Part 1

On the interpretation of scientific theories

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I

Introduction: scientific realism and philosophical realism

1. HISTORICAL BACKGROUND

Scientific realism is a *general* theory of (scientific) knowledge. In one of its forms it assumes that the world is independent of our knowledge-gathering activities and that science is the best way to explore it. Science not only produces predictions, it is also about the nature of things; it is metaphysics and engineering theory in one.

As will be shown in vol. 2, ch. 1.1 scientific realism owes its existence and its concepts to an ancient antagonism between commonsense and comprehensive theories. It arose when Greek intellectuals, guided by a love for abstractions, new kinds of stories (now called 'arguments') and new values for life,[1] denied the traditional views and tried to replace them by their own accounts. It was the fight between tradition and these accounts, 'the ancient battle between philosophy and poetry',[2] that led to a consideration of traditions *as a whole* and introduced *general* notions of existence and reality.[3]

Scientific realism has had a considerable influence on the development of science. It was not only a way of describing results after they had been obtained by other means, it also provided strategies for research and suggestions for the solution of special problems. Thus *Copernicus'* claim that his new astronomy reflected the true arrangement of the spheres raised dynamical, methodological as well as exegetic problems (*SFS*, 40ff). His ideas were in conflict with physics, epistemology and theological doctrine, all of which were important boundary conditions of research. Copernicus created these problems but he also gave hints for their solution and thereby

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[1] The conflict between city life and heroic virtues is one of the main subjects of Greek tragedy. Cf. the analysis of the *Oresteia* and of Euripides' *Medea* and *Alkestis* in Kurt von Fritz's *Antike und Moderne Tragoedie* (Berlin, 1962) as well as George Thomson, *Aeschylus and Athens* (London, 1966). Gerald Else, *The Origin and Early Form of Tragedy* (Cambridge, 1965) traces the history back to Solon.

[2] Plato, *Republic*, 607B6.

[3] The earlier investigations of the Ionian historians led in the same direction but without any *explicit* discussion of the new and more general concepts used. There existed therefore two different movements towards abstraction, a 'natural' development, and the artificial and explicit considerations of the Eleatics which imposed entirely new ideas (cf. also vol. 2, ch. 1.1).

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initiated new research traditions. In the nineteenth century, the *atomic theory* raised philosophical, physical, chemical and metaphysical problems and there were many scientists who wanted either to abandon it as false, or to use it as a convenient scheme for the ordering of facts.[4] Realists developed it further and could finally demonstrate the limitations of a purely phenomenological view. *Einstein's* criticism of the quantum theory initiated interesting theoretical developments and delicate experiments and clarified the basic concepts of the theory (cf. ch. 2.8). In all these cases scientific realism produced discoveries and contributed to the development of science.

Only a few philosophers have examined this fruitful interaction between scientific realism and scientific practice. The reason is that scientists and philosophers are interested in different things and approach their problems in different ways. A scientist deals with concrete difficulties and he judges assumptions, theories, world views, rules of procedure by the way in which they affect his problem situation. His judgement may change from one case to the next for he may find that while an idea such as scientific realism is useful on some occasions it only complicates matters on others (cf. the quotations in vol. 2, ch. 6.9).

A philosopher also wants to solve problems, but they are problems of an entirely different kind. They concern abstract ideas such as 'rationality', 'determinism', 'reality' and so forth. The philosopher examines the ideas with great vigour and, occasionally, in a critical spirit, but he also believes that the very generality of his inquiry gives him the right to impose the achieved results on all subjects without regard for their particular problems, methods, assumptions. He simply assumes that a general discussion of general ideas covers all particular applications.

While this assumption may be correct for *abstract traditions* which are developed from principles and can therefore be expected to agree with them, it is not correct for *historical traditions* where particular cases, including the use of laws and theories, are treated in accordance with the particular circumstances in which they occur and where principles are modified, or provided with exceptions in order to agree with the requirements of these circumstances. More recent research (vol. 2, chs. 4, 5, 6, 8, 9, 11–remarks on Kuhn; cf. vol. 2, ch. 1.2 for general considerations) has made us realize that scientific practice, even the practice of the natural sciences, is a tightly woven net of historical traditions (in mathematics this was first pointed out by the intuitionists; Kuhn has popularized the results for the natural sciences while Wittgenstein has developed the philosophical background). This means that general statements *about* science, statements of logic included, cannot without further ado be taken to agree with scientific practice (the attempt to apply them to this practice and at the same time to give a historically correct account of it has led to the decline of rationalism

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[4] An excellent survey is Mary Jo Nye, *Molecular Reality* (London, 1972).

described in vol. 2, chs. 1.6, 10 and 11). For example, we cannot be satisfied with arguments of type (i) (ch. 1). We must inquire how scientists actually think about 'reality' and what notions of realism they employ. We must study the various versions of scientific realism.

