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Every branch of science starts on the playground of savants, and it is only later that the playthings prove to be mighty weapons in man's everlasting struggle for a better existence. Experimental embryology is still largely at the playground stage, but it can already be seen that it offers immense possibilities for human welfare. Some of these possibilities—as well as the potential dangers of recent developments in this field—are discussed here at some length.

Discovery and invention now have such an important place in the life of mankind that a detailed and objective analysis of the conditions in which they arise is urgently necessary. Such an analysis can only be made on the basis of a comprehensive and detailed survey covering every branch of pure and applied science. But a more limited survey can pin-point the most characteristic features and aspects of scientific discovery and invention, and direct attention to the special factors involved.

This selection from the works of T. H. Huxley gives the characteristic views on science, on society, on civilization, on education, on philosophy, morals and ethics of an eminent nineteenth-century scientist who firmly believed that scientific method could clarify politics and morals just as surely as it was revolutionizing everyday life.
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WARNING AND PROMISE OF
EXPERIMENTAL EMBRYOLOGY

by

H. V. BRONDSTED

Dr. Brondsted is professor of general zoology at the University of Copenhagen. He is the author of various scientific books and papers on cytology, embryology and the problems of regeneration. He has also written several semi-popular books.

Most branches of science have such an obvious impact on society that it can be seen and felt by everybody in his daily life and work. Never have the medical sciences aroused so much public interest as in our own day. Nuclear physics, because of the enormous potentialities it offers in the field of energy production, has caught the imagination of the man in the street in a way which would have astounded the unworldly physicists of the thirties. Genetics has gained widespread recognition in barely fifty years, because of its success in plant and animal breeding. This is natural enough, since health, energy and food are foremost among man's desires.

Experimental embryology is a science of about the same age as nuclear physics and genetics. But unlike these it has few spectacular features which might appeal to the ordinary man. Every branch of science starts on the playground of savants, and it is only later that the playthings prove to be mighty weapons in man's everlasting struggle for a better existence. Experimental embryology is still largely at the playground stage, but it can already be seen that it offers immense possibilities for human welfare. In due course, its impact on society may be no less than that of other sciences.

Mysticism and superstitions, unparalleled in other biological fields, have prevailed in popular notions concerning foetal development. The hidden processes in nature are regarded as the most mysterious ones; and veil upon veil have covered the seemingly miraculous processes which take place in the depths of the pregnant woman. On the other hand, the development of the chicken in the egg, or the transformation of a frog's egg into a tadpole, are so unconcealed that they are taken for granted. Thus the laws governing the dynamics of embryogenesis were not sought for until recently, not much more than half a century ago. Since then experimental embryology has developed rapidly and is today an important and fast-growing branch of the biological sciences.

The methods it has developed and the facts it has established are important

enough in themselves to warrant public interest. But far more important are
the consequences which the progress of experimental embryology cannot fail
to have on the social plane. It is the purpose of this article to visualize some
of these consequences. But before attempting to do so, it is necessary to
outline some basic facts of experimental embryology.

GENOTYPE AND PHENOTYPE

When a sperm successfully penetrates an egg, and its gene-carrying paternal
chromosomes are mingled with the maternal ones, the building up of a new
individual may begin. A complicated biochemical machinery is set in motion.
The structure of this machinery may be called the genotype. But life has
always to fight its way in an ever-changing and precarious environment. The
life processes are, however, to a certain extent adaptable to circumstances,
and in thus adapting themselves they are more or less transformed. As a
result, life exhibits a great spectrum of phenotypes. Two identical brand-new
automobiles of the same make may, after some years, be very unlike one
another, if one has been used for elegant shopping and the other for hard
work on dusty highways and difficult mountain roads. After a while the two
cars, although 'genotypically' alike, exhibit very different 'phenotypes'. The
analogy is, of course, very unsatisfactory, but it may serve to clarify what is
meant biologically by the terms genotype and phenotype. In reality, the
genotype is an abstract notion, because living matter does not exist apart
from environment; in constantly adapting and transforming itself, it makes
the history of mankind. The living substance of the fertilized egg is perform­
ing chemical processes in co-operation with the environment; it is therefore
itself a phenotype. The word genotype is best defined biologically as rather
firmly fixed trends of the integrated sums of biochemical processes, eventually
leading to an increasing complexity of chemical (morphological) structures
and functions.

Genetics concerns itself basically with the genotype, although it is forced
to make its investigations on phenotypes; as far as possible it therefore rules
out environmental influences. Experimental embryology, on the other hand,
deals with the phenotypical development of genotypes by changing the
environment. This is not easily done in mammals because the foetus is not
easily accessible.

It may legitimately be asked whether the environment of the embryo in
the mother's womb is not stabilized so as to guarantee a strictly fixed
unfolding of the given genotype without any deviation from the given path.
In fact, so strong has been the notion about strictly fixed laws for the develop­
ment of the human embryo that the outcome of pregnancy, the new-born
child, has been regarded as a true expression of the genotype, without inter-
ference of environment other than constant temperature and a constant flow of food and oxygen. Until recently, deviations from the genotypically anticipated phenotype were regarded as rare exceptions. It was thought that the child is what it is, almost exclusively on account of its genotype, the environment being considered constant. The popular notion, too, expressed itself in a widespread fatalism concerning gestation and its outcome: 'It could not be otherwise.'

Now that certain facts have been brought out by experimental embryology we are, however, facing an entirely different situation. We are, above all, facing the fact that the environment does change in the mother's womb, and that human embryonic development is affected by changes in environment. That is why experimental embryology has reached a stage at which it may contribute substantially to the welfare of future generations—provided that its potentialities in this direction are better appreciated by society at large, and by those in authority in particular.

**THE BASIS OF EXPERIMENTAL EMBRYOLOGY**

Lower animals have been the main source of information in experimental embryology, because they are comparatively easy to handle. However, certain generalizations have been arrived at which are valid for mammals and which have been proved, by very recent experiments and by inference, to be valid also for human beings. The basic facts are as follows.

The fertilized egg cleaves in two, then into four, eight, sixteen, and later in an irregular number of cells. In man the egg thus divided eventually forms a little hollow sphere a few tenths of a millimetre in diameter, called the blastocyst. If all is normal in the maternal environment, the blastocyst attaches itself after about ten days to the uterine wall. Some of the cells penetrate the superficial cell layer of the uterus, its epithelium, and during rapid cell multiplication grow into the mucous membrane of the uterus. This excessive growth of the embryonic cells into the uterus is in fact a kind of parasitism; the cells of the parasite get all their needs from the cells and the blood of the mother. The parasitic growth is so rapid that it exceeds even that of the most malignant cancers. But whereas cancer destroys the invaded tissues, the embryonic cells, on the contrary, stimulate the uterine cells to rapid proliferation and to the organization of new blood vessels; thus a new organ, the placenta, makes its appearance. In this organ the maternal and foetal tissues are interwoven in an exceedingly complicated way. But whereas billions of cells from the two individuals are in close contact, they never fuse. Material (food, vitamins, oxygen, hormones, water, excretions, etc.) transferred from mother to foetus or vice versa has always to pass a cell boundary called the placental barrier. Blood from the mother never passes
directly into the vessels of the embryo. Therefore, the foetal tissues in the placenta are everywhere a genotypical entity separate from the mother—as is proved by the difference in blood groups. A certain competition between maternal and foetal cells exists in the placenta, the foetal cells generally being more effective in picking up necessary substances if the stores available are scarce.

The foetus itself develops from a little clump of cells in the wall of the blastocyst; elaborate wanderings of cells and excessive cell divisions give rise to the various organs. A description of these processes can be found in any elementary textbook of embryology and is beyond the scope of this article. Moreover, it is not necessary for the understanding of the facts and arguments set forth here.

As might be expected, the basic pattern of organization of the primordial foetal cells into an embryo is the same in all vertebrates, including man. Human beings have inherited from ancestors in remote epochs certain basic genes which are and must be at work in order to ensure the continuity of the history of life. The function of genes is to set up certain chemical processes in the cells. They do this by starting the formation of a host of enzymes. Enzymes are generally exceedingly complicated molecules, mostly consisting of a protein substance, the apo-enzyme, and a more simple substance called the co-enzyme. The latter often contains vitamins and is therefore a prerequisite for normal development. This should be noted because later on we shall speak of maldevelopment due to lack of vitamins.

The enzymes, hormones and related substances act inside the cells, and from cell to cell, in such an orderly manner that some of the primordial foetal cells are chemically directed into certain future functions; they are, as we say, determined. Later the cells begin their functions as specified organ cells and are then said to be differentiated.

Now, it was found that from cells at a certain place in the very young embryo, and prior to any visible organ formation, a chemical force emanated, determining neighbouring cells to differentiate themselves into the rudiment of the nervous system. If such powerful cells were transplanted into other sites of the undifferentiated embryo, they determined the cells in this place to differentiate into a nervous system. So, by altering the environment, some cells could be made to deviate from their normal genotypical path of development.

The discovery of this fact was rightly regarded of fundamental significance, and Hans Spemann was awarded the Nobel Prize for it in 1935. We do not yet know the exact biochemical processes involved in this amazing feature, but we find them everywhere in the developing foetus. This process of determination is called induction.

Another very important fact arises from these experiments. When some cells in the very young embryo can be determined to differentiate into some
future function other than the normal one, they are said to be plastic, i.e. to have several potentialities; which one is to be realized depends on the environment—the neighbouring cells. This fact is the basic clue to understanding how a great variety of malformations or even monsters are produced.

SIAMESE TWINS AND OTHER MONSTROSITIES

It is quite easy experimentally to produce twins in all classes of vertebrates. If, for example, the two cells of a frog’s egg only once divided are separated, each cell will continue to divide in the usual manner, and each will eventually develop into a new individual. Whether both or only one of the two individuals develops into well shaped embryos depends, however, on the direction of the first-division plane. It is imperative for the development of two well shaped embryos that the first-division plane of the egg go through that part of the egg which later will contain the cells endowed with the power to induce the formation of the nervous system. If the first-division plane separates the egg into two cells of which only one contains the potent material, then only this cell will develop into a normal embryo; the other cell, lacking inducing qualities, will sooner or later die without having developed any organs.

If the experiment is done in such a way that the separation of the two cells is incomplete, all sorts of duplications may be produced: monsters with two heads but one abdomen, with two tails but one head, and all kinds of intermediates.

Just the same may be done in all stages of the embryo prior to organ formation, that is, so long as the embryonic cells are not yet determined. In fact, all sorts of Siamese twins known in human teratology can be produced experimentally, not only in fishes, amphibians, reptiles, birds, but recently also in mammals. Experimental embryology has therefore raised the veil covering the causality of the formation of human monsters such as cyclops, four-legged children, two-faced gnomes and so on. We now know that the first stages of the human embryo, after uterine implantation, are a very critical period during which the utmost care as regards the best maternal environment is necessary for the embryo.

The above experiment is not dependent solely on mechanical separation of the egg halves; it may also be performed with chemicals. Calcium-free culture media, for example, loosen the adhesiveness of the cells so that only a gentle shaking is enough to separate them. We do not yet know the cause of complete or partial separation of early embryonic cells in human beings, but it is conceivable that comparatively small alterations in the chemical environment in the uterus are enough to bring about a more or less complete separation. If complete, identical twins ensue. If incomplete, then according
to the degree of incompleteness, all sorts of Siamese twins or other monsters are formed.

Using certain chemicals, it is possible to interfere with the movements of the cells in early embryogenesis. If certain enzymes in the cells are poisoned, the cells themselves may either be delayed in their normal routes, or stopped altogether, or they may be forced to deviate from their ordinary pathways. Thus various cells do not meet one another at the proper sites, normal contact is upset, the inductive processes manifest themselves in wrong places and, as a result, monsters or malformations ensue. Certains chemicals passing through the placental barrier in human beings may thus produce monsters hardly recognizable as human beings in origin, grotesque phenotypes caused by abnormal environmental factors. It is fortunate that such monstrosities are seldom carried through to term; they are generally aborted rather early without the mothers seeing them.

Thus experimental embryology has given us the clue to the understanding of the genesis of such monsters. We shall repeatedly revert to the fundamental notion of false induction processes.

QUALITY AND QUANTITY IN ORGAN FORMATION. THE BRAIN

Normality is a misused word in biology as well as in popular language. What is understood by the phrase 'a normal human being'? In current medical language, the word tends to mean 'average'. Average weight and size is often, quite falsely, called the 'normal', the 'norm', that which is desired and longed for. Uniformity as the desired goal for mankind! What a horrible thought! Nature itself favours diversity, both genotypically—by way of mutations and of intermingling of genes by nature's great invention, sexual propagation—and phenotypically. Diversity is at the core of all evolution. All individuals are different from one another—quantitatively on account of size, colour, etc., and in their chemical variability. The differences affect all organs. But differences in size do not affect the function of all organs in the same way. Hence the quality of different organs is differently affected by quantity. Short legs may be as effective as long ones, although they are made up of fewer cells. But small kidneys may affect urinary secretion unfavourably. Still more seriously, quantity affects the quality of the brain.

Within certain limits the weight of the brain seems to be without apparent influence on intelligence, but below a certain limit in the amount of cells mental deficiency ensues. The brain is a very complicated organ, consisting of a host of anatomical structures. Its genesis in foetal development is also therefore very complicated, depending on extremely intricate cell movements and cell determinations. It is, in fact, little short of a miracle that the ten thousand million cells found in by far the greater majority of cases co-operate
in foetal development in so orderly a way as to make an organ of such amazing powers as the brain of an ordinary man.

Genetics is much concerned with speculation as to whether intelligence in general—a very vague concept—or some specified quality of a mental order is inherited in the same way, i.e. obeying the same basic Mendelian laws, as are other bodily characteristics. It is difficult to consider seriously much of what has been said about the inheritance of certain mental qualities, particularly so long as we do not know how great a part environment plays in producing intelligence and other mental qualities. Too much weight should not be given to the more or less fanciful prophecies that in the atomic age geniuses may be created by increasing and directing mutation rates.

The science of brain physiology and mental functions is still in its infancy. Nevertheless, rudimentary and fragmentary as our knowledge in this field may be, some facts have been established. The brain is an intricate system of organs. A proper functioning of this complex biochemical mechanism is dependent on the smooth functioning of every part, and on the orderly telegraphic transmission of impulses through the nerve fibres connecting the individual parts to the whole. These parts are, of course, composed of nerve cells, each giving rise to fine cytoplasmic processes which differ in kind, some of them being short-range connexions with neighbouring cells, others distant-range connexions to distant parts. Thus we see that complicated anatomy is necessary for complicated physiology. This is also borne out by studying lower mammals and lower vertebrates, where it may be seen that the grade of behaviour pattern is, generally speaking, closely allied to the grade of the brain's anatomical pattern. Therefore, the number of cells and nerve fibres in the brain is a decisive factor of function. The number is largely determined genotypically, and that is why the genotype has been regarded as the sole factor in determining the level of intelligence.

Another fact has contributed to this concept. Several congenital anatomical brain deficiencies—e.g. various forms of microcephaly and hydrocephaly—have been proved to be inheritable: they follow, mostly recessively, the Mendelian laws. Here, surely, the number of brain cells formed during embryogenesis is decisive in producing the low grade of intelligence. But not all congenital brain deficiencies are genotypically determined. Experimental embryology has recently shown that environmental factors may also produce the very same malformations. Here, too, the number of cells formed during embryogenesis is decisive. This leads us to very serious considerations, because environmental factors, when graded in strength and influence, produce malformations in a correspondingly graded fashion. Therefore, whereas the genotype determines either a total malformation or none at all (only slightly modifiable by environment), environment determines malformations which are graded. This means that we have to face a crucial problem: to what extent are environmental factors during embryogenesis responsible for
the diversity of human brains? To what extent is the hardly definable but still real variability of intelligence and of other mental features dependent on foetal brain development?

It seems that we are concerned with three main factors in the shaping of human mentality: a genotypical, a foetal-environmental, and a postnatal-environmental factor. Experimental embryology has shown that the second factor, the foetal environment, plays an important role. And we are beginning to realize how this role is being played.

