Part I

HISTORICAL AND PHILOSOPHICAL CONTEXT

1
CONVENTIONALISM

Robert DiSalle

Conventionalism, as an epistemological doctrine in the philosophy of science, is the fairly straightforward view that some scientific principles – perhaps the central theoretical principles of a given science – are incapable of being decided by empirical evidence, so that their adoption is necessarily a matter of conventional choice by the relevant group of scientists.

This is a relatively uncontroversial view to take of some kinds of scientific proposition, such as those that establish systems or units of measurement. It would obviously be absurd to suppose that a particular system of units is true, or that its adoption is anything but a free choice among equivalent alternatives, which can differ only in their relative convenience. But one generally thinks of a system of units not as a description of the world, but, rather, as a kind of language form that facilitates descriptions of the world; to compare such language forms by their convenience for facilitating scientific descriptions is obviously not to judge their conformity to the truth or to the empirical evidence, and it would make no sense to regard their adoption as anything but a choice. It is an old, even ancient, philosophical aim to identify conventions of the first sort, and to distinguish them from principles that are genuinely descriptive; in this way philosophical inquiry may be thought to arrive at the underlying nature of things, independent of particular modes of description. Then conventions would concern equivalent representations of an underlying structure that is the true object of scientific inquiry.

The less obvious, more challenging application of this view is to the actual scientific description of the world, as the claim that precisely the theoretical description of the world – not just the linguistic or mathematical forms that it employs – depends on conventional choice. There are various considerations from which such a claim might originate, but one obvious source is the underdetermination of theory by evidence: the same finite body of evidence will be compatible, in principle, with any number of theories if it is compatible with one. In that case, the adoption of a given theory necessarily involves some decision: either the choice of one compatible theory over all the others, or the decision simply to ignore the possibility of alternatives altogether and to accept the theory that one has in hand. It could be argued that this, too, is a harmless form of conventionalism, given the actual history of science, in which empirically equivalent alternative theories are not as common, or as easy to construct, as philosophical discussions of underdetermination might suggest. Even so, this form has implications for larger questions in philosophy of science, perhaps especially for the question of scientific realism; the mere possibility of equivalent alternative theories suggests a degree of contingency in our adoption of any one theory, and challenges the notion that empirically better theories are objectively closer to representing reality.

Neither of these views, each profound in itself, captures the historic importance of conventionalism, not only for the history of the philosophy of science, but also for the history of science itself, and particularly the history of mathematical physics. In fact it would be impossible to understand the contemporary place of conventionalism in the philosophy of science – as opposed to its general role as a broadly skeptical theme, from ancient times – without understanding its connection with very specific problems in the foundations of geometry and physics that arose in the middle of the nineteenth century. On the one hand, conventionalism was a response to new developments in geometry, and the foundational questions that those developments posed regarding the relation between geometry and the world of experience. On the other hand, the light that conventionalism shed on these questions influenced further reflections on the nature of mathematical structures and their empirical interpretations, reflections which, in turn, played a decisive role in the dramatic transformations of mathematical physics that took place in the early twentieth century. A clear grasp of the origins and meaning of conventionalism, as well as its relevance to enduring issues in the philosophy of science, begins with an appreciation of its engagement with the foundations of science.

Background: Kant and the synthetic *a priori*

To explain the context in which non-Euclidean geometry came under philosophical scrutiny, and conventionalism eventually developed, it is helpful to recall some aspects of Kant's theory of the synthetic *a priori*. First, the theory highlighted the non-logical content of geometry, suggesting that neither our understanding of the basic principles, nor our ability to derive their consequences, could be separated – at least, with the logical resources of Kant's time – from the representation of geometrical objects in space. So geometry appears to be an *a priori* science that nevertheless derives its content from sensibility. The objects of our geometrical knowledge are not only recognized, but also exhaustively defined, by the constructive procedures outlined in Euclid's postulates. It is in virtue of a constructive definition that we know properties of a triangle, for example, beyond those expressed in the verbal definition of a three-sided figure. It is for the same reason, more generally, that the self-evidence of geometry is irreducibly intuitive, and that the rules to which our geometrical constructions conform – approximately in empirical geometry, and precisely in pure geometry – may be said to constitute the "form" of spatial intuition. From this point of view, it could be argued that the mere existence of non-Euclidean geometries, as formal mathematical possibilities, does not touch the certainty of Euclid's geometry: if our intuitive constructions must conform to, and exhibit, the Euclidean principles, then the latter is justified *a priori* as the geometry of our space. But from Kant's point of view this argument is not even necessary: if geometrical proof is inseparable from intuitive construction, then purely formal alternatives to Euclid's geometry are not even possible. We could neither grasp their first principles nor derive their consequences (cf. Friedman 1992).

