Idealization and Structural Explanation in Physics
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Martin King, 2014

1 Introduction

The focus in the literature on scientific explanation has shifted in recent years towards model-based approaches. The idea that there are simple and true laws of nature has met with objections from philosophers such as Nancy Cartwright (1983) and Paul Teller (2001), and this has made a strictly Hempelian D-N style explanation largely irrelevant to the explanatory practices of science (Hempel & Oppenheim, 1948). Much of science does not involve subsuming particular events under laws of nature. It is increasingly recognized that science across the disciplines is to some degree a patchwork of scientific models, with different methods, strategies, and with varying degrees of successful prediction and explanation. And so accounts of scientific explanation have reflected this change of perspective and model-based approaches have flourished in the explanation literature (Batterman, 2002b; Bokulich, 2008; Craver, 2006; Woodward, 2003).

Of course, not all scientific models are explanatory. Some models are merely calculational tools, whose use in the practice of science is entirely predictive or heuristic, while others are thought to actually explain the phenomena or system they are modelling. The history of scientific explanation in philosophy has focused on articulating independent criteria for what counts as an explanation. In recent work, Alisa Bokulich has argued that idealization has a central role to play in explanation (Bokulich, 2008, 2011, 2012). Bokulich hopes to find a place for certain highly-idealized models to be considered explanatory, even though they are not considered explanatory by causal, mechanistic, or covering law accounts of explanation. She calls these kinds of explanations *structural model explanations* and argues that the structural similarity between the model and the system can debar non-explanatory models (Bokulich, 2008, p. 145). She formulates her account as structural in part to capture models that are not explanatory on Woodward's manipulationist account. She aims to expand the store of explanatory models to include as explanatory those that do not accurately represent, those that model a physical system by means of fictitious entities or processes, what she calls *explanatory fictions*.

The second section of this paper examines Bokulich's account as given in (Bokulich, 2008, 2011, 2012) and articulate her three criteria for explanation. This section will also give an analysis of Bokulich's argument as it pertains to a case study examined in her book, viz. the phenomenon of quantum wave function scarring. She argues that this very interesting quantum phenomenon is best explained by appropriating concepts and formulae from classical closed orbit theory, rather than by employing quantum mechanical models. This prompts the third section of the paper in which her account is confronted with challenges, in part stemming from a review by Gordon Belot and Lina Jannson, in which they voice concerns over this account's ability to debar non-explanatory models such as Ptolemaic astronomy (Belot & Jannson, 2010). I argue that the structural aspect of her account can in fact debar the Ptolemaic explanation when viewed comparatively, but at the same time it fails to find semiclassical models explanatory. Her own solution to this problem is to use a different aspect of the account to debar Ptolemaic epicycles and allow semiclassical models. However, in section four I argue that this points to a larger worry for structural accounts because the structural criterion is not the deciding factor for which models are explanatory and which are merely phenomenological. Thus on Bokulich's account the measure of structural similarity a model bears to its target system is largely irrelevant to its being explanatory. I conclude with some remarks about what can be learned from Bokulich's work and suggest some ways to move the discussion on explanation forward.

2 Structural Model Explanations

This section examines Bokulich's structural model account of explanation as laid out in (Bokulich, 2008) and incorporates the amendments and clarifications made in (Bokulich, 2011, 2012). Bokulich's account of explanation relies on much of the work done by James Woodward (2003), so the relevant aspects of his account will be briefly recapped first. I then show how this account aims to capture semiclassical models by looking at the phenomenon of quantum wavefunction scarring and demonstrating how it satisfies her account's criteria.

On Woodward's account, causality is framed in terms of counterfactuals rather than in terms of causal mechanisms or physical interaction. Of course not all counterfactuals are going to describe causal relations. He distinguishes between interventionist and non-interventionist counterfactuals. Basically, an explanatory counterfactual tells us what would happen to the systems if certain interventions were to take place. The relations that are invariant under certain changes are doing the work of distinguishing the accidental generalizations from genuine causes. Causal relationships, he claims, are out there in the world, but they are given in the reliable variable dependencies of models. Explanation is the activity of gaining information about these causal relations by discovering through intervention which dependency relations are largely invariant. The counterfactual dependency of these relations gives us important information that provides explanatory depth. This is information that answers what-if-things-had-been-different questions, or *w-questions*. Thus, the range of questions that counterfactual dependence answers is related to the explanatory power of that causal relation (Woodward, 2003; Woodward & Hitchcock, 2003).

