobilin, a fact which emphasizes the technical difficulties encountered by the chemist working with insect material. The green coloration of many insects feeding on plants is due to insectoverdin, a combination of a blue bile pigment, mesobiliverdin, and the yellow carotene obtained from the food. Such complexes are thought to be associated with protein

moiety, illustrating the complexity of some of the more simple colours observed in the insect world and the diversity of method used in the formation of similarly coloured pigments. The metabolic significance of porphyrins in cellular oxidative processes is well known to biochemists. They probably serve in this role, as well as a biochrome, in insects – though in the case of the bile pigments little is understood of their function other than as excretory products.

The purines and pterines contribute a major source of colour to the wings of butterflies; the former as a silvery white pigmentation and the latter as white, red, yellow, and orange pigments, which are also found in the integument of wasps. In some species two or more pterines are present; in *Colias edusa* mixtures of erythropterin (red) and xanthopterin (yellow) have been separated. As with the pterobilin, these compounds are only present in small amounts representing in the case of the white leucopterin of Pierid butterflies about 0.18 milligramme per specimen.

Purines are found in the vertebrates as breakdown products of nucleoprotein metabolism, but in fish there is some evidence that the production of guanine (a white purine) is influenced by the visual field of the animal; the biochemical and physiological processes involved are not yet fully understood. The discovery, in recent years, of the relationship between pterine metabolism and a growth factor, folic acid, suggest that this group of compounds may serve other functions besides that of coloration in the insect metabolism. Similarly the association of flavines with synthesis of vitamin B₂ could be connected with the high concentration of this pigment in the eggs of several grasshoppers and caterpillars; but, again, experimental verification of such a relationship has still to be found.

PIGMENTS FROM FOOD

The second main class of pigments, those of exogenous origin, are mainly non-nitrogenous compounds. As they are accumulated from the food of the insect it is hardly surprising that plant pigments should be present in this group. The anthocyanins,

imparting red, violet, or blue colours to many flowers, fruits, and leaves, are present in some beetles, aphids, and wasps which feed on these plants. The pigment of the larva of one beetle is either bluish-violet or orange, depending on conditions, though other blue and reddish-brown anthocyanins found in insects are more stable. No physiological function can be attributed to these compounds which, as suggested previously, may be accidentally accumulated in the course of feeding.

Little is known either of the metabolic significance of the water soluble flavones causing the yellow hues of butterfly wings or of the anthroquinones found in the Coccidae. The economic importance of the latter as dyes has already been mentioned.

Amongst the exogenous pigments the carotenoids have received much study. They have been found in the integument of many species of bugs, beetles, butterflies, dragonflies, bees, and wasps. Together with the melanin pigments they are probably the most widely distributed pigments in the Insecta. Not only is the pigment present in species feeding directly on its plant source but also those preying on carotene-containing insects. In the latter category the parasite *Microgaster* obtains its carotenoids from its host, the Pierid butterflies, and similarly the bug *Perrillus* contains a carotenoid obtained from its prey the Colorado Beetle which, in turn, has obtained it from its plant source.

The true exogenous nature of these pigments has been shown by rearing desert locust hoppers on carotene-deficient diets; their normal yellow background-colour then fails to develop. A further demonstration is afforded by the caterpillars of *Colias philodoe* where two strains are present; one strain is green, the colour being conferred by the presence of insectoverdin, a protein-bound complex of endogenous mesobiliverdin and exogenous carotene, whilst the other strain is blue because of an inherent inability of the caterpillar to absorb carotene and synthesize insectoverdin. The presence of the green complex is of considerable survival value to the caterpillar against the attacks of the parasite, *Apanteles*, which usually feeds on the blue variant only. In the laboratory the parasite fed on green

caterpillars absorbs carotene and incorporates the pigment in the silk of its cocoon. When the blue variant is utilized as food only white cocoons are formed by the parasite because of the absence of carotene in the prey – an illustration of the indirect way in which the pigmentation of a species may vary according to the nature of its food.

Many species are incapable of modifying the basic structure of their dietary carotenoids, whilst others are capable of producing minor changes in the molecular structure. The blood of the silkworm *Bombyx mori* contains several xanthophylls derived from a plant source without further modification; other species, such as the locusts, can undergo the transformation of β -carotene to form pink astaxanthin, a relatively slight change in the end structures of a long chain molecule. The bug *Pyrrocoris* is thought to metabolize lycopene, a compound also present in the beetle *Coccinella*.

Much has been written of the significance of carotene in the synthesis of vitamin A and of its utility in vision, but some insects can exist without either of these compounds. The cockroach, clothes-moth, and the flour beetle have thrived on artificial diets devoid of both constituents; they cannot be of universal importance to insect life. The sexual differentiation of carotenoid distribution, seen in some insects, may eventually play some part in elucidating the role played by this pigment in the insect, but as yet little can be attributed to its function beyond participation in the overall coloration of the insect.

PIGMENTS AND COLOUR

The complete visual coloration of the insect does not depend rigidly on the presence or absence of one or more individual pigments, but rather on their relative quantities and positioning with respect to the rest. The physical colours of the beetles are often profoundly modified by deposition of melanins. Equally, one pigment may mask another; for example the pink tints due to astaxanthin can be completely obscured by carotene deposits. Similarly the greenish-yellow coloration of some locust hoppers is due to the relative amounts of green insectoverdin and

yellow carotene. In this species the effect of positioning of pigments is also seen, for the pink and brown colour of insectorubin is completely obscured by the melanization of the outer cuticle. In butterflies the relative amounts of pterines determine the final shade of their coloration. More striking examples of this phenomenon can be found amongst the stick insects, where one variant is capable of changing from green to brown by movement of pigment granules within the hypodermal cells: the compounds lying nearest the cell surface determine the final coloration.

It is difficult to reconcile the complexity of the various colour systems with the view that their basic components, the pigments, are merely by-products of the metabolism or accumulated waste products. Although many authorities would not accept the suggestion that the presence of pigments necessarily points to a specific function for each, their integral effect has been shown on numerous occasions to have considerable survival value for the species. Their more intimate participation in the metabolism of the insect has not been demonstrated to any great extent, though, by analogy with similar compounds in other animals, they may play a far more active part than the terms waste product or by-product suggest. The change of pigmentation in many species after the final moult suggests further that the pigmentation mechanism remains in close contact with the general metabolic stream throughout the life cycle and, in this respect, may be considered as an index of the physiological state of the individual. A complete understanding of such changes and the role of the pigments within the system as a whole must necessarily await further research into the genetical, physiological, and metabolic problems which are involved in insect coloration as a whole.

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MIND AND MATTER: A MONIST VIEW

J. A. V. BUTLER

SOME time ago* I discussed the consequences of the idea that human beings construct from their sense impressions a 'picture' of the outside world, within which they plan and carry out actions. As I pointed out then, this method of dealing with sense impressions gives a continuity of past and present (since the 'picture' is largely derived from past experience) and a greater degree of freedom in choosing between possible actions.