When the cell movements in the very young foetus, prior to organ formation, have stopped, induction sets in. The cells which form an epithelium on the dorsal part of the embryo are induced to transform themselves into a central nervous system. The main principles are the following: the epithelium of the prospective brain and spinal cord has the shape of an elongated plate which soon, by curling its edges upward and inward, transforms itself into a tube. A series of cell proliferations now starts from the cells lining the inner face of the tube. Every cell divides into two sister cells. One of them, going outwards, is determined to one or other kind of nerve cell, the kind being dependent on its location among the neighbouring cells. The other sister cell remaining in the lining of the nervous tube does not differentiate, but after some time divides again and sends its new sister cell out into the wall of the neural tube, where it differentiates. And so on during embryogenesis. Thus the number of cell divisions decides the size of the nervous system, notably the brain. But the process resulting in differentiated cells is decisive for the orderly and efficient function of the brain.

Basically, both these factors, cell division and differentiation, are genotypically determined, but they may be influenced by environment. Environmental factors may suppress cell divisions altogether, and certain forms of hydrocephaly will then appear; or cell divisions may be diminished more or less in number, and we get more or less under-developed brains. Environmental factors may also influence the differentiation processes deleteriously by suppressing certain enzyme systems or hormonal processes; in this case the various parts of the brain may be put out of gear and thus the orderly and effective function of the brain will be diminished.

These are the main features of brain development, the knowledge of which is indispensable for an understanding of what follows.

Geneticists and embryologists are at present engaged on the problem of how environmental interference with foetal development may throw light on the biochemical processes which the genes are using in producing normal embryogenesis; but although the elucidation of these basic questions is of paramount importance, since they may give us the final clue to the understanding of life itself, it is too theoretical and technical to be discussed here.
It is well known that adequate food—not only in quantity but in quality—is necessary for pregnant women if they are to carry through their child-bearing. It is not so widely recognized, however, that good food conditions are also absolutely necessary for the normal development of the foetus. It is a common saying, even among physicians, that 'the foetus takes all it needs from the mother'. Experimental embryology has, however, recently shown that this opinion is only partly true. The facts underlying the popular view do not give the whole picture.

We all know about starving mothers bringing seemingly well-formed children into being. And it is true that the foetus, being a sort of parasite on the body of the mother, has an astounding power to derive its needs from the maternal blood. Now the maternal body, as the body of all other living animals, is able to store some food material for later use. Therefore, even if a mother is temporarily short of food, her body may have reserves of fat and muscles, which are used up primarily by the growing foetus. But we witness also many instances where starving pregnant women abort. It has been shown that many abortions or still-births are due to deficiency of vitamins or of the other necessary food elements. Extensive series of well-controlled experiments with animals, notably with rats, have proved this true. But these experiments have shown other grave and suggestive facts.

In experiments with rats, the future mothers, when still at a young age—just after weaning—were given a diet free of vitamin A. In order to secure growth and sexual maturing, carotene was administered; no storage of vitamin A in the body takes place with this diet. After conception, the carotene was withheld from the food. So we deal here with mothers of quite normal health at the beginning of pregnancy but devoid of the possibility of furnishing vitamin A to the foetus during embryogenesis. A high percentage of abortions followed. And a high percentage of the young brought to birth showed a great variety of malformations; most frequent were those affecting the eyes, but the urogenital system and the blood system were also affected. If the mothers were given high doses of vitamin A at certain stages of gestation, the percentage of malformations was reduced. Moreover, a very interesting fact was brought to light: it was found that the kind of malformation which was reduced by administering vitamin A was dependent upon the time at which vitamin A was administered in relation to the formation of the organ in question. If the vitamin A was given early enough in relation to the determination of a given organ, the development of the organ was normal. This is logical if we remember that vitamins are part of the co-enzymes necessary for normal cell division and normal cell function.

Other vitamins were tested in the same way. Deficiency of one of the vitamins B, riboflavin, resulted in skeletal malformations: shortening of
mandible and extremities, syndactylyism, fusion of ribs, cleft palate, etc. Here, also, a dose of riboflavin in the diet of the mother could prevent malformations, provided that it was administered before a certain stage of foetal development.

Another vitamin B, pantothenic acid, was tried for its possible effect on embryonic development. It is now certain that deficiency of this vitamin produces congenital malformations of eye and brain, the latter having, of course, very wide effects.

Congenital malformations of genetic origin are, as has been said above, mostly uniform in appearance. In the experiments it was found that congenital malformations due to dietary deficiencies varied in appearance, ranging from very severe ones to ones barely recognizable. Therefore, if the diet of the human mother is slightly deficient in vitamins necessary for brain formation during embryogenesis, it can be inferred that some instances of mental deficiency in children may be due to this lack. Hence these experiments open up wide social perspectives. If we wish, as we certainly do, that as many children as possible be born with the best possible brain development, then the best possible diet, both quantitatively and qualitatively, should be assured to all pregnant mothers. Where there is widespread poverty, it might be preferable to bring into the world fewer but well-formed children rather than greater numbers of inferior quality.

It remains to be seen whether the often postulated lower intelligence quotients of very poor populations may not, in part at least, be ascribed to food deficiencies.

We do, in fact, know that the lack of some necessary trace elements in food, e.g. iodine, causes cretinism; and the degree of cretinism seems to be definitely correlated to the extent of the deficiency of iodine in the mother's diet. The point is that dietary deficiencies are graded; therefore the malformations are also graded. This may be of less importance if they affect the simpler organs, such as the limbs, the ribs, etc., etc.; but the problem gains in importance when the organs are more complicated.

Another important question concerning vitamin deficiency has also been raised by experimental embryology, viz. the problem of fertility.

In embryonic development there are two very critical periods in deciding whether a foetus is to be formed or not; one is the fertilization of the egg, the other is the implantation in the uterine wall. Both have been proved experimentally to depend on the proper vitaminization of the female. In human beings, the problem is rather obscure, because so very many factors may influence these very subtle and delicately balanced biochemical processes. But as we know from animal experiments that vitamin deficiencies impair the two processes, it is of paramount importance that potential human mothers be well vitaminized.

A word of warning must be said in this connexion. Vitamin requirements
vary from one individual to another, often because of slight intestinal dis­
turbances which result in difficulty in assimilating vitamins from food, even
when it is rich in vitamins. The average amount of vitamins necessary for
average individuals may be too small. Therefore, an excess of vitamins for
potential and pregnant mothers is indicated.

RADIATION AND EMBRYONIC DEVELOPMENT

The widespread and increasing use of X-rays for diagnosis, by means of
fluoroscopic machines, constitutes an obvious danger of damage to embryos.
The pelvic region of women is the seat of a great variety of diseases which
may be diagnosed by fluoroscopy. The dose of X-rays used is measured in
units called $r$ (one roentgen). Many fluoroscopic machines emit more than
30$\text{r}$ per minute. This means that during a diagnostic investigation of five
minutes, for example, the deeper parts of the pelvic region may be exposed
to at least 150$\text{r}$.

X-raying as a therapeutic tool involves the use of much more energy than
that emitted by fluoroscopic machines; hence there is danger of damaging a
foetus. Whereas this is recognized by radiologists, the danger of using X-rays
for diagnosis by means of fluoroscopy is not always realized. But experimental
embryology has recently shown that such a danger does exist.

Pregnant animals have been exposed to X-rays of different doses and at
different periods of pregnancy. It has been found that a dose of only 25$r$
produces a certain percentage of malformed new-born. The malformations
may affect many different organs, the most serious being those affecting the
brain, eyes and other parts of the nervous system. But all malformations,
ranging from gross ones to those which are only just perceptible, are
encountered.

Before radiologists had realized the danger of foetal maldevelopment when
the pregnant mother was treated therapeutically with X-rays, all sorts of
abnormalities were reported among new-born children from such mothers.
Among the great variety of these may be mentioned microcephaly, hydro-
cephaly, co-ordination defects, mental deficiencies of slighter gravity, mon-
golism, cleft palate and deformed limbs. Radiologists are now therefore
careful to screen off the foetus if irradiation of some organ in the woman's
pelvis is necessary in order to save her life, and if the necessary dosage
exceeds that which is known to produce malformation. When there has been
no evidence of malformation as the result of small doses, it is tempting for
the radiologist to treat the mother with small therapeutic doses without
screening the foetus. Experimental embryology, however, has recently shown
that irradiation of lower intensity may produce malformations which only
appear later in life, a long time after birth. Therefore, care should be
exercised with small therapeutic doses and even with diagnostic ones.

Recently, experimental embryology has brought out some other significant facts. Roughly, embryonic development may be divided into five periods:

1. Fertilization of the egg.
2. Cleavage of the egg until implantation in the uterine wall (about ten days).
3. Period of major organogenesis in which the gross formation of the organs takes place (from first to third month).
4. Period when finer modelling of organs is finished (fourth to sixth month).
5. General growth and maturing of the foetus (seventh to ninth month).

Experiments, notably with rats, mice and sows, have proved that the periods corresponding to the first, second and third periods of gestation in man are the most sensitive to X-rays. We do not yet know exactly why this is so. But evidence points to the conclusion that young embryonic cells still undifferentiated are more sensitive than differentiated ones. At this stage the cells are just about to divide, or to elaborate the enzyme systems and hormones which later differentiate them. It may be said that they are more sensitive to environmental influences because their metabolic mechanisms are, as it were, in a state of flux. It is also highly probable that the chromosomes are more liable to break, and so disturb the cell severely, at a stage called prophase, prior to cell division.

In man, the most critical stage is found within two to six weeks of the third period of gestation. In all experiments with animals it has been found that the percentage of malformations is three to four times larger when irradiation has taken place in this early phase of embryogenesis. Now it very often happens that a woman is not aware of pregnancy during the first part of the period of major organogenesis. Hence much foetal damage may be the result of even small doses of X-rays. Fluoroscopy may be sufficient to produce damage to the young foetus. In addition, harmful mutations in the eggs of the ovary may take place.¹

Another question concerning the deleterious effects of irradiation on the foetus has not yet been answered, though investigations on animals are in progress. We do not know whether irradiation of parts of the pregnant woman other than the uterus has any effect on the foetus, either by a scattering of the rays or, secondarily, by poisonous substances emanating from damaged cells in the irradiated organ. It is almost certain that such poisons will be carried by the blood stream to the placenta; it is possible that they consist of such small molecules that they are able to cross the placental barrier and enter into the foetal circulation, thus impairing normal development.

The possibility that comparatively small doses of radiation reaching the very young embryo may cause malformations, or at least macroscopically undetectable injuries, notably in the brain of the foetus, should be given


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serious consideration. Female labour will almost certainly be used in many new industries where it will be exposed to radiation. Strict precautions against radiation are already in force; but all restrictions have their loopholes, and huge economic interests may be tempted to underrate the danger of radiation, particularly in view of the possibly high costs of precautionary measures. Carelessness is to be feared, both on the part of the administration and among the workers themselves.

Experimental embryology has thus an important role to play in the atomic age which we are entering. Its findings must seriously be taken into account if society is to avoid not only intolerable individual grief but also an immense economic burden in the form of care for the maldeveloped, the feeble-minded and the idiot.

A report on investigations on children borne by women who went through Nagasaki and Hiroshima is a terrible warning of the dangers of the atomic age. These investigations were carried out in 1951, six years after the catastrophe. In the hypocentre—an area of 2 kilometres in diameter immediately beneath the point of the explosion—among the 1,774 women of childbearing age who survived, 98 were pregnant. Twenty-eight per cent of the foetuses died before normal birth. For comparison, 1,774 women living outside the hypocentre were examined: 113 of them were pregnant. Only 2.6 per cent of the foetuses died prior to normal birth. It has been ascertained that the death rate was greatest among foetuses which had not reached a foetal age of three months when the explosion occurred. This is quite in accordance with the findings of experimental embryology that the period of major organ formation is a very sensitive one. Several of the children born to term died during the first year after birth, others in the following few years. Body length of surviving children borne by heavily hit mothers was 3 cm. shorter on average than normal, their weight 2 kg. less five years after the bombing—a sign of lesser viability. The circumference of the head was 2-3 cm. less than normal, indicating an underdeveloped brain. Some of the children were not able to articulate normal speech at the age of five years. Some children from the hypocentre of Hiroshima also showed severe mental deficiencies. As to the genetic consequences, investigations are in progress and the progeny of the people living in the area of the bomb's impact is under constant supervision. Naturally nothing can be known of deleterious mutations before at least two generations have been produced.

HORMONES

We do know that, rather early during foetal development, the primordia of internal secretion glands produce hormones which seem necessary for normal development. Changes in the balance of this chemical system must necessarily
cause malformations. But since we know next to nothing about the external factors which cause such changes, we had better leave this problem aside, however interesting it may be. Here a few words may be said, however, about experiments with hormones given in rather large doses to the mothers (rats) and causing certain malformations in the foetus.

Cortisone and ACTH (a pituitary hormone) have been studied intensively, as they have given good results in the treatment of certain diseases (arthritis, etc.). But we know that, for various reasons, these hormones have to be used with great caution. Experimental embryology now tells us that caution is also indicated when they are administered to pregnant women. At least, it has shown that large doses of these hormones given to pregnant rats with foetus at the critical morphogenetic stage will produce young with a cleft palate and other malformations, among them certain malformations of the brain. Here again we meet the important problem of a poor development of the brain during embryogenesis caused by environment.

We do not know the minimum dose of these hormones which will have a deleterious influence on the developing foetus, but experiments with rats certainly give a warning as to the medical use of ACTH and cortisone in pregnant women.

These experiments may perhaps throw new light on the old superstitions concerning the origin of malformations.

Stress provokes disturbance of the hormonal balance of the body. Is it possible that severe shocks in pregnant women in earlier stages of pregnancy might provoke such excess of pituitary, adrenal or other hormones that, passing through the placenta, they might interfere with normal embryogenesis and thus produce malformations? Experiments with animals give colour to the old popular notion that a malformed child was the result of the mother having had a terrible shock during pregnancy or having been scared by an 'evil eye'.

The hormone insulin, necessary for the carbohydrate metabolism, has been investigated as to its influence on developing chicks, and it has been shown that it interferes with the normal development of bones. So far, its possible influence on the mammalian foetus is still obscure, because of the hitherto insurmountable difficulties involved in administering the hormone to pregnant mammals in such quantities as might influence the foetus without causing irreparable damage to the mother animal. But the problem should be kept in mind.

POISONS AND EMBRYONIC DEVELOPMENT

It was quite a shock to physicians and embryologists when it became known—only little more than a decade ago—that rubella in pregnant women
caused severe damage to the foetus, including abortion, stillbirth, gross
deformation of head and brain, mongolism, malformations in the circulatory
system, diseases in the blood-forming organs, etc. If in the first two months
of pregnancy a woman is affected by rubella, the situation is considered so
grave that *abortus provocatus* is often resorted to. Rubella is a virus disease,
in itself fairly harmless. Why then should it be so disastrous to the foetus?
The causality is not yet known, but some conjectures concerning interference
with metabolic activities in the cells of the organ primordia have been put
forward. They are only conjectures, as we cannot experiment with human
beings, and a suitable experimental animal has not yet been found. There­
fore, other ways have to be resorted to in the attempt to elucidate the
biochemical mechanism which is put out of gear when developing cells are
attacked by certain poisons. In recent years much work has been done in
experimental embryology in this direction. So far, this work has only
theoretical implications, but it is almost certain that the theoretical know­
ledge thus gained will lead to applications of great value in medical treatment.

The chemicals used in the experiments are mostly those which are known
to influence certain biochemical processes inherent in all cells, notably in
cells of embryonic character, i.e. cells not differentiated into definite patterns
of work. A further consideration in the choice of these chemicals has been
that some of them (sulfanilamides, boric acid), are used in ordinary treatment.
It is therefore of immediate practical interest to study their influence on
embryogenesis. Likewise, the nitrogen mustards, poison gases which are
known to have mutagenic effects in the same way as radiation, have been
investigated as to their influence on embryogenesis, and it has been proved
that they all produce malformations, both in the nervous and the skeletal
systems (e.g. syndactyli).

