A Post-Kuhnian Approach to the History and Philosophy of Science

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What I call the dynamics of reason is an approach to the history and philosophy of science developed in response to Thomas Kuhn’s theory of scientific revolutions. Unlike many philosophical responses to Kuhn, however, my approach, like Kuhn’s, is essentially historical. Yet Kuhn’s historiography, from my point of view, is much too narrow. Whereas Kuhn focusses primarily on the development of the modern physical sciences from the Copernican revolution to Einsteinian relativity theory, I construct an historical narrative depicting the interplay between the development of the modern exact sciences from Newton to Einstein, on the one side, and the parallel development of modern scientific philosophy from Kant through logical empiricism, on the other. I use this narrative to support a neo-Kantian philosophical conception of the nature of the sciences in question—which, in particular, aims to give an account of the distinctive intersubjective rationality these sciences can justly claim. By contrast, Kuhn’s picture led to philosophical challenges to this claim, I argue, precisely because he left out the parallel history of scientific philosophy.

The basic ideas of this approach were presented in my *Dynamics of* Reason (Stanford, 2001), and I here want to discuss two extensions of these ideas. First, I want to make clear how the neo-Kantian conception in question represents a fundamentally *historicized* version of scientific intersubjective rationality, so that the standards of objectivity in question are always local and contextual. Nevertheless, in spite of—and even because of—this necessary historicization, the way in which such standards change over time still preserves the trans-historical rationality of the entire process. Second, I want to make a beginning in extending my narrative from purely intellectual history (both philosophical and scientific) to the wider cultural context. Far from supporting the idea that the relevant kind of scientific change is less than fully rational (because essentially political, for example), I argue that this second contextual extension only further highlights the importance of the neo-Kantian conception I am developing.

I begin with the fact that Einstein’s theory of relativity is the main example Kuhn gives, in Chapter IX of *The Structure of Scientific Revolutions* (Chicago, 1962), of a genuine revolution in science—a case where the post-revolutionary conceptual framework is *incommensurable* or non-inter-translatable with the pre-revolutionary framework. And I agree with Kuhn that Einstein’s general theory of relativity is in an important sense incommensurable or non-inter-translatable with the Newtonian theory of universal gravitation it replaced. Whereas Newtonian theory represents the action of gravity as an external “impressed force” causing gravitationally affected bodies to deviate from straight inertial trajectories with respect to Euclidean space and Newtonian time, Einstein’s theory depicts gravitation as a curving or bending of the underlying fabric of space-time itself. In this new framework, in particular, there are no inertial trajectories in the sense of the geometry of Euclid and the mechanics of Newton, and gravity is not an impressed force causing deviations from such trajectories. Gravitationally affected bodies instead follow the straightest possible paths or geodesics that exist in the highly non-Euclidean geometry (of variable curvature) of Einsteinian space-time; and the trajectories of so-called “freely-falling bodies”—those affected by no forces other than gravitation—replace the straight inertial trajectories of Newtonian theory.

In *Dynamics of Reason*, I explained the relevant kind of incommensurability as follows. It is clear, in the first place, that Einstein’s theory is not even *mathematically* possible from the point of view of Newton’s original theory, for the mathematics required to formulate Einstein’s theory—Bernhard Riemann’s general theory of geometrical manifolds or “spaces” of any dimension and curvature (Euclidean or non-Euclidean)—did not even exist until the late nineteenth century. Moreover, and in the second place, even after the mathematics required for Einstein’s theory was developed, it still remained fundamentally unclear what it could mean actually to apply such a geometry to nature in a genuine physical theory. One still needed to show, in other words, that Einstein’s new theory is *physically* possible as well, and this, in turn, only became clear with Einstein’s own work on what he called the principle of equivalence in the years 1907-12. This principle, as Einstein understood it, builds on the well-known physical fact (at least since Galileo) that all bodies fall the same in a gravitational field to suggest that gravity and inertia are the very same phenomenon. Moreover, as we now understand it, the principle implies that freely-falling bodies follow the straightest possible paths or geodesics in a certain kind of four-dimensional (semi-)Riemannian manifold, and it thereby gives objective physical meaning, for the first time, to this kind of abstract mathematical structure. Einstein’s theory thus required a genuine expansion of our space of intellectual possibilities (both mathematical and physical), and the problem is then to explain how such an expansion is possible. The problem of explaining the rationality of the transition from Newton to Einstein, from this point of view, reduces to explaining how such a conceptual expansion can itself be rational.

My strategy, as already suggested, is to consider the parallel developments in contemporaneous scientific philosophy. I begin with Kant’s original attempt—in his *Metaphysical Foundations of Natural Science* (1786), and also in the *Critique of Pure Reason* (1st ed., 1781; 2nd ed., 1787)—to provide philosophical foundations for Newtonian theory.[[1]](#footnote-1) In the following nineteenth century these Kantian foundations for specifically Newtonian theory were then self-consciously successively reconfigured, as scientific philosophers like Ernst Mach (and others) reconsidered the problem of absolute space, time, and motion, and other scientific philosophers—especially Hermann von Helmholtz and Henri Poincaré—reconsidered the empirical and conceptual foundations of geometry in light of the new mathematical discoveries in non-Euclidean geometry. Einstein’s initial work on the principle of equivalence (which culminated, as I said, in 1912) then unexpectedly put these two earlier traditions together, and thereby led to the very surprising and entirely new conceptual possibility that gravitymay, after all, be represented by a non-Euclidean geometry.[[2]](#footnote-2)

The crucial breakthrough came when Einstein (in 1912) came upon the example of the uniformly rotating disk or reference frame—where, in accordance with the principle of equivalence, we are considering a particular kind of *non*-inertial frame of reference within the framework of special relativity. The result was a non-Euclidean physical geometry as our novel representative of the gravitational field, and Einstein was only able to arrive at this result by delicately situating himself within the earlier philosophical debate on the foundations of geometry between Helmholtz and Poincaré. It is precisely here, I argue, that Einstein was able to connect this debate on the foundations of geometry with the earlier debate on the relativity of space, time, and motion in an entirely unexpected way—so that a radically new kind of space-time geometry then naturally (and rationally) emerges from an unanticipated convergence or intersection between two previously independent lines of thought. More specifically, two continuously evolving traditions of thought in mathematics and scientific philosophy at first developed independently of one another, but then unexpectedly *intersected* with one another at the level of scientific theory itself—and this, in my view, was the source of the genuine conceptual discontinuity that does in fact arise at this level. The upshot, however, is that, although Einstein’s theory remains conceptually incommensurable or non-intertranslatable with the Newtonian theory it replaced, the way in which it was inextricably entangled with the previous traditions in question explains how it was nevertheless rational—for *all* parties to the earlier debates—to accept Einstein’s radical expansion of the Newtonian space of conceptual possibilities as both mathematically and physically possible (as, in Kantian terminology, *really* possible).

