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WHAT MAKES A SCIENTIST?

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THE qualities that characterise a great scientist are very elusive. Before I try to deal with them, I would like to clear the air by touching on two points.

The first is the very real difference between fundamental and applied science, the first being knowledge oriented and the second project oriented. I want to emphasise right away how strongly I dissent from the view that the one is any way finer or more inspiring than the other.

The project oriented problems cover a much wider range than those that face knowledge oriented scientists like myself. Social habits, politics, economics, all enter into them. The time factor is often vitally important. Bold decisions must be made on insufficient evidence. The scientific requirement in their schemes is often the least formidable one to meet. I remember Sir John Baker, the head of the Engineering Department in Cambridge, giving one of the schools lectures at the Royal Institution; his subject was the Morrison shelter in the last war as an example of the many problems that have to be mastered before such a scheme can be launched. The scientific idea behind it was ingenious and sound. The shelter had to provide a reasonably comfortable retreat inside a house, because one could not expect people to sleep in damp, cold dugouts. It therefore had to withstand a bombed house falling down on top of it. Masonry and rubble falling on a brittle structure, even though it is strong, will crack it. Baker realised that this could be avoided by constructing the shelter of yielding steel, so that the energy of the falling building was absorbed as work done in deforming the roof of the shelter. Calculation showed that it could be so made that, though it would yield considerably, its top would still stay well above the sleeper under its cover. So far so good, but

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authorities had to be convinced of the soundness of the plan, priority obtained for the necessary steel, manufacturing and distribution had to be arranged, all a far more arduous task than just having the good idea. Professor Baker had chosen a telling instance to show the young people how much more than just science was involved in an engineer's career.

Like other fundamental scientists, I have had a taste of applied science in two world wars, when we were drawn into the war effort; although our problems were simpler, because making a profit was not a consideration, this experience gave us all, I think, a proper and healthy respect for the applied scientist.

I stress this difference, because it seems to me that the word *science* is often loosely used to describe two quite distinct forms of human endeavour. There is first the search for more knowledge about nature, a movement that can be traced far back, but that really only started in strength in the seventeenth century. This search has built up a body of knowledge and concepts that is continually being extended by scientific research. Then, there is the use of that knowledge for technical ends backed up by an intensive industrial research directed towards the particular project in hand. Man has always exercised his ingenuity in trying new ways of achieving practical ends, but the discoveries of science have, comparatively recently, immensely amplified his powers of invention. For instance, the scientists' discovery of the fundamental laws of electricity and magnetism at the beginning of the nineteenth century opened a new world to technology by starting electrical engineering. Yet the really widespread application of science to industry is mainly a phenomenon of the present century. So, when people talk about all the new and marvellous achievements of technology, they often loosely call them science, bracketing them with the pursuit of fundamental knowledge. The achievements are possible, because the engineer can draw on the body of knowledge that the scientist has created, but they are the product of many social forces to which science may make only a minor contribution.

The second point is that, although the knowledge and skill of the engineer, drawing on the body of scientific knowledge for assistance, has brought about the great extension of technical achievement that we call the scientific revolution, yet the scientific advances that have so increased technical powers have been almost entirely made without any thought of their possible practical use. One can put this more strongly—they would never have been made if their practical application had been regarded as a necessary condition for doing them. I confess that, when I was preparing this talk and consulted the early history of the Royal Society, I wondered if I had been too positive in making the above statement. The early Fellows were assiduous in their protestations that their inquiries would be of great importance to the economy of their country. On reflection, I still believe it to be true of the discoveries in those early days. One cannot help suspecting a certain element of propaganda by the members of the Royal Society, which was struggling to establish itself and gain support. When Charles II was moved to such mirth by the spectacle of the Fellows studying the weighing of the air, I do not think they were pursuing this research with an industrial end in view.

