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ORDER: GOD'S, MAN'S AND NATURE'S

Complexity, Contextual Emergence and Causation

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Abstract
Complexity–basically nonlinear dynamics–is rich with metaphysical & epistemological implications but has received little sustained analysis. Because there has been so little sustained philosophical analysis of causation in complex systems, there is a lacuna regarding our thinking about causation in these contexts. I will explore some of the messiness of causation in complex systems and extract some lessons for further philosophical reflection. Contextual emergence turns out to be and apt framework for systems exhibiting nonlinear dynamics. The punch line is that philosophers may have a lot more to learn from dynamics than is generally realized that can inform us about subtleties in such areas as reduction and emergence as well as causation.

1. Complexity: Nonlinear Dynamics

Quintessential examples of complexity are (1) Rayleigh-Bénard convection, where an extremely small perturbation in a fluid trapped between two plates where a heat differential is maintained can influence the particular kind of convection that arises, and (2) the butterfly effect, where the flapping of the wings of a butterfly in Argentina influences the formation of a tornado in Texas three weeks later. Roughly speaking, when we refer to complex systems, we are actually speaking about *dynamical systems*. Dynamical systems are mathematical models, where time can be either a continuous or a discrete variable (a simple example would be the equation describing a pendulum). Many of them involve nonlinear interactions, on which I'll focus here, but others might involve intricate networks. Such models may be studied as purely mathematical objects or may be used to describe a target system (some kind of physical, ecological or financial system, say).

1.1 Dynamical Systems and Nonlinearity

The equations of a dynamical system are often referred to as dynamical or evolution equations describing the change in time of variables taken to adequately describe the target system. A complete specification of the initial state of such equations is referred to as the *initial conditions* for the model, while a characterization of the boundaries for the model domain are known as the *boundary conditions*. A simple example of a dynamical system would be the equations modeling a particular chemical reaction. The set of equations relates the amounts of the various compounds and their reaction rates, temperature, pressure and so forth. The boundary condition might be that the container walls are maintained at a fixed temperature. The initial conditions would be the starting concentrations of the chemical compounds. The dynamical system would

then be taken to describe the behavior of the chemical mixture over time.

A dynamical system is characterized as linear or nonlinear depending on the nature of the dynamical equations describing the target system. Consider a differential equation system $dx/dt = \boldsymbol{F}\boldsymbol{x}$, where the set of variables $\boldsymbol{x} = x_1, x_2, ..., x_n$ might represent positions, momenta, chemical concentration or other key features of the target system. Suppose that $\boldsymbol{x}_1(t)$ and $\boldsymbol{x}_2(t)$ are solutions of our equation system. It's straightforward to show that for a linear system of equations $\boldsymbol{x}_3(t) = a\boldsymbol{x}_1(t) + b\boldsymbol{x}_2(t)$ is also a solution, where a and b are constants. This is known as the *principle of linear superposition*. When the principle of linear superposition holds, then, roughly, a system behaves linearly where any multiplicative change in a variable, by a factor α say, implies a multiplicative or proportional change of its output by α. For example, if you start with your stereo at low volume and turn the volume control up one unit, the volume increases one unit. If you now turn the control up two units, the volume increases two units. These are examples of linear responses. In a nonlinear system, linear superposition fails and a system *need not* change proportionally to the change in a variable. If you turn your volume control up two units and the volume increases tenfold, this would be an example of a nonlinear response. The loss of linear superposition can lead to the phenomenon of *sensitive dependence*, where even the smallest change in the initial conditions can issue forth in a drastic change in a dynamical system's behavior.[1]

1.2 State Space and the Faithful Model Assumption

Dynamical systems involve a *state space*, an abstract mathematical space of points where each point represents a possible state of the system. An instantaneous state can be defined as the instantaneous values of the variables considered crucial for a complete description of the state. A model can be studied in state space by following its trajectory, which is a history of the model's behavior in terms of its state transitions from the initial state to some chosen final state (Figure. 1). The evolution equations govern the path–the history of state transitions–of the system in state space. [Insert Lorenz attractor. Caption: A state space portrait of the famous Lorenz attractor. A very small change in initial conditions can determine whether a trajectory stays on one wing of the butter fly or the other wing or whether the trajectory will wander back and forth between the two wings.]

