The Philosophy of the Physical Sciences

The various philosophical traditions of the world form an important part of the intellectual and cultural achievements of the civilizations which produced them. Typically, their roots go back thousand of years – as in the cases of India and Greece. There is in them much poetic imagery and logical and deep thinking, as well as a sizeable speculative component. In contrast, modern science as we know it developed barely four hundred years ago, in the seventeenth century, arising in the main out of the combined efforts of Copernicus, Kepler, Galileo, and Newton. It was only then that the importance of controlled experiments and careful and systematic quantitative study of natural phenomena was clearly recognized. However, in spite of these great differences in age, at least in the Western tradition the interactions between modern physical science and philosophy have been deep and profound.

I am not a professional philosopher. I have only been attracted to some philosophical questions, and been impressed by certain philosophical systems, as a result of a study of physics. Thus the content of this article may sometimes reveal a sense of naivety as regards formal philosophical matters, schools of thought, traditions, and the like. Nevertheless, I hope that what follows will be of interest to the readers of this journal, most of whom may not be professional scientists but would still have a lively interest in these matters.

It may not be out of place to mention here some contrasting attitudes to the possible roles and value of philosophical thinking that are evident in the developments in physics over the past century. As a consequence of the European, in particular the continental tradition, the general writings of the two discoverers of quantum mechanics–Werner Heisenberg from Germany and Erwin Schrödinger from Austria – show great familiarity with and interest in various philosophical systems of thought, from the Greeks onwards. While the writings of Niels Bohr and Albert Einstein also often have a philosophical bent, their references to formal systems of philosophy tend to be fewer, but nevertheless important. In contrast, when the focus of work in the new physics shifted from Europe to the US around the middle of the twentieth century, this regard for general philosophical thinking among the leading professional physicists does seem to have weakened. Typical statements of Richard Feynman and Steven Weinberg, for instance,

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display a certain degree of disdain, or certainly a lack of sympathy, for the value of philosophical thinking in the physical sciences.

In any case, in the present account I assume that there is value in looking at the growth of modern physical science from a ‘philosophical point of view’, though it may require some degree of maturity as well as sympathy to adopt this attitude.

We may say for our present purposes that philosophy of science is generally concerned with the nature of knowledge, the way we acquire it, the meaning of understanding, and the evolution of concepts, all in the context of the physical sciences. It may in addition be ultimately concerned with an appreciation of our place in nature. Philosophy of science deals with the understanding of natural phenomena and how this understanding is achieved, with the general features common to the various branches of science, and with the interdependence of these branches. It is more interested in the overall pattern of natural laws than in the details of any particular area of science.

Our aim will be to come up to the modern era in physics, and to see what it has taught us with regard to questions of a philosophical nature. Along the way we shall briefly review some historical developments and ways of thinking or schools of thought, both in philosophy and in physical science. We will consider how concepts are created, how they grow, and how they have sometimes to be greatly modified or even abandoned. Naturally, developments in physics will be covered in slightly greater detail than those in formal philosophy.

Rationalism and Empiricism

In our account of the beginnings of science and philosophical thinking we go back to Greek times. The major creative period, lasting about four hundred years, began with Thales of Miletus (c.624-c. 546 BCE) and included, among many renowned thinkers, Pythagoras (c.580-c.500 BCE), Anaximander (610-c.545 BCE), Democritus (c.460-370 BCE), Leucippus (fl.5th cent.BCE), Plato (427-347 BCE), Aristotle (384-322 BCE), and Euclid (fl.c.300 BCE). In the early period, with Thales, there was a strong impulse towards, as Benjamin Farrington puts it, ‘a new commonsense way of looking at the world of things… the whole point of which is that it gathers together into a coherent picture a number of observed facts *without letting Marduk* [the Babylonian Creator] *in.’*. The attempt was to deal with nature on its own, not bringing in mystical or mythical leanings. To quote from Heisenberg: ‘The strongest impulse had come from the immediate reality of the world in which we live and which we perceive by our senses. This reality was full of life, and there was no good reason to stress the distinction between matter and mind or between body and soul.’

Thales was familiar with the knowledge of geometry developed by the Egyptians, the basic facts of static electricity, and the magnetic properties of lodestone. Later, Democritus and Leucippus propounded the atomic concept of matter, not in a casual manner but based on careful reasoning. However, it goes without saying that philosophical thinking in these early times had a considerable speculative content, and there were others such as Plato and Aristotle who later strongly opposed the atomic hypothesis. This should come as no surprise at all, since as late as the end of the nineteenth century there were influential figures – Ernst Mach and Wilhelm Ostwald – who were still opposed to the idea of atoms. This idea finally triumphed only thanks to the heroic efforts of Ludwig Boltzmann, and Einstein's work on Brownian movement.