What all this shows, in my view, is the need to relativize the Kantian conception of a priori scientific principles to a particular theory in a given historical context and, as a consequence, to historicize the notion of scientific objectivity (the notion of intersubjective scientific rationality) itself. Thus, for example, whereas Euclidean geometry and the Newtonian laws of motion were in fact—just as Kant thought—necessary presuppositions for the objective empirical meaning of the Newtonian theory of universal gravitation, the radically new conceptual framework consisting of the Riemannian theory of manifolds and the principle of equivalence defines an analogous system of necessary presuppositions in general relativity. Moreover, what makes the latter framework rationally acceptable in this new context is precisely the circumstance that Einstein actually arrived at it historically by self-consciously situating himself within the earlier tradition of scientific philosophy represented by Helmholtz, Mach, and Poincaré—just as this tradition, in turn, had earlier self-consciously situated itself against the background of the original conception of “transcendental” scientific rationality first articulated by Kant. It turns out, therefore, that the radically new Einsteinian conceptual framework not only contains a system of possibility-defining necessary presuppositions analogous to those of the Newtonian framework it replaced, but it in fact *evolved from* this earlier framework as well, through precisely an intervening tradition of mathematics and scientific philosophy. Given the historical context within which Einstein’s theory was developed, it arrived at a practically optimal solution to the over-all intellectual problem situation with which it was faced—a situation comprising a complex and subtle mixture of mathematics, physics, and philosophy.[[3]](#footnote-3)

In order further to illustrate the force of the relativization and historicization of scientific rationality I am proposing (and to prepare the way, in addition, for the second part of this essay), I will now briefly describe the historical and conceptual context in which Kant’s original conception was formulated. Kant, like all those seriously interested in natural philosophy and metaphysics in the eighteenth century, was greatly influenced by the stage-setting intellectual debate between Newton and Leibniz culminating in the Leibniz-Clarke correspondence (1715-1716). Kant, from the beginning, was a convinced Newtonian in physics and natural philosophy, but he was also convinced that a broadly Leibnizean metaphysical foundation for this new physics was urgently needed. In particular, Newtonian absolute space was clearly unacceptable on metaphysical (and theological) grounds, but we still needed to account for the distinction between “true” and merely “apparent” motion Newton articulates in the famous Scholium to the Definitions in the *Principia*. Kant’s task, therefore, was to reformulate this Newtonian distinction without Newtonian absolute space, against the background of the fundamental metaphysical concepts—substance, causality, and so on—which have their origin, according to Leibniz, in the logical structure of our pure intellect.

Now recent scholarship has made it increasingly clear that the Scholium to the Definitions in the *Principia* proceeds against the background, in turn, of Newton’s rejection of Cartesian metaphysics and natural philosophy.[[4]](#footnote-4) In particular, Newton needed to reject both the Cartesian version of the relationship between true and apparent motion and the Cartesian conception of the relationship between space and matter in order successfully to arrive at his own revolutionary version of mathematical physics—which, for the first time, introduced Newtonian impressed forces (such as the force of universal gravitation) into natural philosophy. This becomes especially clear in Newton’s unpublished manuscript *De Gravitatione* (whose date is uncertain but may have been composed around 1685 during approximately the same time as the composition of the Scholium); for it is here that Newton defends a metaphysics of space and its relationship to God and the divine creation, indebted to the “Cambridge Platonism” of Henry More, that is explicitly opposed to the corresponding metaphysical and theological views of Descartes.[[5]](#footnote-5)

Newton begins by declaring that absolute space is neither a substance nor an accident, but what he calls “an emanative effect of God and an affection of every kind of being” (*De Grav.*, p. 21). In particular, absolute space or pure extension is even an affection of God himself, since God is omnipresent or everywhere. God can thereby create matter or body (as something quite distinct from pure extension) by endowing certain determined regions of space with the conditions of mobility, impenetrability, and obedience to the laws of motion. And God can do this anywhere in space, in virtue of his omnipresence, by his immediate thought and will, just as our souls can move our bodies by our immediate thought and will. It is essentially this doctrine which surfaces in Newton’s well-known published statements, in the General Scholium to the *Principia* and the Queries to the *Optics*, that space is the “sensorium” of God.[[6]](#footnote-6)

I cannot make the argument in detail here (see note 8 below), but I believe that it was precisely this metaphysical background that made it possible for Newton to achieve his revolutionary break from the then dominant mechanical natural philosophy (as paradigmatically formulated by Descartes). For, in order successfully to formulate his theory of universal gravitation, Newton not only needed to articulate a distinction between true and apparent motion, he also needed to introduce what we now conceive as a fundamental force of nature (gravitation) that acts immediately at a distance. Yet Newton himself rejected action at a distance in the metaphysical sense, as the action of one substantial agent on another not subject to the then universally accepted condition of local presence, and he suggested instead (e.g., in his well-known letter to Richard Bentley of February 1693) that it might well be God himself (or perhaps some ubiquitous immaterial agent directly dependent on God) who is ultimately responsible for gravitational attraction.[[7]](#footnote-7) Newton’s “neo-platonic” metaphysics of space and divine creation thus made it possible for him to accept gravitational attraction as a real physical force without committing himself to genuine action at a distance.

