Forthcoming in J. Saatsi and A. Reutlinger (eds.)
Explanation Beyond Causation
(Oxford University Press, forthcoming/2018)

Searching for Noncausal Explanations in a Sea of Causes

Alisa Bokulich
Center for Philosophy & History of Science
Department of Philosophy
Boston University
Boston, MA, U.S.A.
abokulic@bu.edu

To anyone who, for the first time, sees a great stretch of sandy shore covered with innumerable ridges and furrows, as if combed with a giant comb, a dozen questions must immediately present themselves. How do these ripples form?
--Hertha Ayrton ([1904] 1910: 285)[1]

Abstract
In the spirit of explanatory pluralism, this chapter argues that causal and noncausal explanations of a phenomenon are compatible, each being useful for bringing out different sorts of insights. After reviewing a model-based account of scientific explanation, which can accommodate causal and noncausal explanations alike, an important core conception of noncausal explanation is identified. This noncausal form of model-based explanation is illustrated using the example of how Earth scientists in a subfield known as aeolian geomorphology are explaining the formation of regularly-spaced sand ripples. The chapter concludes that even when it comes to everyday "medium-sized dry goods" such as sand ripples, where there is a complete causal story to be told, one can find examples of noncausal scientific explanations.

I. Introduction

According to a position we might label causal imperialism, all scientific explanations are causal explanations—to explain a phenomenon is just to cite the causes

I would like to express my deep gratitude to Gary Kocurek for very helpful discussions about aeolian geomorphology and defect dynamics. I am also grateful to the editors for providing helpful feedback on this chapter. Any mistakes are of course my own.
[1] This quotation is taken from the first paper ever permitted to be read by a woman at a meeting of the Royal Society of London.

of that phenomenon.[2] Defenders of noncausal explanation have traditionally challenged this imperialism by trying to find an example of an explanation for a phenomenon for which no causal explanation is available.[3] If the imperialist can, in turn, find a causal explanation of that phenomenon, then it is believed that the defender of noncausal explanation has been defeated.[4] Implicit in such a dialectic are the following two assumptions: first, that finding an example of a non-causal explanation requires finding something like an uncaused event, and, second, that causal and noncausal explanations of a phenomenon are incompatible. This has left noncausal explanations as relatively few and far between, relegating them to fields such as fundamental physics or mathematics.

In what follows, I challenge these two assumptions. Noncausal explanations do not require finding a phenomenon for which no causal story can be told. I argue instead that one can have a noncausal explanation of a phenomenon even in cases where a complete causal account of the phenomenon is available. Having a causal explanation of a phenomenon does not preclude also having an alternative, noncausal explanation for that same phenomenon. Causal and noncausal explanations are complementary, and each can be useful for bringing out different sorts of insights.

[2] An example of a defender of such a position is David Lewis (1986), but more often it is a position that is assumed as a default, rather than being explicitly defended. Brad Skow (2014) similarly argues, "what I say here does not prove that there are no possible examples of non-causal explanations, but it does, I think, strengthen the case" (446).

[3] This is arguably why defenders of noncausal explanation have primarily looked to examples in mathematics and quantum mechanics, where causal explanations are thought to be excluded.

[4] As Marc Lange (2013: 498-999) notes, for example in the case of the prime life cycle of cicadas, there is often a causal explanation in the close vicinity of a noncausal explanation that can be conflated if the explananda are not carefully distinguished.

I begin by introducing my approach to scientific explanation, which includes what I call the "eikonic" alternative to the ontic conception of explanation, and which distinguishes two types of explanatory pluralism. I will then lay out my framework for model-based explanation, within which both causal and noncausal explanations can be understood, and illustrate this framework by very briefly reviewing my previous work on noncausal model explanations. I will then turn to an examination of various proposals in the philosophical literature for what is required for an explanation to count as noncausal. After noting the strengths and weaknesses of these proposals, I will extract what I take to be a core conception of noncausal explanation. I will use as a detailed case study, the example of how Earth scientists are explaining the formation of regularly-spaced sand ripples in the subfield known as aeolian geomorphology. I will conclude that even when it comes to familiar, everyday "medium-sized dry goods" such as sand ripples, where there is clearly a complete causal story to be told, one can find examples of noncausal scientific explanations.

II. Model-Based Explanations

Those who defend the causal approach to scientific explanation have traditionally also subscribed--either implicitly or explicitly--to the ontic conception of explanation (e.g., Salmon 1984, 1989; Craver 2007; 2014; Strevens 2008).[5] According to the ontic conception, explanations just are the full-bodied entities and processes in the world themselves. The claim is that the particular baseball, the particular adrenaline molecules,

[5] It is important to distinguish a *conception* of explanation, which is a claim about what explanations are, from an *account* of explanation, which is a claim about how explanations work.

and the particular photons are not just causes or causally relevant, but that they are further scientific *explanations*. As Carl Craver defines it,

> Conceived ontically . . . the term explanation refers to an objective portion of the causal structure of the world, to the set of factors that produce, underlie, or are otherwise responsible for a phenomenon. Ontic explanations are not texts; they are full-bodied things. They are not true or false. They are not more or less abstract. They are not more or less complete. They consist in all and only the relevant features of the mechanisms in question. There is no question of ontic explanations being "right" or "wrong," or "good" or "bad." They just are. (Craver 2014: 40)

In another paper (Bokulich 2016), I have argued that the ontic conception of explanation is highly problematic, if not incoherent. Insofar as one is interested in normative constraints on scientific explanation, one must reject the ontic conception and instead view scientific explanation as a human activity involving representations of the world.

Elsewhere I have defended a version of the representational view that I call the eikonic conception of explanation, named from the Greek word 'eikon' meaning representation or image (Bokulich in progress). Like the ontic conception, the eikonic conception is a claim about what explanations are, and is compatible with many different accounts about how explanations work (e.g., causal, mechanistic, nomological, and of course non-causal accounts of explanation). On the eikonic view, a causal explanation involves citing a particular representation of the causal entities, rather than the brute existence of the causal entities themselves. Rejecting the view that explanations just are the causal entities and processes in the world themselves, makes room for the possibility of a noncausal explanation even in cases where there is a complete causal story to be had about the production of the phenomenon. As we will see in Section IV, a noncausal explanation is an explanation where the explanatory factors cited, the "explanans", are not a direct representation of the causal entities and processes. This very abstract characterization of a noncausal explanation allows for the possibility of different kinds of noncausal explanation, and will be fleshed out in the context of the case study below.

