Some Considerations on the Philosophy of Chemistry

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I consider then that to render a reason of an effect or phaenomenon, is to deduce it from something else in nature more known than itself; and that consequently there may be divers kinds of degrees of explication of the same thing. For although such explications be the most satisfactory to the understanding wherein it is shewn how the effect is produced by the more primitive and catholick affections of matter, namely, bulk, shape and motion; yet are not those explications to be despised, wherein particular effects are deduced from more obvious and familiar qualities or states of bodies. For . . . . every new measure of discovery doth instruct and gratify the understanding.

R. Boyle, 'Certain Physiological Essays', 1772.

Precision is not to be sought for alike in all discussions . . . . It is the mark of an educated man to look for precision in each class of things just so far as the nature of the subject admits.

Aristotle, 'Nichomachaean Ethics'.

1 Introduction

In this review I try to raise some philosophical points about the position of chemistry in relation to other natural sciences. Chemistry is a physical science with some similarities to physics and some to biology. But there are differences of emphasis and style worth recording. No-one questions that biology has many differences from physics, a fact reflected in the style of explanations found in the two sciences. But the position of chemistry in relation to biology and physics is perhaps not so clear. There is a need for some philosophical discussion of this as soon as one asks questions such as—What is it that identifies the science of chemistry? Does the subject matter of chemistry set it apart from physics or biology? Is there something peculiar to the style and procedures of explanation chemists use? Or is the description 'chemical' merely a matter of administrative convenience in government, universities, and industry? These matters are worth considering if only to come to terms with those philosophers and scientists who would have us believe in a simple-minded way that the subject matter of chemistry, and indeed of all the other sciences, is ultimately the subject matter of physics, at least in principle, even if not now in practice.

To some it may seem eccentric to concentrate upon the science of chemistry when most currently published work in the philosophy of science is in fact in the philosophy of physics, and when such philosophy is quite commonly believed to contain all there is of importance in the philosophy of science. And yet the science of chemistry has a history at least as long, complicated and interesting as that of physics. Indeed the chemical activity of mixing A with B and seeing *what* happens is probably older than the more physical activity of trying to discover *why* it happens. Why then is the philosophy of science focussed so much upon physics? The answer I think lies in the general concern of chemistry with things at what might be called an 'intermediate level of physical complexity'. That is to say, it deals with molecules, not atoms, and (this is the important point) it deals with things supposedly more 'complicated' than atoms, and so with things supposedly less 'fundamental' than atoms. On the other hand, it deals with things less 'complicated' than, and therefore more 'fundamental' than the genes, organisms, cells, species and genera of the biological sciences. So the motive behind concentrating upon the philosophy of physics probably originates in the feeling that this is the philosophy which has to do with 'fundamental', 'simple' things. Now if this claim had any clear meaning, one could at least decide for or against it. But what meaning can we in fact give to these predicates, 'fundamental' and 'simple'? Does it make proper sense to suppose that the sciences can be arranged along a scale of esteem according to some notion derived from physics of what is or is not 'simple' and 'fundamental'? If a clear and unprejudiced meaning could be given to the terms 'fundamental' and 'simple', then indeed the plurality of sciences as we know it at present would arguably be a phenomenon of intellectual convenience rather than a reflection of reality, and those philosophers who argue for reduction to a unified science would have a much more persuasive case to present. My own view, however, is that no such meanings can sensibly be given to terms like 'simple' or 'fundamental' in science, and that therefore proposals about the unity of science cannot do justice to the principles and practice of at least one science, chemistry, and are therefore best ignored. To discuss these points, I shall first say something about the alchemical background of modern chemistry, because the philosophy of alchemy has something in common with the philosophy behind a good deal of chemistry, and then I shall go on to discuss the character of explanation in chemistry, and compare it with that in the sciences of physics and biology.