Kant, in the *Metaphysical Foundations of Natural Science***,** reconceives Newton’s distinction between true and apparent motion without Newtonian absolute space, and he also mounts a strenuous defense of gravitational attraction as a true and immediate action at a distance through empty space. In particular, Kant entirely rejects the idea that any other “agent” (including God) is needed to mediate this interaction, and he thereby incorporates the theory of universal gravitation into his own version of a metaphysical foundation for physics. In the context of the more general transcendental philosophy articulated in the first *Critique***,** Kant thus arrives at a two-fold reinterpretation of Newtonian absolute space. On the one hand, space—empty space—is a form of our pure sensibility, within which all outer objects are necessarily perceived. On the other hand, absolute space, as an ultimate frame of reference for distinguishing between true and apparent motions, is reconceived as a forever unreachable regulative idea of reason—where, on the basis of Newton’s three laws of motion, we move from our parochial perspective here on earth to a more encompassing frame of reference fixed at the center of gravity of the solar system, to a still more encompassing frame of reference fixed at the center of gravity of the Milky Way galaxy, to a still more encompassing frame of reference fixed at the center of gravity of a rotating system of such galaxies, and so on *ad infinitum*. In particular, it is *our* pure intellect (not God’s) which injects the Newtonian laws of motion into the form of *our* pure sensibility (not the sensorium of God); and it is in precisely this way that Kant now decisively transforms the metaphysical tradition he inherited (including Newton’s own metaphysics of space) into something radically new: Kant replaces a theological foundation for the metaphysics of nature with his characteristic conception of transcendental objectivity.[[8]](#footnote-8) What is objective, on this view, is precisely that to which all human beings—in virtue of their shared rational faculties of sensibility and understanding—must necessarily agree. And, in this way, Kant’s original conception of transcendental objectivity itself arose as a practically optimal solution to the intellectual problem situation with which *he* was faced.[[9]](#footnote-9)

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I now want to make a beginning in connecting this kind of intellectual history—both philosophical and scientific—with the wider cultural context by sketching an extended historical narrative that depicts how some the developments in modern science and philosophy I have just been considering were inextricably entangled with technological, institutional, and political developments—often in surprising and unexpected ways.

The scientific and philosophical developments in question originate in the history of astronomy—in the attempt to develop rigorous mathematical models of the observed motions of the sun, moon, stars, and planets as seen from our everyday perspective here on the surface of the earth. And this enterprise, in turn, was inextricably entangled, from the very beginning, with a fundamental human interest in keeping track of the progression of the seasons. From this point of view, the most basic astronomical phenomenon involves the observed periodic changes in the daily rising and setting of the sun—as we proceed from the autumnal equinox (September 23rd on the modern calendar), when day and night are equal, to the winter solstice (December 22nd), when night is as long as possible, to the vernal equinox (March 21st), when day and night are again equal, to the summer solstice (June 22nd), when day is as long as possible, and so on. The practice of agriculture, of course, very much depends on our ability to anticipate these seasonal variations, and so does the regulation of the mythical and religious rituals that have gradually grown up surrounding this practice. The calendar, we might say, represents our fundamental material technology for regulating both the practice of agriculture and the associated religious rituals.

But there is a serious technical problem—a technological problem, if you will—in setting up an accurate calendar: the solar year (defined by the periodic progression from equinox to equinox) does not contain an integral number of solar days (defined by the period between one noon—when the position of the sun is highest in any daily cycle—and the next).[[10]](#footnote-10) The earliest (Babylonian) calendars used a year of 360 days, but this led to the result that important seasonal events, like the flooding of the Nile in Egypt, quickly became out of phase with the seasons. The Egyptians therefore added five additional days to the year, but the number 365 is also too short, and we were again out of phase with the seasons after about forty years. Julius Caesar then reformed the calendar in 45 B.C., with technical assistance from the Alexandrian astronomer Sosigenes, using a year of 3651/4 days—so that three years of 365 days were followed by one year of 366 (a “leap year”), and so on. However, the seasonal year is actually 11 minutes and 14 seconds shorter than 3651/4 days, so that, by the time of the publication of Copernicus’s *De Revolutionibus* in 1543, the vernal equinox had moved backwards from March 21st to March 11th. The Catholic Church, during the height of the Counter-Reformation, aimed to regulate the observance of Easter throughout Christian Europe, and it thus needed to reform the calendar once again. (Easter is defined as the first Sunday after the first full moon after the vernal equinox.) The result, the modern Gregorian Calendar, adopted by the Church in 1582, suppresses a normal leap year three times every four centuries: for example, the years 1600 and 2000 were leap years, but the years 1700, 1800, and 1900 were not—neither will be the year 2100, and so on.[[11]](#footnote-11)

The crucial question, from our present point of view, is what exactly this modern reform of the calendar had to do with the modern reform of mathematical astronomy initiated by Copernicus. At first sight, the answer may appear obvious. The Gregorian reform occurred thirty-nine years after the publication of *De Revolutionibus*, and the papal commission formed by Gregory XIII—led by the Jesuit mathematician Christoph Clavius—elected to use the Prutenic Tables based on the Copernican system in place of the older Alphonsine Tables derived from Ptolemy. It turns out, however, that this was a mere accident. Copernican astronomy, although in several respects simpler and more harmonious than Ptolemaic, does not provide an intrinsically more accurate model of the solar orbit (or, in this case, the earth-sun orbit). Astronomy in the Copernican tradition was not able significantly to improve on Ptolemy in this respect until Kepler’s radical innovations early in the following century—whereby circular orbits governed by the principle of uniform (circular) motion were eventually replaced by elliptical orbits governed by what we now call Kepler’s laws. And this came too late, of course, to influence the initial construction and promulgation of the Gregorian Calendar in 1582.

