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I

The restricted and the unrestricted sciences

AT THEIR FOUNDATION, the subject matter of the Tarner Lectures was defined as 'the Philosophy of the Sciences and the Relations, or Want of Relations, between the different Departments of Knowledge'. It is dangerous for a man of science to meddle with philosophical conclusions, even though his work inevitably brings their importance before him. He can hear the echo of that great naturalist John Ray in his Preface to *The Wisdom of God*:[1] 'I am sensible that this Tractate may likely incur the Censure of a superfluous piece, and myself the Blame of giving the Reader unnecessary Trouble, there having been so much so well written of this subject by the most learned Men of our Time...' All the same, Natural Knowledge is increasing so rapidly, so enormously, and in such apparently unrelated ways, that it can be useful for a man of science to discuss the matter, if but an amateur in philosophy, for he is in some position to review the relations or want of relations between the different departments of scientific knowledge as he sees them in practice.

What the practical scientist sees today is indeed a puzzle. However much we choose to classify the sciences together, the nuclear physicist at Harwell and the systematic entomologist identifying and classifying his insects at the British Museum of Natural History at least seem to be trying to do very different things, and their methods seem to differ so greatly that it is by no means obvious why we should lump them together as scientists and talk about their methods of investigation as *the* scientific method.

I shall therefore begin by discussing some views about the apparent relationship of the sciences and the goals of scientific investigation as they are seen today. That leads to discussion of the nature of scientific analysis and the extent to which this necessarily consists of the interpretation of larger-scale phenomena in terms of ever smaller and briefer events. In turn that leads to consideration of the different levels of complexity of natural phenomena and of the manner in which different rules seem to govern gross phenomena from those which hold at and below the molecular level. The nature of living systems is then considered and the special significance for them of this boundary between the gross and molecular levels of structure. This leads us to the scientific importance of determining the class to which a phenomenon belongs and the significance of classification in the sciences. It raises the question of how far such classification is a reflection of the 'real' world, and how far it is a reflection of our own mental machinery; and so we are led to reconsider the scientific method in the different sciences.

Let us begin with the term 'science'. Strictly this means all knowledge. By popular usage it has become more or less restricted to knowledge about objects in the natural world, to natural science. I say 'more or less' because since the seventeenth century it has also included the abstract and deductive science of mathematics. 'The Royal Society of London for improving Natural Knowledge', to give it its full title, arose from 'a designe of founding a Colledge for the promoting of Physico-Mathematicall, Experimental Learning'; and *Chambers's Encyclopaedia*[2] today says: 'Traditionally science has been subdivided according to differences of subject matter, hence the familiar names—mathematics, physics, chemistry, biology and its various branches.' Indeed, the Royal Society itself, forced to make a convenient and practical division in its publications, now gives us 'Series A: Mathematical and Physical Sciences; Series B: Biological Sciences'.

When considering the relationship of the various sciences it at first sight seems convenient to place them in a serial order. Following *Chambers's Encyclopaedia* we might start with mathematics, go on to physics and chemistry, and then pass to biochemistry, physiology and the other biological sciences. But an attempt to arrange the various sciences in such a linear series is unsatisfactory because it cannot be made to include them all or to display all their relationships. Such an attempt recalls the old linear classification of the animal, vegetable and mineral kingdoms into a single *Scala Naturae*. Within the sciences botany and zoology must anyway be placed side by side, so that at least a branching series is required. But even greater difficulties are raised by geology. In the editorial classification of the Royal Society this is arbitrarily placed in the 'B' publications, unless the problem concerns such matters as magnetism or crystallography—which are just as much a concern of the theory of the earth as palaeontology. The new-comer biophysics is in an equally unfortunate position. The relationships of the sciences can in fact only be displayed by a multidimensional network which is highly inconvenient for the administrative machinery of our minds, accustomed as it is to reduce understanding to linear arguments and dichotomous classifications capable of development by deductive logic. Any divisions we make in the range of natural phenomena are in part a matter of our convenience.

At any period the divisions are strongly affected by their historical development. Cambridge, unlike most universities, treats mineralogy and geology as separate sciences. This originated in the tangled politics of this university at the beginning of the nineteenth century, as a result of which an excellent natural historian, J. S. Henslow—later Charles Darwin's director of studies—became Professor of Mineralogy. Almost at once he switched to the Chair of Botany, a science which he preferred. But, the political heat having hatched it, the Chair of Mineralogy continued and on Henslow's resignation passed to William Whewell and on to the present day.