Underlying the use of dynamical systems and their state spaces are some little noticed yet crucial assumptions: namely, that the actual state of a target system is accurately characterized by the values of the crucial state space variables and that a physical state corresponds via these values to a point in state space. These assumptions allow us to develop

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[1]A very popular measure of sensitive dependence involves the explosive growth of the smallest uncertainties in the initial conditions of a nonlinear system. This explosive growth is often defined as an exponential parameterized by the largest *global Lyapunov exponent*. These exponents arise naturally out of linear stability analysis of the trajectories of nonlinear evolution equations in a suitable state space and provide an on average picture of the stability of the dynamics. However, such a global measure of trajectory divergence is of limited pragmatic value (Bishop 2010b, sec. 2.4).

mathematical models for the evolution of trajectories in state space and to consider such models as representing the target systems of interest (perhaps through an isomorphism or some more complicated relation). In other words, we assume that our mathematical models are *faithful* representations of target systems and that the state spaces employed *faithfully* represent the space of actual possibilities of target systems. This package of assumptions is known as the *faithful model assumption* (e.g., Bishop 2005a, 2006). In its idealized limit–*the perfect model scenario* (Judd and Smith 2001)–it can license the (perhaps sloppy) slide between model talk and system talk (i.e., whatever is true of the model is also true of the target system and vice versa).

As we will see in what follows, the faithful model assumption has both metaphysical and epistemological implications.

2. Complex Systems and Hierarchies

In non-complex systems, a hierarchy of physical forces and dynamical time scales provide ontologically distinguishable levels of structure (e.g., elementary particles, molecules, crystals). In many cases the lower-level constituents may provide both necessary and sufficient conditions for the existence and behavior of the higher-level structures. For complex systems, however, levels of structure are often only epistemically distinguishable in terms of dynamical time scales. In this sense, talk of levels is epistemic being more pragmatic and descriptive, hence, we often speak of "levels of description." Different descriptive levels can give us some guidance for focusing ontological features of different domains (e.g., physical, chemical or biological) like properties, capacities and causes. For instance, in the domain of molecules we find particular properties while in the domain of fluid flow we find other properties clearly distinguishable from those of H_2O molecules. The relationship among properties and causes of different domains is a nontrivial one.

Properties in different domains of complex systems are coupled to each other complicated ways (e.g., across multiple length and time scales). This is reflected in the fact that in descriptions at least some of the large scale structures are not fully determined by, and even influence and constrain, the behavior of constituents composing these structures. That is, the constituents composing large scale structures provide necessary but *not* sufficient conditions for the existence and behavior those structures (cf. Bishop 2005b; Bishop and Atmanspacher 2006; Bishop 2008a, Bishop 2010a). Moreover, the system constituents don't provide necessary and sufficient conditions for their own behavior when larger-scale structures and dynamics constrain or otherwise influence the behavior of constituents (e.g., Bishop 2008a). This latter kind of hierarchy is called a *control hierarchy* (Pattee 1973, 75-9; Primas 1983, 314-23).

In complex systems, control hierarchies affect lower-level constituents primarily through constraints. These constraints control lower-level constituents without removing all the latter's configurational degrees of freedom (in contrast to simple crystals, for instance). These top-down constraints may be external, due to the environment interacting with the system. Or such constraints may arise internally within the system due to the collective effects of its constituents

or the evolving dynamics.[2]

The notions of hierarchy and sensitive dependence allow us to formulate a more qualitative distinction between linear and nonlinear systems (though this characterization can also be made empirically precise–see Busse 1978, and Cross and Hohenberg 1993 for examples). Linear systems can be straightforwardly decomposed into and composed by subsystems (a consequence of the principle of linear superposition). For a concrete example of the principle of linear superposition, consider linear (harmonic) vibrations of a string which can be analyzed as a superposition of normal modes. These normal modes can be treated as uncoupled individual oscillators. The composition of the string's vibration out of these component vibrations is then analogous to aggregating these parts into a whole ("the whole is the sum of its parts"). The linear behavior of such systems in these cases is sometimes called *resultant* (in contrast with emergent). In such cases, we have more confidence in the alignment of our levels of description with the ontology of the domains in question (e.g., the musical tone produced compared to the harmonic vibrations that compose it and the string as the medium in which vibrations are realized).