No better example can be taken than the start of 'useful electricity'. It is fun to play the game of imagining that one were able to talk with a distinguished man of the past and thinking how one would explain modern technical achievements to him. I would feel fairly sure of being able to explain a steam engine to a Roman engineer. Though the Romans had not arrived at such an engine, the mechanical principles would appeal to him as natural and familiar, but—a radio set—or even how one could light a room by pressing a knob! I remember that, when my father was Director of the Royal Institution, the American Electrical Engineers, who had built a new headquarters in New York, invited my father to participate in the opening ceremony. He was to strike a match and light a candle in Faraday's candlestick in his study at the Royal Institution and this act was to switch on all the lights in the new home of the Engineers. Now any sixth form schoolboy could guess how this was done—a photoelectric cell activating a relay and switch, a radio signal crossing the Atlantic, which in turn activated a relay and closed the main switch in the building. How simple, yet how magical it would appear to our Roman that lighting a candle in Britain would light a building 2 000 miles away.

How did it start? The ancients knew practically nothing about electricity, except for a few electrified toys. Then, around the start of the nineteenth century, Galvani discovered that the contact with two dissimilar metals made a frog's legs twitch. Volta, dissatisfied with Galvani's explanation in terms of animal electricity, seized on the fact that dissimilar metals seemed essential to build his 'pile'—the first battery and the first time man had at his command the power to study a continuous electric current. Galvani and Volta's names are part of our common language. Every householder knows about volts. It is strange to think that when, for instance, a letter to *The Times* says that this Government department or that needs to be galvanised into action, it literally means that the hind legs of its members should be made to kick by the application of an electric shock.

The availability of an electric current led 20 years later to the discovery that a current produced a magnetic field and this in due course gave an entirely new power to mankind, that of practically instantaneous communication all over the world. This power was based on the fact that some bodies conduct the current almost infinitely better than others. One only has to remember that an electric current, fed into the copper conductor of a cable, prefers to run from one side of the Atlantic to the other rather than to jump across an inch or so of insulation to the surrounding sea. Thirty years later, Faraday discovered that a current could be created by moving a magnet and this in due course led to dynamos and the efficient transmission of power over wide areas with all the changes it has brought about. Yet none of these consequences could possibly have been foreseen when Galvani and Volta, excited by mere curiosity, discovered the existence of a new world by a series of experiments that at the time seemed completely remote from any practical application.

Like all who give talks about new scientific discoveries, I am often asked 'To what use can this discovery be put' and I always give the same answer 'Come back in 50 years' time and I will tell you'. There was a story current in Cambridge that, shortly before he died, Lord Rutherford (who was the outstanding figure in radioactivity and had discovered the nucleus) explained at great length to a visiting notability (I think the American Dr Conant) why it was physically impossible ever to tap the vast stores of energy in the nucleus—this only a few years before the atomic bomb and the atomic power station. Scientists are sometimes adjured to find out knowledge that can be used only for good purposes and to eschew research that could be put to bad purposes. Such an attitude can come purely from a complete ignorance of how science works. There is no difference between good and bad knowledge; all the knowledge goes into a central store from which the technologist draws the many bits of information he wants for some particular scheme. There is rarely a one-to-one correspondence between a discovery and utilisation—in general, each exploitation depends on the work of many scientists in many fields. The scientist cannot foresee and be responsible for the use of his discovery, not because he lives in an ivory castle, but because the future holds so many surprises.

In this broad survey, I shall divide scientists into four categories. If I draw my examples mainly from the field of physics, you will realise that this is because it is the field most familiar to me. First, there are the thinkers, those who establish some new way of regarding the phenomena we observe. Newton si a supreme example in that, following the start made by Galileo, he conceived the earth and heaven as obeying the same fundamental laws. At the time of the Newton tercentenary, the late King paid a visit to Trinity College in Cambridge and various Fellows were detailed to say something to the King about Trinity's greatest son. I had to 'do' gravity. I remember the King saying, 'What's all this about an apple? Had not many people seen an apple fall before?' 'Your Majesty, the point was that Newton realised that the law which governed the fall of the apple to the earth also governed the continual falling of the moon towards the earth.' 'The moon falling towards the earth—that's the first I ever heard of it and the King passed on leaving me discomfited at the inaptness of my explanation.