Very suggestive experiments have been made with a poisonous stain called
trypan blue. When given to the pregnant rat, the offspring show different
malformations, among them such severe ones as hydrocephalus. The trypan
blue could not, however, be demonstrated to have crossed the placental
barrier and penetrated the foetus. Hence, it is concluded that the poison in
some as yet obscure way secondarily produces deleterious chemical agents in
the maternal body; and it is assumed that these agents diffuse through the
placental barrier into the young foetus, where they interfere with normal
organogenesis, thus producing the malformations. Knowing that such in­
fluences are graded according to the dose of the deleterious agent, it is vital
to envisage the problem of poisonous chemicals in the food of the mother.
No pregnant woman is, of course, supposed to eat trypan blue, however
bizarre the taste of a woman in the earlier period of gestation may be; but
some of the chemicals used in preserving food, and certainly some medicines,
must be watched for their possible deleterious effects on the foetus. Research
in this field is urgently needed since such substances are in increasing use.
In several ways experimental embryology can make a significant contribution to the study of cancer.

Cancer tissue is composed of cells which have escaped the growth-controlling forces in the body. Every normal cell has the common quality of life—the ability to grow and multiply. Planted outside the body in tissue culture, most cells exhibit this quality. Normally, however, most of them stop this activity when a full-grown body has been attained. Only such organs as blood-forming tissues, intestines and other epithelia, in which a continuous loss of cells has to be replaced, proliferate throughout life, and even here an excessive proliferation does not occur.

It is one of the aims of experimental embryology to elucidate the physiological and biochemical forces which govern the multiplication of cells in an orderly manner during embryogenesis, and to probe into the question of why multiplication slows down and stops when the fully developed body has been formed. It has been found that the more specialized the state which cells have attained, the more they have lost their power to divide, to propagate. The nerve cell, which is highly specialized, has entirely lost this ability.

The cancer cell has retained the power of unrestricted proliferation, just as has the very young embryonic, and not yet specialized, normal cell. The more therefore we know about normal growth and proliferation, the more we shall learn about malignant growth. On the other hand, the more knowledge we accumulate about intercellular growth restriction capacities in the body, the more we approach the problem of why cancer cells are able to escape this restriction of growth.

All this is, of course, a much more formidable task than it may appear to the uninitiated. It is formidable because the pertinent biochemical processes take place in the proteins, and these are of so complicated a nature that our knowledge about them is still only fragmentary. Notwithstanding this incompleteness, we are approaching a solution along several biochemical paths, too technical to be set forth here.

Genetics has taught us about the mechanism of mutations, notably in the sex cells. We now know that essentially the same mechanism may be at work in all other cells in the body, the so-called somatic cells. If a somatic cell—say a liver cell or a cell in the skin or in the blood-forming tissues, i.e. in every place where a proliferation takes place at a steady rate throughout life—undergoes mutation its progeny will carry the stamp of this mutation, and hence a part of the tissue or organ will eventually exhibit a difference in appearance or physiological capacity from that of the rest. Such somatic mutations will, of course, die with the individual without consequences for future generations. But they may be injurious or even fatal to that individual.

It has been shown experimentally on animals, including mammals, that
chemical influences and irradiations may cause mutations in somatic tissue, and some of these mutations have proved to be cancer cells. Tumors in the ovary have been produced by X-rays. Leukaemia may be a sort of malignant growth; it has also been produced experimentally by chemicals and by X-rays. The incidence of leukaemia among radiologists has been shown to be ten times that of leukaemia among other physicians.

We do not yet know whether every kind of cancer cell is in reality a mutated cell; probably it is not, but some certainly are. A mutation means a new biochemical property, often resulting in serological alterations. This point is being studied intensively in modern experimental embryology. The cancer cell is immune to the surrounding cells to such a degree that it infiltrates them, dissolves them and uses them as nutriment; in fact, the cancer cell is a true parasite, the most predatory form of life known, often even unattackable by bacteria. And these qualities of the cancer cell are perhaps due to no more than one mutation.

It is commonly known that certain organic compounds are carcinogenic. Now it is very suggestive that some of the carcinogenic chemicals are also mutagenic. It has been shown that mutagenic substances may exert their fatal influence secondarily, through intermediate biochemical links. There is some evidence that chemical compounds may induce the formation of carcinogenic cells in the foetus: cancer in Western populations appears at an increasing rate in the younger section of the population, even in children and foetuses. We do not know the cause, but have to face the possibility that the same agents—irradiation and chemicals—that are known to produce foetal malformations may also be carcinogenic. Experimental embryology is much concerned with this vital problem.

DETERMINATION OF SEX AT WILL

Experimental embryology and genetics have been intensively concerned with the problem of sex. Geneticists have shown that the determination of sex is primarily dependent on gene activity. Experimental embryology has proved that environmental factors may override genetic inheritance. Nowhere else has the concept of genotype and phenotype proved itself so useful.

We know that in man sex is determined genetically by the male germ cell, the sperm. Two kinds of sperm exist. In somatic cells of women and men we find 46 chromosomes called autosomes. In the cells of the woman there exist, in addition, 2 chromosomes called the X-chromosomes. In the cells of the man we find, in addition to the 46 autosomes, only one X-chromosome, but also another chromosome called the Y-chromosome. All eggs in the ovary are produced by somatic cells, but in consequence of a very elaborate mode of division, the eggs contain only half the somatic chromosome number,
i.e. 23 autosomes and one X-chromosome. The sperms are also produced by somatic cells in the testes. But here the elaborate divisions result in the formation of two kinds of sperm, the one containing 23 autosomes and one X-chromosome, the other, 23 autosomes and one Y-chromosome. Presumably the two kinds are produced in the same quantity. An egg fertilized by an X-containing sperm will be equipped with 46 autosomes and two X-chromosomes, and hence eventually develop into a female. An egg fertilized by a Y-carrying sperm will contain 46 autosomes and one X and one Y-chromosome, and hence develop into a male. In the course of embryonic development, the genotypically determined sex will be further elaborated phenotypically with the help of hormones arising in the gonads. This phenotypical sex development may, however, fail, thus giving rise to intersexes known as pseudo-hermaphrodites. Cases are recorded where individuals at birth may, on account of physiologically and morphologically maldeveloped external sex organs, falsely be identified as being of the sex opposite to their genotypical one. Experimental embryology has provided extensive evidence that this interpretation of the causes of hermaphroditism is true. Experiments on mammals which are in progress hold out the promise of means enabling us to avoid sexual deformities of this kind.

Recently, certain other trends in experimental embryology have pointed to the possibility of determining the sex of the coming child at will.

The basic reasoning is as follows. Two kinds of sperm mean two kinds of chemicals, and therefore physiologically different male cells. In most animals the sex ratio is about 100:100. This is due to an equal number of male and female-producing sperms, as well as to a random fertilization of the eggs by the two kinds of sperm, which statistically gives of course equal possibilities for development of the two sexes. But environment may in many ways influence the sex ratio. In many animals we know the environmental forces (temperature, degree of moisture, etc.) which shift the ratio in favour of the female or—more seldom—of the male.

In man the sex ratio at birth varies to a certain extent from population to population: in Western countries figures of 120 boys to 100 girls are often found. In abortions in which the sex can be identified, up to 150 male foetuses to 100 female ones are reported. During the course of life the sex ratio shifts towards the female. In Western populations, the overall sex ratio is about 104 males to 100 females, the ratio being 100 to 100 at puberty but 90 to 100 in old age. Here, clearly, environmental forces are at work, but we do not yet know all of them. In the first place, we do not know whether equal amounts of X- and Y-carrying sperms are produced in the testes; we have, as yet, no means of recognizing the two kinds in an ejaculation. Secondly, we do not know whether the fertilizing power is the same in the two kinds of sperm. Thirdly, we do not know whether the eggs are equally fertilizable with both kinds. In the fourth place, we do not know whether
some factors in the female genital tract do not favour the Y-sperms during the fertilization act.

There is strong evidence, however, that this latter is the reason why males are much more frequent than females in the earlier embryonic stages. Among other facts, there is evidence that among first-born children the sex ratio is even more in favour of males than in the earlier embryonic stages. Incidentally, it may be said that this is the cause of the widespread belief that Nature is very wise in procuring more boys after a great war than normally. It is thought that Nature tends to restore the great loss of males. A very wide statistical investigation has recently shown that more boys than usual are born during a great war. But many more young people than usual marry during a war, apart from which many illegitimate children are born to very young mothers. Hence there are many more first births during a war than in peacetime, and thus the sex ratio shifts in favour of boys.

In planning experiments aimed at giving the one or the other kind of male germ cells a favoured access to the eggs, two lines may be followed; one lays stress on the assumption that the conditions in the female tract are decisive; the other regards this environmental factor as comparatively negligible and concentrates on eliminating either the X or the Y-bearing sperms, according to whether it is desired to get a majority of females or of males. Both lines of experiment have been followed.

The first is more difficult, because we know nothing about the nature of the physiological differences in eggs or other parts of the female genital tract which may favour X or Y sperms. Hence the experiments have been rather haphazard—not much more scientific, in fact, than the various attempts in ancient or primitive populations to influence the sex ratio by a kind of magic.

It has recently been claimed that the time of coitus in relation to ovulation may have some bearing on the problem. The leader of the experimental team obtained the consent of a considerable number of married couples to refrain from coitus except on days in the neighbourhood of ovulation, this being fixed at 14 days after menstruation. It was found that the longer the period which elapsed between coitus and the exact time of ovulation, the greater the number of boys conceived. There are, however, so many uncertainties involved in experiments of this sort that no very definite conclusions can be drawn.

The other line of research concerns itself with separation of the two kinds of sperm. The idea is, of course, that sperms differently endowed genetically have different physiological capacities, owing to their different chemical constitution. If it could be found how one kind could be eliminated experimentally and the other kept fertilizable, then we should be able to determine sex at will. Some of the experiments along this line may be related.

The resistance of sperms to alcohol is surprisingly great. In the popular view, alcohol has some influence on sex ratio, it being claimed that more
boys are born when the father is drunk at the time of coitus than normal sex ratio would account for. In rabbits, an animal with multibirth, it is possible to mate the doe with two bucks in rapid succession, so that some of the approximately ten ovulated eggs ready for fertilization may be inseminated by sperms from one buck, and the rest by sperms from the other. If the two bucks are of differently coloured strains, the litter will tell us if the experiment has been successful. This was done in a series of experiments in which the bucks of one strain were alcoholized. The result was that more males were born among the part of the litter which had been fathered by alcoholized bucks. Although the procedure certainly does not recommend itself to human beings, the experiment proves that the two kinds of sperm are differently influenced by certain chemicals.

Physiological differences in cells may also often express themselves in a different electrical charge on the cell surface. If a suspension of two sorts of bacteria is traversed by an electric current, each kind of bacteria will be carried by the current at a different rate, sometimes even in opposite directions, depending on the surface charge. Russian investigators have performed these experiments with sperm suspensions, with the result that X- and Y-sperms of bull semen were separated electrically; then the two kinds were used separately for artificial insemination. The sex ratio of the offspring is said to have been decidedly different in the two cases. It was therefore claimed that means had been found of determining sex at will. So far, however, the results have not been confirmed.

The Y-chromosome is smaller than the X-chromosome. This fact has fostered the suggestion that centrifugation might be able to separate the two kinds of sperm, the X-bearing ones being presumably heavier. It may be foreseen, however, that the experiment will not be successful because overall individual weight differences far override the weight differences due to the size of the X- and Y-chromosomes.

Definite results have not yet been obtained in the technique of determining sex at will, but safe methods are sure to be found, not only on account of scientific interest, but because economic interests are involved, cows being more profitable than bulls. And the question inevitably arises, will these techniques be used for man in connexion with artificial insemination, and which is to be the favoured sex? Fortunately, we have not yet to answer this question.

EGGS AND SPERMS OUTSIDE THE BODY

When considering the possible impact of experimental embryology on society, account must also be taken of the new techniques of artificial insemination and artificial egg implantation.
Artificial insemination of domestic animals is being carried out at an increasing rate. By this technique, which is of great economic importance, valuable genes inherent in certain bulls may be dispersed on a tremendous scale because the bull can fertilize the eggs of thousands of cows instead of a very limited number of them.

Moreover, a new technique now in operation ensures sperm viability long after its production in the testes. By rapid deep-freezing, it is already possible to preserve sperm for more than one year in such a healthy state that, after thawing, it is still able to fertilize eggs normally. Theoretically, the implications are tremendous. When the proper technique has been developed, it may be possible to preserve semen for the fertilization of eggs produced by remote future generations. The possibilities thus opened up for theoretical genetic research, and also for practical breeding, are obvious.

Artificial insemination seems also to be spreading rather rapidly in human society, and this gives rise to some very disquieting thoughts. Human breeding by this method may lead to the danger of a certain genetic standardization in human beings. In an age which has evolved scientific techniques of mass suggestion, there is surely the danger that women may be induced, for one reason or another, to crave artificial insemination from some 'demi-god' or 'superman' in order to bear a child with his stamp. History gives many examples of one man propagating his genes through many women—the practice of *jus primae noctis*, the religious customs of Islam and the Mormons. It is, of course, possible that in certain conditions the technique of artificial insemination might be of benefit to society, i.e. to the entire gene pool of a population. But there is also the danger of multiplication and dispersion of undesirable genes. Moreover, this sort of polygamy would certainly be abhorrent to the way of thinking of wide sections of society.

Nevertheless we ought all to know that the technical conditions for this sort of polygamy on a wholesale scale already exist. We ought all to see to it that artificial insemination is under strict control. To my way of thinking, we should discourage the indiscriminate use of this technique. The real danger is that, in future, we might come to tolerate its systematic use.

Eggs and the resulting foetuses have always been regarded as so intimately belonging to the mother that they were thought of as being inseparable. Some years ago, however, a technique was developed by which fertilized eggs could be transplanted from the mother animal to the uterus of another female which had been physiologically prepared for pregnancy by copulation with sterilized males. In this way it has been possible for strong and well-sized females to mother offspring originating from strains which, though feeble, possessed some desirable genetic traits. This procedure has also been used in theoretical investigations aiming at elucidating possible environmental influences on the developing foetus.
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Recently the whole problem has been significantly widened in scope. By means of a refined technique, fertilized rabbit eggs have been removed from the phallopian tubes, cooled down, sent from one continent to another by air, and implanted successfully in physiologically prepared does, which then gave birth to normal young.

A doe normally produces about ten eggs per ovulation, but by hypophysial injection it may be induced to produce about thirty. Particularly valuable genes from a certain doe may in this way be propagated more widely by letting several of the eggs be mothered by other females. This technique also opens up certain perspectives in human breeding but these can never become a serious problem for society, though they may be important in individual cases.

PARTHENOGENESIS

It is now generally known that some lower animals can produce young without fathers. This mode of producing offspring from unfertilized eggs, parthenogenesis, is widespread in the animal kingdom, as it is among plants. In fact, the male germ cell is not fundamentally necessary. The spermatozoon, by adding its genes to those of the egg, gives colour and variability to the new individual, and thus enhances its strength in the struggle for life. Therefore, sexual propagation is also an advantage in the evolutionary processes. But it is not a sine qua non for life's propagation, not even in such forms in which parthenogenesis is not found in nature. That this is so has been proved by experiments in artificial parthenogenesis. With proper techniques, unfertilized eggs of such widespread types as sea-urchins, worms, molluscs, amphibians and mammals may be induced to develop into foetuses or even sexually mature individuals.

It has been found that the sperm has two main activities. The one is to introduce a complete set of genes into the egg, the other is to activate the egg by stirring the outer layer of the egg, the egg-cortex, and induce cleavage of the egg by giving it some corpuscles called centrosomes. The two activities are separable. The second can be imitated artificially in various ways—by pricking the egg, by heating or cooling it, by treating it with certain chemicals, by shaking it, by stirring it electrically and so on. All these methods, varying from species to species, may induce cleavage, eventually resulting in the development of a new individual 'without father', i.e. without gene material from a male.

Thus the techniques vary accordingly to the species. But fundamentally, it is only a question of finding a proper technique to ensure 100 per cent success. So far, the experiments on mammals (rabbits) have been few, but if the problem were seriously tackled, a reliable method useful for mammals
could certainly be found. It may be worth while to find such methods in view of the economic interests involved. In domestic animals a strain cannot be bred absolutely pure so long as genes from two individuals are mingled in the new individual. Therefore, with the technique of artificial parthenogenesis, a certain very valuable genotype in, say, a cow, might be propagated pure, because chance deviations from the desired type due to new genes coming in from spermatozoa would be ruled out.