These aspects of Kant's view are, perhaps ironically, precisely those that made it possible to unseat Euclidean geometry as the necessary structure of space. Having undermined any purely rational argument for the uniqueness of Euclidean geometry, Kant's account makes its necessity and universality entirely dependent on the evidence of its constructive methods, and indeed denies it any content above or beyond its representation in sensible intuition. So, to justify the viability of a non-Euclidean geometry as an account of "our space," it would be not only necessary, but also sufficient, to show that such a geometry has a constructive representation – an intuitive representation in precisely Kant's sense – and its theorems admit of constructive proof. Given its complete identification of the foundations of geometry with the space of intuitive constructions, the Kantian view would have no room to retreat from such a challenge.

From empiricism to conventionalism: Helmholtz and Poincaré

It is a misconception, therefore, that Kant's account of geometry as synthetic *a priori* knowledge was entirely overthrown by the development of non-Euclidean geometry. The decisive fact was, rather, that the special epistemic ground of Euclidean geometry, as Kant understood it, could provide an equivalent ground for non-Euclidean alternatives. The mere formal consistency of an alternative geometry would challenge Kant's views of mathematical proof. But it would not necessarily establish the possibility of such a geometry as a synthetic account of space. Kant's followers could still argue that Euclidean geometry is uniquely tied to our spatial intuition; alternative geometries could be formally developed, but not "visualized" as a possible space of experience (cf. Torretti 1978). It was Helmholtz who raised the decisive challenge to this view, by a conceptual analysis of what is meant by "visualizing" a geometrical structure:

> By the much abused expression "to represent to oneself [sich vorstellen]", or "to be able to imagine [sich denken] how something takes place," I understand – and I don't see how one could understand anything else thereby, without giving up all the sense of the expression – that one could depict the series of sense-impressions that one would have if such a thing took place in a particular case.
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> (Helmholtz 1870: 8)

Helmholtz showed that, in any sense in which we can visualize Euclidean space, we can visualize a homogeneous non-Euclidean space. Kant had already recognized that the Euclidean structure of space is not something that we immediately "intuit"; what we intuit is, rather, the construction of actual or imagined figures, and the systematic changes in the appearances of things that accompany our changes of perspective. To intuit a non-Euclidean space would be, simply, to find that such constructive processes, and such changes of perspective, exhibit the laws of a non-Euclidean geometry.

This conceptual analysis is a revolutionary step, but also somewhat Kantian in spirit, insofar as it admits no other content to the claim that space is Euclidean, or non-Euclidean, beyond the succession of intuitions that conform to one or another structure. But the analysis leads directly to a further analysis, showing that the intuitive practice of geometrical construction depends on empirical features of the world. The basic notions of this practice are the congruence of figures and the straightness of lines, and we come to know each of these through its practical physical correlate: congruence through the displacement of rigid bodies, and straight lines through the optical line of sight, or the path of light-propagation. That is, the comparison of lengths derives its meaning from our ability to bring bodies into coincidence, and our assumption that in the process their size and shape remain constant; analogously, we determine the straightness of any body or path by comparing it to the line of sight. Helmholtz's analysis thus leads from a broadly Kantian perspective to empiricism: what we bring to spatial experience and geometrical reasoning is not the *a priori* form of spatial intuition, but the expectations we have developed, and completely internalized, in the course of our experience with nearly-rigid bodies and light rays, and the habits and expectations that we have formed regarding the relations between our own motions and our lines of sight. The "conditions of the possibility" of geometry are therefore facts about the world in which our geometrical conceptions have developed, namely that there really are approximately rigid bodies and that light travels in sufficiently straight lines.