Then, in our own times, is the advance made by the great Danish physicist Niels Bohr—and here I would like to pause and examine in some detail what he did, taking as it were a sounding in depth (whereas so far I have been skimming over the surface), because Bohr's work is such a wonderful example of what a new way of thinking can mean.

J. J. Thomson discovered that electrons were constituents of all atoms; Rutherford discovered the heavy positive nucleus at the centre of the atom whose attraction binds the negative electrons in the atomic structure. Models of the structure of the atom built on this basis at once came up against an insuperable difficulty. An electron rotating around the nucleus like a planet going round the sun should give out light, hence energy and eventually fall into the nucleus like an artificial satellite falls to earth when it experiences the resistance of our atmosphere. It does not do so, the atomic structure lasts indefinitely. Again, as it approaches the nucleus, it should circulate faster and faster, raising the frequency of the light it emits. On the contrary, when the atom emits light, it is of one pure frequency. As I once heard it put at a Solvay Conference by the Dutch physicist Ehrenfest, 'Ze problem—vy ze atom a pure tone geef and not a noise like ze leet cat make'.

Bohr cut the Gordian knot. He saw that the difficulty arose not because the right model had not been found, but because new assumptions must be made about the mechanical laws that governed it. Because a steam engine, obeying Newtonian mechanics, is made of atoms, it had been tacitly assumed that an atom obeyed Newtonian mechanics like a very small steam engine. Bohr formulated new laws and, in them, a certain constant h reappeared, which related frequency to a quantum or parcel of energy and which Planck had postulated to explain the properties of radiation. As atomic mechanisms were explored further, the same constant h turned up in other guises. To cut a long story short, it appeared that light, the wave nature of which had appeared to be so firmly established by Young and Fresnel's analysis of interference, had other properties that pointed equally clearly to light being a stream of projectiles, with an energy related to the wave frequency by Planck's constant. Then, to crown it all, Dickinson and Germer and G. P. Thomson showed that electrons, whose particle nature no one doubted, showed interference effects as though they were waves with a wavelength given by Planck's constant. As my father summed up the situation, one had to believe they were waves on Monday, Wednesday and Friday, particles on Tuesday, Thursday and Saturday—and have a rest on Sunday. As time went on, a deeper synthesis became possible. The character of a particle is that it is something at a definite point in space. The character of a wave is that it extends throughout space, though it may have a much greater amplitude in one place than another (some places may be stormy and others quiet). We can sum up the position by saying that, if we are given a definite set of conditions (a cause) and want to calculate what will happen (its effect), we must cast our prediction in the form of a distribution of probabilities and waves in simple cases are a convenient way to describe probability. All we can say is it is much more likely the effect will be this, much less likely it will be that. When the event has happened, whether it is a light quantum hitting a particular silver grain on a photographic plate or an electron making a track through a cloud chamber, it is a history of particles. The moment 'now' is like a sieve passing steadily through time. In front of it is a probability future, a 'wavy' future if you like, in which we can predict only how likely some result is to happen. As time streams through our sieve, it coagulates this wavy future into a particle past, where the precise history of events is recorded.

Why should predictions of the future inevitably have this probability character? Let me take an analogy. Suppose a doctor were so clever by making a thorough examination of a patient for a life insurance company that he could say exactly when that patient was going to die. The very examination, however, gives the patient such a shock that he will now not die at the calculated time. One can tell exactly what the shock has done only by making a further examination and this in its turn upsets calculation by administering a further shock. This is what happens when we examine nature. We say, 'We will find out the present state of affairs and by doing so be able to predict the future', but 'finding out the present state of affairs' means asking the atoms to give signals of what they are doing. Sending out a light signal is a shattering event to an atom, entirely altering its nature. The observer cannot be separated from the observed. If we try to find out what a given system is going to do, the questions we ask it force it to do something that causes it to behave in future in a way quite different from what it would have done if we had not asked it what it was going to do. I hope I make myself clear!