As suggested by the preceding, a second component of my approach to scientific explanation is a commitment to explanatory pluralism. The expression 'explanatory pluralism' has been used to express two different views in the philosophy of science. Originally it was used in opposition to those who argued that all cases of explanation can be subsumed under a single, unitary account, such as the covering-law model or, more recently, the causal account of explanation. Explanatory pluralism in this sense (what I call "type I" explanatory pluralism) is the view that scientists use different types of explanations (at different times or in different fields) with respect to *different* phenomena (e.g., while evolutionary biologists might use the unificationist account of explanation for their explananda, molecular biologists use mechanistic explanations for theirs). More recently, however, explanatory pluralism has come to mean that there can be more than one scientifically acceptable explanation of a single, given phenomenon (what I call "type II" explanatory pluralism). So for example, there could be two explanations for the morphology of a particular river--one that was deductive-nomological in form, while another was mechanistic. Both are scientifically acceptable explanations for why a river has the shape that it does, but they take different forms and appeal to different explanatory factors. Type II explanatory pluralism opens up the possibility that we can have multiple scientific explanations for a phenomenon, some of which are "deeper" than others (e.g., Hitchcock and Woodward 2003). While type I explanatory pluralism has become widely accepted (except perhaps by the causal imperialists), type II explanatory pluralism is more controversial. Type II pluralism not only presupposes type I (that there are different forms of scientific explanation), but goes further in asserting that these different kinds of explanation can be applied to the *same* phenomenon. I suspect that part of the resistance to type II explanatory pluralism comes from a subtle conflation between 'cause' and 'explain' that is endemic to the ontic conception. The sense of explanatory pluralism that I will be most concerned with here is type II, in so far as I will be arguing that there can be causal and noncausal explanations for one and the same phenomenon.

A third component of my approach to scientific explanation is my view that many explanations in science proceed by way of an idealized model, in terms of what I have called model-based explanation (Bokulich 2008a, 2008b, 2011). As we will see, both the causal and noncausal explanations of sand ripples, discussed in Section IV below, are examples of model-based explanation. My account of model-based explanation can be understood as consisting of the following four components. First, the explanans makes central use of a model that (like all models) involves some degree of idealization, abstraction, or even fictionalization of the target. Second, the model explains the explanandum phenomenon by showing how the elements of the model correctly capture the patterns of counterfactual dependence in the target system, allowing one to answer a wide range of what James Woodward (2003) calls "what-if-things-had-been-different" questions (w-questions). Third, there must be a justificatory step by which the model representation is credentialed (for a given context of application) as giving genuine physical insight into the phenomenon being explained; that is, there are good evidential grounds for believing the model is licensing correct inferences in the appropriate way. Explanation is a success term and requires more than just an "Aha!" feeling. Finally, this approach allows for different types of model explanations (e.g., causal, mechanistic, nomic, or structural model explanations) depending on the particular origin or ground of the counterfactual dependence (Bokulich 2008a: 150).

In my previous work on explanations in semiclassical physics, I identified a particular kind of noncausal model explanation that I called structural model explanations (Bokulich 2008a). These particular structural model explanations in semiclassical mechanics involve an appeal to classical trajectories and their stability exponents in explaining a quantum phenomenon known as wavefunction scarring. Wavefunction scarring is an anomalous enhancement of quantum eigenstate intensity along what would be the unstable periodic orbits of a classically chaotic system. Although scarring is a *quantum* phenomenon, the received scientific explanation appeals to the *classical* orbits to explain the behavior of the wavepackets, and the classical Lyapunov exponent to explain the intensity of the scar. According to quantum mechanics, however, there are no such things as classical trajectories or their stability exponents--they are fictions. Insofar as classical periodic orbits do not exist in quantum systems, they cannot enter into causal relations. Hence the semiclassical model explanations that appeal to these trajectories are a form of *noncausal* explanation. In accordance with my generalized Woodwardian approach to model explanation, these semiclassical models are able to correctly capture the patterns of counterfactual dependence in the target system, and the theory of semiclassical mechanics provides the justificatory step, credentialing the use of these classical structures as giving genuine physical insight into these quantum systems.[6]

[6] This expression "physical insight" is the one used by the physicists themselves to describe the advantage of semiclassical explanations over purely quantum ones. It can be further unpacked in terms of the notions of providing true modal information and licensing correct inferences, as above.

Although many might be willing to admit the possibility of noncausal explanations in quantum mechanics, a theory famously unfriendly to causality, the idea that there could be noncausal explanations outside of fundamental physics or mathematics is met with more skepticism. Before arguing that one can find noncausal explanations of familiar macroscopic phenomena like sand ripples, it is important to first clarify what is required for an explanation to count as genuinely noncausal. In the next section, I will show how a core conception of noncausal explanation can be distilled from the recent literature on this topic.

III. What Makes an Explanation Noncausal?

The generalized Woodwardian approach that I used as a framework capable of encompassing both causal and noncausal explanations has more recently been adopted and further developed in different ways by several scholars defending noncausal explanation, such as Juha Saatsi and Mark Pexton (2013), Collin Rice (2015), Saatsi (2016), and Alexander Reutlinger (forthcoming). Even within this general framework, however, the question still remains what distinguishes specifically *noncausal* explanations. Noncausal explanations are typically defined negatively--as conveying explanatory information in ways other than by citing the causes of the explanandum phenomenon. It remains an open question, the extent to which noncausal explanation is a heterogenous kind, including not only the structural model explanations discussed above, but also distinctively mathematical explanations (e.g., Lange 2013), and potentially others as well.[7] In this section, I review several recent proposals for characterizing noncausal explanations, noting their strengths and weaknesses, in order to extract what I take to be a defensible core conception of noncausal explanation.

Robert Batterman and Collin Rice (2014) have defended a kind of noncausal model-based explanation in terms of what they call "minimal model" explanations. The idea of a minimal model can be traced back to the work of physicists such as Leo Kadanoff and Nigel Goldenfeld in their work on complex phenomena such phase transitions and the renormalization group (see, e.g., Goldenfeld and Kadanoff 1999). The central idea is that the essential physics of a complex phenomenon can often be captured by a simplistic model that ignores most of the underlying causal details. Batterman and Rice argue that these minimal models, which are found in a wide range of fields (including biology), can be used to explain patterns of macroscopic behavior across systems that are quite heterogenous at smaller scales. In the context of the LGA (Lattice Gas Automaton) minimal model, they explain,

> [T]he model is explanatory . . . because of a backstory about why various details that distinguish fluids . . . from one another are essentially irrelevant. This delimits the universality class and guarantees a kind of robustness. . . under rather dramatic changes in the lower-scale makeup of the various systems. . . . The renormalization group strategy, in delimiting the universality class, provides the relevant modal structure that makes the model explanatory. (Batterman and Rice 2014: 364).

These simplistic minimal models are explanatory insofar as it can be shown that the minimal model and the realistic system to be explained fall into the same universality

[7] Unfortunately the literature on noncausal explanation is still at the stage of trying to find a core set of examples of noncausal explanation that can be agreed upon. The further task of then trying to create a taxonomy of the different kinds of noncausal explanation still remains to be done.

class and the model displays the relevant modal structure. There is some confusion in the literature over what exactly is meant by 'relevant modal structure' here: On one interpretation, it could just mean what I have discussed above as capturing the relevant patterns of counterfactual dependence in the explanandum phenomenon, a view that I have endorsed. On the other hand, Rice (2015) in particular has emphasized that it should be understood as facts about *independence*, which is an approach that has been criticized by Lina Jansson and Saatsi (forthcoming).[8]

Batterman and Rice go on to argue that these model-based explanations are a noncausal form of explanation, "distinct from various causal, mechanical, difference-making, and so on, strategies prominent in the literature (Batterman and Rice 2014: 349). They reject the "3M" account of Kaplan and Craver (2011) that requires a mapping between the elements of the model and the actual causal mechanisms. They continue,

> Many models are explanatory even though they do not accurately describe the actual causal mechanisms that produced the phenomenon. . . . [And] there are several reasons why the explanation provided by a model might be improved by removing various details concerning causal mechanisms. (Batterman and Rice 2014: 352)

This is precisely what minimal models do: they ignore the causal details that distinguish the particular different members of a universality class. As Reutlinger (2014) has noted, however, one must be careful in that simply failing to "accurately describe causal mechanisms" and "removing details concerning causal mechanisms" does not

[8] This point about an ambiguity in Batterman and Rice's "modal structure" I owe to Juha Saatsi (personal communication).

automatically mean that one has a noncausal explanation.[9] As Michael Strevens (2008) has rightly stressed, many causal explanations do this as well.