Just this principle of geometric empiricism, however, was the first step to conventionalism. For Helmholtz's analysis introduced a radical insight into the subject matter of geometry: insofar as geometry is the science of the structure of space, its subject matter is the possible displacements of rigid bodies. Helmholtz pointed out that this principle of rigid displacement – thereafter known as the principle of free mobility – is not only the foundation of our notion of congruence; it is also the principle that characterizes our experience of space as such. Spatial relations are first characterized for us, and distinguished from other relations, by the fact that we can freely alter them by our own motion. Changes of relative spatial position are distinguished from other kinds of change in our environment by the fact that they can be produced, combined, and reversed by shifts in the perspective of the observer. We believe that we live in an approximately Euclidean world, Helmholtz concluded, because of the entirely contingent fact that the displacements of approximately rigid bodies exhibit an approximately Euclidean structure, observed in measurements of angles and lengths using rigid instruments. For example, the internal angles of triangles approximately sum to two right angles; if such measurements turned out otherwise, we would know, as a matter of fact, that our space is non-Euclidean.

It is not immediately obvious why this empiricist understanding of the foundations of geometry, with its emphasis on physical measurement and approximation, should turn out to be a step toward conventionalism. Poincaré took this step because he saw more clearly than Helmholtz that the empirical principles on which Helmholtz relied are, in fact, principles of interpretation. That light travels in a straight line is not a law of nature, but a physical interpretation of the geometrical concept of straight line; that rigid bodies move freely without change of dimension is a physical interpretation of the concept of congruence. If such principles were laws of nature, we should be able to state, independently of light propagation, what in nature is a straight line, and "light travels in a straight line" would become an empirical claim. In that case the burden of interpreting the concept of straight line, as a geometrical feature of the world, would fall on some other physical principle. This would begin an infinite regress, unless we recognize that some physical principle – on account of its simplicity, convenience, or other practical virtue – has simply been adopted as the physical definition of straight line. Kant had upheld the synthetic *a priori* because he had recognized that certain principles, though they apply to the sensible world, nonetheless partake of a kind of necessity because they "constitute" their objects in a strong sense: these principles are the conditions of the possibility of our experience of those objects as objects of knowledge, rather than as mere appearances. Poincaré saw that such principles constitute, rather, the empirical meanings of geometrical concepts. For this reason they are not analytic in Kant's sense, for they do not merely affirm what is "contained in" those concepts, but provide them with an empirical interpretation; for the same reason, they are revisable, if an alternative interpretation better serves our purposes. They were taken as synthetic *a priori* principles, in short, because they appeared to be necessary principles in the form of laws of nature. But this appearance is deceptive; in fact they are "definitions in disguise" (Poincaré 1902: 56).

The insight behind conventionalism, then, was that certain principles play a peculiar role in our fundamental theories because they determine the meanings, and the criteria for the application, of fundamental concepts around which these theories are constructed. Conventionalism would be an absurd doctrine if it asserted, in light of this insight, that (for example) straight lines are defined by light rays in accord with some explicit decision by a social group. For Poincaré, at least, the connection between the geometrical straight line and the physical propagation of light arises from a long, successful, and largely unexamined history of empirical practice. The implication of its definitional character is not that it was deliberately legislated but, rather, that, because it is not quite an empirical proposition, it can be rewritten without necessarily defying the empirical evidence; equivalently, it can be maintained in the face of empirical evidence that might otherwise have seemed to contradict it. If the optical measurement of large triangles (for example, surveying large triangles near the surface of the earth, or taking the parallax of celestial bodies) showed that their angles don't sum to two right angles, we would not have (as Helmholtz had argued) experimental proof that space is non-Euclidean. Such an experiment can only demonstrate a conflict between the definition of space as Euclidean and the definition of straight line that is presupposed in the measurement. The experiment therefore has two epistemically equivalent interpretations: if straight lines are defined by light propagation, then space is non-Euclidean; if straight lines are defined by their conformity to Euclidean geometry, then the light rays forming the sides of the triangle are, by definition, not straight. In that case the principle that light travels in straight lines becomes a mere hypothesis that has turned out to be false, or perhaps there is a force that is systematically disturbing the motion of light. Poincaré illustrated this point by a physical model of a non-Euclidean world. As Helmholtz had argued, from our theoretical account of the behavior of bodies and light in a non-Euclidean space, and our practical knowledge of visual perception and its adaptation to the motions of bodies and light, we can imagine the course of experience in a non-Euclidean world. Poincaré pointed out, however, that we could equally imagine a world whose atmosphere had a peculiar distribution of heat, so that the refractive index of light and the thermal expansion of bodies varied systematically from place to place. Such circumstances could produce exactly the appearances, and the measurements, that we would expect in a non-Euclidean world. The equivalence of two such models is not a problem of underdetermination, or a lack of evidence to determine which interpretation is true; the point is that the question of truth has no meaning here.