This means, as you will realise, that determinism in the sense of a one-to-one relationship between cause and effect, has no place in the physical world. Metaphysicians may talk about it if they like, and science cannot deny its possible existence, but the nature of the physical world is such that it can never establish such an idea.

Such revolutions in thought are the stuff of which science is made. Science is sometimes said to be a collection of facts. In a sense this is true, but the relationship of facts to science is like the relationship of a painter's palette of colours to his picture—there is more to a Rembrandt than flake white and yellow ochre. The greatest scientists are those who present us with new ways of thinking.

My next category is that of the discoverers. Röntgen's discovery of X-rays, Becquerel's discovery of radioactivity or, as an earlier instance, Oersted's discovery of the effect of a current on a compass are examples. Such discoveries are immensely important events in the history of science, because they open up new worlds. There is a curious feature about most of them, however. The men who make them are justly famous, but they seldom go on to further scientific achievements. They are like the novae in the heavens, stars that burst into extreme brilliance for a few days or weeks, then dwindle into ordinary stars. This is not to belittle their discoveries. As well as being helped by the fortunate chance that came their way when they were looking for something else, they had the wit to realise the immense importance of the strange effect they noticed.

Next, there are the designers who have produced some new form of apparatus that has opened up quite a new range of scientific research. An outstanding example is C. T. R. Wilson's development of the cloud chamber, which has been the vital tool in the study of the ultimate particles of matter. It can tell us the history of a single one of these minute particles, which leaves a trail in the cloud chamber like that left in the upper air by an aeroplane under certain meteorological conditions. Another example is Lawrence's cyclotron for accelerating particles to high energies and studying their reactions. The cyclotron is the parent of all the 'atom smashing' machines. Such machines, costing perhaps a thousand million pounds and covering a square mile, are able to produce in a space the size of a pin's head conditions that resemble those in the interior of a star. The energies of the reactions are astronomically great compared with those of the gentle chemical reactions of coal or dynamite. Like Prometheus, we have stolen this star-fire from the heavens and now we are wondering if the gods will destroy us to punish us for our boldness.

Finally, there is a class, containing some of the most famous names, which I can only describe as 'the hunters'. You will know how a smart dog, which we are taking for a walk, will look into every bush, smell every hole, examine behind every log in the hope of finding something exciting. Faraday was a hunter; one can see from his notebooks how he explored every possible variation of conditions in the search for some new scientific relationship, guided of course by a wonderful intuition about what would be a profitable hunting ground. A famous German scientist once said of him, 'Er riecht die Wahrheit' (he smells the truth). Rutherford, in the field of radioactivity where he reigned, was also a hunter, though he went about it in a far more boisterous way than Faraday. 'There's a big man with a gun and he's having lots of fun', to quote a well-known pop song, reminds us of Rutherford rather than Faraday.

I come next to another classification, which applies to all these types. Scientists are rather sharply divided into heads of teams and lone workers. The lone worker is embarrassed by disciples and he continues to make his own experiments and draw his own conclusions from them. Names that occur to one are C. T. R. Wilson, Aston who established the isotope, Lord Rayleigh who touched on every aspect of classical physics and adorned everything he touched and, to a large extent, G. I. Taylor. Such men tend to maintain their originality all their lives. There is a story of G. I. Taylor attending a meeting in London during the war, to which he was called as a consultant, because our ships of war appeared to be breaking up disconcertingly readily when attacked by a mine. G. I. Taylor is said to have worked out the cause of the constructional weakness on the back of an envelope returning from Liverpool Street to Cambridge. It is one of those stories that, if it is not true, ought to be true, because it is so typical of the man.