Yet another approach to noncausal explanation is Marc Lange's (2013) distinctively mathematical explanations in science. These explanations make use of mathematics, but have as their target physical facts (not mathematical theorems). Not all explanations that make use of mathematics, however, count as distinctively mathematical. Many causal explanations, for example, cite mathematical facts as part of their explanans. Instead, distinctively mathematical explanations are ones where "the facts doing the explaining are modally stronger than ordinary causal laws (since they concern the framework of any possible causal relation)" (Lange 2013: 485). Lange gives as an example of a distinctively mathematical explanation the case of why a parent cannot divide 23 whole strawberries evenly among three children, as being due to the mathematical fact that 23 is not divisible by 3. The explanation depends on the mathematical fact that it is impossible to divide 23 by 3 regardless of the causal entities or processes involved.

Lange argues that distinctively mathematical explanations are a noncausal form of explanation, even though they may include causal information about the explanandum. He writes,

> I agree . . . that distinctively mathematical explanations in science are noncausal. But I do not accept Batterman's ([2010]: 3) diagnosis that what makes these explanations non-causal is that they involve a 'systematic throwing away of various causal and physical details'. (Lange 2013: 506)

[9] Although Reutlinger takes a weak interpretation of Batterman and Rice's claims here, and criticizes them for taking this as sufficient for being noncausal, I believe they intend a stronger reading of these claims, which is in fact more in line with the view being defended here. Either way, further clarifications are required. Reutlinger's views are discussed more below.

It is not whether or not causal facts are mentioned, or mentioned only very abstractly that characterizes non-causal explanation. Rather, for Lange it is whether the facts doing the explaining are 'more necessary' than ordinary causal laws. While Lange is right to call attention to this question of whether or not the explanation works *by virtue* of citing causal facts, it is not clear that a modally stronger notion of necessity is required for a explanation to count as noncausal.

Yet a third approach to noncausal explanation rejects both Batterman's and Lange's approaches. Reutlinger (2014), like Batterman, defends renormalization group (RG) explanations of universal macro-behavior as a case of noncausal explanation. However, he argues that "Batterman misidentifies the reason that RG explanations are noncausal: he is wrong to claim that if an explanation ignores causal (micro) details, then it is not a causal explanation" (Reutlinger 2014: 1169). As Reutlinger notes, more recent advocates of causal explanation allow that all sorts of irrelevant (non-difference making) causal details can be omitted, without undermining its status as a causal explanation. Reutlinger also disagrees with Lange (2013), however, that what he calls "metaphysical necessity [sic]"[10] is the distinctive characteristic of a noncausal explanation. He writes,

> [O]ne need not appeal to metaphysical necessity in order to claim that mathematical facts explain in a noncausal way. All one needs to establish is that the mathematics does not explain by referring to causal facts. (Reutlinger 2014: 1167-68)

In the context of renormalization group explanations he continues,

> RG explanations are noncausal explanations because their explanatory power is due to the application of mathematical operations, which do not serve the purpose of representing causal relations. (Reutlinger 2014: 1169)

[10] It is not clear why Reutlinger switches Lange's "modally stronger" notion of necessity to "metaphysical necessity."

The key question here, which I think is roughly right, is whether or not the explanatory factors are a representation of the causal facts and relations. More needs to be said however, about what is to count as representing causal facts.[11] When this is fleshed out, I think Reutlinger and Batterman are in closer agreement than they might realize.

Yet a fourth approach to distinguishing noncausal explanation is given by Lauren Ross (2015), who sheds further light on this question of what it means to *not* be a representation of causal facts. As an example of a noncausal model explanation Ross discusses a dynamical model in neuroscience known as the "canonical" (or Ementrout-Kopell) model. This model is used to explain why diverse neural systems (e.g., rat hippocampal neurons, crustacean motor neurons, and human cortical neurons) all exhibit the same "class I" excitability behavior. She writes,

> The canonical model and abstraction techniques used in this approach explain why molecularly diverse neural systems all exhibit the same qualitative behavior and why this behavior is captured in the canonical model. (Ross 2015: 41)

In other words, there are principled mathematical abstraction techniques that show how the detailed models of different neural systems exhibiting class I excitability behavior can all be transformed into the same canonical model exhibiting the behavior of interest. The resulting canonical model is a minimal model in Batterman's sense.

Ross further argues that these canonical model explanations are a noncausal form of explanation. She writes,

[11] Reutlinger's own approach here in (2014) and in (forthcoming) is to deploy what he calls the "folk theory of causation" and the 'Russellian criteria' of asymmetry, distinctness of relata, and metaphysical contingency (2014: 1158). While this is an important approach, there are other possible ways one could go about fleshing out what is, or is not, to count as representing causal facts (as will be discussed more below).

> The canonical model approach contrasts with Kaplan and Craver's claims because it is used to explain the shared behavior of neural systems without revealing their underlying causal mechanical structure. As the neural systems that share this behavior consist of differing causal mechanisms . . . a mechanistic model that represented the causal structure of any single neural system would no longer represent the entire class of systems with this behavior. (Ross 2015: 46)

It is important to note that not just any abstraction from causal detail makes an explanation noncausal. Rather, it is because the canonical model is able to explain the behavior of neural systems with very different underlying causal-mechanical details--that is, it is an abstraction across very different causal mechanisms--that this model explanation can be counted as noncausal.[12]

From these four accounts of noncausal explanation, we can begin to see a convergence towards a core conception of noncausal explanation: A noncausal explanation is one where the explanatory model is decoupled from the different possible kinds of causal mechanisms that could realize the explanandum phenomenon, such that the explanans is not a representation (even an idealized one) of any causal process or mechanism. Before elaborating this core conception of noncausal explanation further, it will be helpful to have a concrete example of a phenomenon for which there is both a causal and a noncausal explanation, to more clearly see how they differ. Such an example is found in the explanandum of how regularly-spaced sand ripples are formed.

IV. Explaining the Formation of Sand Ripples

The study of sand ripples belongs to a field known as aeolian geomorphology. Named after the Greek god of wind, Aeolus, aeolian geomorphology is the study of

[12] I will come back to further elaborate this key idea after introducing the central case of sand ripples.

landscapes that are shaped predominantly by the wind, such as the "sand seas" of the Saharan desert, coastal dunes of Namib in southwestern Africa, the Great Sandy Desert of central Australia, the Takla Makan of western China, and the Algodones Dunes of southeastern California (see Figure 1).

Fig. 1: A “sand sea”: the Algodones Dunes of SE California. Note the ripples in the foreground, which are superimposed on the dunes. (Photo courtesy of Eishi Noguchi.)

Not only are sand seas (also known as ergs or dune fields) found all over the world, they are also found on other worlds, such as Venus, Mars, and Saturn's moon Titan (the last of which contains the largest sand sea in our solar system at roughly 12-18 km^2).

