Distinguishing Explanatory from Nonexplanatory Fictions

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There is a growing recognition that fictions have a number of legitimate functions in science, even when it comes to scientific explanation. However, the question then arises, what distinguishes an explanatory fiction from a nonexplanatory one? Here I examine two cases—one in which there is a consensus in the scientific community that the fiction is explanatory and another in which the fiction is not explanatory. I shall show how my account of "model explanations" is able to explain this asymmetry, and argue that realism—of a more subtle form—does have a role in distinguishing explanatory from nonexplanatory fictions.

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1. Introduction. Although there is a growing recognition that fictions have a number of legitimate functions in science, there remains a widespread assumption that fictions cannot genuinely explain. Hans Vaihinger, for example, in his 1911 book *The Philosophy of "As If,"* defends the widespread use of fictions in science, noting that their use is justified by their utility and expediency. He explicitly denies, however, that fictions have any role to play in scientific explanation. Contrasting a fiction, which is known to be false, with a hypothesis, which hopes to be a true description of reality, Vaihinger writes, "The hypothesis results in real explanation, the fiction induces only an illusion of understanding" (Vaihinger 1911/1952, xv). The reason, he explains, is that "every fiction has, strictly speaking, only a practical object in science, for it does not create real knowledge" (88). In other words, explanation and understanding are not to be counted among the ends of science for which fictions can be expedient, precisely because explanation requires having genu-

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ine insight into the way the world is, and fictions—it is claimed—are incapable of giving us this sort of insight.

In the more recent literature on models and fictions in science, this assumption that fictions cannot explain seems to persist. This is perhaps not surprising given the legacy of Carl Hempel's highly influential deductive-nomological account of scientific explanation. For Hempel a minimum condition of adequacy on a scientific explanation is that the sentences constituting the explanans must be true ("Empirical Condition of Adequacy"). He is quite explicit that by "true" he means True with a capital *T*—it is insufficient, he argues, that the explanans be merely "highly confirmed by all the relevant available evidence" (Hempel 1965, 248). *Pace* Hempel, I believe this sets the bar on explanation too high. Hempel's account would suggest that scientists rarely—if ever—succeed in offering explanations—even when there is a consensus in the scientific community that an adequate explanation has been given. The approach I want to take here, by contrast, is to articulate an account of scientific explanation that tracks more closely the scientific community's own understanding of when a genuine explanation has—or has not—been given.

When one surveys examples of explanations being proffered by scientists in fields ranging from physics and chemistry to biology and cognitive science, one finds that scientists are regularly invoking scientific models in their explanations of various phenomena. This use of models to explain is at odds with traditional philosophical accounts of explanation insofar as models are not literally true descriptions of their target systems; rather, they involve all sorts of falsehoods, including idealizations, abstractions, and outright fictions.

Elsewhere I have developed a new model-based account of explanation, which I have argued can make sense of this practice (Bokulich 2008a, 2008b, 2009, 2011). More specifically, I have argued that there are cases in which it is not just the "true parts" of the model that are doing the explanatory work; rather, the fictions themselves can play an indispensible role in the explanation. In what follows I would like to focus on one of the chief objections—or challenges—to admitting the explanatory power of fictional models. In particular, the worry is that, while Hempel has set the bar too high for explanation, I have set the bar too low: once one admits the explanatory power of fictions, it is difficult to rule out other fictions as nonexplanatory. In other words, what is it that distinguishes an explanatory from a nonexplanatory fiction? And what role—if any—does scientific realism have to play in drawing such a distinction?

In what follows, I will approach this problem from the ground up, by examining closely two case studies—one in which there is a consensus in the scientific community that the fiction is explanatory and another case in which there is a consensus that the fiction is not explanatory. As an example of an explanatory fiction I shall examine how physicists are using fictional electron trajectories to explain the conductance properties of quantum dots. At the other end of the spectrum, there are scientific fictions that are clearly not explanatory. As an example in this category I shall consider the epicycles of Ptolemaic astronomy. No scientist today would say that epicycles actually explain the retrograde motion of the planets. I shall show how my account of "model explanations" is able to explain the asymmetry between these two cases, and argue that realism—of a more subtle form—does have a role to play in distinguishing explanatory from nonexplanatory fictions.