In contrast, the leader of a team spreads his influence over a number of disciples, but he can easily lose his direct touch with nature. He inevitably has cares of administration and direction and must largely abandon direct experimentation. His pupils may miss some clue, the importance of which he would have realised. It has seemed to me that the maximum number of other brains with which the leader can be in direct contact is about five. If the 'school' is larger, each of these may have another five under him, making 25 in all. Schools of 125 are not uncommon, but I have never heard of the work of one leader involving 625.

What makes a scientist? What qualities have the great in common? This is a difficult question to answer and the first quality that comes to my mind may seem a surprising one.

It is enthusiasm, which is very necessary. Research is extraordinarily inefficient. It was a saying of my father's that, if one looked back over a year's research, one could see that it could all have been done in a week. This is of course not always true, since a long time must often be spent in a series of measurements. He was referring, however, to all the explored alleys that had blind ends, to all the upturned stones that had nothing beneath them. Faraday was once asked how to do research and his reply was, 'Start it, carry on with it and finish it'. The tempo of research is slow; the unit of time is five years. Thinking back on the young men I have had in my group who have had a brilliant career, I see in them all a sort of bulldog spirit. If you hang on to a problem long enough, it seems to get exhausted and yield up its secret—provided of course that someone else does not get there before you. Enthusiasm and optimism are vital factors in keeping up the morale of a research team.

I find it hard to name the next essential quality. It is partly described as being 'the open mind', a readiness to scrap previous ideas and start on quite new lines. Another ingredient is imagination and originality comes into it. When some genius makes the breakthrough, the answer seems so obvious that one could kick oneself for not having spotted it. What stopped one doing so? It is something to do with its being so hard to take a fresh look. I notice that, when I have settled down to the after-dinner crossword and am absolutely stuck trying to interpret a clue, if I drop off into a short nap as one is apt to do on such occasions, I see the answer at once when I wake up. I do not think this is because my subconscious mind has been at work, I believe it is because I have forgotten the ways I was trying to solve it before. It is for this reason, perhaps, that most great scientists have produced their major contribution while they are young and their minds are fresh. Scientists are often pictured in the popular press as greybeards looking down microscopes. This is the reverse of truth; such people as Rutherford, Bohr and Einstein were in their twenties when they produced the work that made them famous. It is difficult for them in later life to break away from the line they started on when young, scrapping its capital and experience and starting afresh. I remember when my wife and I went to Sweden in early days and were entertained by the famous Arrhenius, my wife asked a Swedish friend what Arrhenius had done. He replied, 'When he was a young man, he made a very famous theory; since then, he has gone round the world accepting honorary degrees.' It is interesting, too, to note the effect of war work. Many scientists, switched off their habitual lines by having to do something quite different for the war effort, had a kind of second flowering and were brilliant again in quite a new way. It is a fascinating thought that it would probably contribute greatly to our scientific potential if we could take all our scientists at the age of 35 and make them drink in the waters of Lethe, so that they forgot all they had studied in the past and started again.

You may have remarked that, in listing the qualities for greatness, I have said nothing about 'cleverness' in the sense of the mental ability that, for instance, leads to success in examinations. It is hard to assess its importance and it is certainly not an essential. Rutherford discovered the nucleus of the atom by noting that alpha-rays were turned back on their tracks. Yet I remember the late Professor Robinson, who was a research student in Rutherford's laboratory at the time, telling me that he and Charles Darwin had to struggle for a month to explain to Rutherford the equation of the orbit of one body repelled by another, an equation that a clever schoolboy could solve. In Bohr's epoch-making first papers, the algebra is of the simplest kind. Faraday had no mathematical training whatever and he never used x and y, yet he was probably the greatest scientist since Newton. One might think that lack of mathematical ability was compensated for by manipulative skill, but again we draw a blank. J. J. Thomson had no great manipulative skill and I have heard that Rutherford's students prayed he would not come near their apparatus, because the results could be so disastrous. The greatness of these men is due to some quality that transcends cleverness.

