World Changes

Thomas Kuhn and the Nature of Science

Edited by Paul Horwich

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Remarks on the History of Science and the History of Philosophy

Michael Friedman

Thomas Kuhn's *The Structure of Scientific Revolutions* (1962) forever changed our appreciation of the philosophical importance of the history of science. Reacting against what he perceived as the naively empiricist, formalist, and ahistorical conception of science articulated by the logical positivists, Kuhn presented an alternative conception of science in flux, of science driven not so much by the continuous accumulation of uncontroversial observable facts as by profoundly discontinuous conceptual revolutions in which the very foundations of old frameworks of scientific thought are replaced by radically new ones. When such a revolution occurs, we do not simply replace old "false" beliefs with new "true" beliefs; rather, we fundamentally change the system of concepts within which beliefs, whether true or false, can be meaningfully formulated in the first place. This picture of science thus driven by revolutionary forces of conceptual change has itself sparked a revolution of sorts in the philosophy of science: logical postivism has been decisively discredited, and a "new" philosophy of science concerned more with questions of historical development than with questions of logic, justification, and truth has taken its place. Whatever the fate of this new philosophy of science may be, it is clear beyond the shadow of a doubt, I think, that careful and sensitive attention to the history of science must remain absolutely central in any serious philosophical consideration of science.

I would here like to discuss an extension of this lesson of Kuhn's in a somewhat different direction. The history of science is not only important for the philosophy of science, it is also of the highest importance for a full appreciation of the history of philosophy more generally. For the fact is that many of the main developments in the historical evolution of philosophy as a subject are themselves generated by just the kind of conceptual revolutions in scientific thinking to which Kuhn has called our attention. Moreover, since our present philosophical concepts are, of course, the product of the historical evolution of the subject, it follows that careful and sensitive attention to the history of science is important not only to philosophy of science as such but also, for example, to epistemology and metaphysics as well. Here, however, I will confine myself to the relevance of the history of science to the history of philosophy.

Now I do not suppose that this claim about the relevance of conceptual revolutions in science to the history of philosophy is a controversial one. Indeed, it is now becoming more and more common for historians of philosophy, especially those concerned with the modern period, to emphasize precisely this relevance. Thus it is now a commonplace that the articulation of characteristically modern philosophy by Descartes and his successors must be viewed against the background of the scientific revolution of the sixteenth and seventeenth centuries. By emphasizing Descartes's concern to replace the Aristotelian-Scholastic natural philosophy with the "mechanical natural philosophy" of the new science, we can achieve a fuller and deeper understanding of such characteristically modern preoccupations as, for example, the distinction between primary and secondary qualities, the "veil of perception," the mind-body problem, and so on. Viewed against the background of the scientific revolution that created modern "mechanistic" natural science itself, these modern philosophical preoccupations no longer appear arbitrary and capricious, as stemming, perhaps, from otherwise unaccountable obsessions with certainty or with "mirroring reality." Instead, they can be understood as natural attempts to come to grips with a profound reorganization of the very terms in which we conceptualize ourselves and our world.

A concern with coming to terms with modern mechanistic natural science is, of course, shared by the philosophers of the modern period quite generally. What I would like to emphasize here is the philosophical importance of a more fine-grained study of the interaction between the history of science and the history of philosophy. In

particular, I think it has only seldom been appreciated that some of the most important developments within the modern tradition have been at least partly driven by fundamental conceptual problems faced by the new science. The problems I have in mind concern the foundations of the new physical dynamics and of the spatiotemporal framework within which this new dynamics is supposed to be articulated.

To get a preliminary sense of the nature of these problems, it is illuminating to contrast the basis of the new physical dynamics with that of Aristotelian-Scholastic natural philosophy. The Aristotelian universe is a finite sphere whose outermost spherical surface contains the fixed stars, and this outermost celestial sphere is uniformly rotating in a westward direction. The physical dynamics of the Aristotelian universe is governed by two principles. The principle of *natural place* governs change within the sublunary region: all elements are naturally in a state of rest in their natural places (earth, for example, is naturally at rest at the center of the finite sphere defining the universe) unless removed therefrom by some *violent* or *forced motion*; if they are so removed, however, they have a tendency to move toward their natural places in straight lines. The principle of *natural motion* governs the superlunary region: celestial spheres on which appear the various heavenly bodies (that of the moon being innermost) form a nested sequence terminating in the outermost sphere described above, and all persist in states of uniform rotational motion.