Conventionalism, in this sense, captured some of the central insights gained in the nineteenth century into the foundations of geometry, and the connections between geometry and physics. Within mathematics, the distinction between geometrical structures and their physical interpretation transformed the distinction between pure and applied geometry. Formerly, this was seen as a distinction between ideal geometrical constructions and their (imperfect) material realizations, both of which were, implicitly, already interpreted through the intuitive notions of straight line and congruence. Now, however, pure geometry was understood as a class of uninterpreted formal structures. At this level, the question of a true geometry, or even an empirically adequate geometry, could not arise; a set of geometrical axioms can only be consistent or inconsistent. The central concepts of geometry are not explicitly defined by an association with intuitive notions, but implicitly defined by the axioms in which they occur. A set of axioms is adequate if it is both consistent and sufficient to deduce the theorems of the geometry that is of interest – desiderata that are completely independent of, and perhaps only clouded by, any association of the axiomatic structure with some particular content. To consider geometry as a theory of space, one must decide upon an interpretation of its elementary concepts – a decision that must be guided by experience but that, by its very nature, cannot be empirically determined, precisely because it is a question of interpretation rather than of fact. Work inspired by this insight culminated in Hilbert's *Grundlagen der Geometrie* (1899).

In physics, according to Poincaré, geometry must be taken for granted at the outset because its central concepts are defined in geometrical terms. But the laws of mechanics, as a system of axioms, must also be seen as implicitly defining the central concepts of the theory. "Force equals mass times acceleration" is an empirical proposition only if force, mass, and acceleration are well defined independently of the law. In fact, it is the law that defines the criteria for being a Newtonian force, and for the measurement of mass. So this law, too, may be regarded as a "definition in disguise." Its empirical content is that we should expect – and are in fact required – to find a physical source wherever we measure an acceleration. As the foundation of an empirical program, this definition of force was an overwhelming success, counting among its accomplishments the discovery of universal gravitation. Its empirical achievements do not alter the fact that its fundamental principles express criteria for the application of its central concepts, rather than directly making empirical claims. The indirect empirical claim is that Newtonian forces will actually be found, and will account for the relative motions that we observe as interactions between Newtonian masses – a claim whose evaluation, according to Poincaré, has an inevitably pragmatic dimension, since its realization is always incomplete.

Conventionalism and twentieth-century science

Poincaré's conventionalism played a decisive role in the emergence of modern philosophy of science, because some of its main ideas were exemplified in the revolutionary changes, at the beginning of the twentieth century, in the foundations of physical geometry. Taking the Newtonian space-time framework for granted, and developing a theory of electrodynamics within it, physicists had reasonably expected that the relative motion of the earth and the ether should have empirically measurable consequences. The failure to detect such consequences, for example in the Michelson–Morley experiments, is not by itself a refutation of the theory, and it was perfectly reasonable to explain it away through the Lorentz contraction; assuming that the spatio-temporal framework imposes criteria on such explanations, and doesn't admit the possibility of an invariant velocity, the framework requires us to construct something like the Lorentz hypothesis to explain the apparent invariance of the velocity of light. The challenge to this prevailing view came from Einstein, who explicitly applied his own version of Poincaré's philosophy. First, he recognized that the problem addressed by Lorentz arose from implicit assumptions regarding the measurement of space and time. Second, he claimed the right to reject these assumptions, and to revise the framework of space and time, by introducing a new definition of simultaneity, based on the stipulation that light signals take the same time to travel equal distances in arbitrary directions:

> I stand by my previous definition … because, in reality, it assumes nothing at all about light. Only one requirement is to be set for the definition of simultaneity: that in every real case it provide an empirical decision about whether the concept to be defined applies or not. That my definition achieves this cannot be disputed. That light requires the same time to travel the path from A to M and the path from B to M is neither a supposition nor a hypothesis about the physical nature of light, but a stipulation that I can make according to my own free discretion, in order to achieve a definition of simultaneity.
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> (Einstein 1917: 15)

In the case of general relativity, Einstein showed that the Newtonian and special-relativistic definitions of inertial frame are undermined by the phenomenon of free fall, and the empirical indistinguishability of an inertial frame from a freely falling frame. His new theory of space, time, and gravity redefined inertial motion as the trajectory of a freely falling particle, and redefined the gravitational field as the curvature of space-time induced by the presence of mass-energy. Analogously to the case of special relativity, it remained logically possible, in the face of the evidence for Einstein's theory, to maintain the framework of flat space-time, so that the relative accelerations of falling bodies would, by definition, indicate the presence of perturbing forces.

Einstein argued, in both cases, that new definitions are justified by an empirical ambiguity in the application of the old definition. Poincaré did not live to see the advent of general relativity, but he argued that special relativity and Newtonian space-time represent conventions between which scientists must choose – not on strict empirical grounds, since both can be reconciled with the evidence, but on more pragmatic grounds of convenience and simplicity (Poincaré 1912). This general idea, as adopted and interpreted by Schlick (1917) and Reichenbach (1928), became a central idea of the logical empiricists, and was most carefully elaborated in Carnap's idea of a linguistic framework (e.g., Carnap 1950; see also Friedman 1999). A theoretical framework in empirical science, by virtue of its defining principles (linguistic rules), determines a class of "internal" questions that can be answered by empirical methods appropriate to the theory; the choice between alternative frameworks, in contrast, is an "external" question concerning the comparative suitability of the frameworks for the purposes they are supposed to serve. For example, the framework of Newtonian gravitation defines internal procedures for answering internal questions regarding the strength of a gravitational field in a given space. The framework of general relativity accomplishes the same empirical ends, but its internal questions concern the measurement of the space-time curvature. Each framework has its own conventions for interpreting theoretical concepts with empirical measurement and observation, variously known as "coordinative definitions," "correspondence rules," or "meaning postulates," but essentially identical to the conventions that Poincaré identified as establishing the connection between geometry and experience.

What diminished Poincaré, as the philosophical founder of this point of view, was his stated conviction that conceptual changes such as Einstein propounded would not actually take place: physicists, he claimed, would always prefer Newtonian physics in Euclidean geometry to non-Euclidean alternatives. One motivation for this claim was Poincaré's view of the relation between geometry and physics: because physics formulates its fundamental principles in geometrical terms, physics must take geometry as fixed *a priori*. In that case it would be reasonable to suppose that physics should begin with the simplest possible geometrical convention, which is, as a matter of mathematical fact, Euclidean geometry. Einstein's idea – that physics could begin with simple geometrical presuppositions, and proceed to physical discoveries that force a revision of those presuppositions and the adoption of a new geometry – would not quite make sense. Instead, Poincaré treated the Newtonian and special-relativistic space-time geometries as epistemically equivalent conventions, and held that physicists would maintain the simpler one. Einstein and the philosophers who followed him naturally could not sympathize with this view. But they interpreted it not as a failing of conventionalism in general, but as a mistaken application of it. A theory of physical geometry rests on a combination of physical and geometrical principles, and so physicists choose not the simplest geometry, but the simplest combination of geometry and physics. When increasingly complicated physical hypotheses are required in order to reconcile the simplest geometry with the empirical evidence, the desideratum of simplicity recommends a change of convention. Thus Einstein and his followers reconciled what they saw as the essence of conventionalism with their conviction that, after all, Einstein's theories were objectively superior to their predecessors. (See Einstein 1922, Schlick 1917, Reichenbach 1928, Carnap 1995.)