Although wind-blown sand might seem like a simple system, it can organize into vast, strikingly patterned fields, such as the barchan dunes of the Arabian Peninsula's Rub' al Khali that can maintain their characteristic crescent shape and size even while traveling across the desert floor and linking to form a vast filigree pattern. There are different aeolian sand bedforms[13] that form at different characteristic spatial and temporal scales (e.g., Wilson 1972). At the smallest scale are ripples, which are a series of regular linear crests and troughs, typically spaced a few centimeters apart and formed in minutes. At an even larger scale are dunes, which come in one of a few characteristic shapes (e.g., linear, barchan, star, crescent, or dome); they are typically tens of meters to a kilometer in size and form over years. At the largest scale are draas (also known as megadunes) which are typically 1 km - 6 km in size, and which form over centuries (or even millennia). Interestingly, it is not the case that ripples grow into dunes, or dunes into draas; rather, all three bedforms can be found superimposed at a single site.

The explanandum phenomenon of interest here is the formation of the smallest scale aeolian bedform: sand ripples. Why do sand ripples form an ordered pattern with a particular characteristic wavelength (i.e., a roughly uniform spacing between adjacent crests)? Although it might seem like a straightforward question regarding a simple system, it turns out that answering it is highly nontrivial. There are currently two (different) received explanations in the scientific literature for the formation of regularly spaced sand ripples. The first is a model explanation introduced by Robert Anderson in 1987 (which I will call the "reptation" model explanation of ripples), and the second is a model explanation introduced in 1999 by Brad Werner and Gary Kocurek (which is called the "defect dynamics" model explanation). These two explanations, each of which will be discussed in turn, are not viewed as rivals or competitors, but rather are complementary explanations (a point I will come back to elaborate below). I will argue

[13] A 'bedform' is a generic term in the geosciences for "pile of stuff," and in the context of aeolian geomorphology it typically means a pile of sand, such as a ripple or sand dune.

that while one of them is properly classified as a causal explanation, the other is a noncausal explanation of the formation of ripples.

Anderson's (1987) model explanation marked an important shift in scientists' thinking about the formation of ripples. Since the 1940s it had been assumed that ripples are formed by a barrage of saltating grains of sand, and that the ripple wavelength is determined by the characteristic path length in saltation. Saltation is the process by which a grain of sand gets lifted off of the surface, momentarily entrained in the wind, before gravity sends it back down to the surface, typically "splashing" the other grains of sand in the bed before bouncing up again on its next saltation hop. The sand grains that are splashed "creep" forward on shorter, much less energetic trajectories in a process called reptation. The processes of saltation and reptation are depicted in Figure 2.

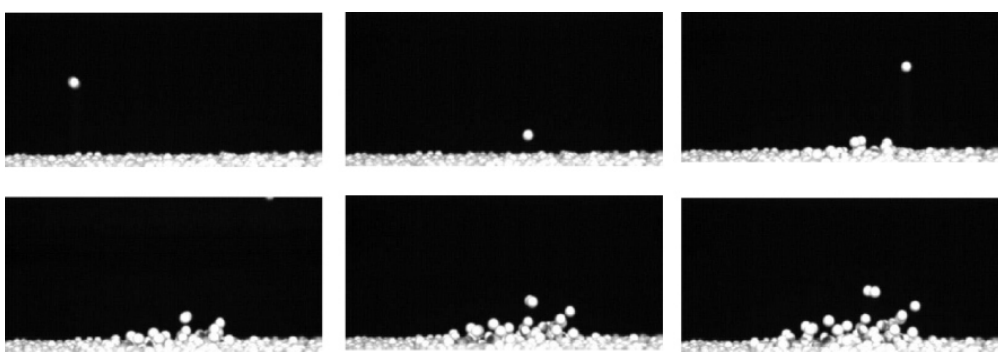

Fig 2: A sequence of high-speed motion photographs of the processes of saltation and reptation. Note the energetic saltation particle coming in from upper left in first frame is already on its way (after its bounce) to its next hop by the third frame. The particles in the bed that were splashed by the impact of the saltating particle, creep forward (but do not rebound) in the process of reptation. (From Beladjine et al. 2007, Fig. 2.)

In his pioneering 1941 book, *The Physics of Blown Sand and Sand Dunes*, Ralph Bagnold hypothesized that the key causal process in the formation of ripples of a particular wavelength is saltation. Bagnold writes,

> This remarkable agreement between the range, as calculated theoretically . . . , and the wavelength of the real ripples, suggest strongly that the latter is indeed a physical manifestation of the length of the hop made by the average sand grain in its journey down-wind. (Bagnold 1941: 64)

This hypothesis ran into several difficulties, however. One of the distinctive features of ripple formation is that the ripples begin close together and then grow in wavelength before reaching a stable characteristic spacing. Even by the 1960s it was realized that "[t]here can be no question about the progressive growth and increase in size of the ripples . . . [and it] is difficult to reconcile with Bagnold's concept of a characteristic path length" (Sharp 1963: 628). It was not until the late 1980s that an acceptable model explanation that could accommodate this feature was formulated.

Anderson agrees with Bagnold that ripple formation is *not* the direct result of fluid forces imposed by the air (Anderson 1987: 944). Unlike Bagnold, however, Anderson identifies reptation as the key causal process in the formation of ripples and argues that saltating grains makes a negligible contribution to ripples. The way in which reptation comes in to explain ripple formation, however, is not as straightforward as one might have hoped. Rather than trying to track the trajectories and forces acting on every grain of sand, Anderson explains the growth and spacing of ripples using an idealized model. This numerical model shows how a seemingly random barrage of reptating grains of sand can surprisingly lead to the emergence of a dominant characteristic wavelength for the ripples.

Anderson's model explanation makes a number of idealizing assumptions. First, the grain-bed interaction is characterized statistically in terms of a "splash function" that, for a given distribution of impact velocities, gives the number of ejected grains and a probability distribution for their ejection velocities. Second, the wide distribution of actual trajectories is idealized to two end members: high energy successive saltations and low-energy reptations, such that "the successive saltation population has zero probability of death [the bounces always perfectly reproduce themselves, never decaying] and the reptations have exactly *unit* probability of death upon impact [they neither reproduce themselves nor give 'birth' to other trajectories]" (Anderson 1987: 947). Third, it assumed that the spatial distribution of saltation impacts on a horizontal surface is uniform, and that they all descend at an identical angle. Fourth, the low number of grains traveling in high energy trajectories, and the low probability they will be incorporated into the ripple bed,

> allows us to ignore their *direct* contribution to ripple transport. Rather, their role in ripple formation and translation is here idealized as merely an energy supply for initiating and maintaining reptation (Anderson 1987: 947).

Here we see the shift to the view that reptation--not saltation--is the key process in ripple formation, and saltation is simply a generic energy source for reptation. Additionally, the role of wind shear stresses is neglected and it is assumed that the bed is composed of identical grains of sand (this latter assumption is reasonable for what are known as 'well-sorted' aeolian sands in places like the Sahara, but fails for places with bimodal or poorly sorted sand).