The physical dynamics of the Aristotelian universe uniquely determines its spatiotemporal framework. Temporal duration is precisely determined by the uniform rotation of the outermost celestial sphere relative to the earth, which is necessarily in a state of perfect rest at the very center of the spherical universe. Moreover, the state of rest of the earth and the state of uniform rotation of the outermost celestial sphere uniquely determine place and motion as well. There is a privileged spatial position at the center of the universe, a privileged line through the center defining the axis of rotation of the outermost celestial sphere, a privileged equatorial plane orthogonal to this axis, and a privileged state of diurnal rotation. Thus any state of translational or rotational motion is uniquely defined and absolute. (Indeed, even the notions of up-down and right-left are uniquely defined and absolute!) Another way to put the point from a modern point of view is that the physical dynamics of the Aristotelian universe admit no nontrivial spatiotemporal symmetries: spatial translations move the privileged central point; spatial rotations about any other axis than that defined by the rotation of the outermost celestial sphere change the orientation of this latter axis; spatiotemporal rotations change the state of rotation of the outermost sphere relative to the earth.

The physical dynamics of the new mechanistic science, by contrast, is based on the law of inertia. The dichotomy between sublunary and superlunary realms is abolished, together with the correlative distinction between natural spatial position in the sublunary region and natural uniform rotational motion in the superlunary region. Instead, the natural state of *all* matter in the universe is one of uniform rectilinear translation: every body in the universe persists in its state of uniform rectilinear motion unless some *force* compels it to deviate from this natural state. This means that the space of the new universe must be infinite Euclidean space, for an unimpeded body will naturally progress along a Euclidean straight line to infinity. It also means that temporal duration in the new universe is measured by this same inertial motion: equal temporal intervals are those during which an inertially moving body traverses equal distances. The basis of the new physical dynamics is thus apparently given by the very simplest elements of Euclidean geometry. Hidden behind this simplicity, however, lies a veritable Pandora's box of fundamental problems.

For how do we apply this framework of infinite Euclidean space and inertially measured time to the nature with which we are empirically confronted? Unlike the rotational motion of the outermost celestial sphere in the Aristotelian universe, we are not in fact given any examples of actual inertial motion at all: all the motions we observe are cases of noninertial motion. So we need to supplement our physical dynamics with a theory of *force* or deviation from the natural inertial state. We need to do this, that is, before we can empirically define the time of the new dynamics in the first place. Moreover, even if we were given actual cases of inertial motion, we would still not be able empirically to determine the notion of place. Nor would it be clear how to determine the notion of change of place over time. Again unlike the finite spherical universe of Aristotelian natural philosophy, infinite Euclidean space has no distinguished

positions; in modern terms, any spatial translation is a symmetry of the spatial structure (as are spatial rotations and spatiotemporal rotations of course). It is therefore unclear how change of place or motion is itself to be empirically defined. It follows that the empirical meaning of the law of inertia is also radically unclear: relative to *what* do naturally moving bodies move rectilinearly and uniformly?

I suggest that some of the principal stages in the evolution of the modern philosophical tradition can be understood as successive attempts to come to terms with this fundamental problem lying at the basis of the new physical dynamics. And doing this will, I believe, result in a conception of the evolution of modern philosophy that is more illuminating than the conventional picture of a succession of largely futile attempts to solve the problem of skepticism about the external world.

Thus, for example, Descartes, who is clearly followed in this regard by Spinoza, conceives of the new physical dynamics as resting on a purely geometrical basis. Inertial motion along a Euclidean straight line is the dominant idea, and deviations from this inertial state are initially conceived in the simplest possible geometrical terms, that is, as perfect reflections or mere changes of direction on impact (this is especially clear in axiom 2 following lemma 3 in Part 2 of Spinoza's *Ethics*). Bodies persist along Euclidean straight lines until they come into contact with one another, whereupon they change their direction of motion but preserve their quantity of motion. We thereby obtain the purely geometrical picture of nature characteristic of "mechanical philosophy": all natural change is to be understood in terms of the sizes, figures, and motions of the parts of matter. This geometrical picture underlies some of the most basic ideas of Descartes's and Spinoza's philosophy, for example, the idea that the substance or essence of material things consists of extension alone (that is, of three-dimensional Euclidean space), the correlative doctrine that the Scholastic notion of substance or "substantial form" must be entirely abandoned, the idea that nature unfolds with purely geometrical necessity.

