Friedman, Galileo, and Reciprocal Iteration

David Marshall Miller[†‡]

In *Dynamics of Reason*, Michael Friedman uses the example of Galilean rectilinear inertia to support his defense of scientific rationality against postpositivist skepticism. However, Friedman's treatment of the case is flawed, such that his model of scientific change fails to fit the historical evidence. I present the case of Galileo, showing how it supports Friedman's view of scientific knowledge but undermines his view of scientific change. I then suggest *reciprocal iteration* as an amendment of Friedman's view that better accounts for scientific change.

1. Introduction. Friedman (2001) offers a novel defense of the rationality of science against postpositivist skepticism. Friedman's defense depends on a model of scientific knowledge as "stratified" into distinct epistemic layers. He then aims to show that the progress of science can be ultimately grounded in a transcendently necessary feature of human reason—communicative rationality. While Friedman's model of scientific knowledge is successful, his model of scientific change fails to fit historical evidence. Galileo's move from circular to rectilinear inertia is a glaring example. 'Glaring' because Friedman himself uses this case to support his view. This article presents the case of Galileo, showing where Friedman seems to go right and where he seems to err. I then offer *reciprocal iteration* as an alternative model of scientific change that better accords with historical evidence and still offers a defense of scientific rationality.

[†]To contact the author, please write to: Philosophy Department, Duke University, 201 West Duke, Box 90743, Durham, NC 27708; e-mail: david.m.miller@duke.edu.

[‡]This article was greatly improved by discussions with Andrew Janiak. Tad Schmaltz, Mary Domski, Maarten van Dyck, Barbara Sattler, and Zvi Biener provided helpful comments. Thanks are also owed to audiences in Las Vegas, Durham, Cincinnati, Johnson City, Montreal, and Boston. All errors are the author's.

Philosophy of Science, 78 (December 2011) pp. 1293–1305. 0031-8248/2011/7805-0048$10.00

2. Friedman's Defense of Rational Scientific Change. All scientific change requires a choice to adopt a new theory in place of an older one. To evaluate the rationality of this choice, one requires, first, a conceptually independent and stable context from which to make the judgment that one theory is preferable. This context has to be conceptually separate from the theories, to allow "impartial observation" apart from considerations internal to them. Second, the theories must be comparable—the concepts of one theory must be at least partially translatable into the concepts of the other, so that one can compare their competing pronouncements against some standard. Finally, one needs a standard of rationality against which the theories are to be measured.

As is well known, the work of Quine and Kuhn (and their successors) questioned the possibility of each of these conditions, thereby challenging the rationality of scientific change. Michael Friedman (2001) proposes a model of scientific knowledge and change meant to save scientific rationality from such worries. He begins by distinguishing three epistemic "strata": (*a*) the empirical principles or laws of a scientific theory, (*b*) the constitutive a priori, and (*c*) the philosophical metaframework. The first stratum consists of the physical principles by which a theory explains phenomena. The second comprises whatever presuppositions are necessary to "secure the empirical content of the theory" (83), including the linguistic framework that coordinates empirical principles with phenomena, as well as any mathematics used by the theory. Together, these epistemic levels constitute a scientific theory.

The constitutive a priori is *relativized* to its scientific theory—it only establishes the meaning of *theoretical* concepts, so a change in the constitutive a priori does not infect the conceptual scheme of the entire language. This leaves room for the philosophical metaframework that "motivates and sustains" scientific change since the meaning of *philosophical* discourse is not affected by changes elsewhere in the theoretical language. This independent standpoint enables advocates of different theories to consider and discuss the philosophical merits of their respective views and to come to consensus in the philosophical parts of the language they share (Friedman 2001, 54).

Viewing successive theories philosophically also allows one to identify conceptual continuity in the constitutive a priori. New constitutive principles "gradually emerge through successive transformations of old concepts and principles," so successive linguistic frameworks are "different evolutionary stages of a single language" (Friedman 2001, 60). This "evolution" of theoretical concepts allows one to pick out the evolute of a concept from one constitutive framework to the next (105). In turn, this allows the pronouncements of the successive theories to be intertranslated and compared; the terms of a later theory can be translated back into their evolutionary precursors. Philosophical discourse provides a stable epistemic platform that underwrites continuity between successive sets of constitutive principles and, therefore, between successive scientific theories.