This last point is important for understanding the place of conventionalism after Einstein, and after the decline of logical empiricism. In the later twentieth century various refutations of conventionalism were proposed, generally arguing for a sound epistemic distinction, and therefore sound epistemic reasons to choose, between geometrical theories that Poincaré would have regarded as equivalent on all but pragmatic grounds (e.g. Putnam 1974, Glymour 1977, and Norton 1994). Evidently such arguments are directed at conventionalism as a problem of underdetermination; they do not undermine Poincaré's point about the crucial role of interpretive principles in establishing the empirical content of geometry. Therefore they are not so far in spirit from the arguments of Einstein and the logical empiricists for special relativity, and later general relativity, as profound improvements in our understanding of space and time. But the latter arguments focused on the interpretive principles themselves: on how Einstein had identified the empirically uninterpreted concepts in existing theories, and had constructed new theories on definitions that satisfied – in the sense of Einstein's remark about the definition of simultaneity – empirical conditions of adequacy (e.g. Reichenbach 1949). In this sense the logical empiricists did not all, or always, see geometry as a purely pragmatic decision between empirically equivalent alternatives. Nor, however, did they provide a completely clear analysis of Einstein's definitions, or their empirical and philosophical significance. Their philosophical discussions of general relativity in particular, much like Einstein's own, were clouded by other philosophical aims, especially their aim to vindicate a broadly philosophical notion of relativity, and to dismiss earlier notions of space-time structure as merely metaphysical. A rational account of conceptual change in the physics of space-time, and of the role of interpretive principles in the sense of Poincaré and Einstein, requires more attention to the interplay between conceptual analysis and empirical evidence in the construction of fundamental principles (cf. Friedman 2002, DiSalle 2002).

Conventionalism and twentieth-century philosophy

The foregoing also clarifies the status of conventionalism in light of what was the most influential critique of it, namely, Quine's critique of the analytic–synthetic distinction (1953). In Quine's account of scientific knowledge as a "web of belief," or a "man-made fabric which impinges upon experience only along the edges" (Quine 1953: 42), no principled distinction can be made between facts and conventions. This is because, in Quine's interpretation, conventions are the principles that are taken to be "true by convention," and that are maintained "come what may" – that is, in the face of recalcitrant experiences. According to Quine, however, all of the propositions that form the fabric of our belief are more or less susceptible to pressure from empirical evidence, and therefore subject to revision on empirical grounds; the difference between empirical hypotheses and fundamental principles, of the sort that the logical empiricists would call conventional, is therefore merely a difference of degree. The former are closer to the periphery, the latter to the center of the web of belief. This implies only that revising the latter to adapt to experience has ramifications for more intervening principles, and is a correspondingly more complex and difficult process.

> Re-evaluation of some statements entails re-evaluation of others, because of their logical interconnections – the logical laws being in turn simply certain further statements of the system, certain further elements of the field. … But the total field is so undetermined by its boundary conditions, experience, that there is much latitude of choice as to what statements to re-evaluate in the light of any single contrary experience. No particular experiences are linked with any particular statements in the interior of the field, except indirectly through considerations of equilibrium affecting the field as a whole.
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> (Quine 1953: 42)

This implies that the interior principles appear to have an essentially different character only because it is more difficult to revise them, rather than vice versa.