Yet as is well known, this Cartesian version of the mechanical philosophy fails to articulate an adequate physical dynamics. First, the above conception of deviation from the inertial state based on pure geometrical reflection works only for perfectly elastic impact viewed from the center-of-mass frame of the interaction. Notoriously, Descartes completely failed in attempting to extend the laws of impact to the general case. Indeed, without any adequate conception of mass, it was even impossible to specify the conditions under which geometrical reflection gives a correct description of impact. (Descartes understands quantity of motion as "size" multiplied by speed.) More generally, however, the Cartesian mechanical philosophy completely fails to articulate coherently the spatiotemporal framework within which the motions it describes are to take place. Descartes defines motion as change of position with respect to the "surrounding bodies," and this leaves us with no consistent conception of motion at all: the same body may be moving with respect to some surrounding bodies and at rest with respect to others; the same body may even be changing its state of motion (moving noninertially) with respect to some surrounding bodies and moving inertially with respect to others; and so on. Finally, even if we ignore both of the above problems, Cartesian mechanical philosophy fails to indicate how time is to be empirically defined in this new universe, for we are so far entirely unable to determine whether the motions we actually observe (such as the motions of the heavenly bodies, for example) are uniform.

Some of the key philosophical moves made by Leibniz can then be understood in terms of his quite deep and penetrating insight into these fundamental problems faced by Cartesian mechanical philosophy. Leibniz was convinced of the inadequacy of a purely geometrical physical dynamics from at least 1671 ("The Theory of Abstract Motion"), but the decisive step was made in his "Brief Demonstration of a Notable Error of Descartes and Others Concerning a Natural Law" of 1686. Following Huygens's general theory of perfectly elastic impact, Leibniz sees that the basic dynamical quantity governing such impact is not the Cartesian quantity of motion but rather "living force" or *vis viva* (mv^2, twice our kinetic energy), that is, living force, or *vis viva* is the operative conserved quantity. Moreover, Leibniz sees that this living force is not a purely geometrical/kinematic quantity: it cannot be constructed purely from the sizes, figures, and motions of the interacting bodies in question. Hence mechanics itself cannot be based on purely geometrical/kinematic concepts and requires a more basic conception of *active force*.

This insight in turn leads Leibniz to a thoroughgoing reevaluation of Cartesian and Spinozistic philosophy. First, Leibniz argues that the substance or essence of material beings does not consist of pure geometrical extension but rather of precisely active force. And this means that Leibniz no longer defines the notion of substance purely in terms of independent existence (as do Descartes and especially Spinoza) but rather reverts to the more Aristotelian idea of substance as that which persists through time and controls the temporal evolution of a thing (as the substantial form of an acorn determines its evolution into an oak). Leibniz, in other words, sees that temporal evolution has been entirely left out of Cartesian mechanical philosophy and seeks to restore its primary place. And in seeking thus to restore the primacy of temporal evolution, Leibniz argues that Descartes's and Spinoza's criticisms of Aristotelian-Scholastic natural philosophy has been pressed too far: substantial forms and therefore an appeal to final causation enter into the very foundations of the new physical dynamics itself. As a result, Leibniz also argues that purely geometrical necessity cannot underly the actual laws of nature; a kind of contingency closely tied to final causes and teleological considerations is in fact essential to the actual world.

I am suggesting, then, that this attempt by Leibniz to reconcile the new mechanistic science with elements of the older Aristotelian-Scholastic philosophy is itself fueled by his discovery of the fundamental dynamic importance of *vis viva* or active force. This comes out very clearly in the "Discourse on Metaphysics" of 1786, where, immediately after a summary of his "Brief Demonstration" of the errors of Descartes in section 17, he appends section 18 on the metaphysical importance of active force. This section is worth quoting in full:

> This consideration of the force, distinguished from the quantity of motion is of importance, not only in physics and mechanics for finding the real laws of nature and the principles of motion, and even for correcting many practical errors which have crept into the writings of certain able mathematicians, but also in metaphysics it is of importance for the better understanding of principles. Because motion, if we regard only its exact and formal meaning, that is, change of place, is not something entirely real, and when several bodies change their places reciprocally, it is not possible to determine by considering the bodies alone to which among them movement or repose is to be attributed, as I could demonstrate geometrically, if I wished to stop for it now. But the force, or the proximate cause of these changes is something more real, and there are sufficient grounds for attributing it to one body rather than another, and it is only through this latter investigation that we