In several laboratories, there are actually in progress investigations which centre around a very interesting phenomenon discovered some thirty years ago. It is possible, by irradiation, to kill the chromosomes in the sperm without impairing the motility and activating power of the sperm. Even doses of up to 120,000 r are not able to prevent sperms from activating the eggs, whereas only a few hundred r destroy the genes in the chromosomes. By artificial insemination of frogs' eggs with irradiated sperms, the eggs were activated, and 93 per cent developed into foetuses. These were nearly all haploid, i.e. they only contained genes from the mother. Less than 1 per cent were diploid, i.e. they possibly contained genes also from the father. It is thought that this technique, when properly elaborated, may also be used in connexion with artificial insemination in cattle.

When this has been achieved, it may be expected that the technique may also be applied to human beings. Scientific curiosity knows no bounds. It will not be stopped. If successful, the procedure will give rise to quite new ethical and legislative concepts and problems. It is to be hoped that such matriarchy in the essential meaning of the word will always be relegated to the realm of science fiction. But of this we cannot be sure.

PSYCHOLOGICAL VALUE OF EXPERIMENTAL EMBRYOLOGY

Fear, when irrational in origin, is more harmful to mental health than fear induced by rational forces.

The laws of pregnancy and foetal development are still largely unknown, even in Western countries. At first sight this may seem incredible. But it is quite recently, and in certain countries only, that the subject has made its entrance into schools. This seems desirable, the old method of leaving it to parents having failed entirely. This kind of enlightenment does much to dissipate fear and to promote a rational, although not necessarily unethical, point of view towards conception and child-bearing. But there is still much to be done in this field.

The situation is, of course, much worse among less educated populations. We all know that healthy child-bearing gives happiness and deep satisfaction to parents of every country and of every class, even if nothing is known of the How, the When or the Why. But we also know how much mental pain a
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woman suffers if she is accused of infertility on religious and ethical grounds, or if, through no fault of her own, she has aborted or produced a stillbirth, or if she has given birth to a malformed child. All such abnormalities are linked up in the popular mind with ethics, guilt and sinfulness, and this causes added suffering to the parents, especially the mother.

If freedom from fear is one of our goals, every man and woman engaged in giving other people technical and mental assistance of any kind should be in a position to give information about sex and foetal development in a clear and straightforward manner. Basic knowledge of experimental embryology should thus be made more widely available. At least a certain knowledge in this field should be obligatory for advisors in family planning.

CONCLUSION

Experimental embryology is a pure science; but it has already given, and in the future will increasingly give, vital impulses to applied sciences, notably to medicine. It has been shown experimentally that congenital malformations of any sort may be produced by foetal environment. So the important question arises how to distinguish between genotypically inherited malformations, and those which are the outcome of environmental factors upon a genotypically healthy germ. Inheritance records of human pedigrees, such as have been installed in Copenhagen by Professor Kemp at the Institute of Human Genetics of the University, can give much help in elucidating this question. When such records have been followed up through a few generations, we should have a fair chance of telling which is which. The importance of being able to discern with certainty between these two modes of malformations is clear. In the first instance, pregnancy should be discouraged in families where deleterious genes are known to exist, not only because of personal distress to parents and relatives, but also because of the economic burden thus laid on society. In the other case, precautions may be taken in further pregnancies.

In this connexion we may briefly discuss the occurrence of idiocy or mental deficiencies among children born in intellectually highly endowed families. I do not know if reliable statistics exist which could prove the popular view that genius is closely related to idiocy. I think such material would be difficult to produce. But it is a fact that idiocy occurring in families of a very high intellectual standard is bound to be taken more notice of than when it occurs in families of seemingly mediocre intelligence. Therefore, until congenital idiocy has been proved to be genotypically determined in families of high intellectual standard, caution in this matter is indicated. The possibility of improper foetal environment as the cause for idiocy should be seriously considered.
Some people hold that a certain—and indeed rather large—percentage of the human population ought to be more or less unintelligent in order to provide cheap labour for unskilled work. This way of thinking is quite out of date, besides being unethical. It seems to me to be also economically unsound. Manual unskilled work which needs no brain will, of course, be increasingly taken over by machines. The deltas and epsilons in Aldous Huxley’s novel *Brave New World* represent an anachronism in this book that is otherwise full of alarming prophesies, some of which experimental embryology is already about to realize in animals.

Our goal should be an ever-increasing standard of intelligence at every level of society. I am not sure that genetics can contribute to this, because the gene flow in mankind is becoming more and more unrestricted, and thus the genes responsible for brain development will in the future be shuffled all too effectively. Nor is it likely that artificially induced mutations will produce geniuses. But it is quite likely that prenatal care will prove effective in raising the brain’s capacity for receiving proper education and mental training later in life—which is the only way whereby intellectual behaviour can be raised to higher levels.

Well-formed children are a guarantee of prosperity for future generations. Prenatal care is one of the necessary means for attaining this. Experimental embryology indicates the route.
DESIGN AND CHANCE
IN DISCOVERY AND INVENTION

by
RENÉ TATON

Dr. Taton, who is Professeur agrégé in mathematics, Secretary-General of the International Union of History of Sciences, and Maître de recherches at the Centre National de la Recherche Scientifique in Paris, is an historian of science who has published a large number of monographs and books, in particular, Causalités et accidents de la découverte scientifique, Paris, 1955.

The progress of science and technology, whose influence on man’s life is steadily increasing, is the result of a continuous sequence of discoveries and inventions, each of which is based, more or less directly, on earlier discoveries and, in its turn, opens the way for fresh advances. This onward march is by no means regular; on the contrary, it is marked by periods of comparative stagnation followed by others in which progress seems to speed up, completely revolutionizing great sectors of science and bringing about far-reaching changes in the living conditions of mankind. There can be no doubt that, since the middle of the nineteenth century, we have been passing through the most brilliant phase in the whole history of science and technology. There has been unprecedented competition among research workers throughout the world and the number of people playing an active part in the advancement of research is rapidly increasing year by year. This growth in numbers has, incidentally, been accompanied by a gradual reduction of the place taken by individual research, in favour of well equipped and systematically organized laboratories and research centres. In the long run, however, this rationalization of ‘creative’ scientific work is liable, if no precautions are taken, to cut off some of the richest sources of scientific discoveries.

Discovery and invention now have such an important place in the life of mankind that a detailed and objective analysis of the conditions in which they arise is urgently necessary. The only possible basis for such an analysis is a comprehensive survey, conducted with strict accuracy and objectivity, covering every branch of pure and applied science. Without anticipating the conclusions to be drawn from statistical work of this sort, there are certain basic questions that could be clarified by a smaller-scale survey which would pin-point the most characteristic features and aspects of scientific discovery and invention and direct attention to the special factors involved.

1. A more detailed study of certain aspects of this question has been made by the author in a recent work entitled: Causalités et accidents de la découverte scientifique, Masson, Paris, 1955.
DISCOVERY AND INVENTION

Before embarking on this brief outline of what is, in fact, the essence of scientific life, it may be useful to place the two main forms in which it takes shape—discovery and invention—in proper perspective. These two aspects of scientific work are often contrasted, discovery being regarded as the usual path of progress in 'pure' science, while invention has to do with the enormous sphere of applied science. We speak, for instance, of the discovery of the law of gravitation by Newton and of the invention of the lead accumulator by Planté. Discovery would thus appear to relate to a law, property or action which, although already existing, had not previously been observed or stated, and the part played by the author of a discovery would seem to be comparable simply to that of a detective penetrating certain secrets of nature. The inventor, on the other hand, would seem to make a more personal contribution; the apparatus, machinery or compound that he sets up, builds, or prepares is in some degree a new creation, at least in the way its parts are put together or its elements compounded.

When we think about it from the epistemological standpoint, however, the distinction is much less sharp than it appears to a superficial observer. There are, of course, a few cases of discoveries which have been made by people who have confined themselves to accurate observation and, without doing anything creative in the strict sense, have noted the existence of a law or a phenomenon which was unknown to their predecessors. But, in most cases, the process of approach towards a discovery is long and hard and the author of it must be regarded as a true creator, as the inventor of a new type of reasoning or novel method of research, observation or measurement.

On the other hand, invention, even in the most technical sense, has certain features which make it akin to discovery. In most cases, it depends on the observation of new phenomena or the discovery of new ways of making use of phenomena already known. Thus, from the purely epistemological standpoint, the distinction between these two concepts of discovery and invention is seen to be much less sharp and clear-cut than it is from the economic and utilitarian point of view. And even from that angle, incidentally, the distinction between discovery and invention does not always coincide with the distinction made, often quite erroneously, between pure science and applied science. There are, in fact, discoveries which can be directly applied in many ways, and inventions which it seems to be impossible to put to practical use. This is very fortunate, of course, for if there were no hope of applying the results of fundamental research quickly, the financial support which is so necessary for it might very often not be forthcoming.

Discovery and invention can thus be studied simultaneously, at least from certain points of view; substantial differences will, however, emerge as we study their economic, social and political background.
DESIGN AND CHANCE IN DISCOVERY

DISCOVERY RESULTING FROM SYSTEMATIC STUDY

The most familiar, and perhaps also the most common aspect of scientific discovery is that in which a logical and studious mind, working with the strictest method, making systematic use of earlier work, and mobilizing all the resources of intuition subject to careful verification, draws a methodical cordon around the subject of his study as the preliminary to its conquest. I shall not dwell upon the qualities of accuracy and method that any scientist must possess, nor upon those which are particularly required in the experimental and natural sciences. But we must not forget that the discoverer or inventor must combine with all those qualities other special, and much more personal, gifts without which the discoveries he makes will be of only minor importance. The capacities of a research scientist can be measured even in the way he chooses the subject of his research and defines it more narrowly or, if necessary, modifies it as his work proceeds. His work may be undertaken to expand or clarify a theory—as is most often the case in mathematics—or in an attempt to dissipate a sense that all is not as it should be, signs of which are apparent in the study of some particular field of science, indicating that the guiding ideas, basic hypotheses or fundamental laws need revision and at least partial amendment. Research may also be undertaken simply to solve a problem arising in connexion with some other work or brought up by developments in another branch of science, or to make a systematic study of a phenomenon which has recently been brought to light. Whatever may be the more or less distant goal to which he is feeling his way, the scientist should not embark on research proper unless he feels very definitely that he has the ability, the taste and the cast of mind for the work. In short, for the best chance of success, research must be undertaken confidently and with pleasure.

The choice and definition of the subject are generally followed by a fairly long period of preparatory work, during which the scientist becomes aware of the difficulties to be solved, the analogies to be explained, and the real or apparent links with other questions to be elucidated. Little by little, guiding ideas emerge and are more or less consciously classified and 'filed' in his mind. The breadth of his knowledge and the qualities of method and intuition he possesses play a direct part in this second stage in the approach to a discovery.

The course of this preparatory work, the length of which will depend on the difficulties met with and the abilities of the research scientist, may vary greatly. If all the obstacles are overcome, it may lead at once to success; or, more often, it may be followed by a quieter period in which the scientist, no longer making any but the slowest progress, turns aside from the straight path and takes up various questions with a more or less immediate bearing on the problem with which he is concerned, or even loses hope and drops
his work to turn to other tasks. All the scientists who have given us accounts of the origins of their discoveries mention such periods, long or short, of weariness and discouragement. The great physicist Hertz, for instance, wrote in a letter to his parents, when he was on the verge of discoveries about cathode rays: 'For the time being, I am trying one thing and another without any particular method. . . . I am re-doing old experiments and setting up new ones which occur to me. . . . I hope that light will burst upon me from one or other of the hundred interesting phenomena with which I am confronted.'

Then, after this waiting period in which progress seems particularly slow, the scientist often has, in a flash of illumination, an intuitive revelation of the way to overcome the difficulty which has been holding him up, or even of the answer he has so long been seeking. Louis de Broglie has given a very vivid description of this sudden revelation, experienced by all research scientists: 'Then, all at once, and generally without the slightest warning, a sort of crystallization comes about: the scientist has an instantaneous, perfectly clear and, from that moment, entirely conscious perception of the essentials of the new fabric of ideas which has secretly been forming within his mind and, at one stroke, he knows with absolute certainty that the application of those new ideas will make it possible to solve most of the problems facing him and to clarify the whole question by showing up analogies and harmonies which were unsuspected before.'

This flash of illumination, incidentally, does not generally come during a bout of concentrated work but often in the middle of a period of rest or relaxation. It results indeed from a crystallization of the products of earlier work, a reorganization and rearrangement of ideas, which have been slowly prepared in the subconscious mind and are more likely to emerge into the conscious mind when free from stress. In this most important stage in the process of invention, certain personal qualities of the research scientist play an essential part, particularly his special type of intuition and his aesthetic sense, which help him to economize effort by thinking along the most productive lines. It would be very difficult to describe or define these qualities, especially as they vary with different fields of study and appear in an essentially individual form in every creative research scientist. But it is a fact that, unless he possesses these qualities, no research scientist, however great his knowledge, can hope to make important discoveries. The true savant must combine with strict method and wide knowledge these vital gifts of daring, intuition and perspicacity.

The research scientist's work is by no means finished, however, after the flash of illumination which shows him a new path to follow. He must thereafter build up the structure of reasoning which will confirm the value of his

ideas, draw all the appropriate conclusions, compare the results of experiments with the forecasts based on his ideas, answer possible objections and finally establish the bounds within which the law or the hypothesis on which he is working can be applied. This final stage in the work is by no means free from difficulties for, as the theory becomes better defined, countless complications in the details become apparent and must gradually be cleared up. In particular, and especially in the theoretical and experimental sciences, after the spurt of enthusiasm which follows the sudden revelation of the new theory, the scientist comes to perceive its limitations and shortcomings with increasing clarity and, so doing, finds his joy mingled with "the slight bitterness of finding after all that the progress he has made is necessarily limited and incomplete".\footnote{L. de Broglie, op. cit., p. 122.}

THE FRUITFUL DISCOVERIES

Certain discoveries, apart from their intrinsic importance, have a very special place in the history of science because of the rich harvest of other discoveries which have followed from them. This applies, firstly, to the basic discoveries which, like that of the law of universal gravitation, set theory, or the principle of relativity, have brought about changes in the general structure of science. It applies also to the inventions which have given scientists a new tool that can be used in countless ways, such as the astronomical telescope, the microscope, and the electron microscope. Finally, there have been other discoveries which, apart from their own importance, have had the merit of suggesting profitable lines of research that have resulted in a whole series of further discoveries. The discovery of X-rays by Roentgen in 1895, for instance, led to that of radioactivity which, in turn, made possible the discovery of radium and the remarkable development of atomic physics in the twentieth century.

But the paths of discovery and invention are often more complex and more difficult to trace, and the comparative scarcity of detailed material and reliable evidence makes it even harder to say exactly what has happened. In this context, the study will be confined to considering a few fundamental problems, quoting as illustrations a number of specific and particularly thought-provoking examples. Such questions, which are deserving of more detailed study, include the role of chance, the importance of which has been to some extent exaggerated by various picturesque, but not necessarily authentic, anecdotes; the fruitful effects of certain errors, a problem which merits very thorough study from the psychological standpoint; and the explanation of various types of failure met with in research. Reference will also be made to the fact that, in many instances, discoveries have been made
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simultaneously and independently, to cases of disagreement about who was
the first discoverer, to the problem of antecedents, and finally to the influence
of various philosophical, religious, political, economic and social factors on
the course of progress in science and technology, with special emphasis on
detailed study of the obstacles with which innovators too often have to
contend.

THE ROLE OF CHANCE

The role of chance in the origin of many discoveries or inventions has often
been over-estimated. Though various accidental observations have undeniably
set research scientists on the way to a number of basic discoveries, it would
be a mistake to argue that chance plays a primordial part in new advances in
science and technology. This thesis may be illustrated by a few examples.

The first necessity is to make sure what exactly is meant by chance. We
shall exclude the sort of 'psychological accident' which consists in the chance
association of two ideas—a common phenomenon that occurs, it might be
said, in every piece of original creation.