Alisa Bokulich adopts aspects of Woodward's account, in particular the idea that giving counterfactual information is central to explanatory power, but she rejects the causal manipulationism. In fact, she aims to give an account that can capture the explanatory power of the structural, non-causal, models that are not captured by Woodward's account. She has in mind the models of semiclassical mechanics. She claims that these models cannot be explanatory on a causal account because the entities involved (electron trajectories) are fictional and have no real causal power. As it will be shown, the morphologies of the quantum systems of interest depend on the particular periodic orbits of semiclassical mechanics, but the orbits cannot be said to cause the wavefunction distributions, even though there is a reliable dependency relation. Bokulich argues that none of the three main types of accounts of explanation (causal, covering law, and mechanistic) can capture the way semiclassical models explain quantum phenomena, and offers her own *structural model explanation* as a supplement. This account highlights the structural similarities between the real world system and the idealized or fictional model. Bokulich argues that structural model explanations are ones in which there is a pattern of counterfactual dependence among the variables of the model, which can be measured in terms of w-questions, and that this dependence is a consequence of the structural features of the target system (Bokulich, 2008, p. 145).

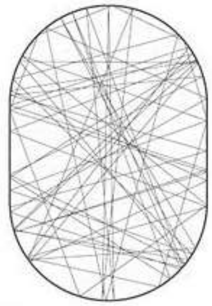
In developing her account, Bokulich draws on a suggestion made by Margaret Morrison that explanation has to do with structural dependencies (Morrison, 1999). Similar ideas have been developed by John Worrall, James Ladyman, and others (Esfeld & Lam, 2008; French & Ladyman, 2003; Ladyman, 1998; Worrall, 1989). Bokulich offers three general requirements for a structural model explanation, which I have enumerated as follows. The first criterion is E1, which states that the explanation makes reference to a scientific model, *M*. E1 specifies that the explanation is a model explanation and not a covering law or mechanistic explanation. The structural aspect of the structural model explanation comes from the second criterion E2, which says that *M* must be explanatory by showing how there is a pattern of counterfactual dependence of the relevant features of the target system on the structures represented in *M*. E2 is intended to determine which models are genuinely explanatory by ensuring that an explanatory model bears a close structural similarity to the counterfactual structure of the phenomenon. This structural 'isomorphism', as she calls it, is given an objective measure in terms of w-questions (Bokulich, 2008, p. 145). The final criterion is E3, which states that there must be a justification that specifies the domain of the application of *M*. E3 is what she refers to as the *justificatory step*, intended to specify "where and to what extent the model can be treated as an adequate representation of the world" (Bokulich, 2008, p. 146).

She applies her criteria for explanation to some cases of semiclassical mechanics as part of a larger project of reconceiving the intertheoretic division between the quantum and the classical. She argues that semiclassical mechanics can be genuinely explanatory of certain quantum systems. Semiclassical mechanics is of particular interest to her because they seem to fall outside of the range of other accounts of explanation. The reason seems to be that the models of semiclassical mechanics are non-Galilean, or highly-idealized. The distinction between Galilean and non-Galilean idealizations is one that was made popular by McMullin and it can help clarify the special nature of these models (McMullin, 1985). Very simply, if one can add detail to an idealized model and continually get closer to the real system, then this is what is known as a *Galilean idealization*. For instance, Galileo, in determining the rate of falling bodies, made use of balls rolling down incline planes that were assumed to be frictionless. This kind of idealization is harmless, and the same mathematical relation at which Galileo arrived can be modified to include friction to increase its accuracy. Models featuring these idealizations can be explanatory for McMullin. They represent the target system in a straightforward fashion and their use in explaining the system is justified in part by the fact that they approximately represent. Robert Batterman has described these models as having "controllable" idealizations, in that the idealizations of the system are justified theoretically (Batterman, 2005, p. 235). Idealizations that are non-Galilean on the other hand, have singular limits and cannot be modified to approach the target system. They are what I refer to as *highly-idealized models*. These models lack the representation that justifies their use in explanation. However, Batterman, Bokulich, and others argue that this does not preclude explanation.

Semiclassical models are prime examples of highly-idealized models because it is not possible to recover the quantum models by adding realistic detail into the semiclassical models. If the semiclassical models have explanatory power, it cannot be due to an underlying causal mechanism of which they are a Galilean idealization. Bokulich thinks that semiclassical models of quantum wavefunction scarring are precisely the kinds of structural explanations that Woodward's 2003 account does not consider explanatory. This is why she allows that the justification of the application of the model to quantum phenomena (E3) can be *top-down* from theory, rather than bottom-up where it would be smoothly recovered in Galilean idealization. For semiclassical mechanics there is no smooth approximation, but there is Gutzwiller's periodic orbit theory. This theory specifies how the classical trajectories can be used to model certain quantum features.