The knowledge of geometry brought by the Greeks from Egypt was perfected and presented in an axiomatic form by Euclid of Alexandria around 300 BCE. The fact that this subject could be presented as a deductive system – a large number of consequences or theorems following logically from a very few 'self-evident' axioms or 'obvious' truths – must have made a deep impression on the Greek mind. It led in course of time to the idea that the behaviour and laws of nature could be derived from pure reason, without the help of direct inputs from experience. This was the so-called *rationalist* philosophy of science, which lay in stark contrast to the initial *empiricist* approach of Thales and Democritus. Plato held that 'knowledge of Nature does not require observation and is attainable through reason alone'. Before Plato, Pythagoras too espoused this point of view, other illustrious followers being Aristotle and, in much later times, René Descartes, Wilhelm Leibniz, and Benedict de Spinoza. One may say that this rationalist philosophy accords a privileged position to human beings in the scheme of things.

The opposite – empiricist – point of view holds that knowledge comes ultimately from experience of phenomena and not from reason As we saw, this was the attitude of both Thales and Democritus; and in later centuries it was revived by Francis Bacon and carried forward by John Locke, George Berkeley, and David Hume as a reaction to the rationalist view on the European continent. We shall return to some of these contrasting philosophies later, only noting now that empiricism goes with a more modest attitude towards our place in nature.

From Galileo and Newton to Kantian Philosophy

Modern science emerged in Europe during the Renaissance – the reawakening of classical ideals in arts, literature, and philosophy during the fourteenth to seventeenth centuries, brought about by a combination of social, political and religious factors. This is not the place to go into this crucial advance in any detail, but we note that it occurred against the background of a liberating intellectual and philosophical atmosphere to which many – including Descartes, Leibniz, and Spinoza – contributed.

***Empirical Advances*:** Nicolaus Copernicus initiated the movement away from a human-centred view of nature with his heliocentric model of the solar system, and Francis Bacon showed the way to freedom from reason alone as the source of all knowledge. Indeed, Bacon said of Aristotle: 'He did not consult experience as he should have done … but having first determined the question according to his will, he then resorted to experience, and … led her about like a captive in a procession.' Copernicus's work, as well as Kepler's discovery of the three laws of planetary motion during the years 1609–19, was but preparation for what was to come in the work of Galileo and Newton.

Galileo, rightly regarded as the founder of modern science, not only discovered the law of inertia in mechanics, the kinematic description of motion, and the law of free fall, but also stressed the importance of performing controlled experiments, of quantitative measurement, and of the use of mathematics in expressing experimental results. He stated this last point with particular emphasis, saying about the 'book of nature': 'It cannot be read until we have learned the language and become familiar with the characters in which it is written. It is written in mathematical language.'

It was Isaac Newton, born the year Galileo died (at least by one calendar), who completed the work initiated by Galileo and his other illustrious predecessors, and paved the way for the systematic scientific investigation of physical phenomena over the succeeding centuries. We can say that without Newton's crowning achievements, this tradition – the Galilean–Newtonian world view – would not have been securely established. Speaking of the importance of what Galileo and Newton achieved, Max Born says: 'The distinctive quality of these great thinkers was their ability to free themselves from the metaphysical traditions of their time and to express the results of observations and experiments in a new mathematical language regardless of any philosophical preconceptions.'

***Scientific Method*:** Newton expressed clearly his views on the independent and absolute natures of space and time, stated his three laws of motion for material bodes as axioms, enunciated his law of universal gravitation, and established mechanics as a deductive system. His whole approach and accomplishments made explicit and clear all the steps in the chain of scientific work: observation and experimental data $\rightarrow$ analysis using mathematics $\rightarrow$ discovery and enunciation of fundamental laws $\rightarrow$ further mathematical deduction $\rightarrow$ predictions to be tested by new experiments. As he put it: 'To derive two or three general Principles of Motion from Phaenomena, and afterwards to tell us how the Properties and Actions of all corporeal Things follow from those manifest Principles, would be a very great step in Philosophy, though the causes of those Principles were not yet discover'd'.