Every discovery which does not result from a simple elaboration of results
already established necessitates an effort of thought on the part of its maker
in which imagination and intuition always have a vital place. And, in most
cases, it is the association of two ideas whose inter-connexions had not
previously been perceived which starts the most creative phase in the
research scientist's work. This association of ideas which opens the way to
a discovery or invention only appears to be an accident; in actual fact, the
ground has been prepared for it by a long preliminary period of research and
thought, and the association itself depends on the intuition and aesthetic
sense of the scientist. In some cases, indeed, the research worker is scarcely
aware of this stage, having a sort of prescient glimpse of the anticipated result
which in fact cloaks a train of reasoning that has been confined to his sub­
conscious mind. This produces the flash of illumination, with which all the
great innovators have been familiar, revealing to them, with a sort of
intuitive certainty, the solution of a problem, or the correctness of a new
hypothesis or law.

Chance in the proper sense, 'external chance', consists in an accidental
happening which may set the student on a new path. Let us, in an attempt
to assess the importance of chance in this sense, begin by considering whether
the part it is supposed to have played in certain famous anecdotes is actually
borne out by the facts.

Plutarch's account of Archimedes' discovery of the principle of floating
bodies is too well known to need repetition. The chance observation which is
said to have been responsible for that discovery—the overflowing of a bath

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filled with water as the body is immersed in it—is too elementary and too common to have played a decisive part in the formulation of the famous principle. The most we can accept, on the assumption that the account is at all reliable, is that Archimedes' 'Eureka' signified the sudden crystallization in his mind of ideas which were already deeply rooted and needed only a suitable occasion to take final shape.

The same applies to the well known story of Newton's apple, which, picturesque as it is, can have had only an insignificant influence in the discovery of the law of universal gravitation. Scientists themselves, incidentally, are often the originators of such stories, as in the case of the French crystallographer, Haiiy, who himself spread the false story that the sight of a broken crystal set him on the track of his crystallographic theory. The rise and spread of such legends is due to the fact that they are picturesque and much easier to understand than a truthful, and necessarily somewhat technical, account would be.

The only real cases of accident left, therefore, are certain chance observations, coming about through a combination of quite unforeseeable circumstances, which lead the scientist on to a new line of research that subsequently proves to be extremely productive.

The invention of the electric battery is one instance which shows what good use a careful observer and a gifted scientist can make of an accidental happening. We know that this discovery resulted from the observation of a curious phenomenon by the Italian doctor and biologist, Luigi Galvani. When dissecting frogs in a room where an electrostatic generator was working, Galvani noticed that, when the crural nerves of one of the frogs were connected by a metallic arc, the leg muscles contracted violently every time the machine produced a spark. This very complex phenomenon showed that physiological reactions attributable to electricity were occurring, and Galvani and his students made a very detailed and careful study of them but did not succeed in explaining them correctly. At this point, the great physicist, Alessandro Volta, began to take an active interest in this problem and embarked on a long controversy which led him away from the study of animal electricity to that of the electrical disequilibria resulting when two dissimilar bodies are brought into contact. Working on this basis, he finally, early in 1800, invented the first direct-current generator, the voltaic pile, consisting of identical pairs of metal plates (zinc and copper) piled up in the same order and separated by discs of wet cloth.

A second instance, in which chance played a more direct part, was the discovery of X-rays by Wilhelm Conrad Roentgen, who was then Professor of Physics and Rector of the University of Würzburg. At the age of 50, Roentgen had not won renown as the author of any important discovery when, in October 1895, infected by the fever which had taken hold upon the scientific world, he embarked on a series of studies on cathode rays,
which had been known for over a quarter of a century and had just, in the space of less than two years, made possible a whole harvest of new discoveries. On 10 November 1895, when watching a cathode ray tube excited by an induction coil and encased in black paper, he noticed a very definite fluorescence on a barium platinocyanide screen standing on the laboratory bench. Much intrigued by this unexpected phenomenon, Roentgen, closeting himself in his laboratory for several weeks, undertook a series of fresh experiments which proved beyond doubt that the fluorescence was due to mysterious rays issuing from the tube, which penetrated the casing of black paper although it was opaque to any known light.

Substituting a photographic plate for the fluorescent screen, the following month he obtained the first X-ray photographs. He immediately published the results of his research and sent copies of his article, together with copies of his first X-ray photographs, to some of the most eminent savants of the time. News of the discovery spread like wildfire, arousing the greatest interest everywhere and, by the end of January 1896, scientific circles and the general public throughout the world were marvelling at the amazing new possibility of photographing the invisible. This enthusiasm was fully merited, for the discovery of X-rays opened the way to practical developments which were to prove extremely fruitful and to a series of other discoveries which marked the beginning of revolutionary changes in one of the most important branches of physics.

Although chance played a part in Roentgen's discovery, the primordial influence of the German physicist's great personal qualities must not be under-estimated, and one cannot but agree with the view of the American philosopher Münsterberg: 'Supposing that chance helped, there were many instances of galvanic reactions everywhere in the world before Galvani happened to see a frog's leg contracting on a wire. Only Galvanis and Roentgens are rare.'

The discovery of the polarization of light by reflection, made by the young French scientist Etienne Malus in 1808, suggests the same thought. Malus was interested in the laws of geometrical optics and, in particular, in the path followed by rays of light in birefractive crystals; one day he was in his room watching the windows of the Palais du Luxembourg with the sun shining on them, when he had the idea of interposing a crystal of Iceland spar in the path of the reflected rays of the sun. He first noted the existence of the familiar double image but then observed, not without surprise, that if the crystal was rotated, each of the images disappeared in turn. This chance observation could not have been made by anyone better prepared to realize all its implications. Malus recognized that the phenomenon was connected with the fact that the light had been reflected from the window-panes and,
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from that, deduced the theory of the polarization of light that Fresnel and Young were to explain a few years later by their hypothesis that light is a transverse wave motion.

The last instance I shall quote is that of the discovery of penicillin by the late Sir Alexander Fleming. In September 1928, Fleming, who was studying the mutations of certain colonies of staphylococci, noticed, when examining them under the microscope, that one of his cultures had been contaminated by a micro-organism from the outside air. At first sight, this was merely the sort of accident which often happens to all research scientists working in laboratories with inadequate material resources. But instead of neglecting the incident and beginning his work over again with other cultures, Fleming inspected the contaminated plate more closely and noticed that the colonies of staphylococci attacked by the microscopic fungus had become transparent over a wide area surrounding the zone originally contaminated. He realized that this effect was due to an antimicrobial substance secreted by the invading micro-organism and diffused into the medium of the preparation. Penicillin, the first of the antibiotics which were to revolutionize enormous sectors of therapeutics in a few years, was discovered in this way.

Completely reorganizing his original programme of research, Fleming then embarked on the study of the principal properties of the antimicrobial substance which had accidentally contaminated his plate. Making the best and most rational use of the modest resources of his laboratory, he succeeded in demonstrating the selective properties of the substance and its effect on various species of microbes; he also established that it was harmless to the leucocytes of several animals, and observed that, even in a dilute solution, its antimicrobial power was greater than that of the most powerful antiseptics. But the difficulties of preparing the liquid secreted, and its impurity and instability, were to check the progress of research, and it was only at the beginning of the second world war that improvements in technique made it possible for new teams of research workers, with great resources at their command, to take up, on a new basis, the thorny problems arising in connexion with the preparation of penicillin and its use in the treatment of disease. More will be said later about this final phase, which illustrates the great part played in most recent discoveries by collective research carried on with ample resources and the help of the most up-to-date techniques.

To many people, Fleming's original observation is the perfect example of the intervention of chance, which they consider to be at the origin of many discoveries. This is a most mistaken view. While the contamination of a culture in a poorly equipped laboratory, where strictly aseptic conditions can hardly be achieved, is a pure accident, it occurs so commonly that it would never be regarded as exceptional enough to attract special attention from anyone familiar with the circumstances. If chance in fact played a part, it lay in the combination of two particularly propitious factors: firstly, the fact
that, of all the many varieties of aerobic micro-organisms which might have contaminated the culture, it was a Penicillium, which is not very often found in the air, that settled on the place; and secondly, the fact that the plate contained colonies of staphylococci, microbes which are particularly sensitive to the antibiotic action of penicillin. Though a stroke of luck played a part in this initial incident, however, it was a stroke of luck for a research scientist who was well equipped to appreciate how enormously important the phenomenon was. For some years past, indeed, Fleming had been trying to develop the ideal antiseptic, combining the maximum strength as a bactericide with almost complete freedom from toxicity to the human system. Moreover, the phenomenon of antibiosis had already been described by several scientists who had not been able to make practical use of all its implications; the English biologist, John Tyndall, and Pasteur and his disciple, Jules Joubert, had observed the phenomenon between 1875 and 1877, but the time was not ripe for the effective exploitation of the discovery. Fleming’s rediscovery of the phenomenon and his invaluable work on it, lengthy research and patient adjustment and readjustment, with the aid of the mightiest technical resources available, were necessary between the making of this simple observation in the laboratory and the enormous development of modern antibiotics. How much ‘accident’ is left in this long history? Surely very little.

The conclusion which seems to emerge from the study of these few cases, selected from the large number of other examples because they appear to include a special element of chance, is that, while it cannot be denied that certain fortunate circumstances have assisted the authors of many discoveries or inventions, accident still plays only a very small part in discovery and invention. A chance happening may, indeed, give a good research scientist a sudden flash of illumination and direct him on to a profitable line of inquiry, but it can help no one who is not already well equipped to realize all its implications by exceptional gifts of intuition, faultless method and great skill in experimental work.

THE ROLE OF ERRORS

There is no doubt that, in the great majority of cases, errors in observation, calculation or interpretation are disastrous to scientific research. Mistakes, and the inaccurate conclusions to which they lead, can often be remedied only by the long, tedious labour of checking and re-checking. Some such errors, moreover, pass unperceived for a long time and so misdirect or delay progress in large areas of scientific work.

Certain errors, however, by putting people on their mettle, lead to great discoveries. Others, by simplifying problems, have played a major part in the discovery of fundamental facts or principles. The apparent simplicity of many
physical phenomena actually represents only a first approximation to something far more complex, which can be understood only by the process of continual approach generally achieved by the use of hypotheses which simplify the question, or observations and measurements which are themselves approximate and which conceal some of the difficulties that would otherwise have hampered the processes of thought.

A typical instance of the sort of error which may give rise to an important discovery was the incorrect hypothesis advanced by the great French scientist, Henri Poincaré, in an attempt to explain the production of X-rays. When, in January 1896, Poincaré received an account of the famous experiments by which the German physicist Roentgen had succeeded in producing X-rays and in taking the first X-ray photographs, he attempted to explain these new phenomena. At a meeting of the French Academy of Science, he remarked that, in the very simple apparatus used by Roentgen, the X-rays were produced at the spot where the cathode rays emitted by the Crookes tube impinged on the wall of the tube. As, in that area, the glass of the tube-wall is made fluorescent by the cathode rays, Poincaré formulated the hypothesis that the two phenomena of fluorescence and emission of X-rays might be closely connected. In actual fact, that hypothesis was incorrect and later observations showed that the two phenomena were independent, but it had the great advantage of leading to a discovery of inestimable importance—that of radioactivity. For it was while making a systematic study, at Poincaré's instigation, of the question whether certain bodies which became fluorescent after exposure to light emitted radiation similar to the X-rays produced with the aid of the Crookes tube that Henri Becquerel, the physicist, discovered a month later that a uranium ore, uranium potassium sulphate, was radioactive. This was the first observation of a phenomenon whose study was to revolutionize large sectors of physics and which was to be applied in countless ways.

Another error which proved productive of good was that which led to the development of the mathematical theory of ideal numbers. In 1845, the German mathematician Eduard Kummer believed he had proved a famous theorem formulated, without proof, by Fermat. As in all similar cases, however, this pseudo-demonstration of Fermat's baffling proposition was to prove incorrect. One of Kummer's colleagues, the brilliant student of the theory of numbers, Lejeune-Dirichlet, discovered the error—the use of a proposition which was considered to be manifest but which in fact required thorough discussion. Kummer then began his study afresh and his research on that occasion put him on the track of an extremely important discovery, that of ideal numbers, which was to lead to the theory of algebraic number fields, one of the keystones of modern algebra.
Errors of over-simplification, and rough approximations to something which is really far more complex, are infinitely more common than hypotheses which are basically unsound, or errors of reasoning which prove to have good results. In the normal course of events, science proceeds by such approximations, which make it possible to master the truth by successive stages, and to isolate difficulties so that they can be overcome one by one.

We know that, in mathematics, the sense of exactitude develops and becomes more perfect as theories are built up and methods of exposition improve. While the eighteenth-century scientists quickly worked out the first foundations of the integral calculus, the looseness of much of their reasoning horrified certain of their successors in the following century who, in their turn, thought they had successfully built up a faultless structure of theory. But set theory and other developments in modern mathematics have led us to revise large parts of their reasoning. The same process is to be seen, moreover, in every branch of mathematics, where each theory is gradually elaborated by a series of new contributions reflecting a gradual increase in the exactitude of reasoning.

The process of successive approximations is also a more or less general rule in the building up of theories in physics. At every stage, the exactness of the explanations furnished by theories is closely related to that of the available means of observation or measurement. Every advance in methods of observation or in methods of measurement brings with it, sooner or later, a revision of the relevant theories and, eventually, the formulation of new laws more in keeping with the facts. Until this concordance has been achieved, theorists will go on seeking to remove the feeling of uneasiness thus produced. In this way, the successive stages in the development of experimental science and observation are linked up with the stages, of comparable advancement and complexity, in the development of theory, too rapid an advance in one of these sectors giving rise to far greater difficulties of adaptation in the other sector.

In the case of the great laws of planetary motion, discovered by Kepler in the seventeenth century, we can trace the combined influence of these two factors in a way which gives much food for thought. When, at the end of the sixteenth century, Kepler began his research on the structure and motions of the solar system, the basis on which he had to work was far from satisfactory: from the theoretical point of view he had Copernicus' heliocentric hypothesis, combined with the Ptolemaic theory of epicycles, the belief in the absolute pre-eminence of uniform circular movement, and a Platonic mysticism which tended to associate the planetary system closely with the 'five regular solids'; from the numerical point of view, he had the observations made by Tycho Brahe with the naked eye, which were, however, far more
precise than any made by earlier astronomers. Starting from these data and working with the driving energy of a mystic, tempered by the special qualities of a scientist of real genius, Kepler began by verifying the trajectory of the Earth. Then, turning to the kinematic study of the motion of the planet Mars, he came, after long calculations and numerous attempts, to adopt the law of equal areas; thereafter, reverting to the geometrical description of the orbit, he found that the theory of epicycles did not fit the results of the observations made by Tycho Brahe. He then, with great daring, staked all on the value of those observations, abandoning both Ptolemaic theory and the traditional belief in the pre-eminence of circular movement, and proceeded to formulate his first two laws regarding the motions of the planets: the laws of elliptical orbits and of equal areas (1609). It was not until 1618 that he arrived at the third law, which links up the orbits of the various planets with the duration of their revolutions. In this way, the wonderful body of theory on which the study of planetary motion is based was built up. No one can help admiring the patience and genius shown by the great German astronomer in this long and difficult struggle. But it is an open question whether, if he had had still more accurate observations than those of Tycho Brahe on which to work—observations which were soon to be made possible by the invention of the astronomical telescope—he would have been as successful in his heroic undertaking. There can be no certainty of this. Kepler's laws are merely a first approximation to the truth, taking account only of the attraction of the Sun and overlooking the disturbances caused by the presence of other stars in the solar system, which are by no means negligible. There can therefore be no doubt that, while the slight additional accuracy for which we have to thank Tycho Brahe enabled Kepler to achieve success, a greater degree of accuracy would have made his work very much more difficult.

It is not necessary to quote further cases to illustrate this gradual conquest of truth, marked by the succession of stages reflecting alike the state of theoretical knowledge and that of methods and means of observation. As knowledge extends and grows more perfect, the physical laws which have so far been accepted as exact are seen to be nothing but more or less close approximations to a truth which is invariably more complex. Theoretical discoveries and technological advances thus combine to enable scientists to gain an ever more exact picture of the truth of the physical world, and yesterday's victories are seen to be simply temporary stages on the way to more and more accurate knowledge.

DISCOVERY, THE MIRROR OF AN AGE

It is no disparagement of the individual labours of the authors of discoveries
and inventions to observe that these mostly occurred at a time made pro-
pitious by the current level of theoretical knowledge and technical pos-
sibilities. There is no denying that, great as the creative genius of many
research scientists may be, science and its applications are marked by steady
—and, one might say, logically predictable—progress rather than by sweep-
ing revolutionary advances. There are, of course, such revolutions, but
careful study of their origin shows that they only break upon the world after
a long period of more or less conscious preparation. The progress of science
and technology is thus found to be a continuous phenomenon in which each
new stage follows on from previous findings, and flashes of genius merely
serve to clarify, to supplement and crystallize results that have been slowly
arrived at by means of little recognized preliminary research.