can determine to which one the movement must appertain. Now this force is something different from size, from form or from motion, and it can be seen from this consideration that the whole meaning of a body is not exhausted in its extension together with its modifications as our moderns persuade themselves. We are therefore obliged to restore certain beings or forms which they have banished. It appears more and more clear that although all the particular phenomena of nature can be explained mathematically or mechanically by those who understand them, yet nevertheless, the general principles of corporeal nature and even of mechanics are metaphysical rather than geometrical, and belong rather to certain indivisible forms or natures as the causes of the appearances, than to the corporeal bulk or to extension. This reflection is able to reconcile the mechanical philosophy of the moderns with the circumspection of those intelligent and well-meaning persons who, with a certain justice, fear that we are becoming too far removed from immaterial beings and that we are thus prejudicing piety. (G. R. Montgomery translation)

Leibniz's insight into the foundations of the new physical dynamics thus provides him with just the room he needs to introduce some of his most characteristic philosophical doctrines.

The above passage from section 18 of the "Discourse on Metaphysics" also illustrates another characteristic concern of Leibniz's, a concern for the metaphysical reality of space and motion. As the correspondence with Clarke makes especially clear, Leibniz sees that the existence of nontrivial symmetries makes the spatiotemporal structure of the new science inherently problematic; for it now becomes radically unclear how the notions of spatial position and change of spatial position are to be applied to our experience of nature. Leibniz also sees clearly that the Cartesian definition of motion as change of position with respect to the surrounding bodies is inconsistent with the law of inertia. Unfortunately, however, although Leibniz clearly understands the problem, it does not appear that he ever arrives at a satisfactory solution, for he never makes it clear exactly *how* his notion of active force enables us to determine, in a system of relatively moving bodies, "to which among them movement or repose is to be attributed." He never explains, for example, how the notion of *vis viva* could possibly help us in deciding the issue of heliocentrism. It is no wonder, then, that Leibniz ultimately consigns space, time, and motion to the realm of mere phenomenal appearances, manifestations of a more basic and essentially nonspatiotemporal reality characterized solely in terms of nongeometrical or metaphysical notions of substance and active force.

Just as some of the key philosophical moves of Leibniz can be understood as attempts to resolve the fundamental problems of physical dynamics bequeathed to him by Descartes, some of the central elements of the Kantian philosophy can be understood as attempts to resolve the above problems left open by Leibniz. From the time of his earliest published work of 1747, *Thoughts on the True Estimation of Living Forces,* Kant expresses the Leibnizean conviction that the new physical dynamics must rest on a metaphysical foundation involving the central notions of substance and active force, to which Kant adds the expressly anti-Leibnizean category of interaction or dynamical community. Yet as this last point suggests, Kant is also convinced from the time of his earliest work that the new physical dynamics has been finally correctly formulated by Newton: Kant consistently takes universal gravitation (rather than the conservation of *vis viva*) as his paradigm of physical law. I believe that much of Kant's philosophy can then be understood as an attempt to synthesize Leibniz's metaphysics with Newton's physics.

Kant's first move (in the 1747 essay) is to replace Leibniz's conception of living force with Newton's conception of *impressed force*: force is not an internal property of a single body by which that body determines the temporal evolution of its own future state; rather, force is an action of one body on another essentially distinct body by which the first body changes the state of the second body. Far from expressing the state of motion of a single body, force has nothing at all to do with the state of motion of the body that exerts it. Force expresses a relationship of *real interaction* between two bodies by which one body *changes* the state of motion of the other. Kant sees, therefore, that Newton's conception of force completely overturns Leibniz's monadology and system of preestablished harmony. This is especially obvious if one accepts, as Kant consistently does, Newtonian gravitation, understood as a genuine action-at-a-distance force. (By contrast, this full Newtonian conception of force is necessarily precluded for Leibniz, for a system in which *vis viva* is conserved is a system in which there is zero potential energy and thus no action-at-a-distance forces.)

Kant's next move (in the "New System of Motion and Rest" of 1758) is to grasp the fundamental importance of Newton's third law of motion: the equality of action and reaction. Since every change of the quantity of motion of one body is counterbalanced by a corresponding change in the quantity of motion of a second body, where the first body is the cause of the change of motion of the second body and vice versa, the third law of motion expresses a dynamical community or real interaction of material substances. (Here quantity of motion is, of course, understood in the Newtonian sense of *momentum* or mass multiplied by velocity.) Further and even more significant, Kant sees that this same third law of motion allows us to give genuine empirical meaning to the notion of motion itself: the true motions in a system of interacting bodies are just those described in the *center-of-mass frame* of the system, that is, exactly those motions that make the third law of motion true. In this way Kant grasps the dynamical significance of the Newtonian conception of mass and sees in particular that the problem of empirically applying the notion of motion in our new spatiotemporal framework can now be solved by regarding Newton's laws of motion as, in effect, amounting to a *definition* of the concept of true (or absolute) motion. (In modern terms, true accelerations are those described in an inertial frame of reference, and an inertial frame of reference is one in which the laws of motion are satisfied.)