In nonlinear systems, by contrast, this straightforward idea of composition fails due to the failure of the principle of linear superposition. When the behaviors of the constituents of a system are highly coherent and correlated, the system cannot be treated even approximately as a collection of uncoupled individual parts ("the whole is *different* than the sum of its parts"). Rather, some particular global or nonlocal description[3] is required taking into account that individual constituents cannot be fully characterized without reference to larger-scale structures of the system. Rayleigh-Bénard convection, for instance, exhibits what is called *generalized rigidity*, where the individual constituents are so correlated with all other constituents that no constituent of the system can be changed except by applying some change to the system as a whole (i.e., systems in some parameter regime become sensitive only to structural or global changes and insensitive to local changes). Such holistic behaviors are often referred to as *emergent* (in contrast with resultant). The alignment of our descriptive levels with the ontology of the domains in question is more subtle in these cases.

3. Identity and Individuation in Complex Systems

The interplay among hierarchical levels in nonlinear systems exhibiting complexity blur distinctions like part-whole, system-environment, constituent-level and so forth (e.g., cases where hierarchies are only distinguishable by differing time scales rather than by ontological features). The mathematical modeling of physical systems requires us to make distinctions between variables and parameters as well as between systems and their environments. However,

[2]Typically fundamental forces like gravity and electromagnetism are not explicitly identified with these latter internally generated constraints.

[3]A nonlocal description in nonlinear dynamics refers to a description that necessarily must refer to wider system and environmental features in addition to local interactions of individual constituents with one another.

when linear superposition is lost, systems can be exquisitely sensitive to the smallest of influences. A small change in the parameter of a model can result in significantly different behavior in its time evolution, making the difference between whether the system exhibits chaotic behavior or not, for instance. Parameters like the heat on a system's surface due to its environment may vary over time leading to wide variations in the time evolution of the system variables as well as temporal change in parameters. In such cases, the distinction between model variables and parameters breaks down. Similarly, when a nonlinear system exhibits sensitive dependence, even the slightest change in the environment of a system can have a significant effect on the system's behavior. In such cases the distinction between system and environment breaks down. For instance, even the behavior of an electron at the 'edge' of the galaxy would affect a system of billiard balls undergoing continuous collisions (Crutchfield 1994, p. 239), so the system/environment distinction becomes more a matter of pragmatically cutting up the 'system' and 'environment' in ways that are useful for our analysis.

These behaviors raise questions about identity and individuation for complex systems. Traditionally, such identity and individuation revolve around numerical identity and the criteria for individuation and identity through time. For instance, Leibniz's principle of the identity of indiscernibles gives us criteria for determining when we have numerically distinct entities. The idea of identifying a complex system as a distinct individual from its environment or of individuating various hierarchies of a complex system presupposes both that a distinct entity can be identified as well as individuated from other entities. Consider the so-called butterfly effect. Earth's weather is a complex system, but its potential sensitivity to the slightest changes of conditions leave its boundaries ill-defined if the flapping of a butterfly's wings in Argentina can cause a tornado in Texas three weeks later. Is the butterfly's flapping an internal or external source of wind and pressure disturbance? As well, the local topography of the Earth's surface affects the convection patterns in the atmosphere (consequently, some areas of the United States are more prone to the formation of tornados than others). Turning towards space, is the magnetosphere surrounding the earth–which can also influence the Earth's weather–a distinct system or a qualitatively different extension of the Earth's weather system?

It certainly seems plausible to consider butterflies, the Earth's weather and the Earth's magnetosphere as numerically distinct entities (or as numerically distinct subsystems of a larger system). After all, by Leibniz's principle, these different "systems" do not share all their properties. On the other hand, systems are generally composed of subsystems that differ in properties, so given the lack of absolute boundaries between them, perhaps the best way to conceive of the butterfly-weather-magnetosphere system is as one very large complex system. For complex systems it is often the case that distinctions between parts and wholes, hierarchies and the like are pragmatic rather than absolute. Classical views of identity and individuation based on Leibniz's principle only yield identification and individuation based on the kinds of questions scientific and other forms of inquiry raise and not a kind of objective ontology of distinct things. This implies that many of our judgements about identity and individuation in nonlinear dynamics are epistemic rather than ontic.[4]

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[4]Whether these kinds of features imply that complex systems represent a case of contingent identity and individuation so that there are no rigid designators (Kripke 1980), is an

4. Complexity, Reduction and Emergence

The issues of identity and individuation in complex systems lead naturally to a discussion of reduction and emergence in. In rough outline, reductionist lore maintains that properties and behavior of systems as a whole are completely determined by the states and properties of their parts (ontological reductionism) or are explainable in terms of the states and properties of their parts (epistemological reductionism). Defenders of emergence deny one or both of these claims. However, the loss of linear superposition and the possibilities for holism and constraining causation lead to the need to consider an alternative to the received views.