Consequently, in every branch of science it can be demonstrated that most
discoveries were made at a time when they had become practically inevitable
and, even if the scientists to whom they are attributed had never lived, they
would not have been long delayed. The fact that many discoveries were
made by several scientists, simultaneously, yet quite independently, is a
decisive argument in support of this theory. A few examples, drawn from
various branches of science, may by mentioned here.

One of the most famous examples in mathematics is the invention of the
basic tool of modern scientific theory—infinitesimal calculus—due to Leib-
nitz and Newton in the second half of the seventeenth century. This decisive
step forward in mathematics was unfortunately marked by a long and pain-
ful dispute—which was only settled in the past century—about who first
made the discovery. It is now known that it was made almost independently
by the two scientists within a few years of each other. And it is perhaps of
interest to note that the ground had been prepared for this brilliant achieve-
ment by the patient research of many mathematicians in various countries,
from Kepler and Cavalieri to Fermat, Pascal, Huyghens and Barrow.

Two of the most remarkable discoveries of the first half of the nineteenth
century were also made independently by several scientists. The existence of
non-Euclidean geometry, the far-reaching significance of which became
clear following the work of Riemann and his successors, was demonstrated
almost simultaneously by three geometers—Karl Friedrich Gauss (German),
the most renowned mathematician of his day, and two young scientists
whose names did not become famous until after their death, Nicolai Ivanov-
vitch Lobachevsky (Russian), Professor at the University of Kazan, and
Johann Bolyai (Hungarian), an obscure engineering corps officer barely
30 years of age. At the same time, the theory of elliptic functions was taken
a step further by means of the inversion of these integrals and the introduc-
tion of imaginary variables through the work of two brilliant young mathem-
aticians, Niels Henrik Abel (Norwegian), and Karl Gustav Jacob Jacobi
(German), who arrived at these results almost simultaneously.
In physics, almost simultaneous discoveries are even more common. Some historic examples may first be recalled. The discovery of the ratio between the pressure and the volume of a given mass of gas kept at a uniform temperature, know as Boyle's or Mariotte's law, was made, within a few years of each other, by these two scientists working quite independently. The Leyden jar, the first form of the capacitor, was invented, within a few months of each other, by von Kleist (German) and Musschenbroek (Dutch). The main laws of electrostatics were brought to light almost simultaneously by Henry Cavendish (English), who did not publish his results, and the French military engineer Charles-Auguste Coulomb. The same is true of the phenomenon of self-induction, established in 1832 by Joseph Henry (American) and rediscovered two years later by the famous English physicist Michael Faraday, who knew nothing of Henry's work.

In the twentieth century, examples of such simultaneous discoveries are still fairly common, although the promptness with which most research workers publish their results is tending to make such occurrences less frequent, and the secrecy in which broad sectors of science and technology are now shrouded for military or commercial reasons is narrowing the field in which the course of scientific progress can be followed with sufficient accuracy. On the other hand, the fertile spirit of competition existing between universities, research centres and laboratories throughout the world is conducive to simultaneous discoveries.

To give only two examples, the theorem of inertia, deriving from the principle of relativity expounded by Albert Einstein in 1905, was discovered almost simultaneously by Einstein himself and by the French physicist Paul Langevin, who was outstripped through postponement of the publication of his work. Again, meson, a particle in the realm of microphysics, discovered in 1935 by the Japanese theorist Yukawa, had been observed in cosmic rays the year before by the French physicist Pierre Auger and by the American A. H. Compton, each working quite independently.

When we turn to the applications of science, we again find frequent examples of virtually simultaneous inventions. But the financial interests at stake intensify the disputes about who was the first inventor, and this often makes any historical inquiry a delicate matter, as doubts can be cast on the reliability of certain evidence. An instance which may be quoted in this connexion is the ring winding, an essential part of the first really usable dynamos, which was described in 1864 by the Italian physicist Paccinotti, before being rediscovered and put to industrial use in 1869 by the Belgian technician Zénobe Gramme.

The fact that many discoveries and inventions were made at practically the same time is the source of ticklish disputes as to their originator, some of which ruffle the calm of discussions between historians of science. In many cases, an impartial analysis of the evidence available would put an
end to all discussion by enabling credit to be given to the true inventor or by revealing the merits of the opposing parties. But this evidence may be distorted for the furtherance of special interests or there may be some doubt regarding its reliability. All too often the facts of the case are thus presented in a wrong light, owing to the excessive vanity of some scientists, the interference of over-enthusiastic disciples, the disastrous effect of national pride and, in the case of inventions, industrial and financial rivalry.

Far more important than the question of who first made the discovery, however, is that of its antecedents.

THE PROBLEM OF ANTECEDENTS

From a careful study of the progress of science it will be seen that there is a long series of preliminary investigations, often by unknown scientists, leading up to most great discoveries. It is one of the tasks of the historian to see that due credit is given to these pioneers and, in so doing, he will gain a better grasp of the complexity and continuity of scientific progress.

But such an undertaking is beset with difficulties and pitfalls. For it is necessary to assess the extent to which each presumed precursor glimpsed the nature, meaning, importance and consequences of the discovery in question, and then to study the repercussions of his findings so as to estimate their influence on the work of the actual discoverer.

Between the genuine precursors who, though they did not bring a particular discovery to completion, nevertheless paved the way for it and foresaw its usefulness and importance, and those who merely foreshadowed later developments but whose ideas were too vague or insufficiently grounded, there is a wide range of pioneers, many of them little known.

To assess the work of these men is a delicate task, especially as it is often difficult to assemble and interpret the documentary material relating to them. Moreover, such evaluation has not always been undertaken with sufficient regard for justice and impartiality; all too often, national pride has played a part in such discussions and wholly distorted the facts. A vague and inconclusive scientific text of the seventeenth century can, of course, easily be made into a clear, precise document by putting its terminology and symbols into modern dress. But surely this would be falsifying the text and misrepresenting the author's thought. There have been too many manoeuvres of this kind for it to be possible to accept any fresh information concerning a supposed precursor without careful weighing of the evidence. However, despite these difficulties, the problem of antecedents is too important to be overlooked. The fact that, in every discovery of any importance, there have been many precursors, some of whom set the stage for the actual appearance of the discovery, shows that it is often a grave injustice to ascribe credit for
it to a single man without regard to the successive contributions which, in combination, made it possible.

Even a cursory study of this problem of antecedents would not be complete without some reference to the fairly frequent cases of forgotten discoveries. Such oversight is sometimes the fault of the discoverer himself, because he neglects or refuses to publish his findings. For instance, the important results obtained in the field of electrostatics by Cavendish in the second half of the eighteenth century had to be rediscovered by Coulomb and Faraday, as Cavendish had put them away among his papers which were not unearthed until a century later. Some famous scientists adopted this attitude to avoid any struggle for recognition of their discovery, as Gauss, for instance, who did not publish his research on non-Euclidian geometry and was thus forestalled by Lobachevsky and Bolyai. On the other hand, other scientists, less renowned, failed to make their work known despite all their efforts to that end. This applies to Mendel, whose celebrated laws of heredity, published in 1865 in a scientific journal in Brno, remained virtually unknown until 1900. After the rediscovery of these laws, Mendel's original writings were disinterred and justice was done to the great scientist.

In every case in which a discovery had to be made several times before being officially recognized, the difficult question arises whether the work of the first inventor had any influence, direct or otherwise, on that of his successors. Absorbing as such questions may be, too much importance should not be attached to them. In the general picture of scientific progress, the identity of the people concerned is of secondary importance, and each discovery becomes effective after it has been perfected and correctly applied.

Forerunners in science are unfortunate inventors who have been unable to carry their work to completion. In studying them, we are led on to a study of the failures which even the best research workers have met with in some of their undertakings.

THE VARIOUS TYPES OF FAILURE

The history of science and technology is not concerned solely with the successes of scientists and inventors, but also with their failures, at least in so far as these are significant. A detailed analysis of the nature and different causes of the ill-success or utter failure experienced by even the best research workers could certainly be most instructive. As it is impossible to embark here on a broad subject of this kind, which has never yet been exhaustively dealt with, we shall confine ourselves to a brief outline of some of its principal aspects.

In the first place, there is a kind of failure whose cause is logical and plain. It is the failure which attends premature attempts to build up a theory,
explain certain facts, demonstrate certain laws and invent new machinery or apparatus, when the total theoretical knowledge of the subject or the technical facilities available fall short of what would be required for success. The history of science can show many examples of such failures, for their causes often become apparent only at a much later date, by which time they seem obvious. In mathematics, for instance, it was useless to attempt the formulation of a general theory of algebraic equations until complex variables had been introduced and the concept of group defined. In astronomy, no general study of the movements of the solar system could be successful until the law of universal gravitation was formulated. And in the field of technological invention, to mention but one example among many, despite the genius of Leonardo da Vinci and several others who imitated him, all attempts to achieve mechanical flight were bound to fail so long as no light yet powerful engine, such as the internal combustion engine, had been devised. What should we think of these scientists and inventors who thus endeavoured, unsuccessfully, to leap ahead in the march of progress? It would be easy, but most unfair, to be severe in our judgment. Though the reasons for their failure seem so clear to us today, we should not judge them on the basis of our present knowledge, but in the light of the resources, limitations and errors of science in their day. It is true that these seekers after knowledge included some visionaries who were bent on solving problems or making marvellous inventions that mere common sense would have shown to be doomed to failure. But there were many who could not have detected in advance the underlying reasons which made it impossible for them to succeed. Nor were all these endeavours, fruitless though they might appear to have been, made entirely in vain. Although they did not achieve the over-ambitious results hoped for, many of these scientists did useful work by adding to scientific knowledge with their incomplete results, by setting out clearly the elements of the problems to be solved or by encouraging others to imitate them profitably. And so, despite their own inevitable failure, they deserve to be considered as forerunners who opened up the way to later successes.

A second type of failure involves more varied and human factors. The path of discovery and invention is indeed often an arduous one, strewn with obstacles of different kinds, to surmount which requires a wide variety of personal qualities and aptitudes which are not easily found in combination. For instance, a mathematician often encounters complicated calculations requiring order, method and patience—qualities that do not always go hand in hand with the most brilliant analytical gifts. And so, after overcoming intricate difficulties of theory, a mathematician may fail when he is very close to success, as a result of errors in calculation or lapses which far less gifted scholars would have been able to avoid. The number of mishaps of this kind would certainly be even greater than it is, if, from other more
general and intuitive methods, the mathematician did not frequently have a fairly accurate knowledge of the result to be expected.

These risks of errors conducive to failure are to be met with in all the theoretical sciences; in the experimental sciences and the sciences of observation they are accompanied by further risks of a similar nature, arising from methods of observation, from the use of instruments and from measuring techniques.

To these factors of a personal nature, we must add others, bound up with the material conditions under which creative work is carried out. Such factors have become more important in our day as a result of the growing complexity of research work in every department of science and technology. Though a mathematician may require only documentation that is perfectly up to date and rationally classified, and the possibility of calling on the services of a suitably equipped outfit for his calculations, the physicist, the chemist, the biologist and the technologist make far greater and more varied demands on outside assistance. They obviously need well equipped laboratories with ample funds at their disposal. But they also need, to an increasing extent, the help of specialists better able than themselves to solve related problems lying outside the field of their main activities. Without equipment and help of this kind, a scientist runs the risk of failing to complete a discovery or invention which he would have been fully qualified to bring to perfection. Whilst the history of science contains many examples of research workers who failed in the final stages of their work for lack of support and material resources, the history of technology offers even more cases of unfortunate inventors who were forced to abandon their invention before it had been fully worked out, for want of the requisite material facilities and funds or because of obstacles which prevented them from continuing their work.

Lastly, there is another kind of failure, more difficult to detect, which derives, at least partly, from the state of mind peculiar to the research worker who is directing his efforts towards a relatively well-defined objective. To achieve this objective, he has to concentrate his whole attention on those factors that seem to him to have some direct bearing on it. In so doing he may overlook some aspects of the question or problem he is studying, or he may fail to draw all the possible conclusions from them. The causes of many failures are thus to be found in over-narrowing of the field of research and excessive concentration on the particular object in view.

Often enough a talented mathematician will obtain results yet fail to draw certain conclusions that may be direct and capable of being turned to account in many ways. In his work on the psychology of invention in the field of mathematics, the French mathematician Jacques Hadamard refers

to many such examples; some of them, in which he himself was involved, are described in detail with great clarity.

A classical example drawn from theoretical physics is that of the theory of relativity, which the great mathematician Henri Poincaré failed to work out, leaving this honour to a young scientist, Albert Einstein, at that time a humble examiner at the Federal Patent Office in Berne. Yet Poincaré had in his possession all the elements required for this synthesis; he realized its urgent necessity and had laid its initial foundations. He also had, at that time, a far wider and deeper knowledge of mathematics and physics than that possessed by the future master of twentieth-century theoretical physics. His failure in this particular line of research, which was to prove so profitable, has been most convincingly explained by Louis de Broglie, who stresses Poincaré's over-critical turn of mind and his rather sceptical attitude towards physical theories.¹

Many similar examples could be drawn from the field of pure physics. One of the most typical is that of the French physicist Ampère, one of the main founders of the theory of electromagnetism, who, when carrying out in 1822 an experiment bringing to light the phenomenon of electromagnetic induction, failed to draw what would seem to have been the inescapable conclusion. This phenomenon was directly linked with the major theoretical problems with which Ampère had been grappling for nearly two years with a considerable measure of success. When in 1831 the great English physicist Michael Faraday, using the simplest of equipment, discovered and studied this phenomenon of electromagnetic induction, which was soon to be put to such important practical uses, Ampère realized how near he had been to discovering this simple, general action. The reason given by him for this particularly striking failure is that, as the only aim of his experiment had been to clarify one aspect of the theory of magnetization that he was then trying to build up, he had completely disregarded all its other aspects.

Various factors may thus be responsible for failures of this type, which are worth special mention only when they relate to very great scientists. Excessive concentration on one single line of research, a preoccupation with ends which obscures possible avenues of reasoning, and the almost unconscious adoption of a worthless hypothesis or of an unduly sceptical philosophical standpoint are the main causes of these failures, which deserve closer study by psychologists.

THE INFLUENCE OF PHILOSOPHICAL AND POLITICAL FACTORS

After studying the influence of a wide variety of individual factors on the work of the creative scientist, we should now turn our attention to the

factors arising more directly from his environment. The study of discovery and invention, which are original creations of the human mind, is essentially within the purview of psychology, at least when these achievements mark the culmination of individual research. However, as the research worker is subject to the influence—and sometimes the direct pressure—of a political, philosophical and religious environment and must comply with social and economic requirements, discovery and invention are likewise affected by these factors. A detailed analysis of the consequences of these various influences would go beyond the scope of the present study. Besides, until preliminary statistical surveys have been carried out, it is too soon to embark on such an undertaking. An analysis of this kind cannot be based on the few partial, and often contradictory, findings of certain authors who are more concerned with polemics than with impartial inquiry. We shall therefore confine ourselves to mentioning some of the salient features of this intricate problem.

History shows that the advance of science and technology has been considerably hampered, at various times, by the existence of scientific or philosophic prejudices. Any scientific theory, inaccurate and provisional though it may be, is worth while as long as it stimulates research and thus gives rise to fresh discoveries. But it very often happens that a theory, whose fragmentary and provisional character was more or less explicitly acknowledged by its author, later turns into a narrow dogma which puts a brake on the progress of science. At all periods this 'hardening' of theories has had a most harmful effect. Stereotyped thinking and orthodoxy are the worst enemies of scientific progress. In the hard battles they have had to wage to gain acceptance of their ideas, innovators have all too often had to contend with the hostility of other scientists who, it would seem, should have been their staunchest supporters. The tragic example of the Hungarian doctor Semmelweis is well known. After discovering the infectious origin of puerperal fever, Semmelweis endeavoured to have antiseptic practices introduced into all maternity hospitals. This discovery and this measure would have made it possible to save many human lives. Unfortunately, Semmelweis was baulked in his repeated endeavours by the fierce hostility of more powerful colleagues and died broken-hearted without having been able to win recognition for his ideas. Many similar, though less tragic, instances could be quoted. This would seem to indicate that it is dangerous at times to give even very distinguished scientists unfettered powers of assessment; for, some scientists, as they advance in years, allow their theories to acquire the force of sacrosanct dogmas and will brook no criticism of them. The young French chemist Auguste Laurent had many years' struggle to gain acceptance of his ideas concerning the structure of organic compounds, particularly his famous theory of substitutions. His chief adversaries were the great Liebig and Jean-Baptiste Dumas, his former teacher who, himself a talented chemist,
availed himself in this dispute of the wide powers at his command in an attempt to reduce his young opponent to silence.

