Kant, Kuhn, And The Rationality Of Science
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Source: *Philosophy of Science*, Vol. 69, No. 2 (June 2002), pp. 171-190
Published by: The University of Chicago Press on behalf of the Philosophy of Science Association
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Accessed: 08/06/2011 14:28

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Kant, Kuhn, and the Rationality of Science*

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This paper considers the evolution of the problem of scientific rationality from Kant through Carnap to Kuhn. I argue for a relativized and historicized version of the original Kantian conception of scientific a priori principles and examine the way in which these principles change and develop across revolutionary paradigm shifts. The distinctively philosophical enterprise of reflecting upon and contextualizing such principles is then seen to play a key role in making possible rational intersubjective communication between otherwise incommensurable paradigms.

In the Introduction to the *Critique of Pure Reason* Kant formulates what he calls "the general problem of pure reason," namely, "How are synthetic a priori judgements possible?" Kant explains that this general problem involves two more specific questions about particular a priori sciences: "How is pure mathematics possible?" and "How is pure natural science possible?"—where the first concerns, above all, the possibility of Euclidean geometry, and the second concerns the possibility of fundamental laws of Newtonian mechanics such as conservation of mass, inertia, and the equality of action and reaction. In answering these questions Kant develops what he calls a "transcendental" philosophical theory of our human cognitive faculties—in terms of "forms of sensible intuition" and "pure concepts" or "categories" of rational thought. These cognitive

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*This paper first appeared in Michael Heidelberger and Friedrich Stadler (eds.) *History of Philosophy of Science: New Trends and Perspectives* (Dordrecht: Kluwer, 2002) © Kluwer Academic Publishers. It appears here with the permission of the editors and of Kluwer Academic Publishers. It also reproduces some passages from my *Dynamics of Reason: The 1999 Kant Lectures at Stanford University* (Stanford: CSLI Publications, 2001).

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Philosophy of Science, 69 (June 2002) pp. 171–190. 0031-8248/2002/6902/0001$10.00

structures are taken to describe a fixed and absolutely universal rationality—common to all human beings at all times and in all places—and thereby to explain the sense in which mathematical natural science (the mathematical physics of Newton) represents a model or exemplar of such rationality.[1]

In the current state of the sciences, however, we no longer believe that Kant's specific examples of synthetic a priori knowledge are even true, much less that they are a priori and necessarily true. For the Einsteinian revolution in physics has resulted in both an essentially non-Newtonian conception of space, time, and motion, in which the Newtonian laws of mechanics are no longer universally valid, and the application to nature of a non-Euclidean geometry of variable curvature, wherein bodies affected only by gravitation follow straightest possible paths or geodesics. And this has led to a situation, in turn, in which we are no longer convinced that there are any real examples of scientific a priori knowledge at all. If Euclidean geometry, at one time the very model of rational or a priori knowledge of nature, can be empirically revised, so the argument goes, then everything is in principle empirically revisable. Our reasons for adopting one or another system of geometry or mechanics (or, indeed, of mathematics more generally or of logic) are at bottom of the very same kind as the purely empirical considerations that support any other part of our total theory of nature. We are left with a strongly holistic form of empiricism or naturalism in which the very distinction between rational and empirical components of our total system of scientific knowledge must itself be given up.

This kind of strongly holistic picture of knowledge is most closely identified with the work of W. V. Quine. Our system of knowledge, in Quine's well-known figure, should be viewed as a vast web of interconnected beliefs on which experience or sensory input impinges only along the periphery. When faced with a "recalcitrant experience" standing in conflict with our system of beliefs we then have a choice of where to make revisions. These can be made relatively close to the periphery of the system (in which case

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[1] The "general problem of pure reason," along with its two more specific sub-problems, is formulated in § VI of the Introduction to the *Critique of Pure Reason* at B19–24. Sections V and VI, which culminate in the three questions "How is pure mathematics possible?", "How is pure natural science possible?", and "How is metaphysics as a science possible?", are added to the second (1787) edition of the *Critique* and clearly follow the structure of the 1783 *Prolegomena to Any Future Metaphysics,* which was intended to clarify the first (1781) edition. This way of framing the general problem of pure reason also clearly reflects the increasing emphasis on the question of pure natural science found in the *Metaphysical Foundations of Natural Science* (1786). For an extended discussion of Kant's theory of pure natural science and its relation to Newtonian physics see Friedman, *Kant and the Exact Sciences* (Cambridge, MA: Harvard University Press, 1992), especially chapters 3 and 4.

we make a change in a relatively low-level part of natural science), but they can also—when the conflict is particularly acute and persistent, for example—affect the most abstract and general parts of science, including even the truths of logic and mathematics, lying at the center of our system of beliefs. To be sure, such high-level beliefs at the center of our system are relatively entrenched, in that we are relatively reluctant to revise them or to give them up (as we once were in the case of Euclidean geometry, for example). Nevertheless, and this is the crucial point, absolutely none of our beliefs is forever "immune to revision" in light of experience:

> The totality of our so-called knowledge or beliefs, from the most casual matters of geography and history to the profoundest laws of atomic physics or even of pure mathematics and logic, is a man-made fabric which impinges on experience only along the edges. Or, to change the figure, total science is like a field of force whose boundary conditions are experience. A conflict with experience at the periphery occasions readjustments in the interior of the field. . . . But the total field is so underdetermined by its boundary conditions, experience, that there is much latitude of choice as to what statements to reëvaluate in the light of any single contrary experience. . . .
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> If this view is right . . . it becomes folly to seek a boundary between synthetic statements, which hold contingently on experience, and analytic statements, which hold come what may. Any statement can be held true come what may, if we make drastic enough adjustments elsewhere in the system. Even a statement very close to the periphery can be held true in the face of recalcitrant experience by pleading hallucination or by amending certain statements of the kind called logical laws. Conversely, by the same token, no statement is immune to revision. Revision even of the logical law of the excluded middle has been proposed as a means of simplifying quantum mechanics; and what difference is there in principle between such a shift and the shift whereby Kepler superseded Ptolemy, or Einstein Newton, or Darwin Aristotle?[2]

As the last sentence makes clear, examples of revolutionary transitions in our scientific knowledge, and, in particular, that of the Einsteinian revolution in geometry and mechanics, constitute a very important part of the motivations for this view.