Our accepted divisions of the sciences owe much to the accident of eighteenth-century benefactions, to botany, to human anatomy, and so on. But this does not mean that our divisions are wholly arbitrary. Thus, however much we properly accent the unity of the biological sciences, plants on the one hand and animals on the other are distinct classes of living things, each with their own

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associated phenomena. The distinction between botany and zoology is not arbitrary. It can be traced to the fact that plants are essentially photosynthetic machines in which the essential adaptive machinery which gives character to the object is at the cellular level of the molecule chlorophyll, and of the minute cellular organs the chloroplasts; whereas animals are essentially predatory behaviour machines, the adaptive character of whose machinery is to be seen at a gross anatomical level of eyes, brains and muscles. Yet even here history has its effect. For bacteria and other micro-organisms constitute a third and different class of living objects which could not be appreciated until microscopes had reached the necessary state of perfection in the nineteenth century. Our classes of the sciences may be valid, but in any age we only appreciate those which fall within our 'sensory spectrum', aided as that is by contemporary instruments.

Of the various sciences, mathematics occupies a peculiar position. Today it has gained immense importance by supplying models to represent the recondite phenomena of the physicist, and at universities training in both these sciences is intimately linked. The mathematician and the physicist are more likely to understand each other's technical conversation than either would understand that of a museum taxonomist. Mathematics, the abstract science, thus seems closer to physics than does physics itself to another concrete science, taxonomy. Even though we must remember that the abstract processes of a mathematician may have a remarkable parallel with the physical operations of a calculating machine, and that the whole success of applied mathematics depends on the accuracy with which mathematical relations can be shown to correspond to what happens in the real world, it may still seem a little strange that abstract mathematics should seem so much nearer to the concrete science of physics than that is to the concrete science of taxonomy. As a science, mathematics is not only acknowledged, it is given pride of place: the Queen of the Sciences. And though one may still say,

> But which Pretender is and which is King
> God bless us all, that's quite another thing,

one has only to look into any scientific journal to see how mathematics ministers to every one of the concrete sciences.

But it is in physical science that the linkage with mathematics is most evident. Indeed, such is their joint prestige that the man in the street, faced with the tremendous impact of physical science and technology upon his everyday affairs, is apt to equate the whole of natural science with mathematics and physics—in London the 'Science Museum' is distinct from the 'Natural History Museum'. Prestige is of course to some extent a matter of fashion. At the beginning of the nineteenth century geology was dominant, and biology took that place after the publication of *The Origin of Species*. But the modern prestige of mathematical physics is more fundamental.

When we try to force the sciences into a linear series, however imperfectly, we are at least trying to exhibit a real quality in their relationship, one which has to do with mathematics. Evidently, in this series we are concerned with phenomena of increasing complexity. We may note that as we pass from biology to present-day physics we are passing from highly complex phenomena, which so often we are not clever enough to analyse, to simple ones which we can represent by mathematical models of exceedingly high intellectual penetration. The enormous advance of the physical sciences has in fact been rendered possible just because they are thus restricted in their scope. The more we restrict the class of phenomena we observe and the number of its variables, the more far-reaching are the possible deductive consequences of our hypotheses. But in so doing much of the grand variety of natural phenomena is systematically excluded from study. Very clever men are answering the relatively easy questions of the natural examination paper. In contrast, in biology such problems as 'What will be the ecological consequences of a general increase in nuclear radiation?' are so difficult that our answers seem paltry and emotional.

It is fair to say that at any period the different sciences are in different states of evolution. In medieval times Wisdom was divided into the three philosophies: Metaphysical, Moral, and

Natural philosophy covering what we would now call natural science. After the scientific revolution of the seventeenth century, Newton's enormous success in the application of mathematics to mechanics and astronomy gradually led to the restriction of the term natural philosophy to the physical sciences. By the beginning of the nineteenth century, however, chemistry had emerged as an experimental and exact science in its own right. Accordingly Playfair in his *Outlines of Natural Philosophy*[3] of 1812 divided the field of natural knowledge into (1) Natural Philosophy, which concerned action that takes place between bodies without permanent change in their internal constitution; (2) Chemistry, which concerned action that takes place between bodies producing permanent change in their internal constitution; (3) Natural History: 'The branch of knowledge which collects and classifies facts is called Natural History...its objects are confined to what are called the three kingdoms, Mineral, Vegetable and Animal.' Physical science and chemistry had achieved the status of 'exact' experimental sciences. The only parts of biology and geology to which reference is made remain at a simpler level of observation and description.