The true story of how the Gregorian reform was in fact inextricably entangled with the new mathematical astronomy has recently been told by John Heilbron in *The Sun in the Church: Cathedrals as Solar Observatories* (Cambridge, Mass., 1999). Beginning before 1582 and continuing well after it, mathematical astronomers took the Church’s overriding concern for extremely accurate calculations of the vernal equinox as a golden opportunity to devise more accurate measurements of the solar orbit (or earth-sun orbit) for their own purposes. They realized, in particular, that the great Catholic cathedrals of Europe could function as especially good gnomons—or *meridiane*—for precisely tracking the solar orbit throughout the seasonal year. An exact north-south line (or meridian) drawn on the floor of such a cathedral which would be illuminated every day by the sun’s light (let in through an aperture high up in the cathedral) at precisely noon: exact measurements of the successive daily progress of the sun’s image could then precisely determine the solar orbit. The most important of these *meridiane* was constructed by the Jesuit astronomer Gian-Domenico Cassini in the basilica of San Petronio in Bologna in 1655—revising and perfecting an earlier meridian line devised by the astronomer Egnatio Danti in 1576. And Cassini’s most striking result, derived by precisely measuring the sun’s image along his perfected meridian line in San Petronio, was that the solar orbit (or earth-sun orbit) is more accurately described by Kepler than either Copernicus or Ptolemy.

What Cassini confirmed, more precisely, was the bisection of the solar eccentricity first introduced by Kepler while exploring an earlier theory of planetary orbits based on an eccentric circle rather than an ellipse (where the orbital speed of a planet was taken to be inversely proportional to its distance from the sun).[[12]](#footnote-12) On this theory, the distance between the earth and the (eccentric) center of the solar orbit is one-half the amount postulated by Ptolemy (and Copernicus), so that, in particular, the sun is considerably closer to the earth at aphelion and considerably further at perihelion. Kepler himself had confirmed this bisection within his evolving planetary theory using multiple observations of Mars at a fixed point in its solar orbit (observations from the earth separated by 687 days, the duration of Mars’s orbital period). Cassini, however, using the great *meridiana* at San Petronio, confirmed it directly (independently of orbital theory) by measuring the changes in the apparent diameter of the sun’s image on the floor of the Cathedral.

In order to see the astronomical significance of this issue, note that Ptolemy had used bisected eccentricity for the planetary orbits, but not for the solar orbit—where, for the planets, this involved the use of an equant point relative to which the angular speed is constant. Moreover, such a Ptolemaic orbit with bisected eccentricity and equant point is very close to the finished Keplerian orbital theory—with ellipse and area law—when the eccentricity is very small. Yet, as we have seen, Kepler did not arrive at this finished theory all at once, and the intermediate stage of using circular orbits with bisected eccentricity (and the inverse-proportionality to distance law for orbital speed) marked a crucial transition in the evolution of his thought. For it showed that the solar orbit (the earth-sun orbit) behaves, in this important respect, just like the other planetary orbits. (When the eccentricity is very small, the inverse-proportionality to distance law is very close to both the area law and the Ptolemaic equant law.)

Heilbron argues, on this basis, that the *meridiane* constructed in some of the great Catholic cathedrals of Europe during the years preceding and following the initial Gregorian reform show that the Church’s relationship to the new mathematical astronomy was much more complicated and interesting than is typically thought. During the same period in which Galileo was very publicly condemned for defending the Copernican system, the Church itself—because of its overriding interest in precisely fixing the date of Easter once and for all—was providing the new astronomy with important observational support. The Catholic Church, on Heilbron’s telling, was thus far from a monolithic opponent of the new astronomy. But what is the precise relevance, we now need to ask, of Heilbron’s lovely story for the modified form of Kantian history and philosophy of science I have been developing?

To begin with, the events described by Heilbron are intimately connected with the purely intellectual narrative presented above. In the very first proposition of Book 1 of the *Principia*, for example, Newton showed that Kepler’s area law—now assumed to manifest the action of a what Newton calls a centripetal force—is mathematically equivalent to the law of inertia. Indeed, it was this fundamental Newtonian derivation that convinced most astronomers of the truth of the area law by indicating its precise dynamical significance.[[13]](#footnote-13) And, although Newton carefully leaves it open, in Phenomenon 4 of Book 3, whether the solar system as a whole is Copernican or Tychonic, he finally arrives, in Propositions 11 and 12 of Book 3, at the result that it is the center of gravity of this system (which is always very close to the center of the sun) that defines a privileged (approximately inertial) frame of reference for describing the totality of orbital motions therein. Newton thereby defines both a privileged absolute space and a privileged absolute time; and Kepler’s description of the earth-sun orbit (and the other planetary orbits) was thus grounded in the abstract theoretical standard of temporal measurement defined by the Newtonian laws of motion. But this standard is also seen to be inextricably entangled, via Heilbron’s story, with the institutional history of the Church; and the metaphysical and theological aspects of Newton’s achievement (his neo-platonic metaphysics of space) are thereby seen to be inextricably entangled with the wider cultural struggles of the time, as the whole of Christian Europe wrestled with the radically new configuration of science, society, religion, and philosophy emerging from the aftermath of the Reformation and the scientific revolution.

Now Leibniz, more than anyone, was deeply involved with the totality of these cultural struggles. He was personally involved, in particular, with what we might call the “second” Gregorian reform of the calendar: the events at the turn of the eighteenth century that finally brought Protestant Europe on board. As Heilbron explains, Cassini found a mistake in Clavius’s original calculation of the lunar cycle that would seriously distort the Gregorian predictions for Easter after 1700 (the first suppressed leap year after the Gregorian reform), and this gave the Church a golden opportunity officially to correct this mistake and thereby get the Protestant lands to go along with the Gregorian calendar as so corrected and revised.[[14]](#footnote-14) Pope Clement XI, with Cassini’s help, commissioned a new *meridiana* in Santa Maria degli Angeli in Rome for this purpose, and the publication of the official results from this *meridiana* in 1703—which confirmed the original Gregorian determination of the vernal equinox—was then an important factor in securing the cooperation of Protestant Europe. The construction of this new *meridiana* was overseen by the astronomer Francesco Bianchini, and Leibniz corresponded with Bianchini about the project (concerning which he was very enthusiastic) during the years 1700 – 1705.[[15]](#footnote-15)

Here, as Heilbron also explains, Leibniz was concerned with both furthering his goal of the reunification of Protestant and Catholic churches and, at the same time, using Clement XI’s interest in astronomy to promote a grand compromise between the Church and Copernicanism in which the Church would allow Copernicans to hold that their opinion is the simplest and most intelligible—and in this sense “truest”—hypothesis, and the Copernicans would concede that there is no need to reinterpret Scripture from a heliocentric point of view. Of course Leibniz failed in both of these grandiose schemes; but the crucial question, from our point of view, concerns the role Leibniz’s theological and political ambitions played in his assimilation and response to Newton’s *Principia*—and the way in which these ambitions, in turn, then impacted on Kant’s assimilation of Newton.