Yet it is important to see that such a strongly anti-apriorist conception of scientific knowledge was by no means prevalent during the late nine-

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[2] From the first two paragraphs of § 6, entitled "Empiricism without the Dogmas," of "Two Dogmas of Empiricism," *Philosophical Review* 60 (1951): 20–43; reprinted in *From a Logical Point of View* (New York: Harper, 1953), pp. 42–43.

teenth and early twentieth centuries—during the very period, that is, when the great revolutions in geometry and mechanics we now associate with the work of Einstein were actually taking place. If we begin with the key figures in the philosophy of non-Euclidean geometry, for example, whereas it is certainly true that Hermann von Helmholtz viewed the choice between Euclidean and non-Euclidean geometries as an empirical one, he also suggested that the more general structure of space common to both Euclidean and non-Euclidean systems (that of constant curvature or what Helmholtz called "free mobility") was a necessary presupposition of all spatial measurement and thus a "transcendental" form of our spatial intuition in the sense of Kant. And, partly on this basis, Henri Poincaré went even further. Although no particular geometry—neither Euclidean nor non-Euclidean—is an a priori condition of our spatial intuition, it does not follow that the choice between them, as Helmholtz thought, is an empirical one. For there remains an irreducible gulf between our crude and approximate sensory experience and our precise mathematical descriptions of nature. Establishing one or another system of geometry, Poincaré argued, therefore requires a free choice, a *convention* of our own—based, in the end, on the greater mathematical simplicity of the Euclidean system.[3]

Nor was such a strongly anti-apriorist conception of scientific knowledge adopted by the first scientific thinkers enthusiastically to embrace Einstein's new theory. These thinkers, the logical empiricists, of course rejected the synthetic a priori in Kant's original form. They rejected the idea of absolutely fixed and unrevisable a priori principles built, once and for all, into our fundamental cognitive capacities. In place of an holistic empiricism, however, they instead adopted a radically new conception of the a priori. Perhaps the clearest articulation of the logical empiricists's new view was provided by Hans Reichenbach in his first book, *The Theory of Relativity and a Priori Knowledge,* published in 1920.[4] Reichenbach distinguishes two meanings of the Kantian a priori: necessary and unrevisable, fixed for all time, on the one hand, and "constitutive of the concept of the object of [scientific] knowledge," on the other. Reichenbach argues,

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[3] For extended discussion of Helmholtz and Poincaré see my "Helmholtz's *Zeichentheorie* and Schlick's *Allgemeine Erkenntnislehre,*" *Philosophical Topics* 25 (1997): 19–50; "Geometry, Construction, and Intuition in Kant and His Successors," in Gila Scher and Richard Tieszen (eds.), *Between Logic and Intuition* (Cambridge: Cambridge University Press, 2000); and *Reconsidering Logical Positivism* (Cambridge: Cambridge University Press, 1999), chapter 4.

[4] Reichenbach, *Relativitätstheorie und Erkenntnis Apriori* (Berlin: Springer, 1920); translated as *The Theory of Relativity and a Priori Knowledge* (Los Angeles: University of California Press, 1965). The distinction between the two meanings of the Kantian a priori described in the next sentence occurs in chapter 5.

on this basis, that the great lesson of the theory of relativity is that the former meaning must be dropped while the latter must be retained. Relativity theory involves a priori constitutive principles as necessary presuppositions of its properly empirical claims, just as much as did Newtonian physics, but these principles have essentially changed in the transition from the latter theory to the former: whereas Euclidean geometry is indeed constitutively a priori in the context of Newtonian physics, for example, only *infinitesimally* Euclidean geometry is constitutively a priori in the context of general relativity. What we end up with, in this tradition, is thus a relativized and dynamical conception of a priori mathematical-physical principles, which change and develop along with the development of the mathematical and physical sciences themselves, but which nevertheless retain the characteristically Kantian constitutive function of making the empirical natural knowledge thereby structured and framed by such principles first possible.

Rudolf Carnap's philosophy of formal languages or linguistic frameworks, first developed in his *Logical Syntax of Language* in 1934, was the most mature expression of the logical empiricists's new view.[5] All standards of "correctness," "validity," and "truth," according to Carnap, are relative to the logical rules definitive of one or another formal language or linguistic framework. The rules of classical logic and mathematics, for example, are definitive of certain logical calculi or linguistic frameworks, while the rules of intuitionistic logic and mathematics (wherein the law of excluded middle is no longer universally valid) are definitive of others. Since standards of "validity" and "correctness" are thus relative to the choice of linguistic framework, it makes no sense to ask whether any such choice of framework is itself "valid" or "correct." For the logical rules relative to which alone these notions can be well-defined are not yet in place. Such rules are *constitutive* of the concepts of "validity" and "correctness"—relative to one or another choice of linguistic framework, of course—and are in this sense a priori rather than empirical.