***Absolute Space and Time*:** For the purpose of developing mechanics, Newton invented the calculus. In his presentation he adopted the Greek attitude to geometry and the style of Euclid. Thus he converted knowledge obtained inductively from (refined!) experience – extension from the particular to the general – into a deductive style of presentation. From his laws of motion and universal gravitation, all the empirical laws of Kepler and Galileo followed as logical mathematical consequences. His clear statements about the natures of space and time were of critical importance at this juncture. They mark an important phase in our understanding of these key components of nature, and as we emphasize later, this understanding is never final but develops continually 'in time' as we gather more and more experience. Who better than Einstein to express all this: 'It required a severe struggle [for Newton] to arrive at the concept of independent and absolute space, indispensable for the development of theory. Newton's decision was, in the contemporary state of science, the only possible one, and particularly the only fruitful one. But the subsequent development of the problems, proceeding in a roundabout way which no one could then possibly foresee, has shown that the resistance of Leibniz and Huygens, intuitively well-founded but supported by inadequate arguments, was actually justified. ... It has required no less strenuous exertions subsequently to overcome this concept [of absolute space].'

***Theory and Experiment* :** In Newton's work we see a confluence of the inductive and deductive methods, each playing its due role. There was a unification of celestial and terrestrial gravitational phenomena, and many previously intractable problems became amenable to analysis and understanding. At one point he went so far as to claim that he made no hypotheses – *'Hypotheses non fingo'* – hinting at pure empiricism; but this actually shows that modern science was still young. As Einstein aptly said: 'The more primitive the status of science is the more readily can the scientist live under the illusion that he is a pure empiricist.' Today the level of sophistication of the physical sciences is such that every worthwhile experiment is heavily dependent on previous and current theory for its motivations, goals, methods, and analysis.

Over the course of the eighteenth century, the Galilean-Newtonian approach to physical science was amazingly successful. It was applied to problems of celestial mechanics or astronomy, fluid dynamics, and elastic media among others. A distinguished line of mathematical physicists – Leonhard Euler, Joseph Lagrange, Pierre Simon de Laplace, and many others – took part in this endeavour. At one point Lagrange complained that, after Newton, there was nothing left to be discovered! Towards the end of the century, the laws of static electricity and magnetism also fell into the Galilean-Newtonian pattern.

***Thought as a Synthetic A Priori*:** Around this time, the philosopher of the Enlightenment, Immanuel Kant, was so impressed by these successes of the Galilean-Newtonian approach that he created a philosophical system to explain or justify them. We mentioned earlier the contrasting rationalist and empiricist schools of philosophy. Kant tried to bring them together and offered an explanation of the triumphs of Galilean – Newtonian science along the following lines. He distinguished between *a priori* and *a posteriori* forms of knowledge – respectively in advance of, and as a result of, experience of nature – and between two kinds of statements: *the analytic*, which are empty (such as definitions and statements of a logical nature); and *the synthetic*, which had nontrivial content and could in principle be false. He saw two paths to knowledge about nature – that which is a priori, and that which results from experience. Some of the basic physical ideas underlying Galilean – Newtonian physics, which were actually the results of long human experience and experiment, were regarded by him as synthetic a priori principles. Thus they were claimed to be available to us innately – as a result, one might say, of pure reason – and were necessarily valid and obeyed by natural phenomena. Some of these synthetic a priori principles were the separate and absolute natures of space and time, as expressed by Newton; the validity of Euclidean geometry for space; the law of causality; and later on even the permanence of matter, and the law of conservation of mass. In effect, Kant took the knowledge of physical phenomena available in his time and made some of it necessarily and inevitably true and binding on nature. These synthetic a priori principles were present in our minds before any experience of nature; they were thought of as preconditions for, rather than results of, science.

Kant's attempt was made about two centuries ago, and today it is clear that it was tied to his age and to the science of his time. Schrödinger characterizes well the impulse that lay behind Kant's attempt: 'One is very easily deceived into regarding an acquired habit of thought as a peremptory postulate imposed by our mind on any theory of the physical world.' We will shortly look at some of the ways in which physical science has gone beyond Kant's framework, and will describe a fascinating new way of understanding the origin of synthetic a priori principles of thought.