For instance, the lack of necessary and sufficient conditions for the behavior of underlying constituents in complex systems directly challenges reductive atomism (e.g., control hierarchies). One of the core principles of atomistic physicalism as identified by Robert van Gulick is that "The only law-like regularities needed for the determination of macro features by micro features are those that govern the interactions of those micro features in all contexts, systemic or otherwise" (2001, p. 18). However, in complex systems control hierarchies and other inter-level causal relations are crucial to determining the behavior of system constituents. The behavior of constituents in such systems is *conditioned* by contexts in which the constituents are situated and are not merely the result of the context-free law-like regularities envisioned in atomistic physicalism.

Recall the characterization of nonlinear systems and the linear superposition principle (sec. 1). When linear superposition holds, a system can be decomposed into its constituent parts and the behavior of each component is independent of the other components. The effects of system components can be "summed" and hierarchies distinguished. Reductionist lore tends to conceive of all systems this way. In contrast, when linear superposition breaks down, as it does for complex systems, behaviors reflecting the fact that individual system components are not independent of each other arise. Moreover, the behavior of individual system components are not even independent of the wholes and various scales in between where structuring or constraining determination is at work. Various structural scales as well as the whole act to enable or constrain various possibilities for component behavior relative to what would be possible for the components if these effects were absent (Juarrero 1999; Silberstein and McGeever 1999; Bishop 2004; Bishop and Atmanspacher 2006; Ellis 2006; Bishop 2008a).[5]

The interplay between parts and wholes in complex systems and their environments leads to the self-organization observed in such systems. Their sensitive dependence on the smallest of changes at the component level is partly guided by the causal relations acting at different scales in such systems (e.g., determining the characteristic features of convecting cells in Rayleigh-Bénard convection arising from initial perturbations and instabilities in the system). This kind of behavior may be fruitfully captured in the framework of *contextual emergence* (see

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open question.

[5]The failure of the laws and conditions at lower levels of description to serve as both necessary and sufficient conditions for higher-level behavior is related to the failure of the constraints to be holonomic (see Symon 1971, sec 9.4, for a discussion of holonomicity).

Bishop 2005b; Bishop and Atmanspacher 2006):

> The properties and behaviors of a system at a particular domain (including its laws) offer necessary but not sufficient conditions for the properties and behaviors in at another domain.

For example, think of the domain of water molecules as the putative reduction or realization base and the convection cells of a Rayleigh-Bénard system as "composed" of molecular realizers. The reference to necessary conditions of the molecular domain means that properties and behaviors of the convective cells may imply the properties and behaviors of molecules. However, the converse is not true as the properties and behaviors of the water molecules alone do not offer sufficient conditions for the properties and behaviors of convective cells. Contingent conditions specifying the context for the transition from the molecular domain to the properties and behaviors of the convective cells are required to provide such sufficient conditions. In complex systems, such contingent contexts are not given by the laws, properties and behaviors of the underlying domain alone.[6]

In this sense, complex systems seem to validate intuitions many emergentists have that some form of holism plays an important role in the determination of the behavior of complex systems that can't be captured by reductionist analyses. However, care is needed with typical emergentist slogans such as "The whole cannot be predicted from its parts," or "The whole cannot be explained from its parts" when it comes to contextual emergence like that exemplified fluid convection or statistical mechanics. Relevant information about the properties and behaviors of constituents in the putative reduction domain *plus* the specification of an appropriate contingent context allows for the (in principle) prediction or explanation of properties and behaviors of the target domain in many cases (e.g. Primas 1998; Bishop 2005b; Bishop and Atmanspacher 2006; Bishop 2008a). So complexity holds surprises for both proponents of reductionism and emergence.

5. Complexity and Causation

Causation in complex systems has received very little sustained analysis in the philosophy literature (Juarrero 1999 is a notable exception). Yet, complexity raises difficult questions for thinking about causation when nonlinear inter-level relationships, sensitive dependence, and concrete contexts can be so important in determining system behavior.

5.1 Identifying Causal Difference Makers

How are we to identify the causes at work in systems where linear superposition has broken down? What to do if quantum effects possibly can play causal roles in macroscopic complex

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[6]Moreover, the conditions for specifying a candidate reduction in terms of the realizers are not well defined until an appropriate contingent context is properly articulated (Hooker 2004, pp. 467-468).

systems (e.g., Bishop 2008c) or electrons dancing about elsewhere in our galaxy possibly can play a causal role in such systems here on Earth? How far down do we have to go to identify the relevant causes at work in a complex macroscopic system (e.g., to butterfly wing flaps, to the atomic level or beyond)? Or how far do we have to extend a complex system to capture all of its relevant causes (e.g., weather near Earth's surface or must we include the stratosphere, troposphere, magnetosphere, solar system, etc.)? Clearly complex systems put pressure on difference-making accounts of causation because there is a genuine problem of specifying the difference-makers aside from the trivial answer: everything!