Quine's argument superficially seems to restate the celebrated holist argument of Duhem (1906), that empirical tests always test the entire body of physical theory, so that, in the case of failure, there is no logical compulsion to fault any particular principle. Yet Duhem's position is in fact closer to Poincaré's than it first appears. Duhem also acknowledged that certain fundamental principles play a distinctive role in the organization of a program of inquiry; he disagreed with Poincaré's inference that such principles could be held immune from refutation – not because they are indistinguishable from empirical hypotheses, but because the program that they define may eventually fail to solve the problems that it was meant to solve. Poincaré, on his side, did not hold that conventions were removed from experience and could be held "true, come what may"; they were guided by experience, and could be abandoned if experience made their use impractical. They were not "true come what may," because they were not the sort of principle to which the notion of truth properly applies. They express relations between concepts, or between concepts and experience, and so they define the framework within which other principles can be formulated, and found to be empirically true or false. In this respect, conventionalism provides a groundwork, without appealing to *a priori* categories of the understanding, for the Kantian idea of "empirical realism." The history of physical geometry, at least, suggests that Poincaré's conventionalism illuminated an aspect of conceptual structure in science that is unfortunately overlooked in Quine's attack on "truth by convention" (cf. Ben-Menahem 2006, Coffa 1983, DiSalle 2002). For this reason it is also unfortunate that conventionalism in the sense of Poincaré and Carnap is associated with the notion of voluntarism; voluntarism historically suggests a willful decision to regard a proposition as true, whereas conventionalism is meant to separate all questions of truth from decisions about the framework within which the truth will be pursued.

A further omission from Quine's account is the relation between conventions and experience. Quine's metaphor of a web, with an interior and a periphery, separates fundamental principles from experience in a way that is difficult to reconcile with the actual history of mathematical physics. Einstein's definition of simultaneity stands at the very center of special relativity, a stipulation on which the relativistic space-time framework is constructed. Yet it touches immediately on experience, insofar as experimental evidence for the variability of the velocity of light would immediately cast doubt on it – contrary to the assertion of Quine cited above. Similarly, experimental evidence that different bodies are differently affected by the gravitational field, that is, evidence against the equivalence of gravitational and inertial mass, would directly affect the fundamental principles of general relativity. The important point here is not merely that the history of science offers counterexamples to Quine's account of science. It is, rather, that his account fails to capture an essential feature of conventions, one that is indispensable to understanding the philosophical interest that conventionalism maintained for a large part of the twentieth century. A convention, in Poincaré's sense, was supposed to characterize the conceptual significance of some outstanding phenomenon – to show that such a phenomenon gives an empirical interpretation to some conceptual structure, and establishes the connection between mathematical formalism and physical reality that makes mathematical physics possible. Neither Poincaré nor the logical empiricists succeeded in articulating this idea quite clearly, without suggesting a degree of arbitrariness that only makes its role in the historical progress of physics harder to understand.

See also Logical empiricism; Space and time; Underdetermination.

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Further reading

The works of Poincaré are easily accessible in translation, and still offer the clearest view of the origins and motivations of conventionalism, in their scientific and philosophical context. See especially Chapter III of *Science and Hypothesis*, available in the volume *Foundations of Science* (New York: Science Press, 1913, and in various reprint editions). Hans Reichenbach's *The Philosophy of Space and Time* (New York: Dover, 1957) shows how conventionalism was understood and applied within the logical empiricist movement, and to the interpretation of relativistic physics. Among later studies of conventionalism, Jerzy Giedymin's *Science and Convention* (Oxford: Pergamon, 1982) offered a new appreciation of its importance to the development of science in the twentieth century. But the most useful recent analysis of conventionalism is Yemima Ben-Menahem's *Conventionalism* (Cambridge: Cambridge University Press, 2006), which clarifies Poincaré's views and their connection with those of Duhem, Hilbert, the logical empiricists, Wittgenstein, and others; it contains a particularly original and penetrating analysis of Quine's critique of conventionalism. On conventionalism in the foundations of geometry, its historical origins, and its connection with the development of formal geometry in the nineteenth century, see Roberto Torretti, *Philosophy of Geometry from Riemann to Poincaré* (Dordrecht: Reidel, 1978) and Lorenzo Magnani, *Philosophy and Geometry* (Western Ontario Studies in the Philosophy of Science, v. 66, Dordrecht: Kluwer, 2002). For detailed analyses of conventionalism and the legacy of logical empiricism, see Michael Friedman's *Reconsidering Logical Positivism* (Cambridge: Cambridge University Press, 1999). Robert DiSalle's *Understanding Space-time* (Cambridge: Cambridge University Press, 2006) situates conventionalism within the history of the physics of space and time. Alberto Coffa's *The Semantic Tradition from Kant to Carnap* (Cambridge: Cambridge University Press, 1993) explains the importance of Poincaré's conventionalism in the development of semantic themes in modern analytic philosophy.