Physical Science in the Nineteenth and Twentieth Centuries

***Fields as Distinct from Matter*:** At the start of the nineteenth century the fields of optics, electricity, and magnetism were separate from one another and from mechanics. Chemistry was a distinct discipline. But over the century many advances were made, which we can only briefly describe here. An early step forward was in the understanding of the nature of light. Thomas Young's experiments on interference brought the wave theory of light back into favour, as against Newton's corpuscular ideas. This was carried forward and firmly established by Augustin Fresnel. Then, as a result of fundamental experimental discoveries by Hans Oersted, André Amperè, and Michael Faraday, the concepts of time-dependent electric and magnetic fields came into being. There were things in natine in addition to and distinct from matter.

Meanwhile, celestial mechanics continued to record stunning successes. Perhaps the most striking example was the prediction by both John Adams and Urbain Le Verrier, based on Newtonian mechanics and gravitation, of the existence of a new planet, Neptune, to account for the observed discrepancies in the motion of Uranus. In 1846 it was found exactly where the astronomers were told to look. (However, a later similar attempt to trace discrepancies in the motion of Mercury to a perturbing planet Vulcan was unsuccessful. The answer came from an entirely unexpected direction – general relativity.)

***Electromagnetism and Light*:** After Faraday's powerful intuition had led to the idea of electric and magnetic fields, James Maxwell put all the known laws in the subject of electricity and magnetism into a coherent mathematical form. He then found an important discrepancy, saw the way to correct it, and was thus led to his comprehensive classical unified theory of electromagnetic phenomena. A prediction of this theory was the possibility of self-supporting electromagnetic waves whose speed when calculated turned out to be exactly the known speed of light. Then Maxwell identified light with these waves, and optics became a part of electromagnetism. During this period, following Fresnel's work, it was believed that the propagation of light needed a material medium, the so-called luminiferous ether, and this concept was taken over by Maxwell as well.

***Non-Euclidean Geometry*:** In the area of mathematics, the subject of geometry witnessed a major advance. We saw that Kant in his philosophy had made Euclidean geometry an inevitable or inescapable property of physical space – it was a synthetic a priori principle. Within mathematics, for centuries the status of one of Euclid's postulates – the fifth one, the parallel postulate (that there is exactly one parallel to a given line through a given point) – had been repeatedly studied: was it logically independent of the other postulates or a consequence of them? During the first half of the nineteenth century, three mathematicians – Karl Gauss, Nikolai Lobachevsky, and János Bolyai – independently showed that it was a logically independent statement. It could be altered, allowing one to create logically consistent alternatives to Euclidean geometry. Thus was born within mathematics the concept of non-Euclidean geometry, which, as we will soon see, was to enter physical science just under a century later.

***Statistical Physics*:** Over the latter half of the nineteenth century, statistical physics and statistical mechanics became established as foundations of thermodynamics. Thus by the century's end the principal components of the physicist's view of the world were Newton's mechanics, Maxwell's electromagnetism, and statistical ideas and thermodynamics.

***Relativity*:** The important departures from the Kantian picture of physical science – from the framework Kant developed to justify the successes of Galilean – Newtonian ideas – came one by one with the revolutionary theories of twentieth-century physics. First came the special theory of relativity, the resolution of a clash between Newton's mechanics and Maxwell's electromagnetism. It turned out that Newton's views of separate and absolute space and time, and the Galilean transformations that go with them, were incompatible with Maxwell's electromagnetic equations. These equations led to a profoundly different view of the properties of space and time. What special relativity achieved was to make clear these properties, show that there was no need for ether as a carrier of electromagnetic waves, and then amend Newton's mechanics of material particles to make it consistent with electromagnetism. The earlier separateness and individual absoluteness of space and time – included among Kant's synthetic a priori principles – gave way to a unified view in which only a combined space-time was common to and shared by all observers of natural phenomena. However, each observer could choose how he or she would split space-time in a physically meaningful way into separate space and time. The earlier absoluteness of the concept of simultaneity was lost, and now varied from observer to observer. For each observer, though, space continued to obey the laws of Euclidean geometry. Special relativity took one more step beyond the Kantian framework – now only a combined law of conservation of matter and energy was valid, not separate laws for matter and for energy.