2. Explanatory Fictions: The Case of Fictional Electron Trajectories in Quantum Dots. A field in which one finds physicists appealing to fictions in their explanations of physical phenomena is in the study of quantum dots. Quantum dots are fabricated semiconductor devices in which electrons are confined within a two-dimensional region, typically less than one micron wide. They are quantum-mechanical systems closely related to atoms insofar as they have quantized energy levels and are small enough to behave as a single quantum phase-coherent unit for which interference effects are important. The quantum dots of interest here are so-called ballistic, closed quantum dots (as pictured in fig. 1).

When the quantum dot is coupled weakly to external leads, there is the possibility of electrons tunneling into the dot. This is typically blocked by the Coulomb repulsion of the electron already in the dot; hence, no current will flow. By changing the gate voltage, however, one can compensate for this repulsion and the charge on the dot will fluctuate between N and $N + 1$ electrons. This results in a series of peaks in the conductance. It turns out that these conductance peaks exhibit a number of surprising features relating to (*a*) the variations in peak height, (*b*) the distribution of peaks, and (*c*) large correlations between the heights of adjacent peaks. One of the central challenges in condensed matter physics is to understand these features of the conductance peaks in quantum dots.

If one considers the classical counterpart of a quantum dot, then the irregular shape of the dot means that, classically, the motion of the electron bouncing around the dot should be chaotic. It is therefore expected that the corresponding quantum wave functions for the dot should exhibit an effective "randomness." Hence, a statistical theory for the Coulomb blockade peaks was developed, based on so-called random-matrix theory, which assumes that the wave functions are completely random and uncorrelated with each other. Indeed the experimental data for the peak heights were found to be in excellent agreement with this theory. As Narimanov et al. write, "It therefore came as a surprise when several recent experiments demonstrated large correlations between the heights of adjacent peaks" (1999, 2640). According to random matrix theory, there are no correlations between the dif-

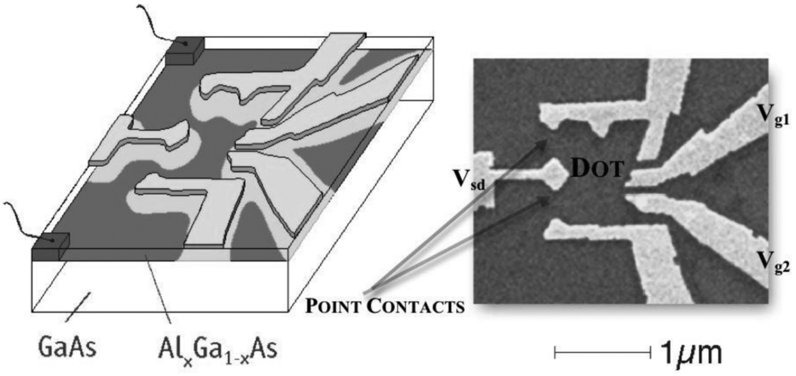

Figure 1. Scanning electron micrograph (*right*) of a ballistic quantum dot (reproduced with kind permission from C. Marcus). Color available as an online enhancement.

ferent wave functions and hence there should be no correlations between neighboring conductance peaks—yet experiments conducted by groups at Stanford and Santa Barbara in the mid-1990s (Folk et al. 1996) clearly showed a slowly varying envelope modulating the peak heights, as can be seen in figure 2.

Here at last we come to our phenomenon to be explained—our explanandum: why are there strong correlations between neighboring Coulomb-blockade peak heights exhibiting this periodic modulation? As Narimanov et al. note, "in subsequent years a number of different effects were investigated as candidates to explain this correlation [all of which were found to be inadequate]" (2001, 1). In the years 2000 and 2001 a consensus started to emerge that these puzzling features of the Coulomb-blockade conductance peaks in a quantum dot were explained by the properties of the particular classical periodic orbits in the dot.

The central idea can be understood as follows. Suppose (contrary to fact) that the electrons in the quantum dot were obeying classical mechanics and bouncing chaotically off the boundaries of the dot like a pinball machine. Although most of the electron trajectories in the dot are chaotic and nonrepeating, according to classical mechanics there will be a small number of unstable periodic orbits in which the electron will retrace its path over and over. It turns out that these few unstable periodic orbits dominate the quantum dynamics. When one of these classical periodic orbits comes close to the tunneling leads on the dot, then the dot-lead coupling is stronger and the conductance is larger—that is, a peak in the conductance occurs. Moreover, the period of modulation of the Coulomb-blockade peaks is determined by the period of the classical orbit that intersects with the leads, the frequency