2 Alchemy, and its Relation to Modern Chemistry

Chemistry as a science of material change is often considered a natural development from alchemy, a view which usually assumes that the philosophy of chemistry is in all important respects the same as that of alchemy. But I think this is too simple as it stands. For we must remember that alchemy was not a physical science as we understand it. It was not simply primitive chemistry, but rather an attempt (usually sincere) to produce a truly *natural* philosophy. In fact alchemy is an admirable illustration of the proper meaning of the term 'natural philosophy', indeed perhaps the only one there is. I have argued this at some length elsewhere,[1] but some of the main points I made are worth repeating in this review. A physical science is a matter of explaining or rationalising (a difference to which I shall refer later) observable material changes in terms of material causes and effects. This requires some carefully formulated conservation principles. Those of matter, as historically understood up to the middle of the nineteenth century, or of some other extensive physical quantity such as energy, electric charge or momentum, are the most familiar. Conservation principles define the boundaries of physical change by defining the term 'physical system' both conceptually and operationally for a given set of circumstances. Without such boundary conditions, physical explanation which can be checked becomes impossible, because there is then no limit to the field of causation which may be invoked.[2] Alchemy was not a physical science within this definition, for it had no physical conservation principles whatsoever. No causally significant physical observations were, could, or even needed to be made by alchemists in the way that scientists today make what they consider to be causally significant observations. For this is the crucial point. Alchemy was, I believe, a serious attempt to understand the philosophical apparatus of Aristotle's metaphysics by seeking its illustration in the directly observable properties of material bodies, such as colour, fusibility, and crystallinity. By such a phenomenological method, alchemists hoped to clarify such important Aristotelian (and later mediaeval) philosophical categories as 'change', 'matter', 'form', 'good', 'perfection', 'actuality', and 'potentiality'. Of course we now see this whole undertaking as something of a muddle, although it was a reasonable and certainly understandable muddle given the state of philosophy and physical science before the sixteenth and seventeenth centuries. For it is a commonplace that science and philosophy did not begin to draw apart until perhaps the sixteenth and early seventeenth century, when in the study of nature, quantity replaced quality, and moral neutrality a certain moral involvement. The transmutation of one material into another no longer exemplified impermanence, imperfection, or moral strife: it revealed nothing but a certain aseptic, material, causal pattern. Alchemy was not replaced by something superior, namely chemistry, doing the same job; for it was not replaced by anything. It is, I think, more correct to say that alchemy declined quite naturally in importance as the Aristotelian philosophy upon which it was parasitic was gradually rejected as an acceptable philosophy in Western Europe, and as philosophers and scientists became aware of their proper roles. The new Cartesian and Newtonian philosophy made the familiar Aristotelian categories seem obscure and even irrelevant, and as a result alchemy was left without its *raison d'être*.

As I have indicated, explanation in alchemy was not quantitative and predictive in the sense we find in modern physics, but rather qualitative, philosophical and rationalising, and I believe that something of this difference has been

[1] D. W. Theobald, 'Alchemy—a Philosophical Reappraisal' *The Technologist*, 1965, **2**, 135; for a different interpretation of alchemy see B. J. T. Dobbs 'The Foundations of Newton's Alchemy', Cambridge University Press, 1975.

[2] Y. Elkana, 'The History of the Conservation of Energy', Hutchinson, London, 1974.

carried over into the methodology of modern chemistry, helping to give it a somewhat different philosophical outlook from physics. It is possible to see now why I do not think that physics has had such a profound involvement with philosophy as has chemistry, since it has never been so directly phenomenological as chemistry. Certainly over the years physics has been provided with a philosophical basis, namely that formulated initially by Locke and others, but it was not generated from such a basis as were alchemy and some early chemistry from Aristotelian metaphysics. I do not find it surprising, then, that to understand the philosophy of physics is not wholly to understand the philosophy of chemistry. Both sciences are concerned with the properties of matter, but I hope to show that the differences between the two are sufficient to make the assimilation of chemistry to physics *simpliciter*, a philosophical error which does a disservice to the practice of chemistry.

3 The Differing Characters of Explanations in Chemistry and in Physics

We can often approach questions about the differences between sciences by considering what can be said about explanation in those sciences, bearing in mind that no science is committed to a single explanatory procedure. Scientific explanations take on a wide range of forms from the highly formal and quantitative explanations encountered in physics, to the informal qualitative explanations of everyday life. This variety is inevitable because explanations often have to serve very different purposes—showing why something is not so surprising as it seemed at first sight, spelling out detailed causes, rationalising extensive arrays of superficially disparate observations, *etc.* Whereas any given science *may* at times make use of different sorts of explanation, a science is usually characterised by its preference for explanations of a certain character—either formal and quantitative on the one hand, or informal and qualitative on the other. It is these preferences I shall describe.

A. Explanations in Physics.—These usually aim at more or less precise quantitative prediction, following closely the model of deductive explanation much discussed by Hempel[3] and subsequently others. This, at its simplest, is as follows. Given a set of universal premises T, which will usually mention some theoretical concepts, be highly formalised mathematically, and which will materially connect being an **X** with being a **P**, where **X** and **P** are observables characterised precisely by numbers, then it can be logically deduced, or predicted, that for any particular **X**,**X**′, **X**′ will be **P**. Alternatively given that this **X**,**X**′ is observed to be **P**, then the universal premises T explain that fact. Of course **X**'s may have other properties **Q**, **R**, but these are ignored by T. So strict Hempelian explanation is a selection procedure for choosing predicates which are conformable to a certain logical and numerical manipulation.