I should now like to consider the nature of the 'picture' which we make from our sense impressions. This problem involves the nature of 'perception', which has been much discussed philosophically. My object is merely the scientific one of attempting to see how perception can be fitted into our existing scientific outlook. The existence of such a 'picture' can hardly be denied. We say we 'see' what is before our eyes. We 'hear' sounds. These sensations may cause us to perform some action, and it is possible and in fact likely that there is a link, or a whole series of links, between the sensations and the actions. The latter might be explained as a mechanical result of the stimulation of the sense organs, allowing for modifications caused by inhibitions, conditioning, etc. But this is not the whole story. We are also 'aware' or 'conscious' of the sights and sounds, and it is necessary to ask how this awareness or consciousness can be fitted into the scientific scheme. How, we might ask, can a collection of atoms of carbon, hydrogen, oxygen, and so forth, in whatever complex ways they are organized, be aware of anything? In other words, what is the relation of consciousness to the material apparatus of the brain?

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Let us approach this question by considering what is already known about what goes on in the brain while mental processes are taking place. Unfortunately we come up against the fact that very little detailed information is available. We are in the position of someone trying to read a difficult book – say, an account of Einstein's work on relativity – without knowing the alphabet with which it is written.

There are good reasons for thinking that all except simple aspects of brain action may remain inaccessible to scientific investigation for a long time. The situation is not unlike that confronting the student of physiology about 1700. He surmised that living things were made of material not very different from that of non-living things, but he had no way of testing or even of stating this belief. It required two centuries of chemical analysis of simple substances to bring science to the point at which it was even possible to talk about the chemical nature of living matter.

The situation within the brain is rather similar. We can follow rays of light into the eye and see them impinge on the retina; we can learn how they activate the rods and cones, and measure the electrical impulses which then travel along the optic nerves into the brain. To some extent these impulses can be traced within the brain. When the eye is excited by a square pattern of light, the pattern of excitement which reaches the surface of the cortex still retains the shape of the original square stimulus. From these cells other waves of excitation spread out, but we can no longer identify the impulses with their origin and it becomes impossible to trace them to their destination. The impulses are lost among the innumerable nerve fibres which connect the brain cells, and no one can tell where the 'picture' of the square which I actually perceive is formed and what physical effects accompany it. This difficulty of finding out in detail what goes on in the brain cells is likely to remain for a long time. This is due to the very small scale of the structures and the extreme complexity of the geography of the brain. It also arises from the fact that detailed information is required. Chemical and physical methods nearly always give information about the average behaviour or com-

position of cells. Something of the geography of individual cells is, of course, known from microscopic studies, but we should need to know what goes on in them from instant to instant. Anything like a complete static study of the brain would be an immense task, but to follow its detailed working from second to second, even if methods were available which could tell one what was going on in all the myriads of brain cells, is all but impossible. This is the main reason why the gulf between psychology and physiology is so immense. The psychologist deals with phenomena which, from a physiological point of view, are fantastically complicated.

Nevertheless, some progress is being made in learning the functions of isolated parts of the brain. Dr Wilder Penfield of Montreal has performed many operations on the exposed brains of patients. As there is no pain, these operations are carried on without anaesthetics and it is possible for the patients, who are fully conscious, to describe their experiences. Different accessible spots on the exposed brain are stimulated by electrodes placed on them and the result of the stimulation is observed. It has been possible in this way to locate the parts of the brain which control the muscles of the different parts of the body. Dr Penfield describes these experiences as follows:

When an electrode is applied to the motor convolution in the central region of the cortex, movement results in the opposite arm, or leg, or face. The jaw may move up or down, the throat may swallow, the mouth may open while the patient vocalizes in a long drawn out tone. Or the eyelids may open and the eyes turn in unison as though looking upwards and across to the opposite side. As far as the patient is concerned, these movements are irresistible. When the electrode is applied, for example, to the motor area of the right hemisphere, he cannot, by the exercise of his will, prevent his left hand from moving, but he can reach over with the other hand and thus hold the moving member still.

Stimulation of other points produces feelings such as tingling in the hand or foot and visual and auditory impressions. Patients reported seeing 'flickering lights', 'dancing lights', 'colours', 'radiating grey spots, becoming pink and blue'. Others received

hallucinations or heard music. The hallucinations are often like dreams. They consist in the reproduction of some remembered experience, in which 'the action goes forward as in a dream and the patient may become frightened and cry out'.

This is the clearest evidence so far obtained that mental states have a physical equivalent and that a physical stimulus can evoke a sensation. It is certainly possible that in time we may find a physical basis of many kinds of sensations. Can we expect, then, that all our mental states will be accounted for as physical happenings in the brain?

However, although we may find a connexion between sensations and physical happenings in the brain, this does not explain what the sensation is. In fact, we are completely at a loss to describe it as a motion of particles of matter, or a vibration, or indeed in terms of any quantities which are used in describing the behaviour of matter.

It is difficult to deal objectively with feelings and sensations because they are absolutely personal and private to each person. There is no way in which they can be shared with other people. You cannot see what your friend sees or feel what he feels. If he tells you he has a pain you can imagine what it feels like, but there is no conceivable way in which you can feel the pain. You merely infer from his behaviour that he has feelings like your own.

My private world of perceptions and feelings is something entirely different from the outer world which I believe to exist. I can look at a scene and interpret my sense impressions of it. I see trees, houses, and perhaps people. I can analyse this picture further and notice that the trees belong to a class of things which I call plants, while the people are in many respects similar to another kind called animals. I can go further and remember that all these objects have been convincingly analysed and shown to be capable of interpretation as consisting of chemical compounds which are themselves made up of atoms. All this is my interpretation of the various perceptions present in my consciousness.

The awareness itself, the mental picture which I am analysing

and interpreting, cannot be discussed at all in any of the terms which are used to discuss and interpret the outer world. I cannot describe my perception as being made up of atoms, or even of space. It cannot be measured, it has no dimensions. The difference between my inner world and the outer world, which I infer from it, is similar to that between what is represented in a painting and what the painting is made of. When you look at a painting you find a certain meaning in the colours and shapes you see. Perhaps you see shapes which you interpret as being a picture of a person and which convey to you information about that person. But this has nothing whatever to do with what the picture is made of – what pigments have been used and what is underneath the paint.

This illustration is defective in that we can, if we want to, examine the nature of the pigments and even look at the canvas. But in our mental picture there is no way of examining the pigments and looking at the canvas. We can, as I have shown, discover something about the physical equivalents in the brain of mental states, but there is a great gulf between the mental state (a feeling or perception) and the physical equivalent. They are incapable of even being described in the same terms.

So we find ourselves in a dilemma. Must the scientific picture of the outside world stop short of mental phenomena and leave us incapable of accounting for what we know best (indeed our only direct knowledge) – namely, our own perceptions and feelings? Must we accept a dual world – an outer world which is the subject of science and an inner world which is incapable even of being described in the same terms?

Some scientists have met this dilemma by denying the existence of the inner world, at any rate as a subject of science. If it can never be approached scientifically, they say, we might as well ignore it. It does not exist scientifically. If the only things that we can study are the physical equivalents of sensations, these are the only matters which science can and should concern itself with. We must be content to describe the surges of impulses in the brain. For the scientist this *is* the sensation. The fact that I am *aware* of something does not concern him.