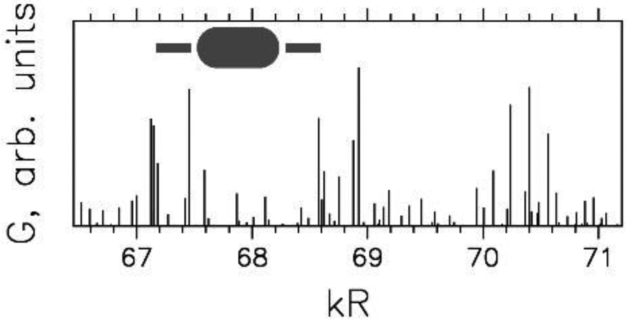

Figure 2. Conductance peaks for a stadium-shaped quantum dot with the leads placed symmetrically on either side (*inset*). Each peak is placed at the wave vector k corresponding to its level, and R is the radius of the half-circle parts of the stadium. Note that there are both strong peak-to-peak fluctuations and a periodic modulation of the Coulomb-blockade peak heights (three periods are shown above). (From Narimanov et al. 1999, 2640; reproduced with kind permission from S. Tomsovic.)

of the oscillations is proportional to the area covered by the orbit, and the peak distribution is determined by the Lyapunov exponent of the classical orbit. Narimanov et al. conclude: “The specific internal [classical] dynamics of the dot . . . modulates the peaks . . . [and] the predicted dynamical modulation is exactly of the type in the experiments” (1999, 2640).

Despite the striking success of this classical-orbit explanation of the many details of the conductance properties of quantum dots, a troubling feature of this explanation is there are no such classical periodic electron orbits in the quantum dot—they are a fiction! The intersection of the classical electron orbit with the dot lead cannot cause the peak in the conductance because strictly speaking there is no such orbit in this quantum system. There are two important features to note about this case: First, the physicists that are proffering this explanation are under no illusion that the electron is actually following one of these classical orbits—they know full well that it is a fiction. Second, it is not the case that these orbits are an approximation to a localized electron wave packet roughly following these trajectories—the wave functions of these electrons are spread out over the entire dot. Nonetheless, there is a consensus among many physicists working on the conductance properties of quantum dots that these orbits adequately explain these many features of the conductance peaks. I argue that we here have an example of an explanatory fiction.

3. Model Explanations. Purported explanations, such as these, that appeal to fictional structures, are not easily accommodated into any of the canonical philosophical accounts of scientific explanation. In my previous work

(Bokulich 2008a, 2008b, 2011) I introduced a new account of scientific explanation—called model explanations—which I have argued can make sense of these sorts of cases. My account of model explanations draws on James Woodward's suggestion that explanations can be understood as providing information about a pattern of counterfactual dependence between explanans and explanandum (Woodward 2003, 11). Woodward fleshes out this idea of counterfactual dependence in terms of what he calls "what-if-things-had-been-different questions," or "w-questions" for short. That is, "the explanation must enable us to see what sort of difference it would have made for the explanandum if the factors cited in the explanans had been different in various possible ways" (11). Unlike, Woodward, however, I do not construe this counterfactual dependence along strictly manipulationist or interventionists lines. It is this manipulationist construal of counterfactual dependence that restricts Woodward's account to specifically causal explanations, and I have argued elsewhere that it is a mistake to construe all scientific explanation as a species of causal explanation.

Very briefly, then, a model explanation is one in which the following three conditions are satisfied: First, the explanans in question makes essential reference to a scientific model, and that model involves a certain degree of idealization and/or fictionalization. Second, that model explains the explanandum by showing how the elements of the model correctly capture the pattern of counterfactual dependence of the target system; that is, the elements of the model can, in a very loose sense, be said to "reproduce" the relevant features of the explanandum phenomenon. More stringently, as the counterfactual condition implies, the model should also be able to give information about how the target system would behave, if the elements represented in the model were changed in various ways. And finally, a third condition that an adequate model explanation must satisfy is that there must be what I have a called a "justificatory step," specifying the domain of applicability of the model and showing where and to what extent the model can be trusted as an adequate representation of the target for the purpose(s) in question.