This Carnapian philosophy of linguistic frameworks rests on two closely related distinctions. The first is the distinction between formal or *analytic* sentences of a given framework and empirical or *synthetic* sentences—or, as Carnap puts it in *Logical Syntax,* between *logical rules* ("L-rules") of a linguistic framework and *physical rules* ("P-rules"). The L-rules include laws of logic and mathematics (and may also, at least in spaces of constant curvature, include laws of physical geometry), whereas the P-rules include empirical laws standardly so-called such as Maxwell's equations of electromagnetism. In this way, Carnap's distinction between

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[5] Carnap, *Logische Syntax der Sprache* (Wien: Springer, 1934); translated as *The Logical Syntax of Language* (London: Kegan Paul, 1937).

L-rules and P-rules closely parallels Reichenbach's distinction, developed in his 1920 book, between "axioms of coordination" (constitutive principles) and "axioms of connection" (properly empirical laws). Carnap's differentiation between logical and physical rules (analytic and synthetic sentences) then induces a second fundamental distinction between *internal* and *external* questions.[6] Internal questions are decided within an already adopted framework, in accordance with the logical rules of the framework in question. External questions, by contrast, concern precisely the question of which linguistic framework—and therefore which logical rules—to adopt in the first place. And since no logical rules are as yet in place, external questions, unlike internal questions, are not strictly speaking rationally decidable. Such questions can only be decided conventionally on the basis of broadly pragmatic considerations of convenience or suitability for one or another purpose. An overriding desire for security against the possibility of contradiction, for example, may prompt the choice of the weaker rules of intuitionistic logic and mathematics, whereas an interest in ease of physical application may prompt the choice of the stronger rules of classical logic and mathematics.

Now it was precisely this Carnapian philosophy of linguistic frameworks that formed the background and foil for Quine's articulation of a radically opposed form of epistemological holism according to which no fundamental distinction between a priori and a posteriori, logical and factual, analytic and synthetic can in fact be drawn. As we have seen, it was in Quine's 1951 paper, "Two Dogmas of Empiricism," where his challenge to the analytic/synthetic distinction was first made widely known, that the holistic figure of knowledge as a vast web of interconnected beliefs also first appeared. But it is important to see here that it is Quine's attack on the analytic/synthetic distinction, and not simply the idea that no belief whatsoever is forever immune to revision, that is basic to Quine's new form of holism. For Carnap's philosophy of linguistic frameworks is wholly predicated on the idea that logical or analytic principles, just as much as empirical or synthetic principles, can be revised in the progress of empirical science.[7] Indeed, as we have seen, Reichenbach's initial formulation of this new view of constitutive a priori principles was developed

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[6] This distinction is first made explicitly in Carnap, "Empiricism, Semantics, and Ontology," *Revue Internationale de Philosophie* 11 (1950): 20–40; reprinted in *Meaning and Necessity,* 2nd ed. (Chicago: University of Chicago Press, 1956).

[7] Carnap explicitly embraces this much of epistemological holism (based on the ideas of Poincaré and Pierre Duhem) in § 82 of *Logical Syntax.* Quine is therefore extremely misleading when he (in the above-cited passage from § 6 of "Two Dogmas") simply equates analyticity with unrevisability. He is similarly misleading in § 5 (p. 41) when he asserts that the "dogma of reductionism" (i.e., the denial of Duhemian holism) is "at root identical" with the dogma of analyticity.

precisely to accommodate the revolutionary changes in the geometrical and mechanical framework of physical theory wrought by Einstein's development of the theory of relativity. The difference between Quine and Carnap is rather that the latter persists in drawing a sharp distinction between changes of language or linguistic framework, in which constitutive principles definitive of the very notions of "validity" and "correctness" are revised, and changes in ordinary empirical statements formulated against the background of such an already-present constitutive framework. And this distinction, for Carnap, ultimately rests on the difference between analytic statements depending solely on the meanings of the relevant terms and synthetic statements expressing contentful assertions about the empirical world.

Quine's attack on the analytic/synthetic distinction—and thus on Carnap's particular version of the distinction between a priori and empirical principles—is now widely accepted, and I have no desire to defend Carnap's particular way of articulating this distinction here. I do want to question, however, whether Quinean epistemological holism is really our only option, and whether, in particular, it in fact represents our best way of coming to terms with the revolutionary changes in the historical development of the sciences that are now often taken to support it.

Quinean holism pictures our total system of science as a vast web or conjunction of beliefs which face the "tribunal of experience" as a corporate body. Quine grants that some beliefs, such as those of logic and arithmetic, are relatively central, whereas others, such as those of biology, say, are relatively peripheral. But this means only that the former beliefs are less likely to be revised in case of a "recalcitrant experience" at the periphery, whereas the latter are more likely to be revised. A reasonable scientific conservatism prefers to revise less central, less well-entrenched beliefs before it is forced to revise more central and better entrenched beliefs. Strictly speaking, however, empirical evidence—either for or against—spreads over *all* the elements of the vast conjunction that is our total system of science, wherein all elements whatsoever equally face the "tribunal of experience." And it is in this precise sense, for Quine, that all beliefs whatsoever, including those of logic and mathematics, are equally empirical.

But can this beguiling form of epistemological holism really do justice to the revolutionary developments within both mathematics and natural science that have led up to it? Let us first consider the Newtonian revolution that produced the beginnings of mathematical physics as we know it—the very revolution, as we have seen, that Kant's conception of synthetic a priori knowledge was originally intended to address. In constructing his mathematical physics Newton created, virtually simultaneously, three revolutionary advances: a new form of mathematics, the calculus, for dealing with infinite limiting processes and instantaneous rates of change; new conceptions of force and quantity of matter encapsulated in his three laws of motion; and a new universal law of nature, the law of universal gravitation. Each of these three advances was revolutionary in itself, and all were introduced by Newton in the context of the same scientific problem: that of developing a single mathematical theory of motion capable of giving a unified account of both terrestrial and celestial phenomena. Since all three advances were thus inspired, in the end, by the same empirical problem, and since they together amounted to the first known solution to this problem, Quine's holistic picture appears so far correct. All elements in this particular system of scientific knowledge—mathematics, mechanics, gravitational physics—appear equally to face the "tribunal of experience" together.