If we are not willing to ignore the inner world of perception, but think we must accept it as real – at least as real as the outer world which we have inferred – we must admit that, although consciousness cannot be described in the same terms as the 'matter' of the outside world, it is curiously associated with it and all our conscious states seem to have some physical background or equivalent. This intimate association of the two worlds (the inner world of experience and the outer world of matter) suggests that they may only be two distinct aspects of a single phenomenon.

We might, then, try to resolve the dilemma as Tyndall did, from another point of view, in his well-known address to the Belfast meeting of the British Association, by ascribing to matter the capability of sensation. He saw that, if life is matter, it was necessary to endow the atoms of matter with the attributes of life. 'Abandoning all disguise,' he said, 'the confession I feel bound to make before you is that I prolong the vision backward across the boundary of the experimental evidence and discern in Matter, which we in our ignorance . . . have hitherto covered with opprobrium, the promise and potency of every form and quality of life.' This is, perhaps, less difficult to accept at the present time when the analysis of matter has led to the loss of much of its 'materiality'. The atoms of matter are no longer thought of as small, hard lumps of substance, but only as complicated systems of electric forces, describable only in mathematical symbols. There is no doubt that many of the properties of these complex systems remain to be discovered. It is perhaps not too far-fetched to think that matter is not utterly incapable of consciousness, although we cannot at present put consciousness into our description of it. We cannot, for example, detect any signs of feeling or consciousness in a pound of salt, nor can we observe or study its mental qualities. If they exist they are of a most rudimentary description. Only when we study those most complicated arrangements called brains, or more precisely, the behaviour of the animals which have brains, can we see any clear evidence of mind.

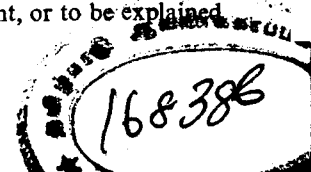
The conclusion we come to is that sensations are real, although

they are apparently entirely different in nature from 'matter'. But the association between matter and sensation is so intimate that we cannot avoid the conclusion that the one goes with the other. As we study the nature of the strange phenomenon called life, we find that we cannot banish feeling and sensation. Living things may from some points of view be described as mechanisms and automata, but behind the mechanical and automatic there is always something else, which in the higher organisms we describe as consciousness and feeling; in the lower ones perhaps only just glimmerings of sensation. Just as the mathematicians and physicists, who in the analysis of matter came, in the end, to think that their description of the material universe was more like pure thought than anything else, so in the analysis of living things, if we pursue it far enough, we find everywhere traces of feeling and sensation. This capability must be a basic property of the universe, a potentiality which existed from the start; but at present we are incapable of describing it further.

The old dualist view of things regarded men at any rate as made up of two entirely different kinds of things – 'mind' and 'matter', which were able in unknown ways to influence each other. The progress of science has steadily pushed back the idea of a special vital principle in living things, as more and more extensive physico-chemical explanations of living processes were arrived at, until most scientists feel now that there is no longer any need for it. Recent tendencies of science have seemed also to be banishing mind as an unnecessary concept. Yet as I have tried to show, there is something which cannot be described mechanically, or at least at present is totally separate from the picture which we make of the physical universe, and this has as much right to be called a basic property as matter. Instead of rejecting 'mind' as an unnecessary excrescence of a material view, we trace it downwards to the material roots of things. We find no point at which we can say, here sensation and feeling begin.

So we arrive at a new monist view that matter and consciousness are two aspects of one phenomenon, but we do not say that either aspect is unimportant or insignificant, or to be explained

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away in terms of the other. What the phenomenon is, and how the two aspects are connected with each other, are questions which are still a profound mystery.

But it seems to me that the door is left just a little open, and the time may come when science can make a little progress in connecting matter and consciousness; but that time has hardly arrived yet. At least we may regard awareness and sensation – the whole world of human consciousness – not as a chimera, a mere illusion, for which there is no room in a universe of forces and atoms, but something which has a real existence. We cannot say where mind and sensation begin because in a rudimentary way they are everywhere.

FURTHER READING

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MILK OUT OF AFRICA

C. H. WADDINGTON, F.R.S.

THERE are rather more cattle in Kenya than people. In the face of the deadly political struggle, and the anguished inter-racial relations of that country, it may seem mere escapism to devote much thought to such gentle inhabitants of the land. But throughout Africa cattle are one of the main recognized forms of wealth – not merely conventional riches, useful for paying the bride-price and establishing a standing in society, but real wealth, which provides a higher standard of living. And where cattle cannot as yet be kept in quantity, as in the forest belt of Nigeria and the Gold Coast, there is an enormous unsatisfied demand for animal protein foodstuffs – for milk and beef – and also for draught animals. It is not at all irrelevant to the history of the African continent, and in the long term may be of overwhelming importance, that the British Colonial Veterinary and Agricultural Services are putting a great deal of hard work into the task of improving both the cattle themselves and ways in which they are kept. A lengthy report* on these endeavours, covering all British Colonial Territories in the continent, has just been produced by D. E. Faulkner, former Deputy Director of Veterinary Services, Kenya, and J. D. Brown, former Deputy Director of Agriculture, Nigeria. It gives one a fairly clear idea of the kind of unspectacular but valuable contribution which the technical side of the Colonial Service is making to the progress of mankind.

There is plenty to do. Only too many African cattle are pretty

**The Improvement of Cattle in British Colonial Territories in Africa*. Colonial Advisory Council of Agriculture, Animal Health, and Forestry, Publication No. 3. London, H.M. Stationery Office, 1954. 10s 6d. pp. 144.

miserable beasts, underfed, slow growing, producing a little bad quality beef and a trickle of milk. The first simple thought is to replace them with high-producing 'improved' European (mostly British) breeds, whose value in their own countries is well known. The remedy has been tried and does not work. Except in a very few special areas where the climate is not typical of Africa, such as the Highlands of Kenya, cattle of British breeds either succumb to disease or lose condition. Later generations, born in Africa, seem to get progressively worse. One would like to know what would happen with cattle from the hotter and drier parts of Europe – South Italy or Spain, or even the well-known Brown Swiss, which are inured to high intensities of sunlight, though usually at considerable altitudes – but, in general, one must accept the conclusion that importations from non-tropical countries are not likely to be of much use.

The problem, in fact, cannot be adequately dealt with in the simple-minded terms in which a beast is considered as something which has value for itself, in isolation, by the mere fact of belonging to an improved breed. It needs an ecological approach, which sees the cow as one item in a complex set of inter-relations. The climate, the natural vegetation, the diseases, set a stage which the cattle must inhabit, and they, by their effect on the farming practices and social organization of their masters, in turn affect the cattle-feed available and the standard of husbandry to which they will be subjected. This is a characteristically biological type of thought (I will forgo considering its humanistic form, which arises if one substitutes 'man' for 'cow' above). Its application is the growing point, at the present time, of our ideas about the most fundamental of biological problems, that of evolution. Practical agriculturists who deal with the undeveloped parts of the world, such as the Tropics and the Arctic, have got perhaps a more intimate understanding of the whole width and depth of such ecological complexes than the academic field worker who studies wild animals which man does not know as individuals from birth to death. This is an example of the way in which technological studies can be carried to a point where they become of the greatest importance to pure science.