With these idealizing assumptions, Anderson introduces the following numerical model of the sand flux as a function of position (Anderson 1987: 951).

$$Q(x) = Q_0 + q_{ej} \cot \alpha \int_0^{\infty} [z(x) - z(x-a)] p(a) da \qquad (1)$$

The first term in Equation (1), Q_0, represents the total expected mass flux across the bed due to both saltation and reptation; the second term represents the spatially varying flux due to the growth and movement of ripples. More specifically, q_{ej} is the mass ejection rate, α is the incident angle of the impacting grains, z is the bed elevation, and $p(a)da$ is the probability distribution of the different reptation lengths. One can then use this equation, along with the sediment continuity equation and expression for bed elevation, to obtain the growth rate and translation speeds of bed perturbations of various wavelengths.

If one considers a reasonably realistic exponential or gamma probability function for the reptation lengths, and then performs a Fourier transform, these yield the dimensionless real and imaginary components of the phase speed. Anderson summarizes the results of this analysis as follows:

> The most striking alteration of the pattern of ripple growth resulting from the introduction of [these] more realistic probability distributions of reptation lengths is the dampening of the growth of the shorter wavelength harmonics. . . . [T]here exists a single fastest-growing wavenumber corresponding to wavelengths on the order of six times the mean reptation length for both the exponential and gamma distributions. (Anderson 1987: 953)

In other words, this model shows how a seemingly random splashing of sand grains can lead to the formation of ripples with a specific characteristic wavelength. Although this analysis vindicates the view that ripple wavelength is controlled by the process of reptation not saltation, Anderson is careful to note that the relation is not one of

> a simple equivalence between transport distance and ripple length. The relevant physics is not a rhythmic barrage of trajectories of length equal to the ripple spacing; it is a pattern of divergence and convergence of mass flux dominated by reptating grains with a probability distribution of reptation lengths. (Anderson 1987: 955).

Not only do observations in nature and wind-tunnel experiments agree reasonably well with the wavelength predicted by this model, but the model also captures the way in which ripple spacing varies with changes in the mean reptation distance under different conditions.

How should we classify this model-based explanation? It is worth pausing to summarize some of the key features of this explanation. First, as we saw, this explanation omits many causal details (e.g., wind shear stresses, the contribution of saltation particles to ripples, etc.). Second, we have a statistical characterization of key processes (e.g., the 'splash function' for grain-bed interaction). Third, the explanation involves many idealizations (e.g., about the allowed kinetic energies and angles of the trajectories). Fourth, it involves highly mathematical models and analyses (e.g., complex phase speeds, Fourier transforms, etc.). Nonetheless, I argue that it is still a causal explanation. This is because the mathematics and model explanation are still a straightforward and direct representation of the relevant fundamental causal processes, causal mechanisms, and causal entities that we know to be operating in that domain. An incomplete, idealized, and statistical representation of a causal process is still a representation of a causal process.

It is helpful to recall that a mathematical model in science really consists of two models. First, there is what is called the *conceptual model*, which is a conceptualization or 'picture' of what is going on in the system.[14] It is a particular conception about what the relevant entities, processes and interactions are in a particular domain, *prior to* any particular mathematical (or physical) representation of those entities, processes, and interactions. Second, there is the choice of a particular mathematical representation of

[14] For a historical discussion of this distinction between conceptual models and mathematical models see Bokulich and Oreskes 2016, Section 41.2.

that conceptual model. There are different possible mathematical representations for one and the same conceptual model, and one and the same mathematical model can be used to represent different conceptual models--even of different physical systems, such as in the case of physical analogies of the sort exploited by James Clerk Maxwell (see Bokulich 2015 for a discussion). So when a model fails, one can ask whether it was due to an inadequate conceptual model or due to an inadequate mathematical representation of that conceptual model, or both. In the case of Anderson's (1987) model of ripple formation, the underlying conceptual model is a causal one. It is a causal model despite its idealized and mathematical character because the mathematics is still a direct representation of the basic causal entities and causal processes in that physical system.

The second model-based explanation of the formation of ripples, due to Werner and Kocurek (1999), is a different story. Instead of formulating the explanation in terms of the relevant fundamental entities and causal processes (e.g., the saltation and reptation of grains of sand moving under the force of gravity, etc.), this second explanation introduces a new "pseudo-ontology" at the more abstract level of bedform structures, and makes them the dynamical variables through which the system evolves and the phenomenon is explained. The pseudo-ontology they introduce is that of a pattern "defect," and the model describes how these defects dynamically evolve and interact over time to produce the regular spacing of ripples.

A defect is defined most broadly as an imperfection in a pattern.[15] Conceptually, one works backwards from the end-state of a perfectly ordered set of parallel ripples, of

[15] When the discussion of defects was first introduced into geomorphology, an analogy was explicitly made to defects in material science, such as in the case of dislocations or defects in a crystal lattice (Anderson and McDonald 1990: 1344). While one might think

uniform height and uniform spacing, whose crest lines span the entire width of the bedform. One kind of defect, called a "termination," is an interruption or break in the crest line. When there are two opposite-facing free ends, these are referred to as a termination and anti-termination pair. A crest line with only one break would have a low density of defects, while a crest line with many breaks would have a high density of defects. Another kind of defect is known as a "join" (or "bifurcation"), where two crest lines, instead of being parallel, form a Y-junction. These two key types of defects are depicted in Figure 3.

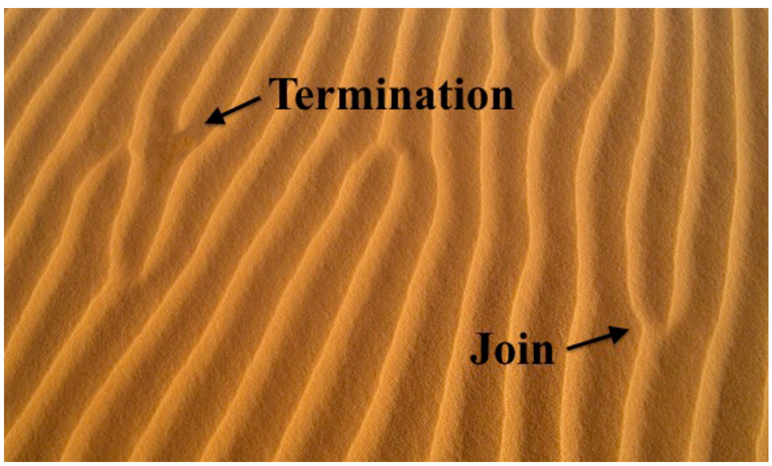

Fig. 3: Examples of ripple defects. As suggested by this photograph, terminations can propagate downwind, joining the next ripple crest ahead of it, becoming a join temporarily before breaking off again on the other side of the ripple.

An aeolian bedform starts out in a largely disordered state with a high density of defects. The crest lines are short, being interrupted by many terminations, and adjacent crest lines begin close together. Detailed field observations show that as these defects

---

that defects are unimportant, the presence of defects in a crystal lattice, for example, can have a tremendous effect on the physical properties of the crystal (see Lifshitz and Kosevich (1966) for a review).

become eliminated (e.g., by termination-antitermination pairs meeting up to form a longer continuous ripple crest line), the spacing between adjacent crest lines (the wavelength) grows rapidly at first, and then slows down over time until the final characteristic wavelength of ordered bedform of ripples is reached.