The other major twentieth-century development in physics was the discovery of the quantum nature of phenomena and the formulation of quantum theory. In many ways, quantum theory is more profound in its implications than the relativity theories. Quantum theory arose out of a clash between Maxwell's electromagnetism and the principles of statistical physics, which, as we saw, provide the foundation for thermodynamics. We can only try to convey why quantum theory has had such a profound influence on the philosophy of science, and cannot venture into much technical detail. The view of the nature of light has swung back towards Newton's corpuscular conception – with important and subtle differences – expressed in the concept of the photon. As for the mechanics of matter, the Galilean-Newtonian picture and description of motion has given way to a much more mathematically elaborate and subtle complex of ideas, which goes by the name of quantum mechanics. Material particles no longer travel along well-defined paths or trajectories in space in the course of time. Their evolution in time can only be given in the language of probability – that is, all the predictive statements of quantum mechanics are probabilistic in nature. The quantitative description of physical properties of systems undergoes two important changes in quantum mechanics: on the one hand, many physical variables show a quantization of the values they can possess – thus, typically, energies are restricted to a discrete set of values rather than a continuum. On the other hand, the physical variables of a given system have such mathematical properties, or are of such nature, that we cannot imagine that each of them always possesses some numerical value which, if we so wish, can be revealed by a measurement. According to Bohr, we can never speak of a quantum system as having such and such a value for such and such a physical property on its own, independent of our measurement of it. And with a pair of so-called incompatible properties, an effort to measure one of them automatically precludes any effort to simultaneously measure the other as well.

We have to learn to use language with much more caution or circumspection when speaking of quantum phenomena than was the case earlier. Many classically meaningful and answerable questions become devoid of meaning in the quantum domain. The kind of 'visualizability' of physical systems in complete detail which was possible in classical physics is denied by quantum mechanics.

From the perspective of Kantian thinking, quantum mechanics has made us give up strict determinism, substituting a kind of statistical causality for it. On the other hand, it has supplied the basic theoretical concepts for all of chemistry, for atomic, molecular, nuclear, and elementary particle phenomena, and for all processes involving radiation. The old law of the permanence of matter has gone, as it can be converted to radiation, and vice versa. Up to the present time, the agreement of quantum mechanics with experiments has been outstanding – nature does seem to behave, in many situations, in classically unreasonable ways.

The Reinterpretation of Kantian Ideas

It is understandable that when physics advanced into new territories involving the very fast, the very large, and the very small – as judged by everyday standards and experience – some of the Kantian synthetic a priori principles had to be given up. As we said, Kant's ideas were rooted in the physical science and Galilean-Newtonian tradition of his time; he could not have foreseen the revolutionary developments that were to come later. This much is natural. However, what is remarkable is that the 'problem' with his philosophical basis for physical science has been illumined during the mid-twentieth century from a rather unexpected direction – namely, biology and the theory of evolution by natural selection. One might wonder if, apart from having to give up particular synthetic a priori principles as a result of advances in physical science, the very concept of such principles has also to be given up. After all, one might ask how principles supposedly known in advance of experience could necessarily constrain our later experiences. The answer to this question involves a subtle reinterpretation of Kant's notions, using ideas not available to him. This fascinating development – the work of Konrad Lorenz – leads to a better understanding of the entire situation, and has been eloquently presented by Max Delbrück.

The basic contrast is between the slow evolution of species governed by the force of natural selection, involving innumerable generations and enormous stretches of time; and the relatively short life span of an individual member of the species. In the former process – phylogenesis – those abilities thrown up by random genetic changes which are beneficial to biological survival are retained and refined. The others are discarded. Those retained include the ability to recognize the most important physical features of the world around us at our own scales of length and time, because it is just these scales that are relevant for biological evolution. Thus, gradual evolution of species governed by natural selection develops these useful capacities, and then endows each individual with them at birth. From the point of view of the individual's development over a single life time – ontogenesis – the capacities in question seem to be given ready-made at birth, in advance of experience; they seem to be a priori. But this argument shows that from a longer time perspective there is nothing a priori about them, as they are the fruits of experience of the species. In Delbrück's words:

> It appears therefore that two kinds of learning are involved in our dealing with the world. One is *phylogenetic* learning, in the sense that during evolution we have evolved very sophisticated machinery for perceiving and making inferences about a real world. … In other words, whereas in the light of modern understanding of evolutionary processes, we can say the individual approaches perception a priori, this is by no means true when we consider the history of mankind as a whole. What is a priori for individuals is a posteriori for the species. The second kind of learning involved in dealing with the world is *ontogenetic* learning, namely the lifelong acquisition of cultural, linguistic, and scientific knowledge.