Applying this framework to the previous example, we can see that the classical periodic orbits provide part of a model explanation of the conductance properties of quantum dots. First, the explanation appeals to a semiclassical model of the quantum dot, where the behavior of the electrons is represented by means of fictional classical trajectories. Second, there is a pattern of counterfactual dependence of the explanandum phenomenon on the elements represented in the semiclassical model. The physicists are able to write down an equation that expresses precisely how the classical periodic orbits modulate the heights of the Coulomb-blockade peaks. The various features of the quantum dot conductance peaks were shown to depend on the particular features of the classical periodic orbit model: the heights of the peaks depend on whether classical periodic orbits intersect with the dot leads, the periodic modulation of the peak heights depends on the period of the classical orbit, the frequencies of the oscillations are proportional to the area covered by the periodic orbit, and the peak distribution depends on the Lyapunov (or stability) exponent of the orbit. Moreover, the semiclassical model allows physicists to answer a wide range of what-if-things-had-been-different questions. As Narimanov et al. write, from this model they now understand "how as a system parameter varies [such as] the magnetic field, for instance, or the number of electrons in the dot ([as] controlled by varying a gate voltage)—the interference around each periodic orbit oscillates. . . . When the interference is constructive for those periodic orbits which come close to the leads used to contact the dot, the wavefunction is enhanced near the leads, the dot-lead coupling is stronger, and so the conductance is larger" (2001, 2). It is important to note that physicists do not take these semiclassical models to be merely phenomenological models—that is, nothing more than useful tools for making predictions. Rather, they take them to be explanatory models that are generating real knowledge and genuine insight into the structure of the wave function of the quantum dot. As Kaplan notes, "the multielectron state inside the dot is not given by a product of single-particle states, nor do we know the electronic Hamiltonian inside the dot well enough to have any realistic hope of being able to compute the wavefunction" (2000, 3476). The semiclassical model is one of the best "windows" that they have into the quantum dynamics of the dot. So *pace* Vaihinger, cases such as this seem to show that fictions *can* "create real knowledge" and genuine understanding.

If my account succeeds in demonstrating the explanatory power of fictions, then one worry is that it does so at the price of admitting too many fictions as explanatory. Without some principled way of distinguishing explanatory from nonexplanatory fictions, it would be a Pyrrhic victory. So let us turn next to an example of a purely phenomenological model, whose fictions we would not want to count as explanatory, and see how my account of model explanation fares.

4. Nonexplanatory Fictions: The Case of Epicycles in the Retrograde Motion of Mars. As an example of a nonexplanatory fiction, let us consider the epicycles of Ptolemaic astronomy. At the heart of Ptolemaic astronomy is the geocentric model, according to which the Earth is at the center, while the sun, moon, stars, and all the other planets orbit in perfect circles around the Earth. In order to maintain the empirical adequacy of the geocentric model, it was necessary to introduce epicycles, which are smaller circular orbits that are not centered on the earth but, rather, on a point on the original circular orbit around the Earth, termed the deferent. As shown in the left-hand side of figure 3, the planet would thus travel in a circle around the epicycle at the

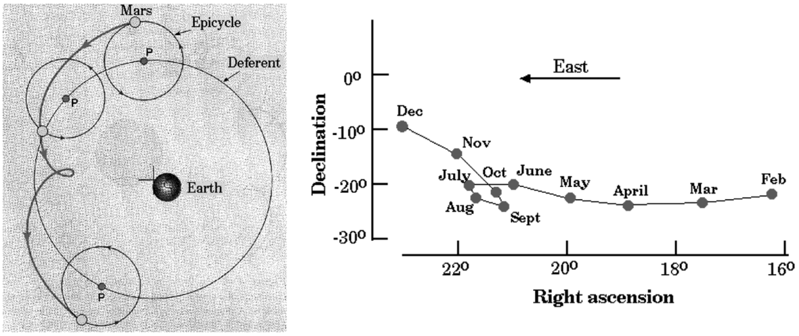

Figure 3. *Left*, "Explanation" of the retrograde motion of Mars according to the geocentric-epicycle model (source: http://cosweb1.fau.edu/˜jordanrg/hist_I/FIG19.GIF). *Right*, Record of the observed position of Mars throughout 1971 illustrating its typical retrograde motion (source: http://cosweb1.fau.edu/˜jordanrg/hist_I//FIG5.GIF). (Reproduced with kind permission by R. Jordan.) Color available as an online enhancement.

same time that the epicycle was traveling around the deferent. As we can see from this figure, epicycles were able to successfully account for phenomena such as the retrograde motion of the planets, which is the periodic apparent reversal of their motion as they travel across the sky (plotted in the right-hand side of fig. 3).