Now if an explanation T models itself upon this pattern, that is if it aims at precise predictions, the concepts which clothe the logical skeleton of T will

[3] *Inter alia*, C. G. Hempel, 'Aspects of Scientific Explanation and other Essays in the Philosophy of Science', Free Press, New York, 1965.

have to be 'simple' in the sense of being able to be characterised by numbers only. The argument then runs that this can be achieved satisfactorily only by the progressive dissection of matter. Explanations, it is argued, must be framed in terms of concepts referring to ever smaller pieces of matter because it is only such concepts which are 'simple' enough to be describable in *all* respects exactly by numbers, so enabling predictions to be made about larger, so-called more 'complicated' systems. Physics then tries to tell us why something behaves as it does by referring to its constitution. But, of course, there are other questions which may be asked, e.g. is this pattern of behaviour unique? What is the purpose behind it behaving in this way? Why is it behaving like this now? *etc.* The answers to these questions will not necessarily require the reductive 'innards' approach of physics just outlined.

We can now recognise precisely therefore what is involved in thinking smaller particles are 'simpler' than larger particles of which they are allegedly constituents. I mentioned earlier that physics was held to be about 'fundamental' things in contrast to chemistry and biological sciences. This is usually taken to mean that physics is about 'simple' things in contrast to chemistry and biology. But in what way is an atom 'simpler' than a molecule, or a molecule 'simpler' than a bulky material sample? The answer to this question is not something independently demonstrable about the world, for epithets such as 'simple' and 'fundamental' can have sense only from a certain point of view, in this case that of physics. In other words the 'simplicity' of physics and the 'complexity' of chemistry and biology arise because we impose a certain logical and numerical requirement upon our interpretation of causal connection. In practice this means we opt for the Hempelian model for explanation.

But the question now urgently arises—is this the only way we can deal with matters of explanation, understanding, and causality? I think history and chemical practice show that it is not. Should we aim in science at a more thorough reductionist approach to explanation, with the conduct of physics in mind, or should we be prepared to recognise limitations to such a philosophy for science? I believe that the science of chemistry throws some interesting light on these questions.

B. Explanations in Physics.—Thackray in a recent book 'Atoms and Powers'[4] has discussed at length some of the methodological differences between Newtonian chemistry and Daltonian chemistry, that is between the chemistry of the sixteenth and seventeenth centuries and that of the early nineteenth century. We find that Newton and his contemporaries vainly tried to understand material change in terms of point particles and inverse power laws, in terms of the forces of physics in fact, whereas Dalton and his successors saw as their objective the rationalisation of material change in terms of units of phenomenological mass. The Daltonian atom was such a unit of phenomenological mass, and this was successfully used to interpret the relative weights of reactants and products in a chemical reaction (one is reminded here of the function of the Mendelian

[4] A. Thackray, 'Atoms and Powers', Oxford University Press, London, 1970.

gene in the biology of reproduction). Dalton avoided any physical specifications for the atom, for as he probably realised, such Newtonian detail would not have been relevant at that moment in the development of chemistry. Indeed it can be argued that scientists' preoccupation with Newtonian theory delayed the start of serious chemistry for nearly 150 years.

What seems clear from Thackray's book is that progress in chemistry, and I imagine in science generally, is not necessarily linked with an uncritical preoccupation with quantitative reductive analysis. There is almost certainly what might be called an 'optimum epistemological level' for the concepts of a science at a given moment in its history, and to try to force a more 'fundamental' character upon them may be to divert that science from its proper course at that time. In other words, perhaps the Hempelian model for explanation is not right for all the sciences all of the time.[5]

Some scientific explanations do undoubtedly have the Hempelian form I have outlined above. At least a great deal of explanation in physics and some in chemistry conforms to it; there is a lot to be said for this after all. It ought to be easy to work with, and it does enable one to make predictions. But perhaps we should not be preoccupied with prediction at the expense of explanation which does not have prediction as a primary function. After all there are many instances where a perfectly acceptable explanation does not enable one to predict like events with any degree of assurance. I think of the connection between drinking and dangerous driving as an example. The reason is that explanation is not purely a matter of logical structure, of events being conformable to some logical scheme. This point is clearly shown by the various published discussions of Hempel's Paradox of the Ravens.[6] Explanations have to be rational, and enable us to understand the events at issue. But this condition is satisfied in explanations by analogy and precedent, such as we have in legal, biological, and geological argument, and in many areas of chemical argument. Predictive power is not relevant in these instances. Rationality is admittedly a logically weaker imposition upon acceptable explanation than conformity to any logical model, but then it is methodologically and epistemologically richer. Rationality means no more than that explanations have to be commonly reasonable *in the circumstances*, and this alone guarantees our understanding.