Robert Batterman was the first to argue that semiclassical appeals to classical structures in quantum phenomena at the asymptotic limit between the two is explanatorily important (Batterman, 1992, 2002b). Bokulich claims that structural explanations are actually quite popular in mechanics where appeals to structural restrictions can account for certain aspects of systems. She argues that semiclassical mechanics can be an important interpretive and explanatory tool for certain quantum phenomena, specifically in the subfield of quantum chaos. Classical chaos is found in a great number of systems in which there is an extreme sensitivity to initial conditions, such that immeasurably small differences in initial conditions may result in an exponential divergence. Of course, sensitivity to initial conditions has no part in quantum theory, but quantum models that also describe these systems must exhibit something like chaos themselves. Both Bokulich and Batterman explain that one expects to find a correlate of classical chaos in quantum systems because of the Correspondence Principle, originally formulated by Bohr as the agreement between classical and quantum mechanics as $\hbar \rightarrow 0$. The reason is that because classical mechanics is the classical limit of quantum mechanics, there ought to be quantum systems that underlie classically chaotic systems as well (Batterman, 1992, pp. 51-52; Bokulich, 2008). One of Bokulich's strongest examples is that of quantum wavefunction scarring in systems known as *quantum billiard models* (described below). Studies of these quantum billiard systems have revealed that there is an unexpected accumulation of the wave functions along the trajectories that would be periodic orbits in a classical chaotic system.

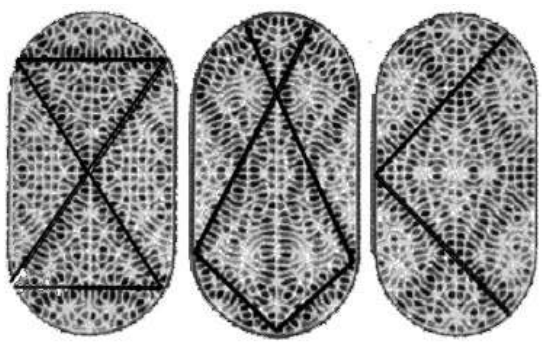
In the classical billiard systems, a stadium shaped enclosed space is inhabited by a free-moving particle whose trajectory is mapped. The shape of the enclosure generally creates a chaotic trajectory that displays an irregular pattern (Fig. 1).This irregular pattern eventually leads to a uniform distribution of trajectories throughout the space. However, there are a few initial conditions that lead to periodic orbits in which the motion of the particle constantly repeats itself. There are certain starting positions and velocities that will not result in a uniformly distributed stadium. This occurs in different shapes including a rectangle, a vee, and a bow tie, among others 0.



(Fig. 1)

Figure 1. A typical example of a classical chaotic trajectory of a particle in a stadium shaped enclosure (Stöckmann, 2010).

In the quantum analog, since no sensitivity to initial conditions plays any part, one would expect to be unable to distinguish the chaotic and periodic orbits. Without orbit theory, there is no reason to expect that anything other than a random superposition of plane waves exhibiting a regular and diffuse pattern. But what one actually finds is that the probability density of the wave functions is significantly higher in certain areas 0. Not all the wavefunctions are evenly distributed. The interesting fact is that they actually converge on the classically stable periodic orbits.



(Fig. 2)

Figure 2. Three eigenstates of quantum billiard stadiums appear to give wavefunction distributions along trajectories predicted by the classical closed orbit theory.

What this suggests is that the shapes of the classically stable orbits in the stadium overlap and make its probability more intense. Gutzwiller's periodic orbit theory is a method of approximating the density of quantum states from classical periodic trajectories by means of the Gutzwiller trace formula (Eq. 1), a semiclassical approximation of Green's function,

(Eq. 1) $$\rho_{osc} \approx \frac{1}{\pi\hbar} \sum_p A_p \cos\left(\frac{S_p}{\hbar} - m_p \frac{\pi}{2}\right)$$

where *S* labels the action of the periodic orbits *p*, *A* is a measure of the orbits' stability and m is the number of times the neighbouring orbits intersect the periodic orbit in one period. Gutzwiller's theory specifies how the behaviour of a Gaussian wavepacket can serve as accurate solutions to the time-dependent Schrödinger equation, and thus how the allowed classical periodic orbits corresponds to the accumulation of wavefunction density observed as the scarring phenomenon. Bokulich's contention is that the scarring phenomenon is explained better by appealing to the periodic orbit theory than it is by solving the Schrödinger equation.

She argues that classical trajectories, though fictions – false of the quantum system – are explanatorily relevant to the phenomenon of quantum wave function scarring. By falsely assuming that the particle travels along a classical trajectory, one correctly expects to find certain scarring patterns in quantum billiard systems, which one would not expect on a simple quantum picture. She argues that this example is a case of bona fide structural model explanation. This example is not an outlier case, but one of many Bokulich examines, including the conductance peaks of quantum dots, the orbits of Bohr's model of the atom, and the resonance peaks of the Rydberg electrons.