Kant's final move is to put the above ideas together in a fundamental reinterpretation of the argument of Newton's *Philosphiae Naturalis Principia Mathematica.* This is depicted most clearly in the *Metaphysical Foundations of Natural Science* of 1786. In particular, Kant understands the argument of the *Principia* not, as Newton does, as an argument by which the true (or absolute) motions in the solar system are *found* or *discovered* but rather as a procedure by which the notion of true (or absolute) motion is given objective empirical meaning in the first place. For what Newton actually does in the *Principia* is to apply his laws of motion to the observed, so far merely relative or apparent motions in the solar system in order to derive therefrom the law of universal gravitation *and at the same time rigorously to determine the center-of-mass frame of the solar system wherein the true motions in the solar system can be first rigorously described.* This center-of-mass frame turns out to be centered sometimes within and sometimes without

the surface of the sun but never very far from the sun's center, and this is the precise sense in which the heliocentric system is closer to the truth. By contrast, prior to the argument of *Principia* not only are we unable to decide the question of heliocentrism, but the very question itself lacks all objective meaning. In this way, then, Kant understands Newton's conception of force, expressed by Newton's laws of motion and instantiated by universal gravitation, as finally providing a satisfactory basis for the new physical dynamics. Thus, after our determination of a privileged center-of-mass frame via Newton's theory of universal gravitation, we are also in a position rigorously to determine the precise degree of uniformity in the orbital motions of the heavenly bodies.

Kant continues to insist, however, that the new physical dynamics requires a metaphysical foundation, for the Newtonian laws of motion must themselves be philosophically grounded: neither an empirical/inductive account nor a purely postulational/hypothetical account is ultimately satisfactory. The basic idea of this philophical grounding has already been indicated above: the laws of motion do not express facts, as it were, about a notion of true motion antecedently well defined; rather, they constitute the sole conditions under which the notion of true (or absolute) motion has objective empirical meaning in the first place. Hence the laws of motion are true a priori, for they represent the necessary conditions for the new physical dynamics to be applicable to our actual experience of nature. Moreover, since the new physical dynamics itself constitutes a necessary condition for a genuinely objective experience of nature, it follows for Kant that the laws of motion are ultimately grounded in the a priori conditions of the possibility of experience. In particular, Newton's concepts of mass, force, and interaction are ultimately grounded in the a priori categories of substance, causality, and community.

Kant thus ends up by turning Leibniz's conception of the relationship between physics and metaphysics on its head. Metaphysical concepts—such as substance, causality, and community—no longer describe a nonspatiotemporal realm somehow existing "behind" the spatiotemporal phenomena of nature. Rather, the entire point and function of such concepts is precisely to ground the sole spatiotemporal framework within which the phenomena of nature can be empirically and objectively described. In Kantian terms, the categories acquire objective meaning only by being spatiotemporally *schematized.* By the same token, however, our conception of the special a priori status of metaphysical concepts is also fundamentally reinterpreted. Metaphysics is a priori, not because it shares in the geometrical necessity of mathematical reasoning, nor because it describes a realm of nonspatiotemporal entities accessible to pure reason alone, but rather because it describes the a priori conditions that make objective *empirical* thinking possible in the first place. That is, metaphysics articulates the a priori conditions of the possibility of experience.

Now the above account of a particular evolution of thought from Descartes and Spinoza through Leibniz and finally to Kant is, of course, only the briefest sketch, and a full understanding of this evolution would certainly require a much more detailed discussion of both scientific and philosophical developments. I hope that I have said enough, however, to indicate the philosophical interest and importance of this kind of approach. One thing already clear, for example, is that, contrary to the opinion of some contemporary historical writers, the philosophers of the modern tradition are not best understood as attempting to stand outside the new science so as to show, from some mysterious point outside of science itself, that our scientific knowledge somehow "mirrors" an independently existing reality. Rather, the philosophers I have been considering start from the *fact* of modern scientific knowledge as a given fixed point, as it were. Their problem is not so much to justify this knowledge from some "higher" standpoint as to articulate the new *philosophical* conceptions that are forced upon us by the new science. Kant puts the point admirably in section 40 of the *Prolegomena:*