This opens up the possibility of scientific rationality. The independent philosophical metaframework allows for a philosophical consensus concerning competing theories. In particular, advocates of competing theories can achieve "communicative rationality" insofar as they are able to convince one another of the superiority of a theory. Friedman claims that this communicative rationality is, in fact, an approximation of a transcendental "ideal community of inquiry." That is, communicative rationality, necessarily extended to all rational beings qua rational, is a Kantian regulative ideal against which different scientific theories can (and must) be measured (2001, 64).

Thus, Friedman rehabilitates all the conditions needed to establish the rationality of scientific change. There is an independent, metatheoretical perspective from which to judge the rationality of scientific change, comparable linguistic frameworks, and a standard by which rationality is measured—communicative rationality.

Friedman's defense of scientific rationality also entails a clear picture of scientific progress. If (i) successive paradigms "evolve" from one another in a continuous way, and (ii) the "evolutionary" progress is motivated and evaluated by comparison to a regulative ideal, then progress must take the form of convergent approximation of the regulative ideal "in the direction of ever greater generality and adequacy" (2001, 63). The regulative ideal exerts "selection pressure" (to extend Friedman's metaphor), so science should evolve continuously toward a better fit. Successive theories should gain more generality and more "adequacy," where 'adequacy' means something like "more persuasiveness," since this is what communicative rationality requires—a universal consensus.

3. Friedman on Galileo. By his own admission, Friedman's position "essentially depends" on the historical accuracy of his view (2008, 96). Let us then consider a case Friedman himself adduces—Galileo's role in the development of classical mechanics out of Aristotelian mechanics—to gauge whether scientific change can be viewed as a convergent series.

Friedman identifies a change in the constitutive a priori grounding physical theory during the early modern period. Spatial phenomena were first conceived in relation to a spatial center, about which the universe was ordered. This led to physical explanations referring to that spatial ordering: for instance, heavy bodies fall because they seek their place near the center. This ordered conception of space was then replaced by a centerless, rectilinear space, in which the modern explanatory notion of rectilinear inertia was framed.

As Friedman correctly notes, Galileo was one of the primary figures who wrought this change:

> An essential intermediate stage is Galileo's celebrated treatment of free fall and projectile motion. For, although Galileo indeed discards the hierarchically and teleologically organized Aristotelian universe, he retains—or better, transforms—key elements of the Aristotelian conception of natural motion. Galileo's analysis is based on two concepts of natural motion: what he calls naturally accelerated motion directed toward the center of the earth, and what he calls uniform or equable motion directed at right angles to the former motion. Unlike our modern concept of *rectilinear* inertial motion, however, this Galilean counterpart is uniformly *circular*—traversing points equidistant from the center at constant speed. Yet, in relatively small regions near the earth's surface, this uniform circular motion is quite indistinguishable from uniform rectilinear motion, and this is how Galileo can treat it mathematically as rectilinear to an extremely good approximation. And it is in precisely this way, therefore, that the modern conception of rectilinear natural inertial motion is actually continuous with the preceding Aristotelian conception of natural motion. (2001, 60–61)

Galileo's contribution to modern physics, the notion of rectilinear inertia, marks the transition from Aristotelian to classical mechanics. However, Galileo's innovation arises on the basis of a rectilinear conception of space continuous with the "hierarchically and teleologically organized . . . universe" that underlay Aristotelian mechanics. Indeed, Galileo's rectilinear space approximates the Aristotelian, spherically ordered space, such that the resulting explanations (rectilinear and circular inertial motion) also approximate one another. Thus, continuity can be identified at the constitutive level; Galileo can be seen as an "evolutionary" stage in the development of physical theory, and the rationality of his move can be judged against the standard of communicative rationality.

4. Galileo on Inertial Motion.

4.1. The Dialogo. The change of which Friedman writes, Galileo's move away from Aristotelian mechanics toward classical mechanics, associated with his introduction of a rectilinear conception of space, is vividly seen in the development of Galileo's thought between the *Dialogo* (1632/1967) and the *Discorsi* (1638/2000). Both texts express Galileo's most important explanatory principle: bodies do not move spontaneously

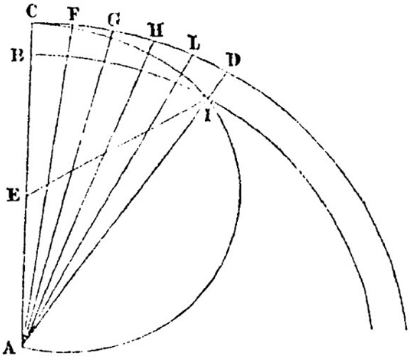

Figure 1. Semicircular trajectory of a falling body in the *Dialogo*.

but require some reason to alter their state of motion. In the *Dialogo*, though, Galileo assumes that places (within the terrestrial system) are distinguished by their distance from the terrestrial center, and these places generate the reasons for a body's motions—their "natural tendency" toward a place. For example, heavy bodies accelerate downward because they seek a place closer to the center (1632/1967, 32). Similarly, circular motion around the center is conserved since such motion is in place.