Finding principled ways to draw the boundary around the "crucial" or "dominant" difference-makers at work in complex systems is difficult, to say the least because one of the lessons that nonlinear dynamics teaches us is that "small" causes are not insignificant when linear superposition breaks down (e.g., Bishop 2008a, 2008c). Suppose we want to pursue a counterfactual analysis of difference-making so that we try to determine the factors whose absence would have led to today's weather in Texas being different than it was. The loss of linear superposition implies that this list of factors may very well include everything. Similarly, suppose we try to pursue a probabilistic account of difference making so that we try to determine what factors raised the probability of today's weather in Texas being what it was. The loss of linear superposition implies that everything may very well have contributed to that probability (some factors may have raised the probability, while some factors may have lowered the probability). The nonlinear nature of complex systems threatens to turn the insight of difference-making into a triviality. The DIFFERENCE-MAKER enabling all other difference-makers appears to be the nonlinearity of the dynamics. In other words, it's the presence of nonlinear interactions in the system that acts as a gateway through sensitive dependence for so many factors to have an influence on something like a weather system.

5.2 Upward Determination and Downward Constraint

Typical metaphysical analyses cash out causal difference-making as "bottom up," taking a reductive view of causation where the system components are the genuine causal actors and systems as a whole have causal power only in virtue of the causal powers of their constituents (e.g., Kim 2007). But what to do about control hierarchies which act to limit constrain or organize the causal influence of system components? Instances like fluid convection, where the molecular domain provides necessary but insufficient conditions for the total behavior of the convection cells and where the convection cells constrain the behaviors of fluid molecules, are rather routine in complexity studies. In such cases the causal powers of constituents, even "lower-level" constituents, in and of themselves turn out to not have necessary and sufficient conditions for governing all of their own behavior. In complex systems the formation of control hierarchies often comes about when a new form of dynamics *arises* on larger spatial scales that exhibits downward constraint on system constituents and is self-sustaining (e.g., Hooker 2004, pp. 449-477; Bishop 2008a and 2008c). Typical metaphysical analyses of causation focus on logical and formal relationships among efficient causes in bottom-up constructions. In contrast, control hierarchies are examples of dynamical top-down constraint due to dynamics and dynamical relations.

While most metaphysicians focus on the "upward" flow of efficient causation from system components to system behavior as a whole, the possibilities for causal relationships among the different dynamics at different size scales in complex systems like convecting fluids present plausible examples of a "downward" flow of constraint on the behavior of system components. Such behaviors clearly raise questions for a program of discovering the causes of complex systems' behavior in the fundamental laws, an approach to causation championed by those who favor physical accounts of causation.[7] Nonlinear dynamics teaches us that the contexts into which fundamental laws come to expression is at least as important as the laws themselves (Bishop 2008a, 2008c and 2010b), so the strategy of looking exclusively to fundamental laws and theories for our causal cues, as causal foundationalism does, will likely miss out much of what's going on causally in complex systems.

Of course, the intuition behind physical accounts of causation that look to fundamental dynamical laws–viewed as causal laws–as our sources for appropriate physical causes is a powerful one, but it's shaped by an important assumption that's questionable in nonlinear dynamics (and perhaps other contexts as well): Natural laws are universal in the sense of being context free (as in the characterization of atomistic physicalism given above in sec. 4). In contrast, one lesson of nonlinear dynamics is that fundamental laws primarily act to structure functions, where the relevant space of possibilities is determined for the behaviors of the constituents guided by them, but such laws do not fully determine which of these possibilities in the allowable space are actualized. The actualization of possibilities can only be fully determined by concrete contexts into which the laws are coming to expression (which may involve causal and/or structuring laws only present in particular domains). For instance, Einstein's theory of general relativity determines the space of possible motions for an apple falling from a tree, but the concrete context where I reach out my hand and catch the apple actualizes a particular possibility among all those allowed while the particular context is not included in general relativity.