With respect to Leibniz’s assimilation and response to Newton’s *Principia*, we can rely on the detailed and insightful work of Domenico Bertoloni Meli.[[16]](#footnote-16) In 1688 Leibniz read the *Principia*, paying particular attention to Proposition 1 of Book 1, and, on this basis, he developed his own mathematical decomposition of orbital motion governed by Kepler’s area law into a circular component and a continuously varying radial component. This led to the publication of his *Essay on the Causes of Celestial Motions* in the following year, where Leibniz embedded this mathematical decomposition within a vortex theory aiming to give the true physical causes of the planetary motions.[[17]](#footnote-17) He appealed not only to Kepler’s laws, but also to Kepler’s notion of “true hypothesis”—as the simplest and most intelligible account of a given phenomenon. And it is clear from “On Copernicanism and the Relativity of Motions,” composed in 1689, that this notion of true hypothesis, for Leibniz, was closely related to the one he used in his attempt to fashion a grand compromise between Copernicanism and the Church.[[18]](#footnote-18)

Leibniz aimed, with his Keplerian vortex theory, to supplant Newtonian orbital theory with his own, and he even pretended that he had developed this theory prior to reading the *Principia*. But Leibniz was not successful in convincing the learned on either count, not even his erstwhile friend and mentor Christiaan Huygens in their correspondence of 1690-1694.[[19]](#footnote-19) Thereafter, Leibniz moved away from directly challenging Newton in celestial mechanics and increasingly concentrated on metaphysical and theological issues, culminating in the publication of the *Theodicy* in 1710. When his friend and patroness Caroline Ansbach became Princess of Wales in 1714, Leibniz seized on this new opportunity, not only to challenge Newton on his own soil, but also to further the project of reconciling the principal Protestant denominations—Lutheran, Calvinist, and Anglican. The enduring result of these endeavors was the celebrated correspondence between Leibniz and Clarke (1715-1716), which, as Bertoloni Meli has convincingly demonstrated, exhibits clear traces of Leibniz’s ecumenical ambitions for reconciling the Churches.

The main question relevant to these ambitions, as discussed explicitly in both the *Theodicy* and Leibniz’s correspondence with Caroline, concerned the precise way in which Christ is supposed to be present in the Eucharist—a question which, as Bertoloni Meli argues, is intimately related to Leibniz’s rejection of both real action at a distance between bodies and the Newtonian doctrine of divine omnipresence in space. Thus, for example, whereas Catholicism taught that the substance of the bread in the Eucharist is miraculously transformed into the substance of the body of Christ, the Lutheran position endorsed by Leibniz held only that both substances, while still remaining separate, were nevertheless miraculously received at the same time and place. Moreover, whereas the Newtonians adopted the absurd position that God was himself substantially present throughout all of infinite space, Leibniz required only God’s virtual presence in space through his action—which, in the Eucharist, brought it about (miraculously) that we are acted upon by both the bread and the body of Christ at the same time and place.[[20]](#footnote-20) Leibniz’s essentially *dynamical* conception of corporeal substance, which took action rather than spatial extension as the mark of its substantiality, was thereby inextricably connected with his ongoing program for Church reunification.[[21]](#footnote-21)

The Leibniz-Clarke correspondence set the stage, in turn, for the great debates in metaphysics and natural philosophy of the eighteenth century, and, in particular, for the critical philosophy of Kant—whose intellectual career, I have suggested, is best understood as a succession of increasingly sophisticated attempts to fashion some kind of synthesis of Newtonian physics and Leibnizean metaphysics.[[22]](#footnote-22) The problem, as it presented itself to the eighteenth century—and, especially, to Kant—was that, since Newtonian physics had clearly won the day, the great metaphysical project of the seventeenth century of showing that it is the new science, after all, that best conforms with orthodox Christian theology, had decisively failed. Leibnizean metaphysics was the last best hope for such an orthodox theological foundation for the new science, and Newton’s own metaphysics—which essentially involves a real (substantial) omnipresence of God throughout all of infinite space—could not possibly be harmonized with any variety of orthodox Christianity. The solution Kant came up with, as I have also suggested, was to break fundamentally with the metaphysical-theological tradition he inherited. The phenomenal world in space and time is indeed Newtonian. It even involves a new notion of substantial interaction modelled on gravitational attraction at arbitrarily large distances across empty space. But the supersensible world beyond space and time—the world containing God and human souls, which Leibniz had correctly characterized in the *Theodicy* as the “kingdom of grace”—is no possible object of theoretical knowledge at all. It is instead the subject of purely *practical* (i.e., *moral*) cognition, as presenting us with an infinitely distant ideal of a perfect moral community (the “kingdom of ends”) that we can only successively approximate but never actually attain.[[23]](#footnote-23) In this way, Kant’s assimilation of Newton, refracted through Leibniz’s complex set of ambitions in physics, metaphysics, politics, and theology, eventually led to the radical new idea of a purely moral religion.[[24]](#footnote-24)

In this essay, more generally, I have been exploring a complicated and subtle set of interactions among mathematics, physics, philosophy, technology, religion, and politics. And it is clear, I hope, that this inextricable entanglement between abstract theory (mathematical, scientific, and metaphysical) and its concrete cultural context is just that—a mutual interaction between equally important quasi-autonomous processes, where, in particular, neither is simply determined by the other. Thus, for example, while the institutional and political interests of the Church substantially conditioned, as we have seen, the practice and reception of the new mathematical astronomy, these interests by no means determined the surprising and entirely unexpected result: that the cathedral observatories constructed in the context of the Gregorian reform of the calendar turned out to provide the new astronomy with one of its most important sources (at the time) of direct observational confirmation. Similarly, the circumstance that the Kantian philosophical synthesis of early modern thought at the end of the eighteenth century was substantially influenced, through the great confrontation between Newton and Leibniz, by the wider cultural struggles emerging from the aftermath of the Reformation and the scientific revolution, by no means detracts from its intellectual integrity. Just as the Kantian synthesis provided a revolutionary solution to the purely intellectual problem situation with which it was faced, it provided a perhaps even more important (and very influential) response to these wider cultural struggles—a response, once again, that fundamentally transformed the original Leibnizean cultural and political ambitions into something entirely new.[[25]](#footnote-25)