There was a tradition when I was a student at Cambridge that one must excel in mathematics in order to do physics. I think this was partly because the tradition of Newton was still so strong. The Mathematical Tripos drew largely on the natural sciences for its exercises and, if the laws of science were not convenient for mathematical treatment, they were suitably modified. In the Tripos, they took on a form that bore the same relationship to nature that a gymnastic climbing frame does to a mountain. The mathematical exercises on which we spent our time and energy have nearly all disappeared from physics courses nowadays.

If it is hard to define the qualities that lead to greatness, it is easy to say what stops research. It is a full engagement book. The muse of science is capricious in her visits and we can never count on her breathing inspiration on us, but we can be quite sure that she will flee from the busy man. When one is trying to work out some knotty problem, a process goes on in one's head like the piling of Pelion on Olympus and Ossa on Pelion in their attempt to scale the heavens. The structure tumbles down each time it is disturbed and has to be started again. There is a story about Newton that he was once discovered boiling his watch with the egg in his waistcoat pocket. True or not, he would not have been Newton if he had not been capable of such feats of complete abstraction. Scientists, when they feel that possibly some light may be going to dawn, are apt to reply by grunts—scientists' wives have a dull life at such times. It is regrettable that, when a man has achieved fame, there seems to be a conspiracy to see that he does no more by demanding that he should become a man of affairs.

Curiosity-prompted research, as Professor Blackett has termed it, has great rewards to offer. Part of the thrill comes, I think, from the fact that one is judged not by one's fellow men, but by nature herself. When some fragment of truth has been discovered, the answer seems so simple and natural and aesthetically satisfying that it almost always carries conviction. In any case, it soon becomes clear whether one is right or wrong from the way the answer fits into the general pattern of increasing knowledge. I have now reached an age when the days of original research are long past, but a researcher recently consulted me about his works and asked for suggestions. In mulling over his results, I experienced once more that wonderful feeling that one grudged having to break away in the evening and could hardly wait till next morning to go on with the hunt. One feels that one is an eye, allowed to see something universal in which man is merely an insignificant incident. The students, I think, catch something of this vision. University unrest is not a phenomenon associated with the science side. I was very interested recently when a young researcher said to me how extraordinary it was that he was actually paid to so something that he enjoyed so much. Here, perhaps, a point might be made—in return for his privileges, I think a researcher ought to put all the energy he can into studying the art of good teaching and passing on his expertise to the next generation. A due amount of teaching is good for a researcher and does not detract from his research. The association of teaching with research in our universities is, I am sure, right.

In conclusion, I would like to deal with two points. The first concerns the relationship of fundamental science to industry. The industrialists often say that fundamental research is attracting too many of the best men, stressing quite rightly that the life of the country depends upon the high technical level of our industries. As I have heard it put, the worst brain drain in this country is to the universities. I think the answer, however, is not to blame the universities for making pure science too attractive; it is to increase the attractiveness of a scientific career in industry. Is there not perhaps still too great a gap between management on the one hand and research and development on the other? A director must know enough about science to know what kind of questions science can answer. If this is not so, the scientist cannot be inspired to give of his best.

My second point concerns the relationship between scientists and the community, the place of scientists in society. They are sometimes accused of living in ivory towers and of shirking the responsibility for the possibly disastrous consequences of the discoveries they make. They indeed have a responsibility, not only for suggesting how to do it, but also for foreseeing as well as they can the dangers of rash exploitation of man's great powers. I think it can be fairly claimed that they do feel the latter responsibility and are among the first to canvass against thoughtless elimination of wild life, careless cultivation leading to erosion and irrigation to ruining of the soil, poisoning of our streets by the traffic and of our food by additives, as well as social habits that lead to diseases. It is unfair, however, to reproach them for discovering knowledge about nature that could be turned to bad ends as well as to good ends. Though the scientist must be ready to explain what science can do, the choice of what shall be done is surely a moral responsibility that we all share equally.