2. TYPES OF REALISM

For the Copernicans the issue is about the *truth of theories*. While the followers of Aristotle looked to physics and basic philosophy for information about the structure of the world, Copernicus and Kepler claimed truth for a point of view that did not belong to the basic theories of the time. As in antiquity the clash was not between a realist position and an absolute instrumentalism, it was 'between two realist positions',[5] i.e. between two different claims to truth.

Claims to truth can be raised only with regard to particular theories. The first version of scientific realism therefore does not lead to a realistic interpretation for *all* theories, but only for those which have been chosen as a basis for research. It may be asserted (a) that the chosen theory *has been shown* to be true or (b) that it is possible to *assume* its truth, even though (ba) the theory has not been established or (bb) is in conflict with facts and established views.

As far as I can see, (a) is adopted by Kepler:[6] Copernicus' views are true not simply because they fit the facts – any false theory can be made to fit the facts – but because they have led to novel predictions *and* because they do not fail when applied to topics similar to those where success was achieved. *They remain true in whatever direction one decides to pass through them.*[7] While the rivals can assert the truth of some parts of their theories (e.g. longitudes and latitudes of the planets) but not of others (mutual penetration of the paths of Venus and Mercury), the Copernican view is found to be true in all its parts and therefore true *simpliciter*.[8]

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[5] P. Duhem, *To Save the Phenomena* (Chicago, 1969), 106.

[6] *Mysterium Cosmographicum*, ch. 1 and Kepler's footnotes to that chapter.

[7] 'Nam jube quidlibet eorum, quae revera in coelo apparent, ex semel posita hypothesi demonstrare, regredi, progredi, unum ex alio colligere, et quidvis agere, quae veritas rerum patitur; neque ille hesitabat in ullo, si genuinum sit, et vel ex intricatissimis demonstrationum anfractibus in se unum constatissime revertetur.' *Ibid.*

[8] According to (b), the Copernican hypothesis has been found to be true in more of its parts than any alternative, it is stronger than the alternatives, its strength is not due to 'an arbitrary addition of many false statements designed to repair whatever faults might turn up' (Kepler) but to the nature of the basic postulates, and these postulates can therefore be *assumed* to be true. It is Popper's merit to have stated in the philosophy of science what is an ancient triviality in mathematics and even in certain forms of scepticism (Carneades): that one *may* (tentatively) assert the truth of a statement not all of whose parts have yet been examined. Popper adds that this is also *required* because of the way in which scientific hypotheses are used (*Conjectures and Refutations* (New York, 1962), 112f): they are not tested like instruments (which we want to retain after some modification) but by selecting crucial

A second version of scientific realism assumes that *scientific theories introduce new entities with new properties and new causal effects*. This version is often identified with the first, but mistakenly so: false theories can introduce new entities (almost all ingredients of our physical universe were introduced by theories now believed to be false), theories containing theoretical terms as syncategorematic terms can be true, not every theory introduces entities and, most importantly, theories can be formulated in different ways, using different theoretical entities and it is not at all clear which entities are supposed to be the 'real' ones (the first known example was the use of an excentre or of an epicycle for the path of the sun). Kepler's interpretation of Copernicus establishes a relation between version one and version two in this special case: the theory is true in all its parts which means that, in the formulation given by Copernicus, all its theoretical entities can be assumed to represent real entities.

The situation is not always that simple, however. A theoretical entity may represent a real entity – but not in the theory in which it was first proposed. An example is the (vector) potential in electrodynamics. Using Stokes' theorem together with div $B = 0$ (non-existence of magnetic charges) we can present every magnetic field as the curl of a vector field, just as any electrostatic field can be presented as the gradient of a scalar. Many physicists have interpreted the potentials as auxiliary magnitudes, i.e. as theoretical entities only indirectly linked to real entities such as charges, currents, fields. Faraday, who introduced the 'electrotonic state'[9] that was later represented by the vector potential,[10] assumed it to be a real state of matter and looked for effects. The *change* of the state has clearly indentifiable effects (induction currents) – but Faraday also looked for effects of the state 'while it continued', and he regarded such effects as necessary conditions of its existence. The criterion behind the search (which I shall call *Faraday's criterion*) is that a theoretical entity represents a real entity only if it can be shown to have effects *by itself* and not merely while changing, or acting in concert with other entities. The criterion considerably complicates the application of the second version of scientific realism.