However, we should not paint too black a picture. Fortunately there are far more numerous examples to show the intellectual courage with which very great scientists have been willing to see their most cherished theories overthrown. These remarks merely go to prove that, whatever their creative genius, the most eminent scientists may possess all sorts of qualities and defects, and that it would be a mistake to regard them as exceptional beings in this respect.

There are many classical examples of obstacles placed in the way of scientific progress by over-powerful philosophical doctrines. As everyone knows, Aristotle's doctrine, modified by medieval thinkers, later became a barren dogma against which scientists had to battle hard before succeeding in establishing the principles of modern science. Although this pressure has been less conspicuous at other periods, it has invariably had a disastrous effect. Cartesianism, which started as a doctrine of intellectual freedom, was turned in less than a century into an anti-progressive force. In the nineteenth century, positivism, which had at the outset adopted a very favourable attitude towards science, later became an instrument of orthodoxy and regression. The basic reason for this retarding action of many philosophic doctrines is that they were devised in the light of contemporary science and then, having failed to evolve, endeavoured to keep science at that same stage.

The well known example of the Catholic Church's sustained opposition to the Copernican System and the persecutions inflicted on several defenders of that system, including Galileo, further illustrate the obstacles encountered by scientific progress. Any dogma some of whose aspects have a bearing on science is, by its very essence, thoroughly harmful.

Apart from the pseudo-scientific, philosophic and religious dogmas, political censures have also militated considerably against discoveries and new theories. In every age, great scientists have been regarded as heretics or as a threat to the established order of society. There is no lack of examples to show that a physical or biological theory based on reliable scientific data may be condemned by the State if it is at variance with the prevailing political philosophy. If his work is to be truly effective, the creative thinker must be quite unhampered by any prejudice or belief which may restrict his freedom of thought and conception in the realm of science. He must be free to advance sound arguments against any theory, however firmly established, and to put forward any new hypothesis that is well grounded.

It is a fact that most of the really fruitful discoveries gave rise, when they were first launched, to a kind of intellectual scandal, and their authors had often to engage in a difficult and unequal struggle to win recognition for them.
As a man of a particular age, country and social class, the scientist or inventor is *ipso facto* subject to certain conditioning factors which may exert a direct influence on his creative work. It is clear that, if this work is to be carried out in the best conditions, the scientist or inventor must be assured of adequate leisure, perfect peace of mind and means sufficient to enable him to meet his own needs and conduct his research with the greatest possible efficiency. Until the seventeenth century, most scientific research workers were drawn from the relatively small class of persons who had had the benefit of a sound education and whose profession allowed them to devote part of their time to scientific research. The growth of universities and of the various schools and academies, from the seventeenth century onwards, gradually extended the field from which scientists were recruited. At the same time, enlightened despotism allowed many scholars to spend almost all their time in research. The increase in the number of teachers and of institutions for scientific and technical training, brought in by the French Revolution, marked the beginning of further progress. The expansion of big industry, the remarkable development of technology and the provision of educational opportunities for all contributed, in their turn, towards a very rapid increase in the number of research workers and likewise in the resources placed at their disposal. In the twentieth century this movement has been speeded up as a result of the increasingly important part played by science and technology in the life of society. However, the needs of laboratories have also increased rapidly. Scientific research can only develop harmoniously if it receives steadily increasing support, and if—this is an essential condition—this support is not confined to aid for projects promising an immediate return. There can only be constant progress in the various branches of technology if there is a parallel advance in the theoretical sciences, and history offers examples of what appeared to be the most abstract discoveries but which were subsequently found to open up a host of practical applications.

The question whether the obvious influence of economic conditions on the life of the research worker, and the resources available for his work, can be said to extend equally to the sphere of scientific creation proper, the origin of all discoveries and inventions, is an intricate one, which calls for lengthy and objective investigation. It has brought forth contradictory replies which may be briefly mentioned here.

The idealistic theory, concentrating on the creative activities of a few great scientists, denies to economic factors any noteworthy influence on discovery or invention. It depicts scientific creation as the bold and original product of exceptional minds, working in complete isolation from the surrounding society which, in its turn, unable to understand or to accept the revolutionary ideas they put forward, reacts towards them by silence or
persecution. Such an interpretation has the serious defect of taking only certain great discoveries into consideration and neglecting a very important section of scientific production. Besides, even taking into account only scientists of undoubted genius, is it possible to consider the work of such men as Archimedes, Galileo, Harvey, Fermat, Newton, Gauss, Pasteur, or Einstein without relation to their economic and social environment? Their choice of a subject for research was surely influenced to some extent by economic and social factors which it is often difficult to identify.

Does this mean, then, that we must adopt the theory of Marxist writers who find the origin of nearly all discoveries and inventions in economic factors? It cannot be denied that many inventions, from the wheel, gunpowder and the printing press to the calculating machine, the steam engine, the internal combustion engine, telegraph, telephone, radio and antibiotics, have been brought about, at least in part, by economic and social pressures. The same is true of certain discoveries in fields more or less directly related to practical problems and to the applications of science. For instance, Pasteur's chief discoveries in microbiology were due to some extent to research being carried out to combat various kinds of microbial infections. This is also the case, although less directly, with the discovery of the laws of thermodynamics, which was connected with the development of the steam engine, and with the first studies of projective geometry, which were the result of a careful study of perspective in art, and of the desire to simplify the work of artists by giving them simple and convenient sketching rules. This latter example shows clearly that the importance of economic factors in bringing about a discovery or an invention largely depends on the personality and philosophic attitude of the author of the discovery in question. Whereas Desargues, the originator of projective geometry, makes his concern for practical questions plain, as do many other scientists (such as the founders of mathematical physics, Fourier in particular) there are numbers of others who, like the great scientist Jacobi, think that the sole object of science is to honour the human intellect and that, in this respect, a question of numbers is as important as a question concerning a system of the universe.

Thus, as against examples of inventions and discoveries arising at least in part from utilitarian considerations and economic factors, can be set others due solely to the disinterested activity of minds seeking to advance the science of their time. This applies to research into the theory of numbers, work on axioms, and a great many discoveries in the fields of geometry, mathematical analysis, astronomy and even theoretic mechanics. In regard to the experimental sciences and the sciences of observation, the situation is more complex, and each example must be examined individually, for concern with utilitarian matters is here often mingled with scientific considerations.

While the influence of economic factors is decisive in the field of technical invention and applied science, it is far less apparent in the experimental
sciences, and relatively rare in the domain of mathematics and the related sciences. Nowadays, no doubt, the support given to science by the public authorities or by industrial firms always has some condition attached to it, of which the most common is that the greater part of the research undertaken shall be directed towards work showing immediate returns. In this connexion a new problem arises which deserves careful investigation—the problem of the rapid extension of team research.

The most important discoveries and inventions of the present day are generally the result of research conducted, not by isolated scientists, but by teams of research workers. This is due to two main reasons: firstly, the growing complexity of research, which necessitates the use of well equipped laboratories, complicated and costly apparatus, rational bibliographical arrangements and the co-operation of research workers in different branches of science; and, secondly, the increasing part played in research by governments and big industry. Such a system has undeniable advantages in that it makes all kinds of facilities available to every research worker; there is also no doubt that much essential research could not be undertaken or brought to completion in any other way.

But mention should be made of certain dangers inherent in this ever larger part played by political and financial interests in the material and administrative organization of scientific research. To begin with, the work of the research scientist cannot be compared with that of the ordinary operative or even of the engineer; and when teamwork is over-administered the effect may be to sterilize some of the richest sources of scientific invention and discovery. Although team-work does provide a means of systematically exploiting certain results or developing new techniques, fundamental discoveries can only be made through the original efforts of scientists who are free to follow their intuition. Team research can only achieve the most fruitful results if it is so organized as to take account of the original talents of every good research worker and to make the largest possible allowance for the various factors which influence creative scientific work.

The second danger attending an over-rapid extension of team research is perhaps even more serious. The direct intervention of political and industrial interests in the preparation of research plans is liable to lead to the neglect of purely disinterested research in favour of work that brings in immediate returns. Such a policy would obviously be short-sighted, for several discoveries that seem at first most unlikely to serve any practical purpose subsequently turn out to be extremely useful.

It would be idle to think of opposing the extension of team research, the need for which is undeniable. Very careful consideration should therefore be given to the best ways of organizing creative scientific and technological work so as to provide the most effective stimulus for the harmonious and fruitful development of science.
PAGES FROM THE PAST

T. H. Huxley: the Statesman of Nineteenth-century Science

In his admirable joint biography of Darwin and Huxley, recently published,1 Professor William Irvine recounts the last meeting between T. H. Huxley and Carlyle towards the end of the latter's life. The old man was walking slowly and alone down the opposite side of the street when Huxley crossed over and spoke to him. Carlyle looked up and observing 'You're Huxley, aren't you? The man who says we're all descended from monkeys', passed on his way.

To the nineteenth-century intellectual elite, Huxley was, more than any other, perhaps even more than Darwin himself, the man identified with the great controversy which split society everywhere into two irreconcilable camps. And it was Disraeli who, in a catch-phrase, gave a label to the two camps. Speaking at Oxford in 1864, he exclaimed: 'The question is this—Is man an ape or an angel? My Lord, I am on the side of the angels.'

Huxley was, of course, on the side of the apes; in fact, it seems rather surprising that it was not he who was the actual originator of the controversy. For, as Professor Irvine rightly remarks, nobody would have been surprised if Huxley had explained evolution. Nearly everyone who has read the facts is a little surprised that Darwin did. In the event, Darwin was 'the quiet sedentary cause; Huxley the brilliant event. Darwin caused history and Huxley made it'.

That is why Huxley is of far more interest to students of the social aspects of science than Darwin could ever be. For in the process of defending evolution against the powerful orthodox opposition which was ranged on the side of the angels, Huxley gradually became not only the champion but the acknowledged statesman of nineteenth-century science. He took science out of its ivory tower and put it right in the centre of the public—and political—arena. With his clarity and great gift for exposition, he succeeded in changing what hitherto had been regarded as a curious occupation of a few eccentric gentlemen into a matter of interest to politicians, businessmen, and even working men. In short, he brought science into the public life of his country. And it was in recognition of this achievement that, a few years before his death, he received from the hands of Queen Victoria the honour of a Privy Councillorship so that he might act on behalf of science in the Councils of the State.

At first, the young professor of paleontology had no great faith in public speaking or writing as a means of converting the incredulous. The turning point came unexpectedly at the famous meeting of the British Association for the Advancement of Science at Oxford in 1860, when Huxley, then a young man of 35, literally annihilated the powers of orthodoxy in the person of Bishop Wilberforce. On his way back to his lodgings, he confided to his

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friend Hooker that this experience had changed his opinion as to the practical value of the art of public speaking. After that, he never looked back, and for the next 35 years—until his death in 1895—there came from his pen a ceaseless flow of essays, articles, addresses, lectures and reviews on almost every conceivable subject, from religion to the emancipation of women, from politics to the vivisection of dogs, from science to literature. But all his writings, on whatever subject, were inspired by the same idea—the firm belief that scientific method could clarify politics and morals just as surely as it was revolutionizing industry and everyday life. Darwinian evolution held out the hope that man might ultimately learn the laws of his social life well enough to rationalize and control his actions; and to that end all of Huxley's writings were ultimately dedicated. He believed that science was the key to everything. This belief was firmly held by nineteenth-century scientists, and it is for this reason—one of historical interest—that some of Huxley's writings are reproduced here as 'Pages from the Past'.

The influence of his writings and lectures on the intellectual life of his day can hardly be exaggerated. As Professor Irvine rightly points out, it is part of Huxley's importance that he brought the man of science as a cultural type into the broader arena of European civilization. Without Huxley, science would not have enjoyed such dazzling prestige among politicians and businessmen, nor figured so prominently in the late nineteenth-century school curriculum. For he was not only politically active in the field of education, but was a prominent figure on every intellectual battlefield in Europe. He said not so much what nobody had thought as what nobody had dared say—and said it so forcefully that many who hardly thought at all were persuaded.

The quotations given below are taken from the following works:


ON SCIENCE

The improver of natural knowledge absolutely refuses to acknowledge authority, as such. For him, scepticism is the highest of duties; blind faith the one unpardonable sin. (C.E., I, 40.)

The man of science has learned to believe in justification, not by faith, but by verification. (C.E., I, 41.)

Anyone who is practically acquainted with scientific work is aware that those who refuse to go beyond fact, rarely get as far as fact; and anyone who has studied the history of science knows that almost every great step therein has been made by the 'anticipation of Nature'. (C.E., I, 62.)

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Ecclesiasticism in science is only unfaithfulness to truth. (C.E., II, 149.)

The scientific spirit is of more value than its products, and irrationally held truths may be more harmful than reasoned errors. (C.E., II, 229.)

Science commits suicide when it adopts a creed. (C.E., II, 252.)

Science is, I believe, nothing but trained and organized common sense, differing from the latter only as a veteran may differ from a raw recruit. (C.E., III, 45.)

The vast results obtained by Science are won by no mystical faculties, by no mental processes, other than those which are practised by every one of us, in the humblest and meanest affairs of life. A detective policeman discovers a burglar from the marks made by his shoe, by a mental process identical with that by which Cuvier restored the extinct animals of Montmartre from fragments of their bones. (C.E., III, 77.)

The scientific imagination always restrains itself within the limits of probability. (C.E., V, 125.)

Science has fulfilled her function when she has ascertained and enunciated truth. (C.E., VII, 151.)

The rapid increase of natural knowledge, which is the chief characteristic of our age, is effected in various ways. The main army of science moves to the conquest of new worlds slowly and surely, nor ever cedes an inch of the territory gained. But the advance is covered and facilitated by the ceaseless activity of clouds of light troops provided with a weapon—always efficient, if not always an arm of precision—the scientific imagination. It is the business of these enfants perdus of science to make raids into the realm of ignorance wherever they see, or think they see, a chance; and cheerfully to accept defeat, or it may be annihilation, as the reward of error. Unfortunately the public, which watches the progress of the campaign, too often mistakes a dashing incursion of the Uhlan for a forward movement of the main body; fondly imagining that the strategic movement to the rear, which occasionally follows, indicates a battle lost by science. And it must be confessed that the error is too often justified by the effects of the irrepressible tendency which men of science share with all other sorts of men known to me, to be impatient of that most wholesome state of mind—suspended judgement; to assume the objective truth of speculations which, from the nature of the evidence in their favour, can have no claim to be more than working hypotheses.

The history of the 'Aryan question' affords a striking illustration of these general remarks. (C.E., VII, 151.)

The great tragedy of Science—the slaying of a beautiful hypothesis by an ugly fact. (C.E., VIII, 244.)

Mathematics may be compared to a mill of exquisite workmanship, which grinds you stuff of any degree of fineness; but, nevertheless, what you get out depends upon what you put in; and as the grandest mill in the world will not
extract wheat-flour from peascods, so pages of formula will not get a definite result out of loose data. (C.E., VIII, 333.)

The vulgar antithesis of fact and theory is founded on a misconception of the nature of scientific theory, which is, or ought to be, no more than the expression of fact in a general form. Whatever goes beyond such expression is hypothesis; and hypotheses are not ends, but means. They should be regarded as instruments by which new lines of inquiry are indicated; or by the aid of which a provisional coherence and intelligibility may be given to seemingly disconnected groups of phenomena. The most useful of servants to the man of science, they are the worst of masters. And when the establishment of the hypothesis becomes the end, and fact is alluded to only so far as it suits the 'Idee', science has no longer anything to do with the business. (S.M., IV, 663).