Nevertheless, there are fundamental asymmetries in the way in which the different elements of this Newtonian synthesis actually function. To begin with the relationship between mathematics and mechanics, Newton's second law of motion says that force equals mass times acceleration, where acceleration is the instantaneous rate of change of velocity (itself the instantaneous rate of change of position). So without the mathematics of the calculus this second law of motion could not even be formulated or written down, let alone function to describe empirical phenomena. The combination of calculus plus the laws of motion is not happily viewed, therefore, as a conjunction of propositions symmetrically contributing to a single total result: the mathematical part of Newton's theory rather supplies elements of the language or conceptual framework, we might say, within which the rest of the theory is then formulated. And an analogous (if also more subtle) point holds with respect to the relationship between Newton's mechanics and gravitational physics. The law of universal gravitation says that there is a force of attraction, directly proportional to the product of the two masses and inversely proportional to the square of the distance between them, between any two pieces of matter in the universe—which therefore experience accelerations towards one another in accordance with this same law. But relative to what frame of reference are the accelerations in question defined? Since these accelerations are, by hypothesis, universal, no particular material body can be taken as actually at rest in this frame, and thus the motions in question are not motions relative to any particular material body. Newton himself understood these motions as defined relative to absolute space, but we now understand them as defined relative to an arbitrary *inertial frame*—where an inertial frame of reference is simply one in which the Newtonian laws of motion actually hold (the center of mass frame of the solar system, for example, is a very close approximation to such a frame). It follows that without the Newtonian laws of motion Newton's theory of gravitation would not even make empirical sense, let alone give a correct account of the empirical phenomena: in the absence of these laws we would simply have no idea what the relevant frame of reference might be in relation to which the universal accelerations due to gravity are defined. Once again, Newton's mechanics and gravitational physics are not happily viewed as symmetrically functioning elements of a larger conjunction: the former is rather a necessary part of the language or conceptual framework within which alone the latter makes empirical sense.

Now the Newtonian theory of gravitation has of course been superseded by Einstein's general theory of relativity, and one might naturally expect Quine's holistic picture of knowledge to describe this latter theory much more accurately. General relativity, like Newtonian theory, can be seen as the outcome of three revolutionary advances: the development of a new field of mathematics, tensor calculus or the general theory of manifolds, by Bernhard Riemann in the late nineteenth century; Einstein's principle of equivalence, which identifies gravitational effects with the inertial effects formerly associated with Newton's laws of motion; and Einstein's equations for the gravitational field, which describe how the curvature of space-time is modified by the presence of matter and energy so as to direct gravitationally affected bodies along straightest possible paths or geodesics. Once again, each of these three advances was revolutionary in itself, and all three were marshalled together by Einstein to solve a single empirical problem: that of developing a new description of gravitation consistent with the special theory of relativity (which is itself incompatible with the instantaneous action at a distance characteristic of Newtonian theory) and also capable, it was hoped, of solving well-known anomalies in Newtonian theory such as that involving the perihelion of Mercury. And the three advances together, as marshalled and synthesized by Einstein, in fact succeeded in solving this empirical problem for the first time.

It does not follow, however, that the combination of mathematical theory of manifolds, geodesic law of motion, and field equations of gravitation can be happily viewed as a symmetrically functioning conjunction, such that each element then equally faces the "tribunal of experience" when confronted with the anomaly in the perihelion of Mercury, for example. To begin again with the relationship between mathematics and mechanics, the principle of equivalence depicts the space-time trajectories of bodies affected only by gravitation as geodesics in a variably curved space-time geometry, just as the Newtonian laws of motion, when viewed from this same space-time perspective, depict the trajectories of bodies affected by no forces at all as geodesics in a flat space-time geometry. But the whole notion of a variably curved geometry itself only makes sense in the context of the revolutionary new theory of manifolds recently created by Riemann. In the context of the mathematics available in the seventeenth and eighteenth centuries, by contrast, the idea of a variably curved space-time geometry could not even be formulated or written down, let alone function to describe empirical phenomena. And, once again, a closely analogous (but also more subtle) point holds for the relationship between mechanics and gravitational physics. Einstein's field equations describe the variation in curvature of space-time geometry as a function of the distribution of matter and energy. Such a variably curved space-time structure would have no empirical meaning or application, however, if we had not first singled out some empirical phenomena as counterparts of its fundamental geometrical notions—here the notion of geodesic or straightest possible path. The principle of equivalence does precisely this, however, and without this principle the intricate space-time geometry described by Einstein's field equations would not even be empirically false, but rather an empty mathematical formalism with no empirical application at all.[8] Just as in the case of Newtonian gravitation theory, therefore, the three advances together comprising Einstein's revolutionary theory should not be viewed as symmetrically functioning elements of a larger conjunction: the first two function rather as necessary parts of the language or conceptual framework within which alone the third makes both mathematical and empirical sense.