Native cattle already fit their environment fairly well. They can stand the high temperatures, the poor nutritive quality of the feed, and are resistant to many of the local diseases. Western veterinary science has made some magnificent contributions in defeating some of the other diseases, such as rinderpest, and controlling the ticks which are a scourge in so many areas. (Incidentally, it has been reported, but not in this work, that the nomadic Fulani herdsman of Nigeria had developed for themselves a crude form of inoculation against pleuro-pneumonia, which is surely, if true, one of the most remarkable examples of preliterate science.) These qualities enable many of the types of cattle to be good beef animals, if properly managed, without need for any further selection. Thus one experiment from Southern Rhodesia is quoted, in which native stock were found to give more beef per year per acre than pure or crossbred imported types; although the native cattle were smaller, they made up for it by producing more calves and having a lower mortality.

But there are some regions in which the local type, although adapted to stand the difficult conditions it has to meet, is not much use for human purposes. For instance, the cattle resistant to tsetse-fly attack in West Africa, and inhabiting the hot, wet-forest belt, are very small and slow growing, little use for beef or draught, and giving almost no surplus milk (Inset 9 and 12). These dwarf 'Muturus' and Ndama present many fascinating scientific problems, which seem to call for much bolder investigations than anyone has yet started. Is their small size and low growth rate (presumably coupled with a low rate of food-intake) essential to their adaptedness, by minimizing the amount of surplus heat they have to get rid of? Dr Norman Wright has suggested this in connexion with the essentially similar cattle found in the hot, wet jungles of Ceylon. One can hardly have a sensible scheme for improving the cattle of such areas until one knows the answer; getting it would require what might be considered pure, academic experimentation on metabolic rates, etc. There has not been time, man-power, or money for such work among the day-to-day commitments of the Agricultural Services. Again, these animals seem to have the most remarkable resistance to

'Nagana' – which corresponds to human sleeping-sickness. Now plant breeders have been very successful in transferring such desirable qualities from less to more productive strains. Little such work has been attempted in animal breeding; it requires several generations of relatively useless animals, the result of inbreeding the hybrids, before valuable results can be expected. But here is a case where it would seem worth while at least to discover whether the resistance is due to a few genes, which would be relatively easy to handle, or many, which would be difficult. Again the problem demands something which may well be outside the capacities of the existing set-up for Colonial Agricultural Research. The continuance of degeneration over several successive generations, mentioned above, is another problem of both practical and academic importance to which we do not know the answer. Is not the time coming to begin at least a little long-term genetical work on animals in the tropical environment, perhaps at one of the Universities of the Gold Coast, Ibadan, Makerere, Ceylon, or Malaya?

The main technological problem, however, is that of producing cattle which are not merely efficient at living in the country, but also produce the surplus milk which is the most convenient product for human use. By far the most important step towards this is the improvement of the African's standard of feeding and husbandry; at present the potential output of the existing cattle is only very seldom attained. It might be thought, indeed, that one need hardly bother about selective breeding at this stage, but concentrate entirely on improving husbandry. But changes in the methods of cattle-raising – for instance, limiting the drastic overstocking of the land, or letting the cattle graze for longer periods and the little boy herdsmen go to school – demand radical changes in African habits and social structures, which will not occur unless the African clearly sees that they are worth his while. And the best way to persuade him of that is to give him the chance to see what his cattle can become, and the real income they could bring him. In a few places, such as the Nandi Reserve in Kenya and in Uganda, this has already been done successfully (Inset 11). In many parts of Africa, the local cattle, even when

well managed, do not seem to be capable of such strikingly impressive performance that the African is convinced; in such areas selective breeding is necessary before one can produce stocks which will really sell the idea of good husbandry, and in all regions it should be a great help.

A great deal of such work is being done, and has been most valuable. But to my mind there is some doubt whether enough emphasis has been put on the paramount aim of raising a small herd of *élite* stock. Most Government stock farms seem to have bought in a number of animals to start off with, and then continued to select from among them, without bringing in any new ones. Under such a system, the need to keep up numbers makes it impossible to reject more than a smallish fraction, however badly they milk. What is needed is a system which goes all out for a few generations (say fifteen years) to raise as high as possible the intensity of selection for yield of milk and readiness to be milked. This would seem to demand frequently bringing in new cows to replace the rejects. There are often great difficulties in doing this, since in many parts the Africans are most unwilling to sell their animals, but it would probably be worth while making strenuous efforts to overcome their reluctance. If there were some system of getting an inkling of the quality of the cattle brought in (for instance by some, even crude testing at demonstration centres), so much the better. One has to consider the possibility that when one is starting to select for milk yield from scratch, there may be, waiting to be picked up, some genes with rather large effects, which in improved breeds are so universal that they no longer enter the picture for the breeder. Everything possible should be done to produce a nucleus of animals of high breeding value; it cannot be done quickly, but it might perhaps be done quicker than it is at present. When real progress has been made, then is the time to start thinking of issuing bulls to improve the general level of the native stock.

A recurrent question in breeding for tough climates is this: should we try to breed the *élite* stock in very good conditions, which will give them a chance to show the best they can do, or should we concentrate on selecting animals which can do well

even when conditions are bad? Again a simple question that lacks a simple answer. High genetical authorities in this country, confronted with the problem, tend like parturient mountains to produce a lot of stuff about mice; and indeed a lot of interesting work on the problem is being done with those convenient little animals. But one may ask whether one could not get the best of both worlds. Could not those cows which, in their first lactation on normal poor diets, do well enough to seem worth selecting, then be given generous supplementary rations for their second lactation, to see how far they could benefit?

In conclusion, I would like to put together three points whose inter-connexions would take too long to discuss in detail. Firstly, food and health are the foundations of any civilization, in Africa or elsewhere; it is the constructive, professional, hard work of the technical officer which really gets to the root of the matter in the Colonies. Secondly, a quotation from this report on cattle breeding: 'The valuable indirect effects of disease control measures in gaining confidence of stock-owning tribes is stressed. . . . In many territories it is often only those Government officials concerned with the control of animal disease who are in frequent and continuous contact with the stock-owning populations.' And lastly the question, how far are technical officers enabled to contribute to the formulation of political policy? Are we nowadays attaching enough importance, either in the organization of the Colonial Service or in the discussion of Colonial politics, to the basic bread-and-butter problems with which the technical services deal?

MATHEMATICS IN INDUSTRY

N. W. FOX

IT is probable that a considerable number of *Science News* readers are employed in some branch of industry, and it will not surprise them, therefore, to learn that industry is becoming more and more specialized. They themselves may, in fact, be specialists in one branch or another. This specialization, while understandable, makes life difficult for those wishing to enter industry, particularly graduates. For science graduates the way is fairly simple, since many organizations now operate training schemes of one form or another to fit the graduate smoothly into the different atmosphere of industry. Even without such schemes a science graduate usually finds industrial work has certain similarities to university work, particularly if he is employed in a purely specialized capacity.