For Bokulich, these examples suggest that there is a "dynamical structural continuity" between the classical and quantum theories, though not as straightforward as relation proposed by Bohr. Because of this she argues that semiclassical fictions, in this case the classical periodic orbit theory applied to a particle, can serve to give counterfactual information about the quantum system. The closed orbits are not real, in the sense that the particle is not actually travelling in a classically defined orbit with position and velocity. Bokulich does not want to argue that the trajectories are real, but rather that they are a special kind of fiction that is also explanatory: "These closed and periodic classical orbits can be said to explain features of the spectral resonances and scarring insofar as they provide a semiclassical model of these phenomena" (Bokulich, 2008, p. 140).

Bokulich admits that it is possible to derive these conductance properties and scarring patterns from a fully quantum picture, by numerically solving the Schrödinger equation, but the dependence of the conductance properties on the classical orbits allows her to say that the semiclassical model is playing an explanatory role here. This dependence conveys physical insight, or structural information, on the quantum dynamics. Of course, in order for Bokulich to claim that there is a genuine explanation here, the semiclassical model must satisfy her three criteria E1-3. And it can be easily shown that they do. The explanation makes reference to a scientific model, viz. Gutzwiller's periodic orbit theory, and so it satisfies E1. The semiclassical mechanics models exhibit the counterfactual dependence of the conductance peaks of the stadiums on the particular classical orbits. It satisfies E2, the structural criterion, because one is able to say how the wavefunction distribution inside the stadium would change if the periodic orbit had been different, or if the shape of the stadium is changed. This putative explanation is also justified in being applied to this domain (E3) because Gutzwiller's periodic orbit theory specifies how to model features of quantum dynamics with classical trajectories.

So for Bokulich, these semiclassical models qualify as explanatory. But Bokulich argues for an even stronger case, viz. that the semiclassical models actually provide *better* explanations than the fully quantum ones. She does not claim that quantum mechanics alone cannot predict these phenomena, but rather that its explanations are deficient because they do not provide as much counterfactual information about the system, which gives us physical insight into the system and grants understanding. In order to get a measure of the information a model gives about the system, she makes use of w-questions and Woodward and Hitchcock's notion of explanatory depth. The more w-questions a model answers, the more information it gives, the deeper the explanation it provides (Bokulich, 2008, p. 152).

For Woodward, the range of w-questions that a model can answer about a phenomenon is directly related to its ability to explain that phenomenon, where models that are more general or more fundamental provide deeper explanations. However, Bokulich claims that the semiclassical model of wavefunction scarring gives counterfactual information about the quantum system, and further that “there can be situations in which *less* fundamental theories can provide deeper explanations than more fundamental theories” (Bokulich, 2008, p. 153). Given that there are full quantum derivations of these scarring phenomena, if Bokulich wants to argue that the semiclassical model is explanatory and the quantum derivation of the same phenomenon is less so, then she has to show that the semiclassical model can answer a wider range of w-questions.

There would be more room for this argument is it could be argued that the semiclassical models offer answers to a different class of w-question, viz. questions about what the quantum wavefunction scarring would look like if the semiclassical orbit were different, or questions about why these particular morphologies are favoured. Information about why particular scarring patterns, as seen in 0, occur is given by the semiclassical model, so the argument would go, because it is easily capable of accounting for the chaotic and the particular periodic trajectories, and can show how the quantum scarring would change if things (the periodic orbits) had been different.

3 Worries about a Structural Criterion for Explanation

I have shown how Bokulich’s account aims to capture the explanatory power of highly-idealized models like those of semiclassical mechanics, and I now turn to examine some worries about these structural model explanations. In the aforementioned review of (Bokulich, 2008), Belot and Jannson are concerned that once the account of structural model explanations allows for such fictions as classical trajectories in quantum systems, it will be unable to reject models that are widely considered non-explanatory, such as those of Ptolemaic astronomy (Belot & Jannson, 2010). The worry is that once she opens the door up to explanatory fictions her criteria are not strong enough to debar non-explanatory fictions, such as planetary epicycles. I shall show that on one reading of Bokulich’s account Ptolemaic models can be shown to be non-explanatory. However, the concerns of Belot and Jannson are not misplaced as I shall show that this same reading fails to conclude that semiclassical mechanics are explanatory.

As is well known, the Ptolemaic model of the solar system makes use of epicycles in accounting for the apparent retrograde motion of the planets across the night sky as seen from Earth. Bokulich is explicit in wanting to allow for the idealizations in quantum dots and quantum billiard systems (fictitious electron trajectories), but not those of Ptolemaic astronomy (fictitious epicycles). Belot and Jannson are right to worry that epicycles and electron trajectories are of the same ilk, but Bokulich might have room for admitting one and not the other. At first glance, it seems that the Ptolemaic explanation for planetary motion satisfies her three criteria for a good explanation.