It will not do, in either of our two examples, to view what I am calling the constitutively a priori parts of our scientific theories as simply relatively fixed or entrenched elements of science in the sense of Quine, as particularly well-established beliefs which a reasonable scientific conservatism takes to be relatively difficult to revise. When Newton formulated his theory of gravitation, for example, the mathematics of the calculus was still quite controversial—to such an extent, in fact, that Newton disguised his use of it in the *Principia* in favor of traditional synthetic geometry. Nor were Newton's three laws of motion any better entrenched, at the time, than the law of universal gravitation. Similarly, in the case of Einstein's general theory of relativity, neither the mathematical theory of manifolds nor the principle of equivalence was a well-entrenched part of main-stream mathematics or mathematical physics; and this is one of the central reasons, in fact, that Einstein's theory is so profoundly revolutionary. More generally, then, since we are dealing with deep conceptual revolutions in both mathematics and mathematical physics in both cases, entrenchment and relative resistance to revision are not appropriate distinguishing features at all. What characterizes the distinguished elements

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[8] For an analysis of the principle of equivalence along these lines, including illuminating comparisons with Reichenbach's conception of the need for "coordinating definitions" in physical geometry, see Robert DiSalle, "Spacetime Theory as Physical Geometry," *Erkenntnis* 42 (1995): 317–337.

of our theories is rather their special *constitutive function:* the function of making the precise mathematical formulation and empirical application of the theories in question first possible. In this sense, the relativized and dynamical conception of the a priori developed by the logical empiricists appears to describe these conceptual revolutions far better than does Quinean holism. This is not at all surprising, in the end, for this new conception of the constitutive a priori was inspired, above all, by just these conceptual revolutions.

It is no wonder, then, that in Thomas Kuhn's theory of the nature and character of scientific revolutions we find an informal counterpart of the relativized conception of constitutive a priori principles first developed by the logical empiricists. Indeed, one of Kuhn's central examples of revolutionary scientific change, just as it was for the logical empiricists, is precisely Einstein's theory of relativity.[9] Thus Kuhn's central distinction between change of paradigm or revolutionary science, on the one side, and normal science, on the other, closely parallels the Carnapian distinction between change of language or linguistic framework and rule-governed operations carried out within such a framework. Just as, for Carnap, the logical rules of a linguistic framework are constitutive of the notion of "correctness" or "validity" relative to this framework, so a particular paradigm governing a given episode of normal science, for Kuhn, yields generally-agreed-upon (although perhaps only tacit) rules constitutive of what counts as a "valid" or "correct" solution to a problem within this episode of normal science. Just as, for Carnap, external questions concerning which linguistic framework to adopt are not similarly governed by logical rules, but rather require a much less definite appeal to conventional and/or pragmatic considerations, so changes of paradigm in revolutionary science, for Kuhn, do not proceed in accordance with generally-agreed-upon rules as in normal science, but rather require something more akin to a conversion experience.

Indeed, towards the end of his career, Kuhn himself drew this parallel between his theory of scientific revolutions and the relativized conception of a priori constitutive principles explicitly:

> Though it is a more articulated source of constitutive categories, my structured lexicon [= Kuhn's late version of "paradigm"] resembles Kant's a priori when the latter is taken in its second, relativized sense. Both are constitutive of *possible experience* of the world, but neither dictates what that experience must be. Rather, they are constitutive

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[9] Kuhn develops this example in *The Structure of Scientific Revolutions,* 2nd ed. (Chicago: University of Chicago Press, 1970), chapter 9. There is some irony in the circumstance that Kuhn introduces this example as part of a criticism of what he calls "early logical positivism" (p. 98).

> of the infinite range of possible experiences that might conceivably occur in the actual world to which they give access. Which of these conceivable experiences occurs in that actual world is something that must be learned, both from everyday experience and from the more systematic and refined experience that characterizes scientific practice. They are both stern teachers, firmly resisting the promulgation of beliefs unsuited to the form of life the lexicon permits. What results from respectful attention to them is knowledge of nature, and the criteria that serve to evaluate contributions to that knowledge are, correspondingly, epistemic. The fact that experience within another form of life—another time, place, or culture—might have constituted knowledge differently is irrelevant to its status as knowledge.[10]

Thus, although Quine may very well be right that Carnap has failed to give a precise logical characterization of what I am here calling constitutive principles, there is also nonetheless no doubt, I suggest, that careful attention to the actual historical development of science, and, more specifically, to the very conceptual revolutions that have in fact led to our current philosophical predicament, shows that relativized a priori principles of just the kind Carnap was aiming at are central to our scientific theories.

But this close parallel between the relativized yet still constitutive a priori and Kuhn's theory of scientific revolutions implies (as the last sentence of our passage from Kuhn suggests) that the former gives rise to the same problems and questions concerning the ultimate rationality of the scientific enterprise that are all too familiar in the post-Kuhnian literature in history, sociology, and philosophy of science. In particular, since there appear to be no generally-agreed-upon constitutive principles governing the transition to a revolutionary new scientific paradigm or conceptual framework, there would seem to be no sense left in which such a transition can still be viewed as rational, as based on good reasons. And it is for precisely this reason, of course, that Carnap views what he calls external questions as conventional as opposed to rational, and Kuhn likens paradigm shifts rather to conversion experiences. It appears, then, that all we have accomplished by defending the relativized yet still constitutive a priori against Quinean holism is to land ourselves squarely in the contemporary "relativistic" predicament, wherein the overarching rationality of the scientific enterprise has now been strongly called into question.

The underlying source of this post-Kuhnian predicament, as we have seen, is the breakdown of the original Kantian conception of the a priori. Kant takes the fundamental constitutive principles framing Newtonian

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[10] Kuhn, "Afterwords," in Paul Horwich (ed.), *World Changes* (Cambridge, MA: MIT Press, 1993), pp. 331–332.

mathematical science as expressing timelessly fixed categories and forms of the human mind. Such categories and forms, for Kant, are definitive of human rationality as such, and thus of an absolutely *universal* rationality governing all human knowledge at all times and in all places. This conception of an absolutely universal human rationality realized in the fundamental constitutive principles of Newtonian science made perfectly good sense in Kant's own time, when the Newtonian conceptual framework was the only paradigm for what we now call mathematical physics the world had yet seen. Now that we have irretrievably lost this position of innocence, however, it would appear that the very notion of a truly universal human rationality must also be given up. It would appear that there is now no escape from the currently fashionable slogan "all knowledge is local."