One of the problems of present-day industry is what to do with the arts graduate; in spite of numerous conferences, it is still a long way from solution. Whether the mathematics graduate is called arts or science is a matter mainly of geographical location, but the problem of fitting him into the industrial scene tends to put him into the arts category. It is the purpose of this article to show that almost all sides of industry have problems which can be solved by mathematical means. Sometimes the mathematics used may be complicated and require an expert to handle it properly, and of course not all problems warrant such treatment. Nevertheless, the use of intuition is no substitute for a scientific approach, when this can be made rapidly and economically. The advantage of such an approach is that the effects of certain courses of action can almost always be expressed in numerical form, either in probabilities or in actual monetary value.

Many firms, of course, already employ mathematicians, and

some larger organizations have mathematical departments. Frequently, however, the mathematician is not called in on a problem simply because the individual in whose department the problem arises is unaware of the contribution which mathematical treatment can make towards its solution. This lack of information may be due in part to the fact that most mathematicians tend to lean toward the theoretical, and are not good at making their subject intelligible to the layman. To assist non-mathematical readers who have not met many applications of mathematics to industrial problems, it is instructive to consider a few of the more important fields.

MATHEMATICAL STATISTICS

The use of mathematics *per se* in industry may be said to have really started with statistics. Statistical quality control is now so widespread, and the articles on it so numerous, that no more than a passing mention will be made here. The principle is to determine the variability of a process when operating under constant conditions and then, using a sampling scheme, to determine when the process variability or average changes. Modifications to this general outline have been made by various users to incorporate special features such as automatic sampling, or to reduce the calculations normally required. The widespread use by war factories of statistical quality control is sufficient recommendation in itself and the system does not require the services of a highly qualified mathematician for its application.

There are other very important uses of statistics which are not so widely known, and for which the mathematician's assistance is of great value. In particular the chemical engineer, who is frequently asked to perform experiments on full-scale plant, can be sure of obtaining the maximum amount of information from the minimum number of experiments by using statistical experimental designs. These are equally applicable to laboratory and to pilot plant work and are based on the fairly obvious fact that the classical method of holding all variables constant except one, and observing results, is practically impossible to apply in industrial practice. Statistically designed experiments make

use of changes in all variables at different levels and the interpretation of results leads both to information on the relations and the interactions between variables.

The fixing of buyers' and sellers' specifications is also given a scientific basis by the use of statistically designed sample schemes. These ensure that the risks of buying or selling inferior goods can be stated as probabilities and the costs of sampling schemes for any specific risks can be estimated. The British Standards Institution recommend statistically designed sampling schemes in their publication on *Sampling Clauses* (P.D.488).

Analytical laboratories may also use statistics as a useful tool in determining the significance of results. Tests may be of a chemical or physical nature such that numerical answers are obtained as a final result of the tests. Such numerical results should be evaluated with a knowledge of the experimental and sampling errors of the particular analytical method employed, otherwise unnecessary trouble may be caused by assuming two results to be different when in fact no *significant* difference exists. For tests which are purely comparative, such as sensory tests, i.e. evaluation of odours or tastes, it is essential to employ statistical significance tests for meaningful results. It must be admitted here that the ranking of various objects or materials in order of merit, while requiring statistical tests for full significance of results, is still the subject of mathematical arguments. It is even more important in cases such as this to have at hand a trained mathematician who is able to follow and interpret modern developments in such fields.

Other examples of statistical methods can be found in the personnel department, where analysis of labour turnover may sometimes produce remarkable conclusions. Again the financial sections, such as audit, cost accounting, and so on, may use sampling methods or regression analysis to assist them in their particular functions. The use of sampling techniques in market research is widely known.

It is fairly true to say that anyone dealing with the taking of samples of few objects from a large number of such objects, or dealing with the examination of such samples, or employing

information derived from such examinations, stands in need of statistical methods to give results which have value, and whose value can be assessed in economic terms.

ELECTRONIC COMPUTERS

These are mentioned here since the services of a trained mathematician are essential to the operation of the larger units. Smaller machines, which have been built for specialized purposes, may not require such services, but it should be borne in mind that even the smaller computers can perform mathematical operations at a fantastic speed, and since they are unlikely to be in constant use a mathematical specialist could probably assist other departments to solve their problems by computing methods, if such solutions are possible.

Punched-card machines, while much simpler than electronic computers, nevertheless have applications other than those for which they are commonly used. Simple computations may be performed on certain types of punched-card machines, and they are widely used by statisticians for the sorting of data. Chemists are also using such machines for classifying infra-red spectra and their use in chemical compound identification from analyses has been proposed.

OPERATIONAL RESEARCH

A lot of operational research is probably carried on in industry by people who may have only a general idea of official definitions of the subject, but the more advanced applications need specialist advice. The mathematician is in a favoured position here, since a fair amount of advanced mathematics may be necessary for certain problems.

One particular application is that of queueing theory. This was employed during the design of London Airport and has also been used for such diverse subjects as omnibus routing, toll gate staffing, and determining the number of grinding wheels required by a toolroom. Any problem which involves the use of 'service' facilities by 'customers' may be treated, although in only certain cases is the treatment straightforward. These usu-

ally involve the assumption of random arrivals at the service point. An illustration could be the use of an overhead crane to service a number of machine tools. It may be necessary to decide, on introducing several more machines into the department, whether the existing crane is adequate. Such a decision would generally be made on the basis of 'try it and see', but this is obviously unsatisfactory. The problem may be treated in a comparatively simple matter by the use of queueing theory, on making a few assumptions. Another possible application may be to the determination of the number of pumps for a chemical plant employing several reaction vessels, or the number of storage tanks required to serve differing processes. Developments are taking place in the mathematical side of this field and its use will no doubt become more widespread in the future.

LINEAR PROGRAMMING

This is one of the newest applications of mathematics and promises to be of great importance, not only in industry but also in many other fields. It was originally conceived in connexion with the operations of military aircraft during wartime, and even today certain material produced by organizations in America working on applications of the method is classified as restricted, and is thus not available for industry. The technique may be employed in two basic types of problem, the 'dynamic' problem in which time is a variable factor, or the 'static' problem in which no time element is present. Dynamic problems include military aircraft strategy, traffic time-tables and scheduling, production planning, and so on. Static problems are usually concerned with formulations of minimum-cost mixtures. In either case the result to be achieved is the minimization of cost in one form or another.

Two methods of approach have been used. The first, by von Neumann, uses the Theory of Games and treats the 'operation' or 'plan' as a two-person zero-sum game. The two contestants may be the planner and nature or two opposing interests. In a problem of minimum cost mixtures, for example, the 'game' would be played between a contestant attempting to sell the

mix ingredients for maximum price, and another contestant attempting to buy at minimum cost. Another approach expresses the problem requirements as linear equations, which are subject to linear inequalities. From these the final solution is derived by using matrix algebra and n -dimensional geometry. The computational effort involved in either method may be laborious, depending on the problem to be solved, but work is proceeding on the simplification of such computation, and in specific cases the use of computers may be possible.

Work is still proceeding on the applications of linear programming and, already, suggestions have been made for its use in livestock feed mixing, production planning, product distribution, buying, stock control and optimum stock covers, and organization theory. It is clear that the potential uses are very numerous, but the mathematics, although reasonably straightforward, requires expert advice to avoid pitfalls.