> Pure mathematics and pure science of nature had, for their own safety and certainty, no need for such a deduction as we have made of both. For the former rests upon its own evidence, and the latter (though sprung from pure sources of the understanding) upon experience and its thorough confirmation. The pure science of nature cannot altogether refuse and dispense with the testimony of experience; because with all its certainty it can never, as philosophy, imitate mathematics. Both sciences, therefore, stood in need of this inquiry, not for themselves, but for the sake of another science: metaphysics. (L. W. Beck translation)

Kant's inquiry into the a priori conditions of the possibility of mathematics and natural science is not intended to provide an otherwise missing justification for these sciences but rather to establish a reorganization and reinterpretation of metaphysics itself.

I believe that this same kind of approach—with the same philosophical moral—can be fruitfully applied to the evolution of contemporary philosophical concepts and problems as well. In particular, it can be fruitfully applied in coming to a more adequate understanding of the development of twentieth-century logical positivism. These thinkers too are best understood as attempting philosophically to come to terms with the profound conceptual revolutions that initiated twentieth-century science. These thinkers too should be seen not as attempting to justify twentieth-century science from some sterile and futile external vantage point but rather as once again refashioning the basic concepts and principles of philosophy so as to accommodate and comprehend the new scientific developments. That is, their aim is not to justify twentieth-century science from some supposed "higher" standpoint but rather to provide a *rational reconstruction* of that science and to find thereby a new, nonmetaphysical task for philosophy.

More specifically, the logical positivists were attempting to respond philosophically to fundamental conceptual revolutions in both mathematics and physics. The relevant mathematical developments are epitomized by the profound shifts in nineteenth-century thinking resulting in Hilbert's beautiful axiomatic treatment of Euclidean geometry on the one hand and Frege's complete delineation of modern quantificational logic on the other. The relevant physical developments are epitomized by Einstein's theory of relativity, which in turn, of course, rests on nineteenth-century work on non-Euclidean geometries. These two sets of developments imply that Kant's conception of synthetic a priori knowledge, with its corresponding picture of an a priori foundation for scientific thought based on a spatiotemporal schematization of the categories, is no longer tenable. For the above mathematical developments destroy Kant's basic opposition between intuitions and concepts, sensibility and understanding: the mathematical structures in question can now be represented purely logically or conceptually with no reliance whatsoever on spatiotemporal intuition. And the above physical developments destroy the idea that there is a *fixed* a priori structure—consisting of the spatiotemporal framework of Euclidean geometry and Newtonian dynamics—lying at the basis of our empirical science of nature.

It is important to see, however, that the logical positivists did not react to these revolutionary developments by adopting a naively empiricist conception of science. They did not, for example, conceive the spatiotemporal framework of physical dynamics as determined purely empirically. On the contrary, they continue to advocate a *modified* Kantian position according to which there is a fundamental distinction between the spatiotemporal framework of physical dynamics and the empirical laws formulated within this framework. Moreover, they continue to agree with Kant that a prior articulation of a spatiotemporal dynamical framework is a necessary precondition for the empirical meaningfulness of our subsequent description of nature. In this sense, the spatiotemporal framework of physical dynamics can still be conceived of as a priori. Yet the a priori has indeed lost its fixed or absolute status: it can change and develop with the progress of science, and it varies from the context of one scientific theory to another (Euclidean geometry is a priori in the context of Newtonian physics, but Riemannian geometry is a priori in the context of the general theory of relativity). As Reichenbach put it in his *Theory of Relativity and A Priori Knowledge* of 1920, we must distinguish two meanings of the Kantian a priori: the first involves unrevisability and the idea of absolute fixity for all time; the second means "constitutive of the concept of the object of knowledge." In acknowledging the profound philosophical importance of Einstein's theory of relativity, we do not abandon the Kantian a priori altogether. We simply discard the first meaning while continuing to emphasize the crucial scientific role of the second. What relativity shows us, in fact, is that the notion of apriority must itself be relativized.