Rather than analyzing this process of ripple formation at the scale of grains of sand that are reptating, the approach of the defect-dynamics model explanation is to couple spacing and number of defects as the relevant dynamical variables. Kocurek and colleagues argue that the other "explanation for these patterns . . . is that they are self-organized. . . . the proposal is that it is the interactions between the bedforms themselves that give rise to the field-scale pattern" (Kocurek et al. 2010: 51). They elaborate on this alternative as follows,

> The self-organization hypothesis represents an alternative explanation to reductionism, in which large-scale processes such as bedform-pattern development are thought to arise as the summation of smaller-scale processes (e.g., the nature of grain transport causes the spacing pattern in wind ripples). (Kocurek et al. 2010: 52).

Although philosophers of science typically use the term 'reductionism' in a slightly different way, it is clear in these quotations that the defect-dynamics explanation is, first, seen as an *alternative* to the reptation model explanation of ripples, and second, seen as an explanation that is *not* a causal story about how grain transport causes the formation of ripples. To understand and assess these two claims, we must take a closer look at the defect dynamics model explanation.

As with Anderson (1987), the explanation is an idealized model-based explanation. The defect dynamics explanation exploits the geometrical properties of an idealized representation of a bedform field with ripple crests and defects. Suppose the bedform field where the ripples form is of width X and length Y. In the limit of a perfectly ordered bedform field, where all the ripple crest lines are continuous across the entire width, X, of the field, and have achieved their final characteristic spacing (or wavelength) λ , then the total (possible) crest length is given by,

$$L = XY / \lambda \tag{2}$$

where the total number of ripples (crest lines of length X) is Y / λ. The two variables being tracked over time are the *mean spacing* between bedforms,

$$\lambda(t) = A / L, \tag{3}$$

and the *defect density*,

$$\rho(t) = N / L, \tag{4}$$

which is the number of defect pairs (terminations and anti-terminations) per unit length of crest line.

As ripples are forming, they translate downwind, in a direction normal to the orientation of the crest line. In order to describe the evolution of the system at this level, one needs to define the mean velocity, v_b at which the bedforms (ripples) migrate:

$$v_b = \gamma / \lambda \tag{5}$$

where γ is equal to the sediment flux times the bedform index (the ratio of spacing to height, which is assumed to be constant).[16] The other relevant "entity" in this model explanation is the defect, which migrates at a mean velocity, v_d, that is roughly three

[16] The presentation here follows Werner and Kocurek (1999) and (1997), where further details can be found.

times the mean velocity of the bedform, $v_d = \alpha v_b$ (Werner and Kocurek 1997: 772). The defects migrate faster than the ripples, because the crestline of a termination is shorter than a full ripple and the termination involves a tapering of the ripple height down to zero; intuitively, they move faster simply because there is less sand to move. If you were to watch this process unfold, you would see the defects (the broken end "termination" of a crestline) propagate toward the crestline ahead of it, meet up with that crest line to form a join (Y junction), before the downwind branch of the Y-junction breaks off, then starts to propagate towards the crestline ahead of it; it then forms another Y-junction again, and the process repeats. The overall appearance is of a single defect passing through successive ripples as it propagates more rapidly downwind.[17]

Each time a defect passes through a bedform crest, it loses a small segment, l_0, of its length, because smaller bedforms tend to merge or get absorbed by larger bedforms. This results in a (slower) lateral movement as well: leftward for terminations and rightward for anti-terminations. So far we have defects propagating rapidly downwind and slowly towards the outside edges of the ripple field. The process by which the defects get eliminated, and the field progresses from a disordered state to a highly ordered state of continuous, uniformly spaced ripples is as follows: when a left facing termination (in its downwind and lateral movement) encounters an anti-termination, the two defects "annihilate" forming a stable continuous crestline. If a defect does not encounter its anti-termination "pair," then it eventually gets eliminated at the boundary of the field when it runs out of sand. Using the general geometrical constraints and

[17] Although the defect looks like a single unified thing, maintaining its identity as it moves continuously through space and time, the sand that makes up that defect is continuously changing.

formulating these processes in terms of the time rate of change for the total crest length, L, and the time rate of change of the number of defect pairs (understood as the sum of the rates of both pair annihilation and boundary annihilation) and expressing these in terms of the variables of defect density, ρ, and mean spacing, λ, leads to the following set of coupled, nonlinear differential equations:[18]

$$\frac{d\lambda}{dt} = -2\frac{dL_d}{dt}\rho\lambda \qquad (6)$$

$$\frac{d\rho}{dt} = -r\left|v_d - v_b\right|\rho^2 + \left(\frac{dL_d}{dt} - r\left|v_d - v_b\right|\right)\frac{\rho}{X} - \left|v_d - v_b\right|\frac{\rho}{Y} \qquad (7)$$

$$\frac{dL_d}{dt} = -\frac{\gamma\left|\alpha - 1\right|l_0}{\lambda^2}, \qquad \left|v_d - v_b\right| = \frac{\gamma\left|\alpha - 1\right|}{\lambda} \qquad (8)$$

We can see why the spacing, λ, grows rapidly at first when there are lots of defects, but then as the defect density goes down, there are fewer opportunities for crest length to become reduced. This means that the total crest length, L, will asymptotically approach some value, which because of the fixed area, $A = XY$, means in turn that the wavelength (mean spacing) $\lambda = XY/L$ will also change more slowly as it approaches a fixed value.

The defect-dynamics explanation, like Anderson's reptation model explanation, is able to produce realistic spacing values for ripples that match observations, and moreover, is able to explain in a very intuitive way how and why that spacing changes over time in the way that it does. How should this model explanation be classified? Werner and Kocurek (1999) argue that what distinguishes the defect dynamics explanation is that it "permits a treatment that bypasses fundamental mechanisms" (p. 727). In other words, they do not see this explanation as working by citing the causal

[18] Further details in deriving these equations can be found in Werner and Kocurek (1999).

processes involved. Indeed they argue that the fact that this explanation can work despite ignoring the operative causal processes "call[s] into question the widespread assumption that bedform spacing approaches a steady-state value characteristic of fluid flow and sediment transport" (Werner and Kocurek 1999: 727), where fluid flow (wind) and sediment transport (saltation and reptation) are clearly the relevant fundamental causal processes in this system. One might worry that *pace* Werner and Kocurek, the defect dynamics explanation really is an explanation in terms of those fundamental causal mechanisms, just those causal mechanisms described at a higher, perhaps aggregated level. As long as it was still those particular causal process (e.g., reptation) that were grounding the force of the explanation, or as I prefer to put it, if the defect explanation was still a straightforward representation of those causal processes, then it would still count as a causal explanation. To see why this is not the case, however, one more feature of the defect dynamics explanation must be explored.

It turns out that the defect dynamics explanation is not just an explanation for the formation of aeolian (wind) ripples, but it is also an explanation for the formation of subaqueous (underwater) ripples.

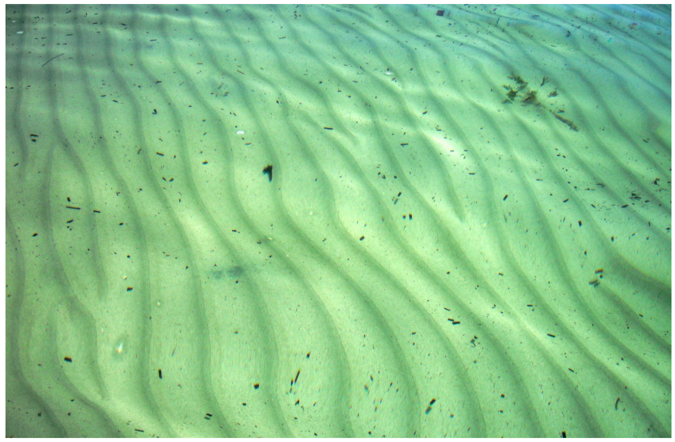

Fig 4: Subaqueous sand ripples on the ocean floor. Note the presence of pattern defects, such as the join (in the upper left), and the termination and anti-termination (in the center right).