The applications of mathematics to industry so far discussed provide justification for the employment of the mathematician as a specialist. Whatever title he or his department is given, his use in enabling industrial problems to be solved on a logical basis is so obvious that the only reason for his present lack of employment can be lack of mathematical knowledge by industrialists. This state of affairs should be remedied in time, with the assistance of publications, courses, and symposia; but, until it is, the mathematician will remain largely outside the industrial sphere, whereas his knowledge should be one of those things we cannot afford to be without.

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RESEARCH REPORT

A. W. HASLETT

BRITISH ASSOCIATION

JUST when it was beginning not only to be accepted but even stated publicly that the production of new material was no longer to be expected at meetings of the British Association, an exception was provided to prove the rule. It came from Professor M. M. Swann of Edinburgh University, and was an account of work in progress on the control of cell division. In its general form this is an essentially complicated problem, as Professor Swann pointed out, and almost certainly must remain so. The question is whether there is any one factor affecting division which can usefully be isolated from the rest and studied by experiment. The experiments described were on the availability of the energy required to support division, and they suggest that a useful lead is, in fact, being obtained – whatever the later course of research.

Looking first at the complications, it is clear that there is a connexion between cell division in higher organisms and differentiation; for some of the most specialized cells, for example, nerve and blood cells, do not divide. There must be an effect also from environment, possibly through 'contact' with other cells; for in regenerating tissues the division of cells proceeds more rapidly. For the same reasons, cell division must be connected, too, with the biochemistry of cancer and of cancer-producing substances. And to these factors, two more, apparently simpler, can be added. One of them, the requirement of energy to support division, has been mentioned already. The other is the possibility that the onset of division may be affected by the size reached already by the cell. There must be a limiting effect from scale, the metabolic requirements of the cell being proportional to its volume, whereas the facility for entry into

the cell is proportional to the area of the surrounding membrane, so that there is a limit to the size of cell possible. But not all cells, even of the same kind, divide at the same size; and, if cells of different kinds are considered, the range of average size is bigger. There are thus reasonable grounds, once stated, for looking first at the energy factor.

As a first approach Professor Swann used carbon monoxide to interrupt the utilization of oxygen during controlled periods, and as experimental material he used the eggs of sea-urchins. Division, if not already begun, was delayed by the same length of time as that during which the utilization of oxygen had been interrupted. This led as a rough model to the kind of tank that fills slowly with water up to a pre-set level, and then discharges by syphon when the level is reached. It might be supposed, therefore, that there was a building up of some energy-rich substance – say, creatine phosphate – and that when enough of it was available cell division would proceed. But there is a further point which is put forward by Professor Swann as significant – the equality between the delay found in division and the duration of interruption, irrespective of the interval in time between them. In the extreme case, division, if already begun, proceeds normally, and the delay, still the same, is then in the following division. This has led to the further hypothesis that the energy required for division is accumulated in a form which serves no other significant function in cellular metabolism. Recently, therefore, a search has been made at the marine station, Millport, for a complex phosphate in the eggs of sea-urchins which varies in quantity according to nearness or otherwise to division. The method of separation by filter-paper chromatography has been used, but the results were not available at the time of the meeting. At this point, therefore, the matter rests. It can be said on the one hand that there may be a loophole in the final reasoning, that other and more complicated factors are likely to operate in most conditions; on the other, that an experimental case has been made out for the study of the energy factor, with all the possibilities to which any new line of research may be expected to lead.

Terrestrial Magnetism

A symposium on the directions of magnetization of rocks formed at different epochs included contributions from the Department of Geodesy and Geophysics, Cambridge University, and the Department of Physics, the Imperial College, London, the two chief centres which have worked recently on the problem. Evidence of reversals of direction, and hence probably of reversals of the earth's magnetic field, has been accumulating over a number of years, and was discussed at the previous year's meeting in Liverpool.* There is still some lingering uncertainty; but at its face value the evidence suggests that there have been reversals of this kind at about million-year intervals during the last 30 million years, and that the time occupied in reversal is short relatively, probably some thousands of years. There are no intermediate positions; the existing magnetic field seems merely to have faded out and been replaced by a reversed field.

A more recent line of interest is in the conclusions which can be drawn as to the apparent direction of the earth's field during longer periods of time, if direct reversals are ignored. This approach has been followed by the Cambridge workers, as was described at the Oxford meeting by K. M. Creer. The starting point was a finding by J. Hospers from his measurements of Icelandic lavas, reported at last year's meeting. For the last about 20 million years he found that the average direction of magnetization during periods of the order of 10,000 years was always close to the present geographical axis of the earth. There were cyclical changes as in historical times, and direct reversals of field; but if these were smoothed out in the one case and ignored in the other, then the magnetic and the geographic axes seemed to have been roughly constant and the same. Measurements made of earlier British rocks show, however, that on a longer time-scale there have been changes in the time-averaged direction of magnetization, the range of variation within shorter periods being of the same order as found by Hospers. The inter-

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pretation suggested is that the magnetic axis has, on the average, been the same in all periods as the axis of rotation of the earth, notwithstanding appearances to the contrary. This is equivalent to assuming that the primary cause of the main magnetic field of the earth is associated in some way with the rotation of the earth's core, as is supposed in most current theories. Changes in the time-averaged directions of magnetization over longer periods are therefore attributed to crustal movements, the axis of rotation of the earth as a whole being dynamically determined. The results from any one country - Great Britain in the Cambridge work - are most simply interpreted on the basis that the movement of the crust has been as a whole, a slipping, as of an intact skin, relative to the material beneath it. If this is so, then the direction of magnetization at any period gives a rough position for the geographic north pole at that time. Such estimates have been obtained from Great Britain for approximate ages ranging from about 600 million years (pre-Cambrian) to 70 million years (Eocene). Successive estimated positions of the north pole, followed by the approximate age in millions of years, are as follows: Arizona (?600); Marquesas Is, central Pacific (less than preceding); Marshall Is (450); Japan (350); near Kamchatka (200 and 150); New Siberian Is (70). The alternative view, which can be neither favoured nor rejected on the strength of measurements made in one area, is that there has been differential movement between one part of the crust and another ('continental drift'), or possibly both types of movement combined. The beginning of work to test this interpretation was mentioned by Professor P. M. S. Blackett of the Imperial College.

CHEMICAL RESEARCH LABORATORY

The continuous culture of an anaerobic micro-organism was shown for the first time during a series of open days held lately at the Chemical Research Laboratory, Teddington, following research at the Porton establishment and later at Teddington. The key to the problem is, rather obviously, the maintenance of suitable steady-state conditions by continuous monitoring and controls; but, although a theoretical treatment was given some

years ago by Professor J. Monod of the Pasteur Institute, the successful operation of such a process is thought not to have been previously achieved. The culture shown was one of sulphate-reducing bacteria. These organisms reduce sulphate to sulphide, as is the first requirement in the recovery of sulphur from industrial wastes, using hydrogen gas as the reducing agent. For the process to be economic on a large scale, it would be necessary that a cheap and plentiful supply of hydrogen should be available; or, alternatively, that a continuous process should be worked out for the breaking down into hydrogen and sulphur of the hydrogen sulphide extracted from the culture chamber, so that the hydrogen could be used again. Neither condition is immediately satisfied; on the other hand either may come about. In any case, the potential interest of continuous anaerobic culture is in no way confined to this particular reaction, on which it merely happens that research has been proceeding because of the recent shortage of sulphur and the need, probably permanent, to conserve supplies.