The one added subtle point is that species evolution endows each individual with the capacity to acquire knowledge about the world outside, but not the knowledge itself. This has to be acquired through the experiences of infancy and childhood, and indeed is a lifelong endeavour. The difference between capacity and content is profound. In this way Kant's conceptions acquire new meaning. We also learn that the biologically evolved Kantian a prioris can only be expected to work for a limited range of natural phenomena, and our 'sense of intuition' is based on this range alone. We should therefore not be surprised if Galilean-Newtonian principles do not extend beyond this limited world to the world of the very fast, very large, or very small. But the truth is that our intuition is so much a part of us that it is very difficult to escape from or transcend it.

Some Important Features of Physical Science

Returning to physical science, there are several important features it has acquired, some more recently than others, with significant philosophical implications.

The descriptions and understanding of natural phenomena given by physical science are always developing or evolving, always provisional and never final. Since this is so very important, let me cite several examples which lead one to this sobering point of view. There have been occasions in the past – with Lagrange in the eighteenth century, and William Thompson (Lord Kelvin) at the end of the nineteenth century – when the feeling was expressed that all the laws of physics had been found and nothing remained to be discovered. Our experiences since then have made us much more modest in our claims. We both recognize the existence of limits of validity for every physical theory or body of laws, even for those yet to be discovered; and admit that future experience can always lead to unexpected surprises. In this important sense Nature is inexhaustible: we will always be learning from her. The lack of finality of every physical theory in this sense means that we can only continually increase the accuracy of our description of the phenomena of 'the real world out there' but can never say we have been able to describe them exactly as they are, or have reached true reality.

Our first example to drive these points home is connected with the Newtonian description of universal gravitation as an instantaneous attraction between any two mass points governed by an inverse square law. Before Newton, the prevailing idea was Descartes' theory of vortices – all physical actions or influences were by contact alone. Newton's law was a major change, giving rise to the concept of action at a distance. Privately, Newton himself expressed uneasiness at what seemed an unreasonable aspect of his law – how could material bodies influence one another instantaneously across intervening empty space? But his law worked, its quantitative predictions agreed with experience (at that time!), and with the passage of time the idea of action at a distance became gradually accepted. Even the initial laws of electricity and magnetism – in the static limit – were expressed in such a framework. The return to action by contact via an intervening field came about in the case of gravitation only in 1915 with Einstein's theory of general relativity.

The next example concerns the nature of light. As we have discussed earlier, the corpuscular viewpoint championed by Newton was replaced by the wave concept after Young's experiments on interference. After Maxwell's classical electromagnetism arrived, light was identified with the propagating waves of Maxwell's theory: now one 'knew' what the waves were made of. But when Einstein developed the photon concept in 1905, our understanding moved once more in the direction of the corpuscular viewpoint, involving a subtle combination of wave and particle concepts which can be properly expressed only in the language and imagery of quantum mechanics. At none of the above stages of development could one claim that one had finally understood the real nature and properties of light. It was always a movement towards improved understanding.

Our third example concerns the explanation of the spectrum of the simplest atom in Nature, hydrogen. Bohr's 1913 theory was the first breakthrough; it gave the vital clue to the wealth of data in the field of spectroscopy. Spectral lines corresponded to transitions of electrons between atomic states with various discrete energies. His model for the hydrogen atom was able to explain the spectral lines of the so-called Balmer series, and also several other series. This vital first step fell within the framework of the old quantum theory. A few years later, Arnold Sommerfeld introduced special relativistic corrections to the Bohr model, and was thus able to explain the so-called fine structure in the spectrum. This was then regarded as a triumph of the existing theoretical framework. But after the advent of quantum mechanics in 1925-6, the 'correct' understanding of the spectrum of hydrogen was supplied by the Schrödinger equation and its solutions. The framework of physical ideas was completely different from Bohr's, but the data explained was the same. Then in 1928, after Dirac had found the relativistic wave equation for the electron, the fine structure came out as a straightforward consequence. After this, the Sommerfeld explanation became a fortuitous coincidence, not to be taken seriously anymore. Almost two decades later, as improved experimental techniques and measurements revealed new and finer details of the hydrogen spectrum – the so-called Lamb shift – one had to go beyond the Dirac equation and appeal to the theory of quantum electrodynamics (QED) for an explanation. This turned out to be one of the triumphs of that theory. Clearly at no stage could we have said that we had understood the origin of the lines of the spectrum of hydrogen in complete detail, or that we had the complete and real truth in our possession.