Although the patterns that these two systems form are the same, the causal mechanisms by which they form are completely different. Recall that in the case of aeolian ripples it was the bombardment by saltating grains of sand that "splashed" into the bed, causing the other grains to reptate. In the case of subaqueous ripples, however, because of the greater density of water, saltating grains of sand impact the bed too feebly to cause either continued saltation or the reptation of other grains. Reptation is not a relevant causal process in the formation of subaqueous ripples. Similarly, while wind-shear stresses were completely negligible in the case of aeolian ripples, in the case of subaqueous ripples, bottom shear stress due to fluid flow is all important, being what directly transports each grain of sand. This important difference was recognized early on by Bagnold who writes,

> That too great a reliance on a similarity of effect as an indication of a similarity of cause may lead to a confusion of ideas, is well exemplified by the case of sand ripples. Everyone is familiar with the pattern of sand ripples on a sea beach. . . . And it would be hard indeed to find a single point wherein they differ in appearance from the wind ripples seen on the surfaces of dunes. Yet the mechanism of their formation cannot be the same in the two cases. The conditions are quite different. The beach ripple is due essentially to the

> *alternating* flow of water backwards and forwards under successive wavelets. (Bagnold 1941: 162 emphasis original)

Despite the very different causal explanations for aeolian and subaqueous sand ripples, they both can be equally well explained by the defect dynamics model explanation. In the subaqueous case, the formation of a well-ordered ripple field of a particular wavelength is also explained by the more rapid propagation of defects through the crests and their annihilation upon encountering an anti-termination pair.

The defect dynamics explanation is, I argue, a *noncausal* explanation. This is not because it is an idealized representation that leaves out many details, nor is it because it involves a characterization of the phenomenon in terms of a highly mathematical model. Rather, it is because the mathematics is not a representation of a conceptual model about the relevant causal processes operating in that system. If we were to take a step back and ask any geoscientist today: What are the relevant causal entities and causal processes involved in the formation of aeolian ripples? The answer would be grains of sand undergoing saltation (initiated by wind, and propelled by gravity) and grains of sand undergoing reptation (due to the splash-down impact, where a little of that kinetic energy is distributed among a much large number of grains of sand). While Anderson's model explanation is a mathematical representation of a conceptual model about these causal processes, the defect dynamics model is not. Similarly, if one were to ask what are the causal processes involved in the subaqueous ripples case, the answer would clearly not be saltation and reptation, which do not occur in this system, but rather fluid shear stresses in an alternating current, directly transporting grains of sand (a different set of causal processes).

While Anderson's (1987) model explanation is an explanation of the formation of aeolian ripples, it is *not* an explanation of the formation of subaqueous ripples. In representing the causal processes involved in the aeolian case, it *cannot* also represent the (different) causal processes in the subaqueous case. They are fundamentally different *types* of causal processes (not merely different token causal processes of the same type causal process, the latter of which could be accommodated by the same causal model explanation). The fact that the defect dynamics model explanation is an explanation of *both* the formation of aeolian ripples *and* the formation of subaqueous ripples makes clear that it is not a representation of the causal processes at all.

V. Conclusion

The question of what it means to be a noncausal explanation turns out to be a subtle issue. Although the different proposals reviewed in Section III were prima facie disagreeing with one another, I argued that they could each be interpreted as orbiting what I take to be a common core conception of noncausal explanation.[19] Moreover, I argued that this core conception is also exemplified by the defect dynamics explanation of the formation of ripples, discussed above. As with Batterman and Rice's (2014) examples, ripple pattern formation can be understood as a kind of universal phenomenon that is realized by diverse causal systems.[20] While there is a sense in which the formation

---

[19] While there may be forms of noncausal explanation that fall outside of this core conception (such as perhaps Lange's distinctively mathematical explanation), this core conception nonetheless is able to capture some of the key features common to many of the examples of noncausal explanation discussed in the literature.

[20] It is in fact even more universal than I have discussed here, being applicable not only to aeolian and subaqueous sand ripples, but also systems of sand bars, what are called 'sorted bedforms' (an underwater sorting of grains of different sizes), and linear dunes,

of the ripple pattern is "modally stronger", as Lange (2013) puts it, than the particular causal laws that realize it in the aeolian case, for example, it is not clear that Reutlinger's (2014) "metaphysical necessity" is the right way to describe this. As Reutlinger (2014) rightly notes, however, a noncausal explanation is one where the mathematical model does not serve the purpose of representing the causal processes, and as Ross (2015) further emphasizes, it is a model explanation that is abstracted across *different types* of causal processes and mechanisms. To reiterate, a noncausal explanation is one where the explanatory model is decoupled from the different possible kinds of causal mechanisms that could realize the explanandum phenomenon, such that the explanans is not a representation (even an idealized one) of any causal process or mechanism.[21]

To say that a particular explanation is noncausal does not entail that the explanandum is a purely mathematical phenomenon. The defect dynamics model explanation is a noncausal explanation of a *physical* phenomenon: the formation of real sand ripples. The defect dynamics explanation simply has the further advantage that it can be applied not only to aeolian ripples, but also to subaqueous ripples. Moreover, to say that these physical phenomena have a noncausal explanation does not mean that they are somehow "uncaused" events. In both the aeolian and subaqueous ripple cases, there is no doubt that there is a complete causal story (or more precisely two different complete

---

which occur both here on Earth and elsewhere, such as on Titan where there are very different grain, atmospheric, and gravitational conditions.

[21] Although universal phenomena are a natural place to look for noncausal explanations, not all noncausal explanations need involve universality. The noncausal semiclassical explanations of quantum phenomena, such as wavefunction scarring, are a case in point: although they do not involve universality, they do satisfy this definition insofar as they are not a direct representation of the causal entities or processes operating in that system (indeed the entities deployed in the semiclassical explanation are fictions).

causal stories) to be told about the formation of these ripples. As we saw in detail for the aeolian case, we even have such a causal explanation in hand.

The existence of a causal explanation does nothing to undermine the explanatory value of a noncausal explanation. As Holly Andersen (2016) has cogently argued, there are many different ways in which causal and noncausal (or what she calls mathematical) explanations can be complementary. The reptation model explanation and the defect dynamics model explanation are not rivals. Each type of explanation serves to bring out different features of the phenomenon more clearly and offers different sorts of insights into its nature. This is what I earlier described as type II pluralism: there can be more than one scientifically acceptable explanation for a given phenomenon at a time. One could even go further and argue that while there are some respects in which the reptation model explanation is deeper than the defect dynamics model explanation, there are other respects in which the defects explanation can be seen as deeper than the reptation explanation.[22] This pluralism, rather than revealing some sort of shortcoming in our understanding of sand ripples, is in fact one of its great strengths.