Yet Kuhn himself rejected such relativistic implications of his views. He continued to hold, in a self-consciously traditional vein, that the evolution of science is a rational and progressive process despite the revolutionary transitions between scientific paradigms which are, as he also claims, absolutely necessary to this process. The scientific enterprise, Kuhn suggests, is essentially an instrument for solving a particular sort of problem or "puzzle"—for maximizing the quantitative match between theoretical predictions and phenomenological results of measurement. Given this, however, there are obvious criteria or "values"—such as accuracy, precision, scope, simplicity, and so on—that are definitive of the scientific enterprise as such. Such values are constant or permanent across scientific revolutions or paradigm-shifts, and this is all we need to secure the (non-paradigm-relative) rationality of scientific progress:

> [W]hether or not individual practitioners are aware of it, they are trained to and rewarded for solving intricate puzzles—be they instrumental, theoretical, logical, or mathematical—at the interface between their phenomenal world and their community's beliefs about it. . . . If that is the case, however, the rationality of the standard list of criteria for evaluating scientific belief is obvious. Accuracy, precision, scope, simplicity, fruitfulness, consistency, and so on, simply *are* the criteria which puzzle solvers must weigh in deciding whether or not a given puzzle about the match between phenomena and belief has been solved. . . . To select a law or theory which exemplified them less fully than an existing competitor would be self-defeating, and self-defeating action is the surest index of irrationality. . . . As the developmental process continues, the examples from which practitioners learn to recognize accuracy, scope, simplicity, and so on, change both within and between fields. But the criteria that these examples illustrate are themselves necessarily permanent, for abandoning them would be aban-

> doning science together with the knowledge which scientific development brings. . . . Puzzle-solving is one of the families of practices that has arisen during that evolution [of human practices], and what it produces is knowledge of nature. Those who proclaim that no interest-driven practice can properly be identified with the rational pursuit of knowledge make a profound and consequential mistake.[11]

Thus, although the process of scientific development is governed by no single conceptual framework fixed once and for all, science, at *every* stage, still aims at a uniform type of puzzle-solving success, Kuhn suggests, relative to which *all* stages in this process (including transitions between conceptual frameworks) may be judged. And there is then no doubt at all, Kuhn further suggests, that science, throughout its development, has become an increasingly efficient instrument for achieving this end. In this sense, therefore, there is also no doubt at all that science as a whole is a rational enterprise.

This Kuhnian defense of the rationality of scientific knowledge from the threat of conceptual relativism misses the point, I believe, of the real challenge to such rationality arising from Kuhn's own historiographical work. For it is surely uncontroversial that the scientific enterprise as a whole has in fact become an ever more efficient instrument for puzzle-solving in Kuhn's sense—for maximizing quantitative accuracy, precision, simplicity, and so on in adjusting theoretical predictions to phenomenological results of measurement. What is controversial, rather, is the further idea that the scientific enterprise thereby counts as a privileged model or exemplar of rational knowledge of—rational inquiry into—nature. And the reasons for this have nothing to do with doubts about the incontrovertible predictive success of the scientific enterprise—they do not call into question, that is, the *instrumental* rationality of this enterprise. What has been called into question, rather, is what Jürgen Habermas calls *communicative* rationality.[12] Communicative rationality, unlike instrumental rationality, is concerned not so much with choosing efficient means to a given end, but rather with securing mutually agreed upon principles of reasoning whereby a given community of speakers can rationally adjudicate their differences of opinion. It is precisely this kind of rationality that is secured by a shared paradigm or conceptual framework; and it is precisely this kind of rationality that is then profoundly challenged by the Kuhnian theory of scientific revolutions—where it appears that succeeding paradigms, in a scientific revolution, are fundamentally non-

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[11] Kuhn, "Afterwords" (note 10 above), pp. 338–339.

[12] See Habermas, *Theorie des Kommunikativen Handelns* (Frankfurt: Suhrkamp, 1981), vol. 1, chapter 1; translated as *The Theory of Communicative Action* (Boston: Beacon, 1984).

intertranslatable and thus share no basis whatsoever for rational mutual communication. Pointing to the obvious fact that science has nonetheless continued to increase its quantitative accuracy, precision, and so on is thus a quite inadequate response to the full force of the post-Kuhnian relativistic challenge to scientific rationality.

Kuhn's notion of normal science, as we have just seen, is itself based on an *intra*-framework notion of communicative rationality—on shared rules of the game, as it were, common to all practitioners of a single given paradigm. What we now need to investigate, then, are the prospects for a comparable notion of *inter*-framework communicative rationality, capable of providing similarly shared principles of reasoning functioning *across* revolutionary paradigm-shifts.

Let us first remind ourselves that, despite the fact that we radically change our constitutive principles in the revolutionary transition from one conceptual framework to another, there is still an important element of *convergence* in the very same revolutionary process of conceptual change. Special relativistic mechanics approaches classical mechanics in the limit as the velocity of light goes to infinity; variably curved Riemannian geometry approaches flat Euclidean geometry as the regions under consideration become infinitely small; Einstein's general relativistic field equations of gravitation approach the Newtonian equations for gravitation as, once again, the velocity of light goes to infinity.[13] Indeed, even in the transition from Aristotelian terrestrial and celestial mechanics to classical terrestrial and celestial mechanics we find a similar relationship. From an observer fixed on the surface of the earth we can construct a system of lines of sight directed towards the heavenly bodies; this system is spherical, isomorphic to the celestial sphere of ancient astronomy, and the motions of the heavenly bodies therein are indeed described, to a very good approximation, by the geocentric system favored by Aristotle. Moreover, in the sublunary region close to the surface of the earth, where the earth is by far the principal gravitating body, heavy bodies do follow straight paths directed towards the center of the earth, again to an extremely good approximation. In all three revolutionary transitions, therefore, key elements of the preceding paradigm are preserved as approximate special cases in the succeeding paradigm.