Turning from physics to mathematics, in the field of geometry we have seen a similar evolution, though over a much longer period of time. As we mentioned earlier, only after almost two millennia was it realized that Euclid's geometry is not the only logically possible system of geometry for space; other non-Euclidean geometries are certainly conceivable and consistent. And after general relativity, the changeable geometry of space-time has become an ingredient in the laws of physics, specifically of gravitation. Today there is talk of the quantum features of geometry, one more step in the continuing effort to understand the natures of space and time.

These examples, and many others, teach us that the problem of what is physically real is a time-dependent one: it always depends on what is known at each epoch in the growth of physical science, and can see dramatic changes at certain points. Concepts like phlogiston and ether seemed essential at certain stages in the history of physics, but were later given up in the light of improved understanding.

The accuracy of observations and measurements and the sophistication of the instruments available for experimental investigation also continually increase, so they too contribute to the transitoriness of physical theories. But it should also be pointed out that at any given time we have trust in certain tested and successful ideas and theories, and keep working with them until we are compelled by new experience to go beyond them; then we modify them or in some cases even abandon them. Thus at the present time, we have full confidence that within their respective domains of validity, Newton's mechanics, Maxwell's electromagnetism and the nonrelativistic quantum mechanics and its later developments can certainly be used.

Mathematics: The Language of Nature

Next we turn to the important role of mathematics in physical science. Galileo's remark about mathematics being the language of Nature has turned out to be true, at least in physical science, to a degree far beyond what anyone might have imagined. In the eighteenth and much of the nineteenth century, as the concepts about the physical universe grew in complexity and subtlety, so did the mathematics used to describe them. The same gifted individuals contributed to both disciplines in these periods – Euler, Lagrange, Laplace, Fourier, Gauss, Hamilton, and Jacobi, to name a few. Thereafter, there was to some extent a parting of ways. The relativity and quantum revolutions in the twentieth century exploited mathematical ideas previously and independently developed purely within mathematics. In any event, there has been a steadily increasing role for mathematical ideas in physical science. In one sense this is connected to the reinterpretation of Kantian ideas sketched in the preceding section. As we move away from the domain of normal daily experience and into unfamiliar realms, it is understandable that our intuition often fails us, and then we depend increasingly on the mathematical structure of physical theory for guidance. Furthermore, the accuracy with which effects can be predicted by modern physical theories, and then checked by experiments, is truly staggering. In Eugene Wigner's view, there seems to be no rational explanation for this to be so.

There are some who regard the body of mathematical truths as an independently existing 'continent out there' and the process of mathematical discovery as the result of continual exploration of this continent. However, it is likely that this is a psychological response from some gifted individuals who have made really deep discoveries in mathematics based on a variety of motivations. A more modest and less problematic attitude is to regard mathematics as a human invention, similar to but far more compact and rigorous than language, given that in the first place evolution has equipped us with the capacity to create it. But then the extraordinary degree of detail and verification of physical theories via their predictions – this is what seems difficult to explain, and what Wigner terms a miracle. In Dirac's view, the reason why the method of mathematical reasoning works so well in physical science is along these lines: 'This must be ascribed to some *mathematical quality in Nature,* a quality which the casual observer of Nature would not suspect, but which nevertheless plays an important role in Nature's scheme'.

Another related point stressed by Dirac should also be mentioned. It turns out that in the long run, the deductive method is not suitable for physical science. One cannot base one's ideas on a fixed, initially stated, and unchanging set of axioms, and then rely on logic to obtain all possible physical consequences. One may adopt this strategy – inspired by Euclid – to a limited extent to grasp the logical structure of a particular set of ideas in a compact way, but one is bound sooner or later to transcend the confines of such a structure. This has been the case, for instance, with Newton's axiomatic approach to mechanics – witness the changes wrought by special relativity on the one hand, and quantum theory on the other. Such may well be the case with the present highly successful quantum mechanics as well. Turning to Dirac:

> The steady progress of physics requires for its theoretical formulation a mathematics that gets continually more advanced. This is only natural and to be expected. What, however, was not expected ... was the particular form that the line of advancement of the mathematics would take, namely, it was expected that the mathematics would get more and more complicated, but would rest on a permanent basis of axioms and definitions, while actually the modern physical developments have required a mathematics that continually shifts its foundations and gets more abstract. ... It seems likely that this process of increasing abstraction will continue in the future and that advance in physics is to be associated with a continual modification and generalization of the axioms at the base of the mathematics rather than with a logical development of any one mathematical scheme on a fixed foundation.