The Ptolemaic explanation satisfies E1, insofar as it references the geocentric model of the solar system. The model is also counterfactually reliable under certain conditions. The Ptolemaic system has trigonometric tables of chords used for calculations, and these give us counterfactual information about the visible solar system. And so it also seems to satisfy E2. It is only on the third criterion E3 that the Ptolemaic models will be debarred according to Bokulich. The geocentric model and its epicycles are not adequate representations of the real structure of solar system, and so not deemed relevant to the explanation of planetary motion by the contemporary state of science (Bokulich, 2012, p. 735). This is indeed true, however, I will return to the third criterion in the following section, but for now I will focus on her assessment of Ptolemaic models and the structural criterion E2.

It is important to remember that E2 is the criterion intended to pick out which models are genuinely explanatory. This is the structural part of structural explanation. The structural isomorphism is meant to replace manipulationist causation in Woodward's picture as the main deciding factor for an explanation. In order to most accurately assess the satisfaction of E2, one needs to actually measure the number of w-answers.

Unfortunately, obtaining a measure of the number w-questions a certain model can answer is not straightforward, and Bokulich gives no real method for obtaining such a measure. The first problem one encounters is in attempting to count individual w-questions. The Ptolemaic system has methods of calculating the positions of the bodies of the solar system for any given day, for any place on Earth, including not just positions in the night sky, but eclipses, solstices, equinoxes, and so on. Importantly, these bodies have cycles and epicycles that are continuous, and so one could get an infinite number of w-question answers, along each of the points on the lines of the spherical trigonometry. And so the number of w-questions the model can answer cannot be meaningfully counted.

Bokulich does not explicitly frame w-questions in a comparative way, but I suggest that Ptolemaic epicycles do answer fewer w-questions (provide fewer w-answers) than the Copernican model, and it can be debarred in that fashion. As we have seen, a quantitative method for counting is not possible, so a simple quantitative comparison cannot be made. However, there is a sense in which an intuitive comparison of the classes of w-questions is possible. Because there is a lot of overlap of the information one gets from the Ptolemaic model and the Copernican model, an argument could be made that the Ptolemaic model has a narrower scope, which is to say that the Copernican model can give all or nearly all the w-answers that the Ptolemaic model provides, but also a lot of additional w-answers as well, such as accounting for the phases of Venus and giving counterfactual information about the positions of the planets when not seen from Earth.

The Copernican model answers more w-questions on this kind of comparison, so perhaps epicycles are not explanatory. With this kind of comparison there seems to be a way after all in which Bokulich can have her structural criterion E2 decide between explanatory and non-explanatory models.

If this comparative framework works for Ptolemaic astronomy, does the same hold in the case of semiclassical mechanics? Well, when one returns to the semiclassical models and attempts to compare the w-information with that provided by quantum mechanics, the comparison does not seem to lead to the conclusion that semiclassical mechanics is explanatory. The semiclassical model can give counterfactual information about the distribution of probability densities in the enclosure in straightforward way. There is a certain range of questions that can be answered about the dependence of the scarring on the classical orbits. It seems that "rather than obscuring the genuine mechanisms at work, this idealization actually brings them into focus" (Batterman, 1992, p. 64). So it seems that there could be a class of w-questions that are better, or more intuitively, answered by the highly idealized model. The highly-idealized model is indifferent to the details and particulars of the dynamics and allows certain features like scarring phenomena to be highlighted.

However, the Schrödinger equation *can* derive the results that are obtained in the semiclassical models, as Bokulich freely admits. But in addition to this, the quantum model can also provide w-answers about many other quantum systems, ones in which the semiclassical model fails to hold. This seems to give the same comparative relation between Ptolemaic and Copernican models of the solar system. The quantum system can be seen to give more w-answers because it includes the semiclassical and much else. It can be seen that the comparison fails to side in favour of semiclassical mechanics. If there were a domain of phenomena in which the more fundamental theory could not derive the desired results (and I am certain there are many), then the best explanation would be given by the less fundamental theory. In this case however, Bokulich admits that the quantum models *can* account for the scarring phenomena described by the semiclassical models. And so it turns out that even though the classical trajectories can answer interesting w-questions about the particular morphologies of the wavefunction scarring, models from the more fundamental theory will always win out in terms of w-questions when they can account for the same phenomena.