A simple formulation of rational explanation would go something like this. X's are usually **P**, but this particular X,X′, turns out not to be **P**. A reasonable explanation for this may be given in terms of the absence or presence of some *special* condition, **Q**. Spelling out such an explanation will not in general involve appeal to highly formalised theoretical premises, for prediction is not involved here. We are concerned with a special case, and a special condition **Q**. Indeed such an explanation is much more likely to involve appeal to analogy and precedent, rather than to quantitative laws and theories; it is an integrating explana-

[5] M. Hocutt, 'Aristotle's Four Becauses', *Philosophy*, No. 190, 1974, **49**, 385; M.Mandelbaum, 'The Problem of Covering Laws', in 'Philosophy of History', ed. P. Gardiner, Oxford University Press, 1974.

[6] D. W. Theobald, 'Introduction to the Philosophy of Science', Methuen, London, 1968, and refs. cited.

tion. To take an example from organic chemistry, suppose that an acid and an alcohol fail to react to form an ester under conditions when esterification usually does occur, then we may be able to explain it by referring to some peculiar structural feature **Q** of the acid or the alcohol involved. We confidently expected them to react—in fact we were in no position to predict that they would not—and yet we can still explain their failure to react. Our explanation is not likely to carry precise predictive implications either, because we may not meet another case exactly like it, such is the abundance of experimental results in chemistry. But it is nonetheless a rational explanation which may serve our future purposes as precedent or analogy. To put the matter otherwise: it is possible to argue 'no esterification **E** *because* **Q**', without being committed to any predictive law-like generalisation of the form, 'whenever **Q**, then no **E**'. We are committed to the logical 'if **Q**, then no **E**', but that is a logical, not an empirical, corollary of our explanation.

In chemistry we are often setting out to understand what *has* actually occurred rather than deliberately contriving to fulfil predictions. We are, so it has been said, telling 'likely stories' rather than hazarding and testing prophecies. As we shall see, it is this difference of temporal emphasis which aligns chemistry with biology as much as with physics. The sorts of explanations chemists use are often looser and less analytical then the full Hempelian model of parts of physics. But this does not mean to say that chemistry is a primitive science compared to physics. It reflects a frequent and real difference between the character of some of the concepts used in chemistry and the character of concepts used in more formalised sciences such as physics.

4 Concepts Used in Chemistry

First consider some of the concepts chemists use every day; the following list is of course far from exhaustive:

substance	equilibrium
molecule	bond
functional group	bond strength
reactivity	solvation
steric interaction	valency
stability	transition state
symmetry	

Now these concepts are static, organising and descriptive concepts more like concepts in biology than the dynamic causal concepts of so much of physics. Consider now these biological concepts:

organism	genus
organ	evolution
gene	natural selection
function	natural balance
purpose	life
behaviour	death
species	environment

There is a temptation to see some striking analogies between some of these concepts and some of the chemical concepts listed previously: for example, between molecules and organisms; between atoms and genes as the units of inheritance in chemical reactions and biological evolution; between a functional group in a molecule and an organ of an organism; between death and decomposition; between the chemical equilibrium between molecules and the ecological balance of competing organisms. There are of course striking disanalogies, but that is to be expected between a science of the living and a science of the dead. But it is worth recalling briefly here what was said earlier about alchemy, when it was argued that alchemy was an attempt to illustrate Aristotelian philosophical argument in material terms. Aristotelian philosophy as we know was man-centred and biologically conceived, and the analogies mentioned previously between certain biological and chemical concepts are perhaps no more than a continuation of the involvement of alchemy and some early chemistry with such philosophy.