These explanatory and constitutive principles coalesce in Galileo's treatment of a ball dropped from the tower. Before the ball is released, it shares the daily, circular rotation of the earth, the tower, and everything else. Once released, it conserves this rotation, subtending equal angles around the terrestrial center in each moment. This uniform circular motion is then combined with a radial acceleration to the center. Galileo concludes that the resulting path is a semicircle terminating at the center of the earth: "The semicircle *CIA* [see fig. 1] is described, along which I think it very probable that a stone dropped from the top of the tower *C* will move, with a motion composed of the general circular movement and its own straight one" (1632/1967, 165). In Friedman's terms, Galileo employs empirical principles—corporeal indifference to motion or rest and natural tendency to places—in conjunction with a constitutive framework of places ordered around the terrestrial center. Circular motion is uniform and conserved because it does not change a body's place, which is true because place is defined in relation to the center. The constitutive framework makes Galileo's inertia circular.

4.2. The Discorsi. Even writing the *Dialogo*, Galileo was unsure that "the descent of heavy bodies does take place in exactly this way" (1632/

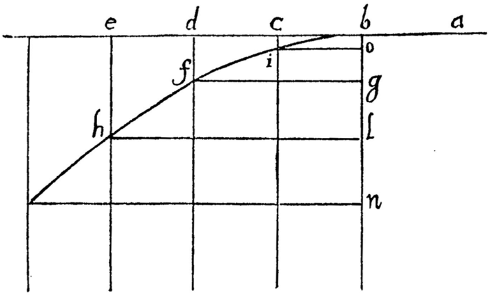

Figure 2. Parabolic trajectory of a projectile in the *Discorsi.*

1967, 167). In fact, the derivation leads to obvious absurdities, and within a few years, Galileo dismissed it as a “daring jocularity” offered in “jest” (Drake 1978, 377). In its place, Galileo offered the parabolic trajectory of projectiles presented in the *Discorsi.*

There, Galileo considered the case of a ball rolling off the end of a table. As in the *Dialogo*, the resulting motion is explained by a natural acceleration downward and a conserved horizontal motion. The empirical principle at work is essentially the same in both texts: bodies are indifferent to motion and rest except insofar as they tend toward their natural places. In the *Discorsi*, however, Galileo employs a different constitutive framework. Instead of conceiving the region of space as centered, Galileo posits a vertical orientation in relation to which other directions are described. The natural fall of heavy bodies is coordinated with a downward direction that is everywhere parallel to itself. The “horizontal” is a flat plane everywhere perpendicular to the orientation. Thus, accelerated vertical motion and conserved horizontal motion, each everywhere perpendicular to the other, compose a parabolic trajectory of the falling body (see fig. 2). In this constitutive framework, inertial motion means rectilinear motion. That is, inertia has become rectilinear not because the empirical laws have changed, but because their coordination with phenomena has changed. Galileo has introduced a new constitutive a priori.

Galileo knew he had introduced a new way of representing the phenomena, and he was aware that the new framework was problematic. In particular, the rectilinear conception of space did not properly square with the way motion was explained. A body’s inertial conservation of motion is derived from its indifference to motion at a constant distance from the center (“neither up nor down”). In the new framework, a body is again indifferent to motion “neither up nor down,” but this is only because of an equivocation on the phenomenal coordination of the terms. It is away from or toward the center in the first case and along opposite senses of the orientation in the second. Yet the horizontal is now a straight line always receding from the “common center,” so a heavy body would not be indifferent to horizontal motion (1638/2000, 251).

In fact, Galileo admits that the assumptions underlying the derivation of the parabolic trajectory are “fallacious to this extent, that neither will the horizontal motion be uniform nor the natural acceleration be in the ratio assumed, nor the path of the projectile a parabola, etc.” (1638/2000, 251). The constitutive conception of a rectilinear space in which the vertical and horizontal are self-parallel does not accurately represent the phenomena.