cases in which the thesis is expected to fail if not true. This alternative is hardly convincing: some artifacts are withdrawn from circulation after a single decisive test (example: drugs), while hypotheses are modified and improved after crucial experiments (e.g. Lorentz's content-increasing modification of the theory of electrons after the Michelson–Morley experiment). A much better argument is (bb), that ascribing truth to an unsupported hypothesis that conflicts with facts and well-supported alternatives increases the number of possible tests and thereby the empirical content of the latter. This argument is prepared in ch. 2, described in greater detail in ch. 3 and applied to Copernicus and the quantum theory in ch. 11.

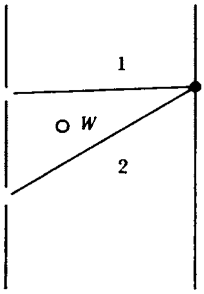
[9] *Experimental Researches in Electricity* series 1, sections 60ff. The brief quotation further below is from section 61, first sentence.

[10] A. M. Bork, 'Maxwell and the Vector Potential', *Isis*, 58 (1967), 210ff.

It also makes us understand why so many scientists rejected the atomic theory as an account of the constitution of matter despite its ability to explain familiar facts and to predict unfamiliar ones (independence, over a wide range of values, of the density and the viscosity of a gas): the predictions involved mass phenomena and did not depend on the peculiarities of individual molecular (atomic) processes.[11] These enter only in Brownian motion – which therefore became a crucial phenomenon for the kinetic theory. Furthermore, we realize that it may be reasonable to retain theoretical entities not satisfying Faraday's criterion: new theories might introduce new connections and provide means for finding the needed effects. The potentials are a good example for the developments I have in mind.

The electric potential 'became real' when the theory of relativity turned differences of potential energy into measurable mass differences (mass-defect of nuclei). The vector potential 'became real' when Bohm and Aharonov[12] showed the existence of quantum effects, as follows: in quantum theory the phase change along a trajectory passing a magnetic field is:

Fig. 1



$$\delta = \frac{q}{\hbar} \int_{\text{trajectory}} A ds$$

and the total phase change in an interference pattern:

$$\delta = \frac{q}{\hbar} \oint A ds = \frac{q}{\hbar} \text{ (flux of } B \text{ between } 1 \text{ and } 2)$$

Now assume that B is the field of a solenoid W situated between path 1 and path 2 (fig. 1). The $B = 0$ along the paths and we can either assume that B acts at a distance or that the observed phase changes are due to the potential A, for $A \neq 0$ along 1 and 2.

Examples such as these show that a direct application of the second version of scientific realism ('theories always introduce new entities') and a corresponding abstract criticism of 'positivistic' tendencies are too crude to fit scientific practice. What one needs are not philosophical slogans but a more detailed examination of historical phenomena.

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[11] Berthelot, Mach and others pointed out that nobody had ever 'seen' an atom – a somewhat crude but sensible application of Faraday's criterion.

[12] 'Significance of Electromagnetic Potentials in the Quantum Theory', *Phys. Rev.*, 115 (1959), 485ff.

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The crudity of a purely philosophical approach becomes even clearer when we turn to a *third version of scientific realism* which is found in Maxwell, Helmholtz, Hertz, Boltzmann and Einstein.[13]

Naive realists – and many scientists and philosophers supporting the second version belong to this group – assume that there are certain objects in the world and that some theories have managed to represent them correctly. These theories speak about reality. The task of science is to discover laws and phenomena and to reduce them to those theories. Newton's theory was for a long time regarded as a basic theory in the sense just described. Today many scientists, especially in chemistry and molecular biology, have the same attitude towards the quantum theory. Seen from such a point of view, the nineteenth-century quarrels about atomism were quarrels about the *nature of things*, carried out with the help of experiment and basic theory.

Naive realism occurs in commonsense as well as in the sciences and it has been criticized in both. In the nineteenth century, the scientific criticism consisted in pointing out that theoretical entities and especially the theoretical entities of mathematical physics have a life of their own which may conceal the matter under examination. 'Whoever does mathematics', writes Ernst Mach on this point,[14]

> will occasionally have the uncanny feeling that his science and even his pencil are more clever than he, a feeling which even the great Euler could not always overcome. The feeling is justified to a certain extent if only we consider how many of the ideas we use in the most familiar manner were invented centuries ago. It is indeed a partly alien intelligence that confronts us in science. But recognizing this state of affairs removes all mysticism and all the magic of the first impression[15] especially as we are able to rethink the alien thought as often as we wish.