This type of convergence between successive paradigms allows us to define a *retrospective* notion of inter-framework rationality based on the

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13. In Kuhn's own discussion of the theory of relativity (see note 9), he explicitly denies that classical mechanics can be logically derived from relativistic mechanics in the limit of small velocities. His main ground for this denial is that "the physical referents" of the terms of the two theories are different (*op. cit.,* pp. 101–2). Here, however, I am merely pointing to a purely mathematical fact about the corresponding mathematical structures.

constitutive principles of the later conceptual framework: since the constitutive principles of the earlier framework are contained in those of the later as an approximate special case, the constitutive principles of the later framework thus define a common rational basis for mutual communication from the point of view of this latter framework. But this does not yet give us a *prospective* notion of inter-framework rationality accessible from the point of view of the earlier framework, of course, and so it does not yet provide a basis for mutual communication that is truly available to both frameworks.[14] Nevertheless, such a prospective notion of inter-framework communicative rationality also begins to emerge when we observe that, in addition to containing the constitutive principles of the older framework as an approximate special case, the concepts and principles of the revolutionary new constitutive framework evolve continuously, as it were, by a series of natural transformations of the old concepts and principles.

The Aristotelian constitutive framework, for example, is based on Euclidean geometry, a background conception of a hierarchically and teleologically organized universe, and conceptions of natural place and natural motion appropriate to this universe. Thus, in the terrestrial realm heavy bodies naturally move in straight lines towards their natural place at the center of the universe, and in the celestial realm the heavenly bodies naturally move uniformly in circles around this center. The conceptual framework of classical physics then retains Euclidean geometry, but eliminates the hierarchically and teleologically organized universe together with the accompanying conceptions of natural place. We thereby obtain an infinite, homogeneous, and isotropic universe in which all bodies naturally move uniformly along straight lines to infinity. But how did we arrive at this conception? An essential intermediate stage was Galileo's celebrated treatment of free fall and projectile motion. For, although Galileo indeed discards the hierarchically and teleologically organized Aristotelian universe, he retains—or better, transforms—key elements of the Aristotelian conception of natural motion. Galileo's analysis is based on a combination of what he calls naturally accelerated motion directed towards the center of the earth and uniform or equable motion directed horizontally. Unlike our modern conception of rectilinear inertial motion,

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14. That the convergence in question yields only a purely retrospective *reinterpretation* of the original theory is a second (and related) point Kuhn makes in the discussion cited in note 13 above, where he points out (p. 101) that the laws derived as special cases in the limit within relativity theory "are not [Newton's] unless those laws are reinterpreted in a way that would have been impossible until after Einstein's work." I believe that Kuhn is correct in this and, in fact, that it captures a centrally important aspect of what he has called the non-intertranslatability or "incommensurability" of pre-revolutionary and post-revolutionary theories.

however, this Galilean counterpart is uniformly *circular*—traversing points equidistant from the center at constant speed. But, in relatively small regions near the earth's surface, this circular motion is quite indistinguishable from rectilinear motion, and Galileo can thus treat it as rectilinear to an extremely good approximation. And it is in precisely this way, therefore, that the modern conception of natural (inertial) motion is actually continuous with the preceding Aristotelian conception of natural motion.

An analogous (if also more complex) point can be made concerning the transition from Newtonian mechanics and gravitation theory, through special relativity, to general relativity. The key move in general relativity, as we have seen, is to replace the law of inertia—which, from the space-time perspective inaugurated by special relativity, depicts the trajectories of force-free bodies as geodesics in a flat space-time geometry—with the principle of equivalence, according to which bodies affected only by gravitation follow geodesics in a variably curved space-time geometry. How did Einstein actually make this revolutionary move, which represents the first actual application of a non-Euclidean geometry to nature? Einstein's innovation grows naturally out of the nineteenth-century tradition in the foundations of geometry, as Einstein interprets this tradition in the context of the new non-Newtonian mechanics of special relativity. The key transition to a non-Euclidean geometry of variable curvature in fact results from applying the Lorentz contraction arising in special relativity to the geometry of a rotating disk, as Einstein simultaneously delicately positions himself within the debate on the foundations of geometry between Helmholtz and Poincaré. In particular, whereas Einstein had earlier made crucial use of Poincaré's idea of convention in motivating the transition, on the basis of mathematical simplicity, from Newtonian space-time to what we currently call Minkowski space-time, now, in the case of the rotating disk, Einstein rather follows Helmholtz in taking the behavior of rigid measuring rods to furnish us with an empirical determination of the underlying geometry—in this case, a non-Euclidean geometry.[15]

In each of our revolutionary transitions fundamentally philosophical ideas, belonging to what we might call epistemological meta-paradigms or meta-frameworks, play a crucial role in motivating and sustaining the transition to a new first-level or scientific paradigm. Such epistemological meta-frameworks guide the all-important process of conceptual transformation and help us, in particular, to articulate what we now mean, during a given revolutionary transition, by a natural, reasonable, or responsible conceptual transformation. By interacting productively with both older

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15. For a detailed discussion of this case see my "Geometry as a Branch of Physics," in D. Malament (ed.), *Reading Natural Philosophy* (Chicago: Open Court, 2002).

philosophical meta-frameworks and new developments taking place within the sciences themselves, a new epistemological meta-framework thereby makes available a prospective notion (accessible even in the pre-revolutionary conceptual situation) of inter-framework or inter-paradigm rationality.