In the first part of this essay I explained the way in which Kant’s original philosophical synthesis was successively modified by scientist-philosophers like Helmholtz, Mach, Poincaré, and Einstein, who responded to Kant’s system in the light of striking new discoveries in mathematics and mathematical physics: the development of non-Euclidean geometries, the rise of the wave theory of light, the discovery of the conservation of energy and the development of thermodynamics, the formulation of the modern theory of electricity and magnetism by Maxwell, the theory of the electron articulated by H. A. Lorentz following Maxwell’s work, and finally the special and general theories of relativity. Helmholtz, for example, made fundamental and original contributions to both the new geometry and the discovery of the conservation of energy; and it was the work of both Poincaré and Einstein on the deep problems afflicting the electrodynamics of moving bodies in the wake of Lorentz’s theory that eventually led to first special and then general relativity.[[26]](#footnote-26)

Just as in the development of modern mathematical astronomy in the sixteenth and seventeenth centuries, these scientific developments were also inextricably entangled with a corresponding set of wider cultural processes.[[27]](#footnote-27) Conservation of energy and the new thermodynamics, for example, were inextricably entangled (through the invention of the steam engine) with the industrial revolution of the nineteenth century; and the new theories of electricity and magnetism, culminating in the electrodynamics of moving bodies, were inextricably entangled, in turn, with the emerging electrical technology of the late nineteenth and early twentieth centuries.[[28]](#footnote-28) Just as, in the case of the abstract theories themselves, there is no way fully to understand their development (as I have argued) without taking account of the parallel developments in post-Kantian philosophy with which they interacted, there is also no way fully to understand both the developments in abstract theory and the corresponding developments in post-Kantian philosophy without also taking account of this wider set of social and technological entanglements.

In all such cases, the fact that we are dealing with mutual interactions among quasi-autonomous cultural processes (rather than unidirectional determination) results in the emergent appearance of unpredictable novelty. Who could have predicted, for example, that Maxwell’s equations, through the development of the theory of the electron, modern microphysics, and the theory of relativity, could eventually lead to the invention of atomic weapons (and atomic energy)—or, to take a rather different example, that the industrial revolution could eventually lead to the revolutionary transformation of post-Kantian German idealism effected by Marx (see note 25 above)? And who could have predicted, finally, that the further mutual interactions among all of these processes could lead to the great cold war between East and West arising in the wake of the second world war—together with its completely unexpected, and in many ways even more terrifying, aftermath? Although, of course, we now have no idea what the future will bring, its very unpredictably—which is due, as Kant already saw at the height of the eighteenth-century Enlightenment, to the fundamental unpredictably of all human affairs—provides room for a rational hope (and perhaps even for what Kant called rational faith [*Vernunftglaube*]) that the future may be better than the past.[[29]](#footnote-29)