Rethinking the alien thought means trying to view reality in a different way; it means trying to separate concepts and things conceptualized.

A well-known example of this attempt at a separation are Hertz's remarks in the introduction to his version of classical mechanics. According to Hertz, 'we make ourselves inner phantom pictures [*Scheinbilder*] or symbols of the outer objects of such a kind that the logically necessary [*denknotwendigen*] consequences of the picture are always pictures of the physically necessary [*naturnotwendigen*] consequences of the objects pictured . . . Experience shows that the demand can be satisfied and that

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[13] My attention was drawn to this version by C. M. Curd's excellent thesis *Ludwig Boltzmann's Philosophy of Science* (Pittsburgh, 1978).

[14] 'Die oekonomische Natur der physikalischen Forschung', lecture before the Vienna Academy of May 25, 1882, quoted from *Populaerwissenschaftliche Vorlesungen* (Leipzig, 1896), 213.

[15] This unanalysed magic and mysticism is the starting point of Popper's world three: cf. vol. 2, ch. 9.10.

such correspondences do in fact exist.'[16] Pictures are judged by their logical properties; they must be consistent, correct and distinct. 'Considering two pictures of the same object . . . we shall call the one more distinct that reflects more relations of the object than the other. Considering two pictures which are equally distinct we shall call the picture that . . . contains fewer superfluous or empty relations the more appropriate.' Using these terms we can say, on the basis of what is believed to be the case today, that a picture of quantum-mechanical processes that does not contain any 'hidden variables' is more appropriate than a picture that does, while a picture of gases that contains atoms such as the kinetic picture is more distinct than a phenomenological picture that does not. Note that the theoretical entities of a distinct and appropriate picture are still separated from the objects represented and that their nature as 'phantom pictures' or fictions is never forgotten.

According to Boltzmann, who accepted Hertz's account of scientific theories,

> the lack of clarity in the principles of mechanics may be explained by the fact that one did not at once introduce hypothetical mental pictures but tried to start from experience. One then tried to conceal the transition to hypotheses or even to find some sham proof to the effect that. . . no hypotheses had been used, creating unclarity by this very step.[17]

Boltzmann adds[18] that the use of partial differential equations (in the phenomenological approach to thermodynamics) instead of mechanical models does not eliminate pictures but simply introduces pictures of a different kind, and he sums up Hertz's position:

> Hertz made it quite clear to physicists (though philosophers most likely anticipated him long ago) that a theory cannot be an objective thing that really agrees with nature [*etwas mit der Natur sich wirklich Deckendes*] but must rather be regarded as merely a mental picture of phenomena that is related to them in the same way in which a symbol is related to the thing symbolised. It follows that it cannot be our task to find an absolutely correct theory – all we can do is to find a picture that represents phenomena in as simple a way as possible.[19]

Note the similarity between this point of view and that of Duhem. 'Theoretical Physics', writes Duhem,[20] 'does not have the power to grasp the real properties of bodies underneath the observable appearances; it cannot, therefore, without going beyond the legitimate scope of its

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[16] *Die Prinzipien der Mechanik* (Leipzig, 1894), 1ff.

[17] L. Boltzmann, *Vorlesungen ueber die Principe der Mechanik* (Leipzig, 1897), I, 2.

[18] *Ibid.*, 3. Cf. *Populaere Vorlesungen* (Leipzig, 1905), 142f, 144, 225f.

[19] *Populaere Vorlesungen*, 215f. Note that the distribution between the picture and the things pictured remains even if one denies, as Boltzmann did, that theories can ever be 'absolutely correct'.

[20] *The Aim and Structure of Physical Theory* (New York, 1962), 115.

methods, decide whether these properties are qualitative or quantitative. . . . Theoretical physics is limited to representing observable appearances by signs and symbols.'

The accounts just given assume two different domains, or layers. On the one side we have phenomena, facts, things, qualities as well as concepts for the direct expression of their properties and relations. On the other side we have an abstract (quantitative) language in which the 'phantom pictures,' i.e. scientific theories, are formulated. The pictures are correlated to the phenomena, facts, things, qualities of the first domain. Attention is paid to the language of the pictures or the 'theoretical language', as one might call it, and one considers ways of modifying and improving it. Little attention is paid to the 'observation language'. Vol. 2, ch. 2 describes Newton's version of this *two layer model* of scientific knowledge (which *does* pay attention to the observational level, or the 'phenomena'), vol. 2 ch. 3 describes Nagel's more technical presentation of the model, chs. 2, 4 and 6 criticize the technical presentation. I shall presently return to this point.