The chemical concepts I have listed are, like the biological concepts mentioned, organising concepts. They are not vulnerable to vulgar testing, for they are designed to make sense of large and timeless ranges of experience rather than to explain the details of particular individual cases. No doubt these and other chemical concepts could be given a reductive and analytical interpretation. But do they need to be? Would such an analysis be relevant to the chemists' requirements. Is a molecular biological analysis of the Mendelian gene always relevant to the biologist? Is a physical analysis of the chemical molecule always relevant to the chemist? For *that* is the question—relevance. To the chemist it is not a question of what is or is not comprehended by the science of physics, but of what is or is not relevant and necessary to understanding the chemical problem in hand. The fundamentals of chemistry have nothing *necessarily* to do with the fundamentals of physics.

Let us return to the familiar chemical reaction already referred to, namely the esterification of alcohols by acids. The variety of recorded reactions is too vast to allow a Hempelian account based upon highly formalised physical theory to be anything but useless, because this is inordinately cumbrous. Instead we use some of the general organising concepts of chemistry as listed, to bring out the pattern which runs through the different examples. The chemist is not always interested in detail, but often in the general scheme of things chemical, in the way that a biologist is interested in the general scheme of living things and their interactions.

5 Differences in Interpretations arising from Chemistry and Physics

The chemist usually does not need to look further than the molecule, atom, and electron to understand chemical phenomena. However, his is not the atom and electron conceived as putative historical (and so causal) precursors of molecules, but the atom and electron construed as parts of molecules, *i.e.* conceived from a *molecular point of view*. The statement 'the purpose of these electrons is to hold this molecule together' may be compared as an explanation with 'the purpose of this organ is to allow this organism to survive'. But neither the organism nor the molecule is logically derivative upon the organ or the electron. Nor are they empirically derivative. A part of an organism may give us some information about the structure of the organism from which it comes and also may tell us what role that part plays, but it will not tell us how that organism behaves as a whole. Similarly an analysis of molecules into atoms can tell us nothing extensive about the parent molecule. For the atoms in a molecule only have significance *within* the molecule, in relation to the other atoms. It is the society of atoms which matters, that is the whole molecule, rather than the separate atoms themselves.

To the question 'what is an electron?', there will be many answers which will reflect many different physical interests, for example, the quantum theory and the band theory of solids and metals, as well as the theory of chemical bonding. These answers are not necessarily relevant to one another. The chemist should not therefore automatically be preoccupied with adjusting his picture of the electron devised for chemical interpretation to the demands of other areas of physical science. In short the chemists' atom and electron ought not to be identified *simpliciter* with the physicists' atom and electron.

It might be countered that the properties of a molecule or of a bulk material sample are predictable in principle, if not in practice, in the Hempelian way from a knowledge of the atom and electron in physics as premise. But are they, in fact? There is always some disagreement between the experimental parameters and such predictions of them. Moreover this might not be solely due to experimental error, but to the *fact* that molecules conform to *different* laws from the physicists' atoms and electrons; or to put it another way, to the fact that molecules follow chemical laws different from those to be obtained by an extrapolation of the physical laws of physics. Chemical laws may not be the simple Cartesian push–pull laws of physics, and perhaps even a non-Cartesian formulation of them will have to be devised.[7] The only condition one can specify in advance is that molecules must conform to those most fundamental laws of energy, the laws of thermodynamics, which provide the boundary conditions of all physical change. But these say nothing of the time scale or the path of change, and nothing therefore follows from them about the forces operative in molecular or chemical reactions. So there is no *a priori* physical reason why these forms should be the same as those we recognise in physics. Most philosophers recognise that individual human behaviour follows patterns which are not to be obtained by an extrapolation of the laws of neurophysiology; and that the behaviour of collections of individuals is not predictable from the behaviour of the individuals comprising those collections. There are indeed real differences here. What conclusive argument is there that there is not such a difference between the behaviour of atoms and the electrons and the behaviour of those collections of atoms and electrons we call molecules? I do not believe that the philosophical doctrine of 'emergence' is to be rejected out of hand in pursuit of

[7] D. Bohm, 'Classical and Non-Classical Concepts in Quantum Theory', *British J. Phil. Science*, 1962, **12**, 265.

a single chimerical Truth. The recognition of emergent properties, far from restricting the course of scientific research as some advocates of the unity of science argue, provides challenging new material for scientific thinking. It is difficult indeed, because it challenges old habits of thought. But it is perhaps a more honest recognition of the variety of an evolutionary universe.