And this is what I believe Woodward and Hitchcock had in mind when they introduced the notion of w-questions. For Woodward and Hitchcock, the models of the more fundamental theory is able to provide more information, to give answers to more w-questions (Woodward & Hitchcock, 2003). For them, this implies that the deeper explanation is given by the more fundamental theory; e.g., General Relativity has more explanatory depth than Newtonian mechanics because it answers a wider range of w-questions. If a theory is more fundamental, then its models can answer a wider range of w-questions. Woodward might accept that these highly-idealized models are explanatory, but less explanatory than fundamental models that offer much deeper explanations, as long as they satisfy his criteria for explanation by exhibiting a degree of invariance under a range of interventions. However, this will not work for Bokulich, because it will not favour the models of semiclassical mechanics over those of quantum mechanics because they have overlapping domains. It is important for Bokulich, not only that semiclassical models be explanatory, but that they actually be better explanations of some quantum phenomena than the fully quantum explanations: "Without knowledge of the classical orbits, our understanding of the quantum spectra and wavefunction morphologies is incomplete" (Bokulich, 2008, p. 154).

A further concern is that this kind of comparison seems only to work in cases where there is overlap in the domain of the phenomena. Where there is no overlap, an intuitive sense of which model answers more w-questions, does not seem to have any bearing on the explanatory power of one theory or the other. If one compares semiclassical mechanics with Ptolemaic astronomy, regardless of how the w-information balance tips, E2 still has no real bearing on whether the models of semiclassical mechanics are themselves explanatory. When there is no overlap in the domain of the models, the comparison is not helpful.

Even if there were a quantitative way to measure the structural similarity using something other than w-questions, this problem persists for Bokulich. Imagine it was possible to give a compressed scalar rating of all the complex representations of structural similarity given by a complicated process of calculations and perhaps insights from measure theory. Now suppose that Ptolemaic epicycles were given a rating of 4, Copernican orbits a 9, and semiclassical mechanical models a generous 12. Even though it received a higher ranking than something like Ptolemaic explanations, it is still reasonable to ask "are the models of semiclassical mechanics explanatory?" And so it does not seem that there can be any way that such a comparative framework can provide a general criterion for explanation. It is only when the domain of the phenomena overlap that this will work. However, because a comparison that ranks semiclassical mechanics as less explanatory than quantum mechanics is inconsistent with her view, this measure will not be helpful for Bokulich.

The main worry for a structural criterion for explanation is that a measure of structural similarity can be given to almost any model, no matter how inaccurately it represents. And so if one wishes to debar the worst of these then a comparison must be made. However, this comparison, when possible, will always side in the favour of the models of the more fundamental theory and not the highly-idealized model of high-level theory. This does not serve Bokulich's end, but it is not in itself problematic. The general problem is that this comparison is only helpful for models with overlapping domains, and leaves unanswered the question of whether a particular model explains its target phenomenon. Philip Kitcher offers a comparative account of explanation, but it is intended to function irrespective of domains (Kitcher, 1981, 1989). It is also comparative in a winner-take-all fashion, where only the most unifying theory was explanatory. The winner-take-all aspect would be problematic for Bokulich because it would not favour quantum mechanics, but this is not in itself a problem, nor a problem for Kitcher, though his purely syntactic approach to explanation theory choice has its other downsides, which willnot be covered here.

4 Worries about the Justificatory Step

Bokulich's own solution is to debar Ptolemaic epicycles, not with the structural criterion E2, but with the justificatory criterion E3. And so in this section I will analyze this aspect of Bokulich's account and raise some concerns about it playing the major role in distinguishing explanatory from non-explanatory fictions.

This justificatory step has three aspects, which Bokulich has expanded upon in (Bokulich, 2012, p. 736), and which I have labelled here as J1-3. The first, J1, is that an explanatory model involves a contextual *relevance relation* set by the contemporary state of science, which ensures that scenarios like falling barometers causing storms are simply not even candidate explanations. The justification also involves an articulation of the *domain of applicability* J2, wherein it is an adequate representation of the system. To satisfy this there must be either a top-down or bottom-up justification of the model's use, as I described above (Sec. 2). Lastly, and closely related is J3, a *translation key* of sorts that allows information about the model to be translated into conclusions about the real system. There must be some reason why information gained in the model is applicable to conclusions about the world. For example, Gutzwiller's periodic orbit theory specifies how the trace formula (Eq. 1) is related to the actual observed morphologies in the quantum stadium billiard. E3 taken together is something like the explanatory standards of contemporary science. It ensures that the model makes reference to the right kinds of accepted entities, states, and processes, and that the relation between the model and the real system is not merely accidental.

Bokulich does not appeal to E2 in order to debar Ptolemaic explanation, rather she argues that the models fail to be explanatory because they do not qualify as adequate representations of the solar system in contemporary science. Explanatory fictions "represent real entities, processes, or structures in the world, while [non-explanatory ones] represent nothing at all" (Bokulich, 2012, p. 734). She wants to allow for fictions to be explanatory, but only fictions that count as adequate representation – something that can only be decided by the relevant scientific community.