At the same time, however, the notion of apriority must also be *logicized* or incorporated into the new logical framework due to Frege and Russell. For Frege and Russell have shown us how to dispense with the Kantian synthetic a priori in *pure* mathematics by demonstrating how to embed pure mathematics within the new logic. In this way mathematics retains its a priori status but now becomes purely analytic. (Again, however, I emphasize that a naively empiricist conception of mathematics is simply out of the question for the logical positivists.) Moreover, this achievement of Frege's and Russell's makes it clear that the new mathematical logic must provide the ultimate framework for rigorous philosophical thinking. But it is not yet clear how Frege's and Russell's new logic is related to the relativized notion of apriority lying at the basis of *physical* science. We cannot simply maintain, for example, that the spatiotemporal framework of physical dynamics is itself a part of logic! Once again, therefore, the attempt philosophically to comprehend the totality of the new scientific developments generates fundamental philosophical problems.

The logical positivists were initially tempted to explain the relativized a priori lying at the basis of physical dynamics on the model of Hilbert's axiomatization of geometry. This tendency is especially clear in the work of Schlick and Reichenbach. The idea is that the axioms of geometry *implicitly define* the basic concepts of that science, and this is why geometry is a priori—*analytic,* a priori of course. Points, lines, and planes are any objects that make the axioms of geometry come out true. Thus these axioms do not assert facts, as it were, about some independently given objects. Moreover, if we switch to a different system of geometry, we implicitly define a different system of objects, and so there is no real question of which system of geometry is "true." On the contrary, the choice among such different systems is a mere pragmatic matter of convenience and simplicity. In this sense, it is purely conventional.

Yet this Hilbertian account of the relativized a priori is incompatible with the logicist conception of analyticity due to Frege and Russell. The logicist conception demands *explicit definitions* of basic concepts in purely logical terms, and from this point of view, mere implicit definitions, strictly speaking, cannot count as specifications of meaning at all. Moreover, the method of implicit definition really amounts to nothing more than providing a perspicuous axiomatization of a science. In principle, then, it can be carried out for any science whatsoever, whether the science in question is formal and a priori or empirical and a posteriori. The method of implicit definition is therefore quite incapable of delineating the fundamental distinction between the a priori and the empirical, the analytic and the synthetic, which, I suggest, is of absolutely central concern to the logical positivists.

In any case, however, Carnap, who is clearly the deepest as well as the most rigorous of the positivists, consistently rejects the method of implicit definition. For example, in the *Aufbau* (1928) he attempts to delineate the formal or a priori elements of empirical knowledge by means of a hierarchy of explicit definitions framed within Russellian type theory. The idea is to characterize the content of all empirical concepts by means of what Carnap calls "purely structural definite descriptions." The visual sense modality, for example, is the one and only one sense modality having exactly five dimensions (two of spatial position and three of color quality). Thus each empirical relation is defined or characterized by its purely formal or logical properties, and the empirical or a posteriori content of scientific knowledge is represented by the assertion that there *exist* such relations. In this way Carnap hopes to articulate a distinction between the a priori and the empirical within a conception of logic congenial to Frege's and Russell's logicism. Unfortunately, this attempt ultimately fails for technical reasons—roughly, because even the statement that there *exist* such and such formally characterized relations will turn out to be a truth (or falsehood) of set theory.

Carnap, in his next great work, the *Logical Syntax of Language* of 1934, a work that I take to represent both the high point and the denouement of logical positivism, attempts a radically new approach to the problem. Here Carnap reacts to the important advances in logic and the foundations of mathematics made since the collapse of the original logicist program, specifically, the development of axiomatic set theory, the development of constructivist and intuitionist approaches, and most important, the development of Hilbert's conception of metamathematics. Carnap reponds to these developments by relativizing the logicist conception of logic itself. There is no longer a privileged framework of logic, given by Frege's *Begriffsschrift* or Russellian type theory, for example. Rather, *any* formally or syntactically specified system of formation and transformation rules defines a perfectly legitimate logical system or *linguistic framework* (this, of course, is Carnap's famous principle of tolerance). Yet although there is thus no single privileged logical framework at the level of the *object language,* there is still a privileged framework at the level of the *metalanguage,* namely, the system of logical syntax itself wherein we precisely and purely syntactically describe the infinite multiplicity of

possible object-language logical frameworks. This system of logical syntax is, as Gödel's fundamental researches have shown, essentially equivalent to elementary arithmetic, and it is within this relatively neutral and uncontroversial framework that we characterize and specify the logical structure of all richer and more controversial frameworks, for example, the framework of classical mathematical physics.