A different perspective upon this philosophical point is gained by considering levels of organisation in matter. Consider for a moment what we mean when we say that chalk is made up of molecules, and that these molecules are made up of atoms, and so on. Now whereas we can talk of the systems of molecules which make up the chalk, we cannot meaningfully talk of systems of atoms making up this substance. An analogy would be as follows. We can appreciate the arrangement of bricks which make up a house, but we do not thereby imply recognition of any arrangement of grains of sand and lime which make up the bricks of the house. So quite properly one does not speak of houses as being built of sand and lime because houses *to those concerned with them* are built of bricks and *not* sand and lime. Likewise in chemistry, where we are dealing with the properties of substances like chalk, we ought not to think of them as being composed of arrangements of atoms, but properly as systems of molecules, because it is of such things that substances are composed. The molecule is the chemical brick, and is a quite proper terminus for chemical inquiry. This is not to say that the make-up of the molecule should not be explored by those theoreticians whose proper concern it is. But the builder who selects a brick because he knows what sort of properties it has does not need to know the detailed properties of sand and lime from which it was made.

The matter can be put another way. Membership of a class or system is not transitive, whereas membership of a collection or aggregate is. Thus an individual plant is a member of the class called the 'species', but is not properly a member of the 'genus' to which that species belongs, though it is a member of the aggregate called the 'plant kingdom'. Now what of atoms, molecules and substances?

I do not think that substances can be said to be heaps, aggregates, or collections of molecules, nor yet that molecules can be said to be heaps, aggregates, or collections of atoms. I would argue that the formula 'H_2O' refers to that class of molecules every member of which is composed of H and O atoms related in a certain way, whereas the term 'water' refers to that class of substances each member of which has 'H_2O' molecules as members related in a certain way. So whereas molecules are properly said to be parts of water, and atoms properly parts of molecules, atoms are not properly speaking parts of water. I would be prepared to contend therefore that there are certain levels of organisation to be recognised in the study of matter, and that these cannot be short-circuited without talking nonsense.

6 The Special Role of Chemistry in Science

What does all this amount to? I think it may go some way towards persuading (and it is *only* persuading) chemists that their *alter ego* need not be a physicist.

Chemical science has not so far been infected by mathematico-physical methods to the extent of some other sciences. Whereas physics has been forced to abandon the familiar concept of substance, chemists so far have not. During the height of Newtonian fashion in the seventeenth and eighteenth centuries, Boyle was notable in predicting the fruits of Newtonian method, namely, no concept of substance and an immaterial universe. Some of the great analytical and synthetic successes of chemistry would not have been possible if Newtonian method had been adopted in the eighteenth and nineteenth centuries. For chemistry is the science of a substantial universe with observable qualities. The chemist is traditionally the scientist who first and foremost wants to know what happens when X is mixed with Y. He may wish to rationalise what he observes, but initially his is a species of idle, natural curiosity. Chemical curiosity is much less disciplined than physical curiosity, and it is this element of indiscipline in chemistry which makes it particularly easy to exploit technologically.

Many more things have been discovered in chemistry than have been rationalised, and this is because chemical work has never been quite so dependent for its impetus on theory as has work in the more mathematical sciences. In physics it is sometimes difficult to find enough observations to test a theory (for example in cosmology) but this could never be said of chemistry. Theories are rarely highly controlled by observation in chemistry, since theories are, as I have explained, generally rationalising constructions covering vast arrays of experimental data, rather than precise mathematical formulations vulnerable to a single quantitative misfortune. There is a further point which adds to this difference. Whereas it is possible to talk about *the* electron (a highly specified particle), it is not possible to talk about *the* ester, *the* salt, and so on, because no one ester or salt is exactly like another. For these are *types*, representing a classification of individuals. These explanatory descriptions S_N1 and S_N2 given by organic chemists to certain substitution reactions in organic chemistry are no more than classifications in terms of extreme types. The biological parallel is obvious. And this has its effect upon the character of mechanistic descriptions of chemical reactions which are, as I have said, rationalising rather than predictive.

Chemistry then stands between physics on the one hand and biology on the other, as an area in which rationalising, pattern explanations rub shoulders with Hempelian, deductive explanations to a greater extent perhaps than in any other science. This is, in my view, the principal value of chemistry as the basis of a scientific education. But chemists will continue to enjoy this stimulating position only if they resist the temptation to model their science exclusively on either physics or biology. This would be methodologically indefensible, besides being a severe limitation upon the chemical imagination. There is more in heaven and earth than can be comprehended by the philosophy of any single science. Of course I cannot prove this point, but then I am consoled by the fact that the converse cannot be proved either. Chemists must not fall into the trap of Tristram Shandy's father (together with modern reductionists)—'who like all systematic reasoners would move heaven and earth, and twist and torture everything in nature to support his hypothesis'.