What then, motivates the use of the oriented, rectilinear framework? Why does Galileo employ a constitutive framework he thinks is “fallacious”? For one thing, Galileo took it as a philosophical principle that nature could and should be described mathematically, and the rectilinear conception of space makes the geometry of the trajectory tractable. In order to assimilate the path to a conic section, Galileo had to assume that the components of the motion were rectilinear and always perpendicular. Galileo was also committed to the view that physical explanations should conform to observations. The rectilinear representation of the phenomenon allowed Galileo to calculate predictions for the trajectory of a ball rolling off a table, which he confirmed by experiment (Drake 1973; Naylor 1980).

Finally, and most importantly, Galileo could employ the rectilinear framework because the inconsistencies arising from it could be excused by what might be called the “Archimedean approximation”:

> But, on the other hand, I ask you not to begrudge our Author that which other eminent men have assumed even if not strictly true. The authority of Archimedes alone will satisfy everybody. In his Mechanics and in his first quadrature of the parabola he takes for granted that the beam of a balance or steelyard is a straight line, every point of which is equidistant from the common center of all heavy bodies, and that the cords by which heavy bodies are suspended are parallel to each other. . . . Some consider this assumption permissible because, in practice, our instruments and the distances are so small in comparison with the enormous distance from the center of the earth. (1638/2000, 251)

The rectilinear framework can be introduced as a small-scale approximation of the large-scale spherical framework. The rectilinear constitutive framework and the rectilinear inertia that results are good enough for dealing with small-scale phenomena.

5. Galileo for and against Friedman. Friedman is exactly right: Galilean inertia is fundamentally circular since Galileo adheres to the Aristotelian framework of an ordered, spherical space. But in small regions, this spherical space is indistinguishable from rectilinear space, which allows Galileo to treat motion "mathematically as rectilinear to an extremely good approximation." Thus, "the modern conception of rectilinear natural inertial motion is actually continuous with the preceding Aristotelian conception of natural motion." The continuity allowed by the Archimedean approximation makes it possible to evaluate the rationality of the move from circular to rectilinear inertia—the move from Aristotelian to classical mechanics. There is no radical discontinuity of meaning between the frameworks. In fact, the Archimedean approximation provides a straightforward translation of the language of one framework into that of the other. 'Horizontal' in one framework is directly substituted for 'horizontal' in the other, and so on.

However, and here is the rub, Galileo's move to the rectilinear fails Friedman's test of rational scientific change. Galileo does not refine his theory "in the direction of ever greater generality and adequacy." The new, rectilinear framework is less general than the older, spherical one: the older framework contains the newer framework as an approximate limiting case. And the new framework is less adequate: strictly speaking, the approximation is false. The vertical is not everywhere parallel to itself; the horizontal is not a plane.

Thus, Friedman must either judge Galileo's introduction of rectilinear inertia to be irrational or give up his account of rational scientific progress. I think we must take the latter course since it seems exceedingly odd to say that Galileo's innovation, so important in the history of physical science, is irrational. In my view, the case demonstrates that rational scientific progress cannot be seen as convergent toward transcendental communicative rationality.

It is not clear how Friedman might respond. In some parts of the *Dynamics of Reason*, he suggests that we can only evaluate scientific rationality retrospectively, from the point of view of later constitutive frameworks. Thus, Friedman might say that Galileo is merely a transitional or "intermediate" figure whose rationality can only be judged from a post-Newtonian perspective, in which the predominant framework had stabilized and the explanatory reach of Aristotelian science had been recovered (2001, 95–101). This does not seem to help. It puts one in the odd position of being unable to say anything about the rationality of individual developments during the revolutionary period, even in retrospect. Rationality would not emerge until the older paradigm could be rationally reconstructed and its empirical significance recovered. So if one is unable to say whether Galileo's move was rational, one is presumably unable to judge Kepler's elliptical astronomy, Descartes' laws of motion, Huygens's fluid mechanics, and so on. Further, if we can only judge rationality once the new framework has become at least as general as the former framework, one of Friedman's two criteria, generality, is made trivial. Finally, this move seems to give up the fundamental success of Friedman's model—the continuity of scientific change. If one can only evaluate discontinuous, stabilized paradigms, the door is once again open to skeptical worries about nonintertranslatability and incommensurability.