Now although one can use the models of Ptolemaic astronomy to make very precise predictions about the locations of the planets in the night sky, one would not want to say, for example, that Ptolemaic astronomy actually explained the apparent retrograde motion of Mars. As the venerable problem of asymmetry drives home, prediction is not the same thing as explanation. The geocentric model of Ptolemaic astronomy is at best merely a phenomenological model. But to press the question, why don't the Ptolemaic epicycles explain the apparent retrograde motion of Mars? The naive realist answer—Because they are fictions!—is blocked on my account.

5. Distinguishing Explanatory from Nonexplanatory Fictions. In their recent review of my book *Reexamining the Quantum-Classical Relation*, Gordon Belot and Lina Jansson have raised precisely this worry for my account of model explanations. They write:

> What is to stop you from viewing the Ptolemaic model of the solar system as giving an adequate structural model explanation of this phenomenon? Indeed an appeal to the Ptolemaic model on this question would appear to

> satisfy all . . . [the] requirements. . . . (i) A well-defined scientific model is employed. (ii) There is counterfactual dependence of the features of the target system on the features of the model. (iii) We are able to specify the domain of adequacy of the model—for the sort of phenomenon in question, the domain under which the Ptolemaic system gives a good approximation to the Copernican or Keplerian systems is well-understood. (Belot and Jansson 2010, 82–83)

While I want to argue that fictional classical periodic orbits do genuinely explain the conductance properties of quantum dots, I want to deny that Ptolemaic epicycles explain the retrograde motion of Mars. Can I eat my proverbial cake and have it too?

To strengthen your suspicions that I cannot, let me add that there are a number of close points of analogy between the present Ptolemaic case and the quantum dot case discussed earlier: First, they both involve real entities (that is, planets and electrons) that we currently take to exist. Second, what is fictional is their ascribed behaviors: electrons do not actually follow the periodic orbits cited in the conductance-peak explanations and planets do not follow the epicycles cited in the retrograde-motion explanation. Third, both explanations appeal to the dynamics (or kinematics) of superseded theories.

So what is the crucial difference that distinguishes the periodic-orbit-model explanation of the quantum dot conductance peaks from the Ptolemaic-model explanation of retrograde motion? One might have hoped that my second criterion for a model explanation—namely, that the pattern of counterfactual dependence in the model mirrors the pattern of counterfactual dependence in the target system, enabling us to answer a range of what-if-things-had-been-different questions—might have done the job. However, I don't think it can: although the range of w-questions that a phenomenological model can answer will typically be more limited, scope alone cannot distinguish between explanatory and phenomenological models.

More generally, I do not think that one can find the explanatory difference between the two cases in the structure or form of the explanations themselves: the world might have been such that our "solar" system had the structure of the geocentric model, in which case that model (despite its various idealizations, etc.) would have explained the retrograde motion of Mars. I think it is unreasonable to expect there to be something in the form of the explanation itself (such as the number or variety of w-questions answered) that would timelessly reveal that the epicycles were not, in fact, a genuine explanation.

This suggests that the difference between explanatory and nonexplanatory models is determined by something like a contextual relevance relation set by the current state of scientific knowledge. While this is surely right, more needs to be said about how scientists construct this relevance relation on a more fine-grained level. That is, given the context of the current state of scientific knowledge, how does the scientific community determine which items are to be included in the explanatory store?[1] It has long been recognized that the existence of the entity, property, or process in question is not a sufficient condition for explanatory relevance. As the well-worn "problem of asymmetry" drives home, falling barometers do not explain impending storms and characteristic emission spectra do not explain atomic structure. The relevance relation is designed precisely to solve this traditional problem of asymmetry—given the current state of scientific knowledge, we know that while the behavior of storms is relevant to explaining the behavior of barometers, the behavior of barometers is not relevant to explaining the behavior of storms. The asymmetry of the relevance relation accounts for the asymmetry of explanation.

Where I want to part company with traditional philosophical accounts, however, is on the question of whether truth or existence is even a necessary condition for explanatory relevance. In particular, I want to argue that fictions can be explanatorily relevant. That is, truth or existence is not a necessary condition for an item to be admitted to the scientist's explanatory store. However, such a position threatens to trivialize scientific explanation without some principled way of determining which fictions are to be counted as explanatory. This brings us back to the problem with which we started, namely, how do we distinguish an explanatory from a nonexplanatory fiction?