I am now ready to state the *third version of scientific realism* which one might call, somewhat paradoxically, the *positivistic version of scientific realism*. It was this version which was most frequently used in connection with the debates about atomic reality and the reality of hidden parameters in the quantum theory. Making judgements of reality here amounts to asserting that a particular 'phantom picture' (e.g. the phantom picture containing the locations of numerous mass points) is preferable to another phantom picture. 'The differential equations of the phenomenological approach', writes Boltzmann on this point,[21] 'are obviously nothing but rules for the forming of numbers and for connecting them with other numbers and geometrical concepts which in turn are nothing but thought pictures [*Gedankenbilder*] for the presentation of phenomena. *Exactly the same applies to the atomic conceptions* [*Vorstellungen der Atomistik*] so that I cannot see any difference in this respect.' According to Boltzmann even the general idea of the reality of the external world is but a (very abstract) picture,[22] and the philosophical doctrine of the reality of the external world asserts no more than that this picture, this *Scheinbild*, is preferable to other pictures such as solipsism.

The clearest and most concise account of the positivistic version is found in Einstein (cf. vol. 2, ch. 6.4). In his essay 'Physics and Reality',[23] Einstein criticizes the quantum theory for its '*incomplete* representation of real things'.[24] but explains at once what is meant by 'real existence':

> Out of the multitude of our sense experiences we take, mentally and arbi-

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[21] *Populaere Vorlesungen*, 142; my italics.

[22] *Ibid.*, ch. 12.

[23] *J. Frankl. Inst.*, 221 (1936), reprinted in *Ideas and Opinions* (New York, 1954), 290ff. I am quoting from the latter source. Einstein was thoroughly familiar with the writings of Boltzmann and Mach.

[24] *Ibid.*, 325f.

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> trarily, certain repeatedly occurring complexes of sense impressions . . . and correlate to them a concept – the concept of a bodily object. Considered logically this concept is not identical with the totality of sense impressions referred to; but it is a free creation of the human (animal) mind. On the other hand, this concept owes its meaning and its justification exclusively to the totality of the sense impressions we associate with it. The second step is to be found in the fact that, in our thinking (which determines our expectations), we attribute to this concept of a bodily object a significance which is to a high degree independent of the sense impressions which originally gave rise to it. This is what we mean when we attribute to the bodily object a 'real existence'.[25]

We see that according to Einstein the quantum theoretical issue is not an 'ontological' issue; it is an issue over the choice of systems for the correlation of 'impressions'.

3. MAXWELL AND MACH

The ideas of Maxwell and Mach differ from all the versions I have explained so far. They are also more subtle. They were developed in close connection with research and it is therefore somewhat difficult to isolate their philosophical components. But one feels a sense of relief when transferred from the fruitless technicalities and ontological primitivisms of modern 'philosophers' to the brief, simple, but profound remarks of these scientists.

Maxwell introduced his philosophy before and not after he had made his discoveries, as a guide for finding a new theory of electromagnetic phenomena. He distinguishes between 'mathematical formulae', 'physical hypotheses' and 'analogies'.[26] Mathematical formulae may help us to 'trace out the consequences of given laws' but at the expense of 'los[ing] sight of the phenomena to be explained'. Also 'we can never obtain more extended views of the connections of the subject'. What Maxwell means is that mathematical formulae fail to keep the subject matter before the eye of the scientist, and they also lack in heuristic potential. This is a brief and powerful criticism of theories such as the one proposed (much later) by Hertz and of more recent formalistic tendencies.

A physical hypothesis does provide a guide and it also keeps the subject matter before our eyes. However, it makes us see the phenomena 'only through a medium'. Maxwell seems to fear that physical hypotheses may be imposed upon the phenomena without the possibility of checking them independently. As a result we cannot decide whether the phenomena are correctly represented by these hypotheses.

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[25] *Ibid.*, 291.

[26] 'On Faraday's Lines of Force', *Trans. Camb. Phil. Soc.*, 10, part 1, read on Dec. 10, 1855 and Feb. 11, 1856 and quoted from *The Scientific Papers of James Clerk Maxwell* (Dover, 1965), 155f.