Looking Back Philosophically

Philosophical insights into and speculations about Nature go far back in time; modern science in comparison is very recent. We have followed the growth of physical science from its modern beginnings at the hands of Galileo and Newton, and the impact it had on philosophy in that period. We saw how classical physics seemed to have achieved a kind of completeness at the end of the nineteenth century, after which the relativity and quantum revolutions occurred.

In discussing or evaluating ancient philosophical ideas in the light of knowledge attained much later, a great sense of balance is needed. Such comparisons can easily be misunderstood. On this point, Heisenberg explains:

> It may seem at first sight that the Greek philosophers have by some kind of ingenious

David Bohm and Renee Weber on Physics and Maths

Weber The modern physicist is more like the materialist.

Bohm Basically; except for this tremendous emphasis on mathematics, which is like saying that God is a mathematician. If you emphasize mathematics as much as scientists now do, without any physical picture of matter, you are tacitly saying that the essence of the world is something abstract and almost spiritual, if you really think about it.

Weber Mathematics is pure thought.

Bohm That's right. You won't find it anywhere in matter.

Weber You are saying that even today's physicists who might be least inclined towards anything spiritual are practically forced to assume that it is beyond the material.

Bohm Tacitly, anyway. Physicists may not accept this, but they are attributing qualities to matter that are beyond those usually considered to be material. They are more like spiritual qualities in so far as we say there is this mathematical order which prevails, which has no picture in material terms that we can correlate with it.

Weber Is it an aesthetic principle of something deeper still that makes them hold out for one rather than for three or four ultimate laws? Is it a spiritual drive, without their realizing it?

Bohm It probably is a universal human drive, the same one which drives people to mysticism or to religion or art....

Weber Feynman said that those who don't understand mathematics don't realize the beauty in the universe. Beauty keeps coming up, together with order and simplicity and other Pythagorean and Platonic categories.

Bohm Order and simplicity and unity, and something behind all that which we can't describe.

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intuition come to the same or very similar conclusions as we have in modern times only after several centuries of hard labour with experiments and mathematics. This interpretation of our comparison would, however, be a complete misunderstanding. There is an enormous difference between modern science and Greek philosophy, and that is just the empiricist attitude of modern science.... This possibility of checking the correctness of a statement experimentally with very high precision and in any number of details gives an enormous weight to the statement that could not be attached to the statements of early Greek philosophy. All the same, some statements of ancient philosophy are rather near to those of modern science.

It is important to stress, as Bohr particularly did, that science is a social human activity crucially dependent on communication among individuals. Each scientific theory is properly viewed as a human creation. Here is Yakov Zeldovich's expression of this aspect: 'Fundamental science is ... needed, among other things, because it satisfies man's spiritual requirements. Scientific endeavour is a remarkable manifestation of human intellect. It perfects human intelligence and ennobles the soul'.

We have seen how difficult it is to give precise definitions of what is physically real; any statement reflects the state of knowledge at the time it is made, and may have to be revised later. From a philosophical stance, the importance of mathematics in physical science, and the changing ways in which it is used, are noteworthy. In the discussions about quantum mechanics we see the extreme care required in the use of language (not to mean, of course, that we can be careless in other realms!).

Again, from a philosophical standpoint, we see that pure empiricism and a purely deductive approach are both limited in scope. We need to combine caution, flexibility, and rigour – all at the same time. Nature is inexhaustible, and only experience hand in hand with reason can guide us to dependable knowledge. These seem to be the characteristics of a philosophy useful for the physical sciences.

Suggested Reading

[1] Benjamin Farrington, *Greek Science*, Spokesman, 1980.

[2] Erwin Schrödinger, *Nature and the Greeks*, Canto imprint, Cambridge University Press, 1996.

[3] Hans Reichenbach, *The Rise of Scientific Philosophy*, University of California Press, 1959.

[4] Werner Heisenberg, *Physics and Philosophy*, Harper and Row, 1962.

[5] Konrad Lorenz, *The Natural Science of the Human Species*, MIT Press, 1997.

[6] Max Delbruck, *Mind from Matter? An Essay on Evolutionary Epistemology*, Blackwell Scientific Publications, 1986.

[7] Jean-Peirre Changeux and Alain Connes, *Conversations on Mind, Matter and Mathematics*, Princeton University Press, 1995.

[8] Eugene P Wigner, *Symmetries and Reflections – Scientific Essays*, Ox Bow Press, Woodbridge, Connecticut, 1979.

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