My answer begins with the observation that some fictions are representations of real entities, processes, or structures in the world, while other fictions represent nothing at all. We can even recognize that some fictions do a better job of representing certain features of the world than other fictions. What I want to say in answer to the challenge, then, is that only those fictions that are an adequate representation of the relevant features of the world are admitted into the scientist's explanatory store. However, what does it mean to say that a fictional representation is adequate? It has to be more than mere empirical adequacy. Unfortunately, here is where I think abstract philosophical generalizations purporting to hold across all model explanations give out, and one needs to turn to the nitty-gritty details of the science in question. What is to count as an adequate fictional representation is something that has to be negotiated by the relevant scientific community and will depend on the details of the particular science, the nature of the target system, and the purposes for which the scientists are deploying the model. To connect this to my general account of model explanations, the defense of a fiction as an adequate

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[1] The expression "explanatory store" is borrowed from Kitcher (1981) and refers in this context to the set of entities, mechanisms, etc. that scientists can legitimately appeal to in explaining a particular phenomenon.

representation involves the articulation and defense of the very details summarized in the third criterion for a model explanation, which I called the "justificatory step."

6. Realism and Representation in Model Explanations. Returning then to our concrete examples, why are the classical periodic electron orbits in the quantum dot considered an explanatory fiction while the Ptolemaic epicycles are not? The answer goes something like this. Given the relevance relation set by contemporary science, epicycles are irrelevant to the explanation of retrograde motion. This is not simply because they are fictional but, rather, because they fail to be an adequate fictional representation of the real structure of our solar system. Hence, although the geocentric model is predictively accurate within some domain, it is merely a phenomenological model, failing to give any genuine insight into the dynamics of planetary motion and the structure of our solar system.

By contrast, the classical periodic orbits of the electrons in the quantum dot *are* an explanatory fiction. This is because, given the relevance relation set by contemporary physics, the classical periodic orbits are able to capture, in their fictional representation, real features of the quantum dynamics in the dot. That is, reasoning with the fictional electron orbits (in accordance with the strict guidelines set down by semiclassical mechanics) yields genuine physical insight into the true electron dynamics. It is at this more fundamental level that realism comes in to distinguish explanatory from nonexplanatory fictions. The periodic orbits in the dot are explanatory—not because they are a literally true description of the electron's behavior—but because they are a fictional representation that is able to generate genuine knowledge of the true underlying quantum dynamics.

Indeed the theory of semiclassical mechanics provides physicists with what we might call a well-defined translation key, whereby statements about classical trajectories can be translated into true conclusions about the actual morphology of the wave function of the quantum dot. Note that the translation key given by semiclassical mechanics, which is what would be articulated in my third justificatory step, is not from the empirical predictions generated by the fictions to the empirical predictions generated by the true description, as it would be in translating from the Ptolemaic model to the heliocentric one. Rather, the translation key is from statements about the fictions to statements about the underlying structures or causes of the explanandum phenomenon. This is reflected in the fact that physicists value semiclassical mechanics, not primarily as a predictive tool but, rather, for the physical insight they see it generating into what is otherwise often the opaque quantum dynamics.

Returning then to my account of model explanations, we have seen not only that fictions can be genuinely explanatory, as in the case of the explanations of the conductance properties of quantum dots, but that it is the "justificatory step" that must do the heavy lifting in distinguishing explanatory from nonexplanatory fictions. In particular, we saw that the justificatory step consists of the following three interrelated components: First, there is a contextual relevance relation set by the current state of scientific knowledge, which specifies what sort of entities, states, and processes are potentially relevant to the explanation of the explanandum phenomenon. This contextual relevance relation is important for addressing the problem of asymmetry (that is, when one has prediction without explanation), and implies that explanatory relevance is something that is not judged trans-historically (by something like brute number of w-questions) but, rather, is a function of the current state of scientific knowledge.

Second, the justificatory step involves the articulation of the domain of applicability of the model, specifying where—and to what extent—the model can be trusted as an adequate representation of the relevant features of the world for the purpose(s) in question. Finally, the third, related component of the justificatory step is the requirement that there must be something like a key that allows scientists to translate statements about the fictional or idealized elements in the model into correct conclusions about the target system.[2]

As we saw in the preceding case studies, these three components of the justificatory step are satisfied in the case of the periodic-orbit explanation of the conductance properties of quantum dots but fail for the case of the epicycle explanations of retrograde motion. While the naive deployment of realism to distinguish explanatory from nonexplanatory models is blocked, a moderate realism does have a role to play in distinguishing which fictions are generating real physical insight and knowledge, and hence can be genuinely explanatory, and which fictions are not.

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[2] This translation key will not involve anything like a "one-to-one and onto" mapping. Roman Frigg (2010) has used the metaphor of a city map to illustrate a similar idea.

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