6. Reciprocal Iteration. Friedman's antiholistic "stratification of knowledge" is vindicated by Galileo's Archimedean approximation. The use of the approximation itself indicates Galileo's own distinction between explanatory principles and the constitutive framework that coordinates them with phenomena. Only Friedman's account of rational scientific change fails. Nevertheless, I think Friedman's stratification of knowledge can be used to develop a model of rational scientific change that succeeds in making Galileo come out rational. In particular, we can locate the three necessary grounds for evaluating the rationality of scientific change—a conceptually stable perspective, conceptual continuity between theories, and a standard of rationality—among Friedman's three epistemic levels (constitutive a priori, empirical principles, and metatheoretical framework), but not in the way Friedman suggests.

Consider first the conceptual continuity between theories. On Friedman's account, continuity is guaranteed at the metatheoretical level, from which one recognizes the evolute of one concept into another. However, Friedman's antiholism seems to open up the possibility of evaluating conceptual continuity from within a scientific theory by using one epistemic level, either constitutive a priori or explanatory principles, to guarantee continuity through shifts at the other. Indeed, this is how the Archimedean approximation works.

Take, for example, the concept of "conserved motion." For Galileo, the meaning of this concept has two sources, corresponding to Friedman's two epistemic levels. First, 'conserved motion' bears a meaning relative to the other concepts among the empirical principles of the theory. Hence, it can be intensionally defined via such notions as "neither up nor down," "in place," "uncaused," and so on. The concept gains a meaning from its "conceptual role" in theoretical explanations. At the same time, however, "conserved motion" also has an ostensive definition relative to phenomena established by the coordinative principles of the constitutive a priori. 'Conserved motion' means its extension in the phenomenal world, such as the movement of a ball on top of a tower or rolling on a horizontal plane.

When Galileo introduces rectilinear conserved motion by using the Archimedean approximation, he only changes one epistemic level at a time. Specifically, he holds the explanatory principles—indifference to motion and tendency to natural place—fixed while he adjusts the coordinative framework in which it is deployed. As a result, he only changes a discrete part of the meaning of the concept. He changes the extension of the concept but leaves its relation to explanation intact. This, moreover, guarantees that the concept can be continuously identified across the scientific change since one can always pick out what changes by referring to what stays the same. In fact, it allows Galileo to provide a direct translation between concepts. From an explanatory point of view, small-scale straight-line motion is the same thing—the conserved motion explained by the theory as "neither up nor down," and so on—as circular motion in the large scale.

On this view, the continuity of scientific concepts is guaranteed by part of the scientific theory itself, not the philosophical metaframework, as in Friedman. The empirical principles provide a stable basis for judging the conceptual continuity between successive versions of the constitutive a priori. And this allows one to avoid Kuhnian worries about incommensurability and evaluate the rationality of the scientific change. The empirical principles give us a basis for comparing the competing coordinative definitions.

As we have seen, Galileo has clear reasons to introduce rectilinear conserved motion by way of the Archimedean approximation. He is motivated by his philosophical commitment to empirical adequacy and mathematical tractability. The classical theory of natural motion clearly satisfies those desiderata better than the Aristotelian theory. Thus, one can say, from Galileo's own philosophical point of view, that he (for himself) had good reasons to make the move he does and that his move was therefore rational. On this account, then, the philosophical metaframework provides the standard for judging the rationality of the change. Galileo's explanatory principles simply come off better with regard to empirical adequacy and mathematical tractability if they are coordinated with a rectilinear space, at least in the small scale.

While the case we have been discussing is not an example, the relative functions of the epistemic levels within a theory for ensuring conceptual continuity in scientific change can be inverted. That is, conceptual continuity across changes of explanatory principles can be guaranteed by the constitutive level. One can adjust the conceptual role of a concept in its theory without changing its ostensive definition. (This is perhaps the more familiar sort of scientific change—new explanations in an existing linguistic framework.) Competing explanatory principles can then be evaluated against prevailing philosophical commitments.

Altogether, this suggests a reciprocal iteration model of scientific change, wherein the epistemic levels constituting scientific theory slide across one another, each shift at one level guaranteed by fixity at the other, while motivated by philosophical considerations generated in metatheoretical discourse. I think this model, at least in one of its modes, accurately represents the Galileo case, and elsewhere I have pointed to something like it in Kepler (Miller 2008). I also think it can be used to explain the other cases Friedman appeals to—the moves to general and special relativity. For instance, the changing conception of "mass" can be seen as adjustments of its conceptual role, while the extension of 'mass' (i.e., masses) remains fixed. Although I do not have space for a thorough defense here, I believe that this provides sufficient inductive grounds for the generalization of this model.