1. For Kant’s work on the foundations of Newtonian physics, see M. Friedman, trans. and ed., *Immanuel Kant: Metaphysical Foundations of Natural Science* (Cambridge, 2004). I discuss the relationship between the *Metaphysical Foundations* and the *Critique of Pure Reason* in the Introduction to this volume. See also M. Friedman, *Kant and the Exact Sciences* (Harvard, 1992). [↑](#footnote-ref-1)
2. For more details on the developments described in this paragraph and the next, see also M. Friedman, “Geometry as a Branch of Physics: Background and Context for Einstein’s ‘Geometry and Experience’,” in D. Malament, ed., *Reading Natural Philosophy: Essays in the History and Philosophy of Science and Mathematics Presented To Howard Stein on the Occasion of His 70th Birthday* (Chicago, 2002), pp. 193-229. [↑](#footnote-ref-2)
3. I further develop the idea of a practically optimal solution to a given (historically contingent) problem situation for this case in M. Friedman, “Einstein, Kant, and the Relativized *A Priori*,” in M. Bitbol, P. Kerszberg, and J. Petitot, eds., *Constituting Objectivity: Transcendental Perspectives on Modern Physics* (Springer, 2009), pp. 253-267. [↑](#footnote-ref-3)
4. See, for example, H. Stein, “Newton’s Metaphysics,” in I. B. Cohen and G. E. Smith, eds., *The Cambridge Companion to Newton* (Cambridge, 2002), pp. 256-307. [↑](#footnote-ref-4)
5. An improved translation of *De Gravitatione* by Christian Johnson, made with the assistance of Andrew Janiak, and consulting an earlier unpublished translation by Howard Stein, appears in A. Janiak, ed., *Isaac Newton: Philosophical Writings* (Cambridge, 2004): my parenthetical page references to *De Grav.*—and to Newton’s writings more generally—are to this volume. [↑](#footnote-ref-5)
6. In Query 31, for example, Newton describes God as “a powerful ever-living agent, who being in all places, is more able by his will to move the bodies within his boundless uniform sensorium, and thereby to form and reform the parts of the universe, than we are by our will to move the parts of our own bodies” (p. 138). [↑](#footnote-ref-6)
7. Thus the letter to Bentley (pp. 102-103): “It is inconceivable that inanimate brute matter should, without the mediation of something else, which is not material, operate upon and affect other matter without mutual contact, as it must be, if gravitation in the sense of Epicurus, be essential and inherent in it. And this is one reason why I desired you would not ascribe innate gravity to me. That gravity should be innate, inherent, and essential to matter, so that one body may act upon another at a distance through a vacuum without the mediation of anything else, by and through which their action and force may be conveyed from one to another, is to me so great an absurdity, that I believe that no man who has in philosophical matters a competent faculty of thinking can ever fall into it. Gravity must be caused by an agent acting constantly according to certain laws; but whether this agent be material or immaterial, I have left to the consideration of my readers.” [↑](#footnote-ref-7)
8. For details, see M. Friedman, “Newton and Kant on Absolute Space: From Theology to Transcendental Philosophy,” in Bitbol, *et. al.*, *op. cit.* (note 3), pp. 35-50. [↑](#footnote-ref-8)
9. Compare note 3 above, together with the paragraph to which it is appended. In my article cited there I explain the sense in which Kant’s conception was practically optimal as follows (*op. cit.*, pp. 255-256): “Kant’s answers to the questions ‘how is pure mathematics possible?’ and ‘how is pure natural science possible?’ therefore operate against the background of an existing set of intellectual resources in a particular historical context. Geometry, for Kant, is limited to the classical system of Euclid; the pure understanding or pure intellect is delimited by the logical forms of Aristotle; the available conceptions of space and time are exhausted by the Leibnizean and Newtonian alternatives; and so on. Kant’s theory of our faculties of sensibility and understanding can only be understood against the background of precisely these resources—mathematical, logical, metaphysical, and theological—as Kant delicately navigates within them and eventually radically transforms them. The revolutionary and completely unexpected result, that space and time are pure forms of our (human) faculty of sensibility and that, considered independently of sensibility, our faculty of understanding yields no (theoretical) cognition at all, then emerges as the practically unique solution to the problem set by the existing intellectual resources: it is the only available conception of our rational faculties that does simultaneous justice to both Newtonian mathematical physics and Leibnizean (as opposed to Newtonian) natural theology and metaphysics.” [↑](#footnote-ref-9)
10. I am here closely follows T. Kuhn, *The Copernican Revolution* (Cambridge, Mass., 1957), pp. 11-12. [↑](#footnote-ref-10)
11. The Gregorian reform was not accepted in Protestant Europe until the turn of the eighteenth century. The Gregorian Calendar (in the South) and the Julian Calendar (in the North) competed with one another throughout Europe until then. I shall return to this matter below. [↑](#footnote-ref-11)
12. See C. Wilson, “How did Kepler Discover His First Two Laws?,” in his *Astronomy from Kepler to Newton* (London, 1989), pp. 1-14. I am indebted to George E. Smith for helping me to get clearer about the details of Kepler’s earlier orbital theory. [↑](#footnote-ref-12)
13. A variety of empirically acceptable alternatives to Kepler’s area law existed at the time. For a detailed discussion of how Newton’s *Principia* first led to the recognition of Kepler’s rules as “laws,” see C. Wilson, “From Kepler’s Laws, So-called, to Universal Gravitation: Empirical Factors,” *Archive for History of Exact Sciences* 6 (1970): 80-170. [↑](#footnote-ref-13)
14. See note 11 above. The English delayed acceptance of the Gregorian reform for another fifty years. [↑](#footnote-ref-14)
15. This correspondence appears in E. Celani, “L’epistolario di Monsignor Francesco Biancini,” *Archivo veneto* 36 (1888): 155-187. [↑](#footnote-ref-15)
16. See D. Bertoloni Meli, “Leibniz on the Censorship of the Copernican System,” *Studia Leibnitiana* (1988): 19-42; *Equivalence and Priority: Newton versus Leibniz* (Oxford: 1993); “Caroline, Leibniz, and Clarke,” *Journal of the History of Ideas* (1999): 469-486. Heilbron cites the first of these in the discussion we have been summarizing. [↑](#footnote-ref-16)
17. A translation of the *Essay* can be found in Bertoloni Meli’s *Equivalence and Priority* (note 16 above), which I am closely following here. [↑](#footnote-ref-17)
18. A translation of this work can be found in R. Ariew and D. Garber, trans. and eds., *G. W. Leibniz: Philosophical Essays* (Indianapolis, Ind., 1989), pp. 90-94. Leibniz there presents his grand compromise as follows (*op. cit.*, pp. 92-93): “[M]ost distinguished astronomers have openly admitted that they are held back from presenting the Copernican system only by the fear of censure. But they would not need such caution any more and could freely follow Copernicus without damaging the authority of the censors, if only they were to recognize, with us, that the truth of a hypothesis should be taken to be nothing but its greater intelligibility, . . . , so that henceforth there would be no more distinction between those who prefer the Copernican system as the hypothesis more in agreement with the intellect, and those who defend it as the truth. For the nature of the matter is that the two claims are identical; nor should one look for a greater or a different truth here. And since it is permissible to present the Copernican system as the simpler hypothesis, it would also be permissible to teach it as the truth in this particular sense. This would preserve the authority of the censors, so that a retraction would never be needed in the future, . . . , while at the same time, there would be no violence done to the distinguished discoveries of our age through the outward appearance of official condemnation.” Leibniz then explicitly links this idea to his vortex analysis of the area law (p. 93): “[The Copernican] system has done itself one better in Kepler, who was the first to lay bare to mortals ‘the laws of the heavens, the regularity [*fides*] of things, and the laws of the Gods,’ observing that all the phenomena can be derived if the earth and all of the primary planets are assumed to travel on an ellipse in whose focus is the sun, and it is assumed that it is a law of motion for the orbiting of a planet that the areas swept out with respect to the sun are proportional to the times. It remains to be said that a physical explanation can be given for such an unexpected law, an explanation that has at last come to us, to our great delight. For I found that this universal motion of the planets can be explained beautifully by means of a vortex around the sun common [for all of the planets].” [↑](#footnote-ref-18)