A good summary of the supposed position of the sciences at the beginning of this century is given by Mellone[4] in an elementary text-book of 1902:

> Without experiment, mechanics, physics and chemistry could scarcely exist; these are fundamental sciences in an advanced state. In physiology experiment plays a much smaller part, for if made at all it must be made on the organs of the living body. In the sciences of description and classification—botany, zoology and mineralogy—the range of experiment is more restricted; while in astronomy, geology and meteorology we may say that experiment so far as we are concerned is impossible. We say 'so far as we are concerned', because Nature sometimes produces phenomena of so remarkable a character that she may be said to be making an experiment herself—as in an 'eclipse of the sun'.

To this we may add the comment of Jevons[5] in 1870:

> Every question of science is first a matter of fact only, then a matter of quantity and by degrees becomes more and more precisely quantitative.

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We thus get a picture of successive sciences becoming progressively more experimental and more quantitative. The experience of the last sixty years certainly seems to justify this. Mellone's summary, in fact, does less than justice to the experimental character of physiology even in 1902. Since then, along with mineralogy (particularly through crystallography), biochemistry and many others, it has become an exact science.

Consider the problem of nervous excitation, on which today so much of our interpretation of the action of the brain depends. Already before 1920 Keith Lucas[6] and Adrian[7] had demonstrated the nature of the impulse which passes along an excited nerve fibre. I shall discuss their work again later. For the moment I would remind you that their analysis depended on the application of brief electrical stimuli of measured intensity, duration and interval. By the use of such stimuli they showed that there was a precise threshold for stimulation of the nerve fibre which must be passed if a nervous impulse is to be propagated; and they showed that the propagated impulse was followed by a brief refractory period during which the nerve fibre was inexcitable. By their experimental analysis they showed that, provided the stimulus sufficed to provoke the impulse, the size of the impulse as measured by its effect was independent of the intensity of the stimulus. If the stimulus was effective at all, the effect was 'all or nothing'. What they did in these very important experiments was to establish the *class* of phenomenon to which the nervous impulse belonged: unlike the attenuating wave of sound that is sent down a speaking tube, the impulse maintains its intensity as it passes along a nerve fibre, just as a wave of combustion is maintained as it passes along a train of gunpowder. The establishment of the class to which a phenomenon belongs is precisely what a physicist did when he established the undulatory nature of sound, and what he is endeavouring to do with the properties of his mesons and hyperons. Classification is not just something done in museums.

Consideration of such experiments as those on nervous conduction suggests that the division between the exact and the descriptive sciences is moving back into the biological and geological sciences themselves. Not only do the individual sciences become increasingly quantitative and exact, but in so doing analysis of the phenomena with which each is concerned seems to become dependent on another science which deals with systems of smaller size and less complexity into which their parts can be broken up. The biological processes of the parts of an organism—nerves, muscles and so on—are analysed by the physiologist; the operation of these processes is then related to the biochemistry of its molecular changes, the interpretation of molecular combination is given by the chemist, and his work rests on what the physicist can tell us of the behaviour of atoms and electrons. The physicist himself during the last hundred years has carried the same process of analysis further. In the nineteenth century we had reached the atom, and that seemed to be the end of this sort of analysis. During the early years of this century atoms were decomposed into protons and electrons. Again for a brief period it looked as though we had reached finality. For general assumptions about the nature of the universe Eddington[8] in 1933 proposed that the number of particles in the universe could be enumerated. There were to be about 10^{79} electrons and a like number of protons. But this limit too was passed—and without any prediction that this would be the case. Today there are already known several dozen particles besides these: neutrons, mesons, hyperons and the rest; and to an outsider there seems no prospect of an end to this analysis, incomprehensible as the nature of the particles may be to him.