The ultimate goal of Carnap's program in *Logical Syntax* is then to delineate, for any possible object-language linguistic framework, a purely formal or syntactic distinction between *analytic* and *synthetic* sentences of that framework—a distinction that he hopes will capture the informal and intuitive distinction between a priori and a posteriori or logical and empirical knowledge. In particular, he hopes to show that in a suitable axiomatization of classical mathematical physics, both the purely mathematical part (consisting essentially of real analysis) and the geometric/kinematic part (consisting of the basis of spatiotemporal physical dynamics) will turn out to be analytic, whereas Maxwell's equations, for example, will turn out to be synthetic. In this way Carnap hopes finally to integrate the logicist conception of analyticity due to Frege and Russell (essentially modified under the direct influence of Hilbert) with the relativized a priori lying at the basis of physical science, which, as we have seen derives ultimately from Kantian and neo-Kantian ideas.

Once again, however, Carnap's ingenious construction fails for technical reasons. Roughly, Carnap's conception of analyticity is such that all the truths of classical arithmetic should count as analytic. Yet, as we know, Gödel's incompleteness theorem shows that the notion of arithmetical truth cannot be specified within elementary arithmetic: an essentially richer and more controversial framework is therefore required at the level of the metalanguage. But this means that there is no privileged neutral and uncontroversial meta framework within which the logical syntax of all possible object-language frameworks can be described. Carnap's attempt to relativize the logicist conception of analyticity ultimately collapses in on itself. It is this situation that forms the immediate background of Tarski's articulation of the semantic concept of truth and also, I believe, of Quine's thoroughgoing rejection of any notion of apriority. It is here, I believe, that the ultimate failure of logical positivism must be located.

If this is correct, however, then my attempt briefly to sketch a certain line of historical interaction between philosophy and the sciences has resulted in a rather surprising dialectical twist. For taking the interaction between the history of science and the history of philosophy seriously has led us to a point where it now appears that the currently popular diagnosis of the failure of logical positivism (a diagnosis due largely to the work of Kuhn and his followers) is fundamentally misleading. Indeed, it now appears that the underlying philosophical motivations of the logical positivists cannot happily be described as either naively empiricist, naively formalist, or naively ahistorical. Their empiricism was qualified by, and, I believe, entirely subordinated to, an essentially Kantian preoccupation with the a priori framework within which alone empirical claims have a definite meaning in the first place. Their formalism rested on the idea, which itself evolved naturally from the important developments taking place in the formal sciences themselves, that this a priori framework for empirical knowledge must be specified within the radically new conception of formal logic due to Frege and Russell. Finally, although the logical positivists' preoccupation with the a priori did indeed thereby preclude them from using the history of science as a philosophical tool, this did not prevent them from recognizing the profound philosophical significance of conceptual revolutions in science. On the contrary, their effort to articulate a coherent conception of the *relativized* a priori must, I think, count as the most rigorous attempt we have yet seen philosophically to come to terms with precisely such conceptual revolutions. Of course, as we have also seen, this heroic attempt of the logical positivists was in the end a failure. Yet I do not myself think that we will ever progress beyond this point until we possess a fuller appreciation of the historical evolution of our own philosophical predicament. And this means, as I have tried to emphasize throughout, that we must attend more closely to the history of science, the history of philosophy, *and* to the essential interaction between them.

Rationality and Paradigm Change in Science

Ernan McMullin

As we look back at the first responses of philosophers of science to Thomas Kuhn's classic *The Structure of Scientific Revolutions*, we are struck by their near unanimity toward the challenge that the book posed to the rationality of science. Kuhn's account of the paradigm changes that for him constituted scientific revolutions was taken by many to undermine the rationality of the scientific process itself. The metaphors of conversion and gestalt switch, the insistence that defenders of rival paradigms must inevitably fail to make contact with each other's viewpoints, struck those philosophical readers whose expectations were formed by later logical empiricism as a deliberate rejection of the basic requirements of effective reason giving in the natural sciences.

Kuhn responded to this reading of *SSR* in a lengthy Postscript to the second edition of his book in 1970 and in the reflective essay "Objectivity, Value Judgement, and Theory Choice" in 1977.[1] He labored to show that the implications of his new account of scientific change for the *rationality* of that change were far less radical than his critics were taking them to be. But his disavowals were not, in the main, taken as seriously as he had hoped they would be; the echoes of the rhetoric of *SSR* still lingered in people's minds. It seems worth returning to this ground, familiar though it may seem, in order to assess just what Kuhn *did* have to say about how paradigm change comes about in science. We will see that the radical thrust of his account of science was indeed not directed so much against the