In the transition from Aristotelian-Scholastic natural philosophy to classical mathematical physics, for example, at the same time that Galileo was subjecting the Aristotelian conception of natural motion to a deep (yet continuous) conceptual transformation, it was necessary to eliminate the hierarchical and teleological elements of the Aristotelian conceptual framework in favor of an exclusively mathematical and geometrical point of view—which was encapsulated, for the mechanical natural philosophy of the time, in the distinction between primary and secondary qualities. Euclidean geometry, as an exemplar of rational inquiry, was of course already a part of the Aristotelian framework, and the problem then was, accordingly, to emphasize this part at the expense of the hylomorphic and teleological conceptual scheme characteristic of Aristotelian metaphysics. This task, however, required a parallel reorganization of the wider concepts of Aristotelian metaphysics (concepts of substance, force, space, time, matter, mind, creation, divinity), and it fell to the philosophy of Descartes to undertake such a reorganization—a philosophy which in turn interacted productively with recent scientific advances such as Copernican astronomy, new results in geometrical optics, and Descartes's own initial formulation of the law of rectilinear inertia. Similarly, in the transition from classical mechanics to relativity theory, at the same time that Einstein was subjecting the classical conceptions of space, time, and motion to a deep (yet continuous) conceptual transformation, philosophical debate on the foundations of geometry between Helmholtz and Poincaré, in which empiricist and conventionalist interpretations of that science opposed one another against the ever-present backdrop of the Kantian philosophy, played a central role—and, in turn, was itself carried out in response to mathematical advances in the foundations of geometry made throughout the nineteenth century.[16]

So what we see here, I finally want to suggest, is that a reconceived version of Kant's original philosophical project—the project of investigating and philosophically contextualizing the most basic constitutive principles defining the fundamental spatio-temporal framework of empirical natural science—plays an indispensable orienting role with respect to conceptual revolutions within the sciences precisely by generating new epistemological meta-frameworks capable of bridging, and thus guiding, the revolutionary transitions to a new scientific framework. This peculiarly

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[16] See again the reference cited in note 15 above.

philosophical type of investigation thereby makes available prospective notions of inter-framework rationality in the light of which radically new constitutive principles can then appear as rational—as Descartes's appropriation and transformation of the concepts of Aristotelian-Scholastic metaphysics made the new mechanical natural philosophy a reasonable option, for example, or Einstein's appropriation and transformation of the earlier epistemological reflections of Poincaré and Helmholtz did the same for relativity theory.

In place of the Quinean figure of an holistically conceived web of belief, wherein both knowledge traditionally understood as a priori and philosophy as a discipline are supposed to be wholly absorbed into empirical natural science, I am therefore proposing an alternative picture of a thoroughly dynamical yet nonetheless differentiated system of knowledge that can be analyzed, for present purposes, into three main components or levels. At the base level, as it were, are the concepts and principles of empirical natural science properly so-called: empirical laws of nature, such as the Newtonian law of gravitation or Einstein's equations for the gravitational field, which squarely and precisely face the "tribunal of experience" via a rigorous process of empirical testing. At the next or second level are the constitutively a priori principles that define the fundamental spatio-temporal framework within which alone the rigorous formulation and empirical testing of first or base level principles is then possible. These relativized a priori principles constitute what Kuhn calls paradigms: relatively stable sets of rules of the game, as it were, that make possible the problem-solving activities of normal science—including, in particular, the rigorous formulation and testing of properly empirical laws. In periods of deep conceptual revolution it is precisely these constitutively a priori principles which are then subject to change—under intense pressure, no doubt, from new empirical findings and especially anomalies. It does not follow, however, that such second-level constitutive principles are empirical in the same sense as are the first-level principles. On the contrary, since here, by hypothesis, a generally-agreed-upon background framework is necessarily missing, no straightforward process of empirical testing, in periods of deep conceptual revolution, is then possible. And here our third level, that of philosophical meta-paradigms or meta-frameworks, plays an indispensable role, by serving as a source of guidance or orientation in motivating and sustaining the transition from one paradigm or conceptual framework to another. Such philosophical meta-frameworks contribute to the rationality of revolutionary scientific change, more specifically, by providing a basis for mutual communication (and thus for communicative rationality in Habermas's sense) between otherwise incommensurable (and therefore non-intertranslatable) scientific paradigms.

None of these three levels are fixed and unrevisable, and the distinctions

I am drawing have nothing to do, in particular, with differing degrees of certainty or epistemic security. Indeed, the whole point of the present conception of relativized and dynamical a priori principles is to accommodate the profound conceptual revolutions that have repeatedly shaken our knowledge of nature to its very foundations. It is precisely this revolutionary experience, in fact, that has revealed that our knowledge *has* foundations in the present sense: subject-defining or constitutive paradigms whose revision entails a genuine expansion of our space of intellectual possibilities, to such an extent, in periods of radical conceptual revolution, that a straightforward appeal to empirical evidence is then no longer directly relevant. And it is at this point, moreover, that philosophy plays its own distinctive role, not so much in justifying or securing a new paradigm where empirical evidence cannot yet do so, but rather in guiding the articulation of the new space of possibilities and making the serious consideration of the new paradigm a rational and responsible option. The various levels in our total evolving and interacting system of beliefs are thus not distinguished by differing degrees of epistemic security at all (neither by differing degrees of centrality and entrenchment in the sense of Quine nor by differing degrees of certainty in the more traditional sense), but rather by their radically different yet mutually complementary contributions to the total ongoing dialectic of human knowledge—a dialectical process in which mathematical scientific knowledge continues to provide us with the best exemplar we have of human rationality (that is, our very best example of *communicative* rationality) in spite of (and even because of) its profoundly revolutionary character.