This tendency of sciences, when they become quantitative, to interpret their phenomena in terms of smaller grades of structure can be seen in biology itself. Anatomy at the beginning of the nineteenth century was concerned with the gross dissection of organs. During that century the development of the light microscope enabled analyses of organs into cells and finer structures. The power of analysis of the light microscope met a limit set by the wavelength of light. The invention of the electron microscope has opened up the analysis of cells into still finer structures. Does this imply that all the properties of complex structures are to be displayed by considering the properties of their simpler components, and so on? Are we to assume that, with the aid of the theory of probability, the mathematical physicist building the universe from his contemporaneously ultimate particles could, at least in theory, answer all our questions? One sees at once the difficulties in supposing this to be true of living organisms, but before we go on to biology let us consider the investigation of a problem among the complex structures of the inanimate world.

Geology deals with complex inanimate structures: rocks, rivers, mountains and glaciers. Let us consider the investigation of a problem of such things as these. One of the striking features of the scenery of this and other countries all over the world is the existence of high plains or plateaux. For instance, starting from the Welsh sea coast in Carmarthenshire, and walking up the valleys, we do not simply meet hills which get irregularly higher. At a height of about 500–600 feet we reach a plateau, a plateau dissected by rivers but stretching between and beyond them for a considerable distance. Farther inland there is evidence of a second plateau at a higher altitude. In these plains both the harder and the softer rocks are worn down to more or less the same level.

There is an extensive scientific literature about the origin of these plateaux.[9] Ramsay,[10] about a hundred years ago, ascribed them to marine denudation. Coastal erosion is a powerful agent and can undoubtedly plane down a land surface as it advances inland. At a much lower level round our coasts there are limited shelves and plains which can certainly be ascribed to this cause, for beach deposits of shells make it clear that they correspond to the oscillations of the level of the ocean during the Pleistocene. But the plateaux we are considering are higher and certainly much older.

The alternative to their marine origin is that these plateaux are peneplains; that is, they are the result of subaerial denudation acting on a land surface for an immense period, till the outstanding features have been worn away to a common level. Whichever view is taken, the total amount of rock which has been removed from the present land surface in Wales during the course of geological time is immense—a thickness of at least 10,000 feet of overlying strata has been removed.

There was no obvious way of deciding between the marine and the subaerial hypothesis for the origin of the plateaux. It is interesting to note that, as C. B. Travis pointed out in his review of the matter, geologists in Britain with their direct experience of coastal erosion were disposed towards the first view, whilst American geologists with their continental experience of subaerial denudation in their Western Territory surveys held the second view. Like poetic imagery, scientific hypotheses have a historical background depending on our own experience. Neither Tennyson nor Meredith would have used imagery from the sea if they had spent their lives in the Middle West.

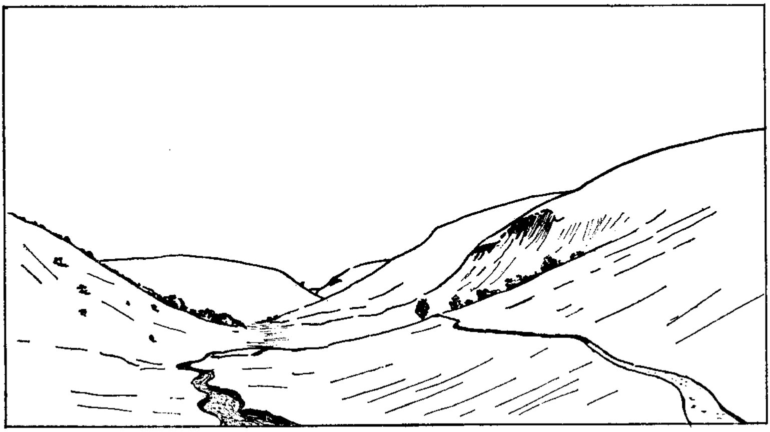

Figure 1. Upper part of the Towy Valley showing mature features (from O. T. Jones, 1924).

Important new evidence about the origin of the Carmarthenshire plateaux was produced some forty years ago by Professor O. T. Jones.[11] He had an intimate knowledge of the geology and geography of the plateaux, and was struck by certain features of their streams and valleys, particularly by the head waters of the drainage system of the upper Towy. He perceived that if the plateaux are the result of subaerial denudation the river systems might give some indication of this.