The analysis presented here suggests that noncausal explanations may not in fact be as rare or strange as they have hitherto been assumed to be. We are increasingly learning that universal phenomena, across fundamentally different types of causal systems, are widespread among the sciences (whether it is phase transitions in different substances, class I excitability in diverse neural systems, or ripple formation in different environments). The defect dynamics model explanation of ripple formation is able to

[22] For a discussion of the different possible dimensions along which explanatory depth can be measured see Hitchcock and Woodward (2003).

account for this universality by decoupling the explanation from the particular types of causal stories that might realize it. It is not because the model explanation is idealized, leaves out many causal details, or because it is formulated in terms of an abstract mathematical model, that makes it noncausal. The defect dynamics explanation is noncausal because it is not a representation of the causal processes at all. If it were a representation of the causal processes occurring, for example, in the case of aeolian ripples, then it could not also be an explanation for the formation of subaqueous ripples, and vice versa. Moreover, the fact that we can give a causal explanation in the aeolian ripple case does not rule out there being a scientifically accepted noncausal explanation of aeolian ripples as well. As the defect dynamics model explanation teaches us, we can indeed find noncausal explanations in a (sand-) sea of causes.

Works Cited

Andersen, H. (forthcoming), "Complements, Not Competitors: Causal and Mathematical Explanations" *British Journal for the Philosophy of Science*: doi: 10.1093/bjps/axw023.

Anderson, R. (1987), "A Theoretical Model for Aeolian Impact Ripples" *Sedimentology* 34: 943-956.

Anderson, R. and R. McDonald (1990), "Bifurcations and Terminations in Eolian Ripples" *Eos* 71: 1344.

Ayrton, H. ([1904] 1910), "The Origin and Growth of Ripple-mark" *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character,* 84/571: 285-310.

Bagnold, R. ([1941] 2005), *The Physics of Blown Sand and Desert Dunes*. Dover.

Batterman, R. [2010]: 'On the Explanatory Role of Mathematics in Empirical Science', *British Journal for the Philosophy of Science*, 61, pp. 1–25.

Batterman, R. and C. Rice (2014), "Minimal Model Explanations", *Philosophy of Science* 81/3: 349-376.

Beladjine, D., M. Ammi, L. Oger, and A. Valance (2007), "Collision Process between an Incident Bead and a Three-Dimensional Granular Packing" *Physical Review* E 75: 061305, 1-12.

Bokulich, A. (2008a), *Reexamining the Quantum-Classical Relation: Beyond Reductionism and Pluralism*. Cambridge: Cambridge University Press.

Bokulich, A.(2008b), “Can Classical Structures Explain Quantum Phenomena?” *British Journal for the Philosophy of Science* 59/2: 217–35.

Bokulich, A. (2011),“How Scientific Models Can Explain.” *Synthese* 180/1: 33–45.

Bokulich, A. (2015), “Maxwell, Helmholtz, and the Unreasonable Effectiveness of the Method of Physical Analogy,” *Studies in History and Philosophy of Science* 50: 28-37.

Bokulich, A. (2016), "Fiction As a Vehicle for Truth: Moving Beyond the Ontic Conception" *The Monist* 99/3: 260-279.

Bokulich, A. (Forthcoming), "Representing and Explaining: The Eikonic Conception of Explanation", *Philosophy of Science* (Proceedings).

Bokulich, A. and N. Oreskes (2017), "Models in Geosciences" in L. Magnani and T. Berlotti (eds.) *Springer Handbook of Model-Based Sciences*. Dordrecht: Springer.

Craver, C. (2007), Explaining the Brain: Mechanisms and the Mosaic Unity of Neuroscience. Oxford: OUP.

Craver, C. (2014), “The Ontic Account of Scientific Explanation” in M. Kaiser et al.(eds.), Explanation in the Special Sciences: The Case of Biology and History. Synthese Library 367. Dordrecht: Springer.

Goldenfeld, N. and L. Kadanoff (1999), “Simple Lessons from Complexity”, Science 284 (April 2nd): 87-89.

Hitchcock, C. and Woodward, J. (2003), "Explanatory Generalizations, Part II: Plumbing Explanatory Depth", Noûs 37/2: 181-199.

Jansson, L. and J. Saatsi (forthcoming) "Explanatory Abstractions" *British Journal for the Philosophy of Science*.

Kaplan, D. and C. Craver (2011), “The Explanatory Force of Dynamical and Mathematical Models in Neuroscience: A Mechanistic Perspective.” Philosophy of Science 78/4: 601–627.

Kocurek, G., R. Ewing, and D. Mohrig (2010), “How do Bedform Patterns Arise? New Views on the Role of Bedform Interactions Within a Set of Boundary Conditions” Earth Surface Processes and Landforms 35: 51-63.

Lange, M. (2013), “What Makes a Scientific Explanation Distinctively Mathematical?” *British Journal for the Philosophy of Science* 64: 485-511.

Lewis, D. (1986), "‘Causal Explanation’, in his *Philosophical Papers* Volume 2, New York: Oxford University Press, pp. 214-240.

Lifshitz, I. and A. Kosevich (1966), “The Dynamics of a Crystal Lattice with Defects” *Reports on Progress in Physics* 29 (Part I): 217-254.

Reutlinger, A. (2014), “Why is There Universal Macrobehavior? Renormalization Group Explanation as Noncausal Explanation” *Philosophy of Science* 81: 1157-1170.

Reutlinger, A. (forthcoming). ‘Is There A Monist Theory of Causal and Non-Casual Explanations? The Counterfactual Theory of Scientific Explanation.’ *Philosophy of Science*.

Rice, C. (2015), “Moving Beyond Causes: Optimality Models and Scientific Explanation” *Noûs* 49/3: 589-615.

Ross, L. (2015), “Dynamical Models and Explanation in Neuroscience” *Philosophy of Science* 82/1: 32-54.

Saatsi, J. (2016), “On Explanations from ‘Geometry of Motion’.” *The British Journal for the Philosophy of Science*, DOI:10.1093/bjps/axw007.

Saatsi, J. and M. Pexton (2013), "Reassessing Woodward's Account of Explanation: Regularities, Counterfactuals, and Noncausal Explanations", Philosophy of Science 80/5: 613-624.

Salmon, W. (1984b), *Scientific Explanation and the Causal Structure of the World*. Princeton: Princeton U Press.

Salmon, W. (1989), “Four Decades of Scientific Explanation” in P. Kitcher and W. Salmon (Eds.) *Scientific Explanation*, Minnesota Studies in the Philosophy of Science, Vol. XIII. Minneapolis: U of MN Press, 3-219.

Sharp, R. (1963), “Wind Ripples” *The Journal of Geology* 71/5: 617-636.

Skow, B. (2014), "Are There Non-Causal Explanations (of Particular Events)?" *British Journal for the Philosophy of Science* 65: 445-467.

Strevens, M. (2008), *Depth: An Account of Scientific Explanation*. Cambridge, MA: Harvard University Press.

Werner, B. and G. Kocurek (1997), “Bedform Dynamics: Does the Tail Wag the Dog?”, *Geology* 25/9: 771-774.

Werner, B. and G. Kocurek (1999), “Bedform Spacing from Defect Dynamics”, *Geology* 27/8: 727-730.

Wilson, I. (1972) “Aeolian Bedforms—Their Development and Origins” Sedimentology 19: 173-210

Woodward, J. (2003), Making Things Happen: A Theory of Causal Explanation. Oxford: Oxford University Press.