In the context of these two examples, the Ptolemaic model is non-explanatory because the orbits are not adequately representative of the real structure of planetary motion: "given the relevance relation set by the state of 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," whereas "the classical periodic orbits are able to capture, in their fictional representation, real features of the quantum dynamics in the dot" (Bokulich, 2012, p. 735). So the adequacy of the fictional representation as determined by the criteria of E3 can debar Ptolemaic epicycles.

In her response to the worry of Belot and Jannson cited above (Sec. 3), she says: "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." (Bokulich, 2012, p. 733) She offers instead the idea that the current state of scientific knowledge precludes the possibility of Ptolemaic epicycles being counted as explanatory, in the same way that it ought to preclude falling barometers causing storms – neither satisfy J3. It was shown in the previous section that E2 also debars both Ptolemaic epicycles and semiclassical models. Semiclassical models are not so obviously inadequate as to be excluded from the explanatory store, like shadows explaining flagpole heights, and so they satisfy J1. However, for J2 and J3, the semiclassical models of interest employ Gutzwiller's periodic orbit theory to justify their application and provide a means of getting real-world information from the fictional model. And so the semiclassical models seem to satisfy E3 as a whole and are justified in being used in these systems exhibiting quantum chaos, even though it was shown that they did not satisfy E2. Bokulich has provided a reason for thinking that her account can debar this kind of standard counterexample. The Ptolemaic model is simply not a candidate explanation to begin with, because the fictions it employs are too empirically inadequate for them to be considered representations of the structure of the system.

In the remainder of this section I will raise three worries about E3 and about this kind of criterion as the main deciding factor for explanation. The first worry is that even though she insists that electron trajectories in semiclassical models capture real features of the systems dynamics and Ptolemaic epicycles do not, it is not clear that in distinction from epicycles, classical electron trajectories *are* representative of the true electron dynamics, of the *real* structure of the quantum systems, as she claims (Bokulich, 2012). Part of the requirements of E3 is that entities and processes of the model are considered by scientists to be potentially relevant to the explanation (J1). Earlier, I conceded that the semiclassical models should not be dismissed from potential explanations outright, but this does not imply the positive claim that they do capture real quantum structures. Consider the fact that the predictive success of semiclassical models is rather unexpected. This is so precisely because they are not true descriptions of the systems. It may be that there is a certain range of counterfactual information about the systems' morphologies that can be gathered, but it is not readily understood why it is that the dependency relation holds. Given only the full semiclassical explanation, it is still a bit mysterious why the *quantum* effect would be dependent on the *classical* trajectory. However, if one were able to derive this phenomena and render it expectable on a fully quantum picture, that mystery would disappear. This seems to suggest that the *real* structure of the system is only given in a fully quantum picture, in the same way that the numerical coincidences of Ptolemaic calculations are revealed by more fundamental theories.

The second worry is that because this is supposedly a structural explanation, a lot should depend on the satisfaction or degree of satisfaction of E2, but this does not seem to be the case. E2 is not capable of doing the work of distinguishing explanatory from non-explanatory fictions in the way that Bokulich wants, since it debarred both Ptolemaic models and those semiclassical mechanics in favour of models with broader scopes from more fundamental theories. Due to this, E3 has to do most of the heavy lifting. However, if E3 is largely responsible for maintaining a threshold for explanation, then there is not much of a sense in which these 3 criteria taken together are independent criteria for explanation. The deciding factor is what satisfies E3, i.e. what is consistent with that currently considered to be explanatory in science, and not with the structurally analogous models. The structural criterion that was intended to pick out which models were genuinely explanatory by showing whether the models exhibited the relevant structural properties of the system failed to do so. In order to make a strong case that semiclassical mechanics can provide *structural* model explanations, the structure that allegedly links the models to the real-world system should determine that.

The last related concern is not only that E2 should distinguish explanatory from non-explanatory in a structural explanation, but that E3 is too context sensitive to do this. It seems as though E3 could be determined, or estimated, with structural information. If one wanted to assess the adequacy of a model's depiction of reality, to determine whether its relation was numerological or correlational and know if the model's information is applicable to the real world system, then its ability to give a wide range of reliable counterfactual information about that system seems a reasonable measure. This information is something that the model can provide on Woodward's account, because it is explicitly manipulationist. But because Bokulich does away with the causal interventions and only imports the notion of explanatory depth, this must be added on as a separate criterion and loses objectivity. On Bokulich's account, there can be no interventions to separate the correlational from the causal, instead it falls on the scientific community to decide if it is adequate. E3 is not meant to employ the measure of w-questions – it is not a measure of structural similarity, but a criterion for ensuring that the model is not known to be phenomenological. The criterion is context sensitive and particular to the details of the model and the current views in science regarding what explains and what accurately represents. What counts as an adequate fictional representation (J1) is a moving target, and may or may not be unanimously agreed on across a discipline.