Cuvier was one of those happily endowed persons in whom genius never parts company with common-sense; and whose perception of the importance of sound method is so great that they look at even a truth, hit upon by those who pursue an essentially vicious method, with the sort of feeling with which an honest trader regards the winnings of a gambler. They hold it better to remain poor than obtain riches by the road that, as a rule, leads to ruin. (S.M., IV, 669.)

We men of science, at any rate, hold ourselves morally bound to 'try all things and hold fast to that which is good'; and among public benefactors, we reckon him who explodes old error, as next in rank to him who discovers new truth. (L.L., III, 18.)

Science reckons many prophets, but there is not even a promise of a Messiah. (L.L., III, 322).

ON THE POPULARIZATION OF SCIENCE

I have not been one of those fortunate persons who are able to regard a popular lecture as a mere hors d'oeuvre, unworthy of being ranked among the serious efforts of a philosopher; and who keep their fame as scientific hierophants unsullied by attempts—at least of the successful sort—to be understood of the people.

On the contrary, I found that the task of putting the truths learned in the field, the laboratory and the museum, into language which, without bating a jot of scientific accuracy shall be generally intelligible, taxed such scientific and literary faculty as I possessed to the uttermost; indeed my experience has furnished me with no better corrective of the tendency to scholastic pedantry which besets all those who are absorbed in pursuits remote from the common ways of men, and become habituated to think and speak in the technical dialect of their own little world, as if there were no other.

If the popular lecture thus, as I believe, finds one moiety of its justification in the self-discipline of the lecturer, it surely finds the other half in its effects on the auditory. For though various sadly comical experiences of the results of my own efforts have led me to entertain a very moderate estimate of the
purely intellectual value of lectures; though I venture to doubt if more than one in ten of an average audience carries away an accurate notion of what the speaker has been driving at; yet is that not equally true of the oratory of the hustings, of the House of Commons, and even of the pulpit? . . .

At the same time it must be admitted that the popularization of science, whether by lecture or essay, has its drawbacks. Success in this department has its perils for those who succeed. The 'people who fail' take their revenge, as we have recently had occasion to observe, by ignoring all the rest of a man's work and glibly labelling him a mere popularizer. If the falsehood were not too glaring, they would say the same of Faraday and Helmholtz and Kelvin. (C.E., VIII, p. v.)

Of the affliction caused by persons who think that what they have picked up from popular exposition qualifies them for discussing the great problems of science, it may be said, as the Radical toast said of the power of the Crown in bygone days, that it 'has increased, is increasing, and ought to be diminished'. (C.E., VIII, p. viii.)

ON SOCIETY

That which is to be lamented, I fancy, is not that society should do its utmost to help capacity to ascend from the lower strata to the higher, but that it has no machinery by which to facilitate the descent of incapacity from the higher strata to the lower. (C.E., I, 254.)

The doctrine that all men are, in any sense, or have been, at any time, free and equal, is an utterly baseless fiction. (C.E., I, 313.)

With all their enormous differences in natural endowment, men agree in one thing, and that is their innate desire to enjoy the pleasures and escape the pains of life; and, in short, to do nothing but that which it pleases them to do, without the least reference to the welfare of the society into which they are born. That is their inheritance (the reality at the bottom of the doctrine of original sin) from the long series of ancestors, human and semi-human and brutal, in whom the strength of this innate tendency to self-assertion was the condition of victory in the struggle for existence. That is the reason of the aviditas vitae—the insatiable hunger for enjoyment—of all mankind, which is one of the essential conditions of success in the war with the state of nature outside; and yet the sure agent of the destruction of society if allowed free play within. (C.E., IX, 27.)

The notion that the value of a thing bears any necessary relation to the amount of labour (average or otherwise) bestowed upon it, is a fallacy which needs no further refutation than it has already received. The average amount of labour bestowed upon warming-pans confers no value upon them in the eyes of a Gold Coast negro; nor would an Esquimaux give a slice of blubber for the most elaborate of ice-machines. (C.E., IX, 171.)

So long as unlimited multiplication goes on, no social organization which has ever been devised, or is likely to be devised, no fiddle-faddling with the
distribution of wealth, will deliver society from the tendency to be destroyed by the reproduction within itself, in its intensest form, of that struggle for existence the limitation of which is the object of society. And however shocking to the moral sense this eternal competition of man against man and of nation against nation may be; however revolting may be the accumulation of misery at the negative pole of society, in contrast with that of monstrous wealth at the positive pole; this state of things must abide, and grow continually worse, so long as Istar holds her way unchecked. It is the true riddle of the Sphinx; and every nation which does not solve it will sooner or later be devoured by the monster itself has generated. (C.E., IX, 211.)

It appears to me that the amount of freedom which incorporate society may fitly leave to its members is not a fixed quantity, to be determined a priori by deduction from the fiction called 'natural rights'; but that it must be determined by, and vary with, circumstances. I conceive it to be demonstrable that the higher and the more complex the organization of the social body, the more closely is the life of each member bound up with that of the whole; and the larger becomes the category of acts which cease to be merely self-regarding, and which interfere with the freedom of others more or less seriously. (C.E., IX, 227.)

At the present time the important question for England is not the duration of her coal, but the due comprehension of the truths of science, and the labours of her scientific men. (L.L., I, 400.)

There is such a thing as a science of social life, for which, if the term had not been so helplessly degraded, Politics is the proper name.

Men are beings of a certain constitution, who, under certain conditions, will as surely tend to act in certain ways as stones will tend to fall if you leave them unsupported. The laws of their nature are as invariable as the laws of gravitation, only the applications to particular cases offer worse problems than the case of the three bodies. (L.L., III, 337.)

ON CIVILIZATION

Modern civilization rests upon physical science; take away her gifts to our own country, and our position among the leading nations of the world is gone tomorrow; for it is physical science only that makes intelligence and moral energy stronger than brute force. (C.E., VIII, 226.)

The whole of modern thought is steeped in science; it has made its way into the works of our best poets, and even the mere man of letters, who affects to ignore and despise science, is unconsciously impregnated with her spirit, and indebted for his best products to her methods. I believe that the greatest intellectual revolution mankind has yet seen is now slowly taking place by her agency. She is teaching the world that the ultimate court of appeal is observation and experiment, and not authority; she is teaching it to estimate the value of evidence; she is creating a firm and living faith in the existence of immutable moral and physical laws, perfect obedience to which is the highest possible aim of an intelligent being. (C.E., VIII, 226.)
We are in the midst of a gigantic movement greater than that which preceded and produced the Reformation, and really only the continuation of that movement. But there is nothing new in the ideas which lie at the bottom of the movement, nor is any reconciliation possible between free thought and traditional authority. One or other will have to succumb after a struggle of unknown duration, which will have as side issues vast political and social troubles. I have no more doubt that free thought will win in the long run than I have that I sit here writing to you, or that this free thought will organize itself into a coherent system, embracing human life and the world as one harmonious whole. But this organization will be the work of generations of men, and those who further it most will be those who teach men to rest in no lie, and to rest in no verbal delusions. (L.L., II, 111.)

I conceive that the leading characteristic of the nineteenth century has been the rapid growth of the scientific spirit, the consequent application of scientific method of investigation to all the problems with which the human mind is occupied and the correlative rejection of traditional beliefs which have proved their incompetence to bear such investigation. (L.L., III, 322.)

ON EDUCATION

If I insist unweariedly, nay fanatically, upon the importance of physical science as an educational agent, it is because the study of any branch of science, if properly conducted, appears to me to fill up a void left by all other means of education. (C.E., VIII, 218.)

Though under-instruction is a bad thing, it is not impossible that over-instruction may be worse. (L.L., II, 220.)

PHILOSOPHICAL REFLECTIONS

M. Comte's philosophy, in practice, might be compendiously described as Catholicism minus Christianity. (C.E., I, 156.)

There are some men who are counted great because they represent the actuality of their own age, and mirror it as it is. Such an one was Voltaire, of whom it was epigrammatically said, 'he expressed everybody's thoughts better than anybody'. But there are other men who attain greatness because they embody the potentiality of their own day, and magically reflect the future. They express the thoughts which will be everybody's two or three centuries after them. Such an one was Descartes. (C.E., I, 167.)

There is assuredly no more effectual method of clearing up one's own mind on any subject than by talking it over, so to speak, with men of real power and grasp, who have considered it from a totally different point of view. (C.E., I, 202.)

Logical consequences are the scarecrows of fools and the beacons of wise men. (C.E., I, 244.)
The only question which any wise man can ask himself, and which any honest man will ask himself, is whether a doctrine is true or false. (C.E., I, 244.)

Time, whose tooth gnaws away everything else, is powerless against truth. (C.E., I, 255.)

Orthodoxy is the Bourbon of the world of thought. It learns not, neither can it forget. (C.E., II, 52.)

History warns us that it is the customary fate of new truths to begin as heresies and to end as superstitions. (C.E., II, 229.)

The struggle for existence holds as much in the intellectual as in the physical world. A theory is a species of thinking, and its right to exist is coextensive with its power of resisting extinction by its rivals. (C.E., II, 229.)

There are men (and I think Priestley was one of them) to whom the satisfaction of throwing down a triumphant fallacy is as great as that which attends the discovery of a new truth, who feel better satisfied with the government of the world, when they have been helping Providence by knocking an imposture on the head; and who care even more for freedom of thought than for mere advance of knowledge. These men are the Carnots who organize victory for truth, and they are, at least, as important as the generals who visibly fight her battles in the field. (C.E., III, 13.)

All truth, in the long run, is only common sense clarified. (C.E., III, 282.)

If a little knowledge is dangerous, where is the man who has so much as to be out of danger? (C.E., III, 299.)

The great end of life is not knowledge, but action. What men need is, as much knowledge as they can assimilate and organize into a basis for action; give them more and it may become injurious. One knows people who are as heavy and stupid from undigested learning as others are from over-fulness of meat and drink. (C.E., III, 422.)

Men can intoxicate themselves with ideas as effectually as with alcohol or with bang, and produce, by dint of intense thinking, mental conditions hardly distinguishable from monomania. (C.E., V, 136.)

Agnosticism, in fact, is not a creed, but a method, the essence of which lies in the rigorous application of a single principle. That principle is of great antiquity; it is as old as Socrates; as old as the writer who said, 'Try all things, hold fast by that which is good'; it is the foundation of the Reformation, which simply illustrated the axiom that every man should be able to give a reason for the faith that is in him; it is the great principle of Descartes; it is the fundamental axiom of modern science. Positively the principle may be expressed: In matters of the intellect, follow your reason as far as it can go. (C.E., V, 136.)

1. By 'new truths' Huxley here means 'hypotheses', in this particular context, the Darwinian doctrine of evolution (Note by Editor).
will take you, without regard to any other consideration. And negatively: In matters of the intellect do not pretend that conclusions are certain which are not demonstrated or demonstrable. That I take to be the agnostic faith, which if a man keep whole and undefiled, he shall not be ashamed to look the universe in the face, whatever the future may have in store for him. (C.E., V, 245.)

Faith is the power of saying you believe things which are incredible. (C.E., V, 313.)

Platonic philosophy is probably the grandest example of the unscientific use of the imagination extant. (C.E., VI, p. viii.)

To say that an idea is necessary is simply to affirm that we cannot conceive the contrary; and the fact that we cannot conceive the contrary of any belief may be a presumption, but is certainly no proof, of its truth. (C.E., VI, 144.)

Nature is never in a hurry, and seems to have had always before her eyes the adage, 'keep a thing long enough, and you will find a use for it'. (C.E., VIII, 159.)

The more rapidly truth is spread among mankind the better it will be for them. Only let us be sure that it is truth. (L.L., II, 266.)

Your astonishment at the tenacity of life of fallacies, permit me to say, is shockingly unphysiological. They, like other low organisms, are independent of brains, and only wriggle the more, the more they are smitten on the place where the brains ought to be. (L.L., II, 275.)

It is not to be forgotten that what we call rational grounds for our beliefs are often extremely irrational attempts to justify our instincts. (L.L., III, 142.)

ETHICAL AND MORAL REFLECTIONS

A man's worst difficulties begin when he is able to do as he likes. (C.E., III, 236.)

There is but one right, and the possibilities of wrong are infinite. (C.E., III, 236.)

My experience of the world is that things left to themselves don't get right. (C.E., III, 439.)

The most considerable difference I note among men is not in their readiness to fall into error, but in their readiness to acknowledge these inevitable lapses. (C.E., V, 157.)

In a large proportion of cases, crime and pauperism have nothing to do with heredity; but are the consequences, partly, of circumstances and, partly, of the possession of qualities, which, under different conditions of life, might
have excited esteem and even admiration. It was a shrewd man of the world who, in discussing sewage problems, remarked that dirt is riches in the wrong place; and that sound aphorism has moral applications. The benevolence and open-handed generosity which adorn a rich man may make a pauper of a poor one; the energy and courage to which the successful soldier owes his rise, the cool and daring subtlety to which the great financier owes his fortune, may very easily, under unfavourable conditions, lead their possessors to the gallows, or to the hulks. (C.E., IX, 39.)

It is none the less true that, since law and morals are restraints upon the struggle for existence between men in society, the ethical process is in opposition to the principle of the cosmic process, and tends to the suppression of the qualities best fitted for success in that struggle. (C.E., IX, 30.)

There is another fallacy which appears to me to pervade the so-called 'ethics of evolution'. It is the notion that because, on the whole, animals and plants have advanced in perfection of organization by means of the struggle for existence and the consequent 'survival of the fittest'; therefore men in society, men as ethical beings, must look to the same process to help them towards perfection. I suspect that this fallacy has arisen out of the unfortunate ambiguity of the phrase 'survival of the fittest'. 'Fittest' has a connotation of 'best'; and about 'best' there hangs a moral flavour. In cosmic nature, however, what is 'fittest' depends upon the conditions. Long since, I ventured to point out that if our hemisphere were to cool again, the survival of the fittest might bring about, in the vegetable kingdom, a population of more and more stunted and humbler and humbler organisms, until the 'fittest' that survived might be nothing but lichens, diatoms, and such microscopic organisms as those which give red snow its colour; while, if it became hotter, the pleasant valleys of the Thames and Isis might be uninhabitable by any animated beings save those that flourish in a tropical jungle. They, as the fittest, the best adapted to the changed conditions, would survive. (C.E., IX, 80.)

The practice of that which is ethically best—what we call goodness or virtue—involves a course of conduct which, in all respects, is opposed to that which leads to success in the cosmic struggle for existence. In place of ruthless self-assertion it demands self-restraint; in place of thrusting aside, or treading down, all competitors, it requires that the individual shall not merely respect, but shall help his fellows; its influence is directed not so much to the survival of the fittest, as to the fitting of as many as possible to survive. It repudiates the gladiatorial theory of existence. It demands that each man who enters into the enjoyment of the advantages of a polity shall be mindful of his debt to those who have laboriously constructed it; and shall take heed that no act of his weakens the fabric in which he has been permitted to live. Laws and moral precepts are directed to the end of curbing the cosmic process and reminding the individual of his duty to the community, to the protection and influence of which he owes, if not existence itself, at least the life of something better than a brutal savage. (C.E., IX, 81.)

Ethical nature may count upon having to reckon with a tenacious and powerful enemy as long as the world lasts. But, on the other hand, I see no limit
to the extent to which intelligence and will, guided by sound principles of investigation, and organized in common effort, may modify the conditions of existence, for a period longer than that now covered by history. And much may be done to change the nature of man himself. The intelligence which has converted the brother of the wolf into the faithful guardian of the flock ought to be able to do something towards curbing the instincts of savagery in civilized men. But . . . I deem it an essential condition of the realization of that hope that we should cast aside the notion that the escape from pain and sorrow is the proper object of life. (C.E., IX, 85.)

Society differs from nature in having a definite moral object; whence it comes about that the course shaped by the ethical man—the member of society or citizen—necessarily runs counter to that which the non-ethical man—the primitive savage, or man as a mere member of the animal kingdom—tends to adopt. The latter fights out the struggle for existence to the bitter end, like any other animal; the former devotes his best energies to the object of setting limits to the struggle. (C.E., IX, 202.)

Of moral purpose I see no trace in Nature. That is an article of exclusively human manufacture—and very much to our credit. (L.L., III, 172.)
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