The rate of the sulphate-reducing reaction is greatest when the growth-rate of the micro-organisms is also greatest. The essential requirements are therefore to discover, and then to maintain, the conditions of maximum growth. The turbidity of the culture is monitored optically. Acidity or alkalinity is also monitored, and with the medium now being used is maintained slightly on the alkaline side of neutrality. Yeast extracts are at present included in the medium to provide a growth-factor, which, if identified, could be added separately. During the course of the experiments, the mean generation time has been reduced from 35 hours at first to about 5 hours, and continuous culture has been maintained without difficulty for up to 2,000 hours. A theoretical point has been raised in relation to the stability of the culture. It has been put forward as an objection that mutant strains must be expected to appear, and consequently that continuous culture could not be maintained indefinitely. It seems a reasonable answer that, in conditions adjusted to the maximum growth-rate of the initial strain, this will be automatically favoured compared with any mutants which may appear. In

other words, it is felt that biologically as well as chemically the system should be self-adjusting.

Several other lines of work were shown which are potentially of general interest. One of them was a development of the laboratory's earlier research on the separation of metals in solution by the methods of filter-paper chromatography. With encouragement from the Royal School of Mines, procedures have been worked out or adapted for the analysis of soil samples under field conditions, so that geochemical prospecting can be done by jeep. The analysis of, say, fifty to sixty samples could be readily divided in their various stages between evening and morning, and a rough estimate suggests that, for copper, cobalt, and nickel, somewhere about 3,000 analyses could be carried out with twenty pounds weight of materials. Geochemical surveys for these elements have been done in the copper belt of South Africa using the methods developed, and for niobium in Uganda and Sierra Leone. Methods are also available for tantalum and for lead, as also for uranium – although a portable Geiger counter remains more convenient in the latter case.

A further recent development, shown for the first time at the open days, has been the development of semipermeable membranes made of methoxymethyl nylon which can be used in dialysis for the separation of dissolved substances on the basis of their molecular weights. Apart from research uses in the laboratory, there are potential industrial applications, for example, in the textile industry and in the purification of glycerol, as soon as larger films are available.

RADIO TELESCOPES

Two new radio telescopes have lately been brought into use. With one of them – strictly a large interferometer – M. Ryle at Cambridge is said already to have discovered hundreds of new 'radio stars'. Some preliminary information on this instrument was given by W. H. Marshall in his article 'Interferometry in Astronomy' in *Science News* 31. The other, in Australia, was to have been completed in June of this year, and there has been no time as yet for operational experience. The emphasis is on

accuracy of location in each case. It is indeed a principal object in radio astronomy to provide accurate enough positions of radio-emitting areas in space – not necessarily stars in the ordinary sense – to enable identifications to be established with the corresponding objects photographed in optical telescopes. As well as these two instruments, there is the 250-ft steerable radio telescope now under construction at the Jodrell Bank Experimental Station, Cheshire (*Science News* 25, 118); and an offer has been made by the Carnegie Corporation of New York towards the construction of a similar southern-hemisphere telescope in Australia. The fate of the latter project is still undecided at the time of writing; it is likely to depend on the extent of private support which is forthcoming in Australia.

The extent of discovery resulting from the new Cambridge interferometer is briefly indicated in the current issue of *Occasional Notes*,* published by the Royal Astronomical Society. The issue has been compiled by workers at the Jodrell Bank station, under Professor A. C. B. Lovell, and gives a compact summary of research in the whole field of radio astronomy, from the recording of meteor trails in the earth's atmosphere to the study of extra-galactic radio sources. Sections on telescopes and techniques are also included, and it is in this connexion that the statement of Cambridge results is made. The issue as a whole provides an interesting foretaste of the contribution which may be expected from these newer instruments.

The new Australian instrument (Inset 5–7) was designed by B. Y. Mills, and has been built at St Mary's, 30 miles from Sydney, New South Wales, for the Commonwealth Scientific and Industrial Research Organization. In one respect it can be regarded as a compromise between the Cambridge interferometer, which for one direction of movement relies on the earth's rotation, and the new Manchester telescope. Like the latter it provides an effectively 'pencil' beam of reception. This is an advantage in interpretation, since the results obtained are simple and direct. The beam-width is $\frac{1}{4}^\circ$, compared with the $\frac{1}{2}^\circ$ beam-

*No. 16 (1954), p. 79, 6s.

width for which the Manchester telescope has been designed. On the other hand it is limited to reception on a fixed wavelength, and like the Cambridge interferometer, it relies on the rotation of the earth for control in an east-west direction. The narrow beam-width is obtained by the use of two long, thin arrays, disposed in the form of a cross, north-south and east-west. Either array separately has a fan-shaped beam of reception, but it can be arranged that the effective direction of reception is that common to the two beams. Elevation is controlled in a north-south direction by adjustment to the corresponding array. In this way much of the advantage is secured of a steerable telescope, but at a small fraction of the cost; it was built by ten men in nine months. The principle has been tested already in a smaller telescope, and has been found to work. On the other hand, it is a one-purpose instrument. But even with its limitation to a single wavelength, it should lead to a rapid advance in sources of radio emission visible from the southern hemisphere.

Inset 4 and Inset 8 show two further examples of radio-astronomical instruments built in Australia. Inset 4 is the most recent version of the radio spectrometer, used at Dapto, New South Wales, to record the rapidly changing wavelengths found in radio-emission from the sun during different types of outburst. This has been an essentially Australian contribution. Inset 8 shows the Australian version of a steerable radio interferometer.

FASTEST CAMERA

A short account of what is probably the world's fastest camera has been given in *Physics To-day*, published by the American Institute of Physics. It has been developed at the Los Alamos Scientific Laboratory for the photography of explosions, and achieves the astonishing speed of 15 million frames per second, 96 consecutive exposures being taken on standard 35-millimetre film in about 1/150,000th of a second. The camera is of that class in which a beam of light is directed by a lens of long focal length on to a rapidly rotating mirror by which it is directed on to each in turn of a series of small lenses, which form the

final succession of pictures. The primary source of speed is the very high rate of rotation, 23,000 revolutions per second; this is achieved on oil-pressure lubricated bearings in an atmosphere of helium. A further gain comes from the use of a three-sided steel mirror, which gives usable angles of reflexion in all positions. The mirror is made of a special steel with a tensile strength of more than 300,000 pounds per square inch, and is powered by a small helium-driven turbine. Finally, the high-speed shutter action needed to prevent double-exposure of the film is provided by an electrically detonated explosion which shatters a glass block in the light path between the primary lens and the mirror. The block is so mounted and the explosion arranged that the block is rendered opaque rather than being physically disintegrated; and the immediate shutter action is followed by the closing of a mechanical shutter.

Physics To-day, Vol. 7, No 8, p. 8 (August 1954).

SOME BOOKS RECEIVED

NUCLEAR SPECIES by H. E. Huntley (London: Macmillan & Co. Ltd, 1954), pp. 193, 21s.