Even if what represents and what explains were widely agreed upon, there is something missing in this kind of justification – a degree of normativity. When Bokulich argues for the explanatory power of semiclassical mechanics she concludes from the work of Wintgen, Richter, and Tanner (1992), as well as others, that it is more than a tool or a method for generating more simply reliable predictions. Bokulich cites physicists as saying that semiclassical descriptions are desirable because the full quantum-mechanical calculations are cumbersome and elaborate and that the "simple interpretation of classical and semiclassical methods assists in illuminating the structure of solutions" (Wintgen et al., 1992, p. 19). It is in getting the structure of solutions that the semiclassical methods are most useful, i.e. they have much heuristic value. Batterman has argued along similar lines citing the work of W.H. Miller: "Semiclassical theory plays an interpretive role; that is, it provides an understanding of the nature of quantum effects in chemical phenomena, such as interference effects in product state distributions and tunnelling corrections to rate constants for chemical reactions" (Miller, 1986). While these quotations are clearly in favour of the value, and explanatory value, of semiclassical mechanics, it is important to remember that the scientists are unlikely to have in mind a rigorous and philosophically robust notion explanation, complete with independent criteria. And that even if some scientists, or even a majority, do find these models to be explanatory, there is more to a philosophical account of explanation than merely capturing that. An account of explanation should not be merely descriptive, but provide independent criteria capable of assessing putative explanations.

Traditionally accounts of explanation have tried to provide a bar above which certain models are counted as explanatory. (Hempel & Oppenheim, 1948). Woodward also seemed sensitive to this, particularly when he provided motivation for his manipulability account (Woodward, 2003, p. 93). It is not enough to describe the accepted use of causation (or in this case explanation) without providing sufficient motivation for why that particular conception should adopted.

5 Conclusions and Suggestions for Moving Forward

Semiclassical mechanics is still a very fruitful research avenue, and it is intuitively powerful. It allows us to picture and grasp systems that we should not be able to picture, and frame them in familiar terms. And quite astonishingly, it can give us simple and reliable counterfactual information about certain quantum systems. Semiclassical mechanics is certainly more relevant to the current state of science than Ptolemaic epicycles, because its models are heuristically valuable in providing frameworks for investigating and calculating quantum systems. Bokulich's work on explanation and highly-idealized models is largely connected with her larger project of reconceiving the quantum to classical transition. She has, in explicit detail, gone over cases that cast doubt on a simple reductive picture. The concerns remaining for a structural account should not diminish the contributions she makes to our understanding of Bohr's Correspondence Principle and the intricacies of the quantum to classical transition.

Bokulich has taken bold steps forward in offering an objective measure for determining structural similarity in terms of w-questions. However, this measure proves difficult to determine. I have argued that because an independent, objective measure of structural similarity cannot be made, that an objective comparison can also not be made. I further argued that an intuitive comparison is no help for Bokulich. It can be made, but it always sides in favour of the more fundamental explanation and not the highly-idealized model, thus ruling out semiclassical mechanics, and other minimal models. I was able to show that the epicycles of Ptolemaic astronomy need not be considered explanatory, but the worry then becomes that semiclassical models, because they give less w-information than quantum models, are also not explanatory. Further, this distinction is of no use when the domains of the models are completely distinct. The remaining problem for structural accounts is that even if an objective measure were possible, it would still give no information about whether a model is explanatory across domains or independently. Therefore, I argue that structural similarity cannot distinguish between explanatory and non-explanatory fictions.

Because of this, the other criteria in Bokulich's account had to do the heavy lifting with regards to drawing a line between explanatory and non-explanatory models. But these criteria alone seem only to reflect what is currently thought about whether a model is considered explanatory, and do not give independent reasons to conclude that a model is explanatory. The strong role her third criterion plays is also worrying, not only because the structural aspect of the structural explanation is downplayed, but because it takes away the normative aspect that an account of explanation ought to have, and has traditionally aimed for.

There are many lessons we can take away from the new direction this account has taken and the problems that remain. Highly idealized models are common in science and as other have argued (Batterman, 2002a; Batterman & Rice, 2014; Wayne, 2011), there is reason to consider them explanatory. Stepping out of the shadow of Woodward and expanding the scope of explanation is a next major step in the philosophy of science. Bokulich tries to do so by providing a quantitative measure for structural similarity but it ends up not working in her favour. The purely structural criterion is not helpful in distinguishing explanatory from non-explanatory idealizations, but more than that, an account of explanation should continue the tradition of offering independent normative criteria for explanation, and be descriptive of, and critical of, the explanatory practices of science.

If Bokulich is correct about the limits of causal accounts and the explanatory virtue of highly-idealized models, and there are good reasons to think that she is, then developing an extended account of explanation and idealization is a worthy aim, and she has contributed a great deal to that end.

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