To summarize, the rationality of scientific change is evaluated from the conceptually stable perspective of the metatheoretical, philosophical level according to the standard provided by philosophical discourse. Conceptual continuity, meanwhile, is grounded in the conceptual stability of one part of the scientific theory itself. Thus, all of the necessary grounds for evaluating rational change have been recovered among Friedman's epistemic levels, and Galileo comes out as rational. However, the grounds for evaluation are located differently among the levels than in Friedman's account.

There are other points of contrast and discussion to be drawn. Most importantly, the reciprocal iteration model dispenses with Friedman's transcendental regulative ideal. On the one hand, this avoids the criticism others have leveled at this part of Friedman's position, namely, that the regulative ideal tacitly makes a commitment to realism that Friedman explicitly disavows (2001, 118–19; see, e.g., Slowik 2006; Chang 2008; van Dyck 2009). The ostensive definitions established by a coordinative framework can be completely conventional, as in Reichenbach and Poincaré; they need not pick out anything "real," such as natural kinds. On the other hand, reciprocal iteration abandons Friedman's transhistorical notion of scientific progress. Rationality is instead historicized—it must be evaluated in the historical moment according to the philosophical standards operative at the time. One can defend the rationality of science by pointing to the rationality of (all of) its individual practitioners in the light of their own philosophical commitments, but we cannot point to the necessary rationality of science in general. It may turn out that science is always committed to some standard of rationality or another, such as empirical adequacy, but this would be a contingent fact. Alternatively, a philosophical commitment to some standard might be taken as definitive of science, so that scientific progress according to that standard would be necessary in a trivial sense.[1]

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[1] Friedman (2008) seems to move toward a more historicized evaluation of scientific rationality than offered in *Dynamics of Reason*. He writes that each scientific change

Another thing to note is that conceptual continuity across scientific change is also historically localized. Once a full cycle of explanatory and coordinative change has occurred, there is no longer conceptual continuity between an older theory and a newer one. Both the intensional and extensional meanings of a concept have changed. Hence, reciprocal iteration does not obviate worries about incommensurability between temporally separated theories.

Finally, there is nothing in this model that dictates how new theories are generated. For instance, one is free to make adjustments at either epistemic level within a theory to assimilate an anomaly. This accommodates the Quinean observation that any part of a scientific theory is subject to revision in light of empirical observations. The same is true, however, of philosophical observations. One might seek to adjust a scientific theory in light of changing philosophical commitments as philosophical discourse develops. Again, how the theory should be changed in such a case is left open.

The two "strata" constituting a scientific theory, the constitutive a priori and the explanatory principles, are constrained in two respects: on the one hand by the behavior of the phenomenal world, which gets into the theory in virtue of its coordination with theoretical terms, and on the other hand by the metatheoretical considerations that determine the desiderata of a satisfactory theory—that is, scientific values such as empirical adequacy and mathematical tractability. However, the coordinative and explanatory principles only encounter these constraints in unison. Only together do the two parts of the theory generate explanations, descriptions, predictions, and so on, with empirical content, so it is only together that the theory can be tested and judged. Independent of one another, coordinating and explanatory principles have merely partial meanings, so there is nothing to judge.[2]

7. Conclusion.

Friedman's "stratification of knowledge" is vindicated by Galileo's Archimedean approximation. The approximation itself indicates Galileo's own distinction between explanatory principles and the consti-

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should be judged according to the "inner logic" stemming from the "associated rational necessity" operative at the time of the change. Thus, "integrated intellectual history of both the exact sciences and scientific philosophy takes over the role of Kant's transcendental method" (98–99). Nevertheless, Friedman resists the "collapse into total contingency" suggested here, but he does not explain how the historicized "inner logic" can be derived from or otherwise grounded in the transcendental regulative ideal of communicative rationality, which is supposed to gird against such a collapse.

[2] There is an element of holism here, insofar as theories are evaluated as integrated wholes, but this is not Quinean holism, which denies the possibility of articulating any principled distinction between epistemic "strata."

tutive framework that coordinates them with phenomena. However, the case of Galileo shows that Friedman's appeal to a transhistorical regulative ideal is not promising. As a result, we should be willing to give up his notion of rational progress toward some transcendental ideal. Still, Friedman's constitutive a priori is a valuable notion in trying to defend the rationality of scientific change, and we can use his insight to construct a reciprocal iteration model of scientific change that successfully avoids Kuhnian worries about conceptual incommensurability and allows a limited, historicized account of rational scientific change.

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