Professor Huntley's book has the great merits that he takes a general view of his subject, strays from it only in minor respects for the sake of background, and writes with unusual clarity. The result is an account of the composition, properties, and, within reasonable limits, the theory of nuclear species, which justifies his own hope of providing a readable introduction suited to students of chemistry as well as physics, while offering something to the more advanced worker in physics and at the same time being 'intelligible also to the layman with scientific training'. With obvious reservations about future revisions, it should become a well-deserved classic.

ROCKET EXPLORATION OF THE UPPER ATMOSPHERE edited by R. L. F. Boyd and M. J. Seaton in consultation with H. S. W. Massey, F.R.S. (London: Pergamon Press Ltd, 1954), pp. 376, 75s.

The ability to make direct observations of the upper atmosphere at limiting heights which have so far ranged from 75 to about 200 kilometres according to the type of measurement has been the scientific legacy from London's V2 bombardment. The present handsomely produced volume contains the papers presented at a conference arranged in August 1953 at Oxford by the Upper Atmosphere Rocket Research Panel of the United States and by the Gassiot Committee of the Royal Society. The combination of technical, experimental, and theoretical interest which are about equally represented make it of wide appeal, subject to price.

MAN AND ENERGY by A. R. Ubbelohde, F.R.S. (London: Hutchinson's Technical and Scientific Publications, 1954), pp. 247, 18s.

It may be said of Professor Ubbelohde's book that it 'germinated out of talks on the B.B.C. Third Programme'; alternatively that it is about the development of man's sources and use of energy and the

problems that these raise, about the understanding of energy contributed by his own subject, thermodynamics, and about some of the consequences of thermodynamics and of 'limits laws' in general. But essentially it is Professor Ubbelohde enjoying himself, as much as explaining and pointing or half-suggesting morals, and an experience to be shared.

SCIENCE AND THE COMMON UNDERSTANDING by J. Robert Oppenheimer (London: Oxford University Press, Geoffrey Cumberlege, 1954), pp. 127, 10s 6d.

The B.B.C. Reith Lectures for 1953 are here published in book form essentially as broadcast. They consist, as to the first four, of a historical development of the idea of an inherent complementarity between the physical concepts of waves and particles; and, as to the two last, of possible similar, but not necessarily identical, interpretations first in other departments of science and then in human affairs. The criticism of the book, as of the lectures, is that, for the general reader the approach to complementarity is slow and its significance difficult, while the proposed extensions of the principle, if stimulating as ideas, are but lightly sketched.

THE DISTRIBUTION OF THE HUMAN BLOOD GROUPS by A. E. Mourant (Oxford: Blackwell Scientific Publications, 1954), pp. 438, 42s.

For the specialist reader Dr Mourant has provided as complete a review as possible of research on the distribution of human blood groups since the publication of Professor W. C. Boyd's *Blood Groups* in 1939; for those interested primarily in results there are maps displaying the results of all work to date on three (out of nine) systems. The fact that the other six are not so displayed is one indication of the large amount that still remains to be done; another is that there is information about only one system in the case of the U.S.S.R. In relation to Heyerdahl's (Kon-Tiki) theory that the Polynesians are the result of two distinct migrations from America, the author states that evidence in respect of three systems is consistent with Heyerdahl's theory, and that, even if this were otherwise proved untenable, 'there would still be a strong suggestion that Polynesians and North American Indians had in the not very distant past received many genes from a common pool'.

THE ENGLISH CLIMATE by C. E. P. Brooks (London: English Universities Press, 1954), pp. 214, 12s 6d.

Dr Brooks worked for many years in the Climatology Division of the Meteorological Office, and was its assistant director. He writes easily, is sparing in his display of statistics, and discusses climate not only in terms of those factors which make it 'bracing' or 'relaxing', but also in relation to working efficiency, on which he has devised a provisional marking system, and even the choice of sites for houses.

PEARS CYCLOPAEDIA (Isleworth: A. & F. Pears Ltd, 63rd —edn, 1954), pp. 1008, 12s 6d.

Primarily *Pears Cyclopaedia* is a well-trying source of information on an extraordinary variety of subjects, backed for some readers by nostalgic memories of the flags of the world seen together and in colour at an early age. An innovation in the new edition is a 60,000-word section on modern science written in plain language. The point of view is that of man in the universe and society, and both selection and treatment are, by and large, excellent.

ABOUT OUR CONTRIBUTORS

A. P. BARNETT came up to King's College, London, when he was 16, took a first in chemistry in 1948, then a Ph.D. in the Theoretical Physics Department. In 1951 he took part in the Shelter Island Conference, organized by the U.S. National Academy of Sciences, on valence theory, his main subject of research; then became interested in several uses of small digital computers, including mass spectrometric analyses of petroleum. He has worked with the British Rayon Research Association, and in August 1953 was awarded a Senior Government Research Fellowship.

M. BONDI was a student at Newnham College, Cambridge, and obtained her Ph.D. in 1950. She has worked on the theory of stellar structure with F. Hoyle and H. Bondi.

BONDI was born in Vienna in 1919 and came to Cambridge in 1937 as an undergraduate at Trinity College. He has been a Fellow of Trinity College and a Lecturer in Mathematics at Cambridge University, and is now Professor of Mathematics at King's College, London. His main interests have been in astrophysics, and he has worked in this field with T. Gold, F. Hoyle, and R. A. Lyttleton.

V. BUTLER, who has been a lecturer at Edinburgh University, a Rockefeller and a Courtauld Fellow, is now Professor of Physical Chemistry in the Chester Beatty Research Institute, the Royal Cancer Hospital, London. Among his publications are a text-book on *Chemical Thermodynamics*, and a popular account of the nature of life *Man is a Microcosm*. He is also joint editor of *Progress in Biophysics* and *Biophysical Chemistry*.

FOX obtained a degree in physics at Sheffield University, after service in the R.A.F. on radar. He entered Unilever as a production management trainee, and proceeded via chemical engineering to the applications of mathematics in industry. He is now working for Port Sunlight on the production management side.

KAHN is a Research Fellow in Astronomy in Manchester University. Born in 1926 in Germany, he came to England in 1938. He studied mathematics at Oxford, then worked for two years with Professor Sydney Chapman; became interested in interstellar material through reading an account of the 1947 Harvard Symposium; and

spent the last year working with Professor J. H. Oort in Leiden. Married, one daughter.

B. NICKERSON took a degree in zoology at King's College, New castle upon Tyne, and is at present working for the Anti-Locus Research Centre in London on insect pigmentation.

C. H. WADDINGTON, F.R.S., is one of the best known of present-day embryologists and geneticists. He is Professor of Genetics and head of the Institute of Animal Genetics in the University of Edinburgh.

J. W. WESTWATER was born in 1919, obtained a B.S. in chemical engineering from the University of Illinois in 1941, and in 1944 received the first Ph.D. granted by the University of Delaware. He became interested in the phenomena of boiling twelve years ago at Delaware, and expects to continue with their study definitely.

G. M. WYBURN graduated at the University of Glasgow in 1929. From 1929 onwards he has been in turn demonstrator, senior lecturer in anatomy and, since 1948, Professor of Anatomy in the university. He was twice awarded the Struthers Gold Medal and Prize - for work on embryology and on the repair of peripheral nerve damage.