19. Selections from this correspondence are translated in Ariew and Garber, *op. cit.* (note 18 above), pp. 307-312; and also in L. E. Loemker, trans. and ed., *Gottfried Wilhelm Leibniz. Philosophical Papers and Letters* (Dordrecht, 1969), pp. 413-420. [↑](#footnote-ref-19)
20. See Bertoloni Meli, “Caroline, Leibniz, and Clarke” (note 16 above), which shows that Leibniz makes a paradox for the Newtonian position that is implicit in § 19 of the Preliminary Discourse to the *Theodicy* fully explicit in his correspondence with Caroline (*op. cit.*, p. 475): “[T]he Newtonian pretend to portray as natural their theory of gravity, whereby a body acts at a distance without being present. The Lutheran doctrine of the eucharist, however, implying the real and substantial presence of the body of Christ, was portrayed by them as absurd and even denied the status of a miracle.” In the relevant § 19 of the *Theodicy*, trans. E. M. Huggard, ed. A. Farrer (La Salle, Ill., 1985), after explaining (in § 18) that the Calvinists reject the Scholastic dogma of transubstantiation, and that there is considerable room for reconciling the Calvinist and Lutheran positions, Leibniz continues as follows (*op. cit.*, pp. 85-86): “Thence we see that the dogma of real and substantial participation can be supported (without resorting to the strange opinions of some Schoolmen) by a properly understood analogy between *immediate operation* and *presence*. Many philosophers have deemed that, even in the order of Nature, a body may operate from a distance immediately on many remote bodies at the same time. So do they believe, all the more, that nothing can prevent divine Omnipotence from causing one body to be present in many bodies together, since the transition from immediate operation to presence is but slight, the one perhaps depending upon the other. . . . Thus the theologians of the Augsburg Confession [i.e., Lutherans] claim that God may ordain not only that a body operate immediately on divers bodies remote from one another, but that it even exist in their neighbourhood and be received by them in a way with which distances of place and dimensions of space have nothing to do. Although this effect transcends the forces of Nature, they do not think it possible to show that it surpasses the power of the Author of Nature.” [↑](#footnote-ref-20)
21. These issues of Church reunification, together with Leibniz’s hopes for a grand compromise on the Copernican question, converge in his correspondence with Bianchini concerning the second Gregorian reform of the calendar (see note 15 above). In particular, in a postscript (dated 13 October 1703) to a letter to Bianchini (dated 6 July 1703), in the midst of technical astronomical questions relevant to the dating of Easter, Leibniz writes (*op. cit.*, pp. 181-182): “I have often considered in my thoughts that there is no greater obstacle for the excellent Italian thinkers than that they cannot philosophize with as much freedom as would be reasonable. I do not number among those who believe in loosening any restraints upon license, as I see this happening too much here and there, nor do I deem it wrong for a magistrate to prohibit the publication of any books speaking against the precepts of religion. . . . I have shown that the essence of a corporeal substance does not lie in extension but in that which is dynamical, and thus there is nothing in it that prevents it from existing at the same time in many places through God’s power; and in order to diminish the Schism I have also shown other things which perhaps some day our posterity will come to know and to praise, and which, I think, will also be welcomed by the most eminent men of your Church and the Pope himself [i.e., Clement XI]. But I am astonished at your rejection of the indubitable truth of the Copernican system, testified (if there is anything in nature that is so testified) by phenomena and rational arguments—which [rejection] is one of the main reasons that the right way of philosophizing and the system of nature are both disturbed.” I am indebted to Vincenzo De Risi for providing me with both a copy of the correspondence with Bianchini and a translation of this passage. [↑](#footnote-ref-21)
22. For discussion of the development of Kant’s thought from this perspective, see again the two works cited in note 1 above. [↑](#footnote-ref-22)
23. Kant provides an especially striking re-interpretation of the Newtonian doctrine of divine omnipresence in a footnote appended to the General Remark to the Third Part of *Religion Within the Limits of Reason Alone* (1793). I quote from the translation by T. M. Greene and H. H. Hudson (New York, 1960), p. 130 (slightly amended): “When Newton represents [the universal gravitation of all matter in the world] as, so to speak, divine universal presence in the appearance (*omnipæsentia phenomenon*), this is not an attempt to explain it (for the existence of God in space contains a contradiction), but rather a sublime analogy, in which it is viewed merely as the unification of corporeal beings into a world-whole, in so far as we base this upon an incorporeal cause. The same would happen in the attempt to comprehend the self-sufficient principle of the unification of the rational beings in the world into an ethical state and to explain the latter from the former. We know only the duty that draws us towards this; the possibility of the intended effect, even when we obey this [duty], lies entirely beyond the limits of all our insight.” [↑](#footnote-ref-23)
24. For a classic discussion, see A. Wood, *Kant’s Moral Religion* (Ithaca, N.Y., 1970). This idea decisively shaped nineteenth-century German Protestant theology, as represented by such figures as Frederick Schleiermacher and Ludwig Feuerbach. [↑](#footnote-ref-24)
25. For the practically optimal solution Kant constructed to the purely intellectual problem situation with which he was faced, see note 9 above. In order to trace the development of the radically new cultural context to which Kant then decisively contributed, one would need to consider such topics as, for example, the influence of Hegel and Feuerbach (see note 24 above) on Karl Marx, and the way in which this influence, in turn, was entangled with Marx’s response to the nineteenth-century industrial revolution. [↑](#footnote-ref-25)
26. General relativity, in particular, then continued the successive refinement of mathematical astronomy begun by Newton. As is well known, general relativity gives the correct result for the anomaly in the precession of the perihelion of Mercury that was left unaccounted for in the Newtonian theory of universal gravitation—just as that theory had earlier corrected Kepler’s original formulation of the laws of planetary motion by showing that the perihelia of the planetary ellipses (due to gravitational perturbations arising from the mutual attractions of the bodies in the solar system on one another) are not fixed in space but rather precess. [↑](#footnote-ref-26)
27. I here present only the barest sketch of how I think this story should go. A more adequate discussion would require at least as much detail as I have provided above in connection with the Gregorian reform of the calendar in the period from 1582 to 1793. [↑](#footnote-ref-27)
28. For an interesting recent discussion of this last set of entanglements, see P. Galison, *Einstein’s Clocks, Poincaré’s Maps* (New York, 2003). [↑](#footnote-ref-28)
29. The initial ideas for this essay were conceived while I was a Fellow at the Center for Advanced Studies in the Behavioral Sciences at Stanford in the academic year 2006-2007. I am indebted to the Center for this Fellowship and also, especially, to discussions with two other Fellows during this year: the cultural historian Paula Fass and the historian and sociologist of modern science Andrew Pickering. [↑](#footnote-ref-29)