The point, here, is consistent with contextual emergence (sec. 4): while fundamental laws establish some necessary conditions for the possible behaviors of objects, contingent contexts must be added in to establish jointly necessary and sufficient conditions for actual behaviors. Fundamental clearly laws play structuring roles in nature in the sense of structuring or defining the possibility spaces for physical behaviors. Whether such laws do more depends on the particular context. Concrete contexts into which laws come to expression are at least as important as the laws.[8] We should, then, resist the tendency to focus exclusively on fundamental laws for developing our causal repertoire when seeking physical accounts of causation. Sound accounts of causation in complex systems are likely to involve both appeals to fundamental laws as well as ordering/constraining structure via the interrelationships among the various kinds of dynamics

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[7]For a nice discussion of difference-making and physical accounts of causation, see (Ney 2009).

[8]Similar lessons about laws can be gleaned from continuum and statistical mechanics even in cases where systems are not exhibiting complexity.

being exhibited at different scales within the system.[9]

Working out the connection between fundamental laws and causation is tricky because our fundamental physical theories largely avoid the language of efficient causation. What is readily apparent about such laws is their function of structuring the spaces of possibility for the behaviors of physical objects. If fundamental laws primarily structure possibility spaces but do not fully determine the outcomes within these possibilities, then there must be other sources of constraint, some of which may have nomological character. Dynamics of different spatial/temporal scales as well as that of wholes in complex systems act to constrain or direct the possibilities made available by fundamental laws.[10] It is possible that the structuring function played by control hierarchies and wholes in complex systems are the result of some as yet unknown nonlinear dynamical laws, which may be causal or structural as well as emergent with respect to the contexts where nonlinear interactions are dominant. Even so, fundamental laws still would be necessary for structuring the possibility space for emergent nonlinear laws, though particular features of contexts might be required for nonlinear dynamical laws to arise.

5.3 Laws, States and Context

The interest in causal laws among philosophers stems from their construal as governors or specifiers of the history of state transitions a system makes given some initial starting conditions (and appropriate boundary conditions). The concept of structuring laws has received much less sustained analysis. Nevertheless, the typical objection to treating fundamental laws as legislating possibility spaces rather than determining specific behaviors of systems within these spaces flows out of the heart of causal foundationalism in its physicalist form: the fundamental physical laws express nomological determination relations among states at different times such that the state $s(t_a)$ at t_a plus the fundamental laws necessitate the state $s(t_b)$ at t_b.[11]

There are difficulties with this line of objection, two of which I'll discuss here. The first is a subtlety in the discussions of laws that has an important connection to contextual emergence. As sketched in sec. 1, states of physical systems are typically specified by values of the key variables characterizing the system at some time t represented in some state space. A given state $s(t_a)$ characterizes a system at the particular time t_a. For classical particle mechanics, the states that evolution equations evolve are point-valued states (e.g., a state might be fully specified by the point values of its position and momentum). In statistical mechanics, the states that dynamical equations evolve are probability distributions. In quantum mechanics, the states that dynamical equations evolve are state vectors defined on Hilbert space (or some more

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[9]See Chemero and Silberstein (2008), sec. 4 and Bishop (2008b), sec. 5.2 for some discussion as to how these two features might be brought together fruitfully in the service of explanation.

[10]Note there is no reason to suspect that such constraining effects would somehow lead to violations of fundamental laws.

[11]For example, see Kutach (2007) for an articulation of this view.

sophisticated space such as a rigged Hilbert space). So there is a logical relationship between laws expressed as evolution equations, on the one hand, and the kinds of states they govern on the other.

The connection with contextual emergence is as follows. A key feature of this scheme is the notion of stability conditions. Such conditions are necessary for the identification of system states as well as the stability of their identity under various kinds of changes. Stability conditions exist in the target domain (e.g., in the domain of statistical mechanics), and allow a contextual topology[12] to be introduced by picking out particular reference states and defining the appropriate observables for these states. Evolution equations always presuppose stable, appropriately structured states but the conditions making such states possible are never given by those governing laws. For instance, the dynamical laws for point particle mechanics presupposes appropriate point particle states though these laws don't include the conditions necessary for the existence, stability and identity of such states.[13] As another example, the dynamical equations for quantum chemistry presuppose appropriate molecular configuration states but don't include the conditions necessary for the existence, stability and identity of such states.

It is typically the case in physical sciences that the laws and properties of the presumed underlying domains don't contain the stability conditions required for the existence of stable target domain states. These latter states are only specifiable due to the enriched context of the target domain. This is another way of saying that underlying domain provides only necessary but not sufficient conditions for the properties and behaviors of the target domain. One way features of the target domain may enter in is through coarse graining. For instance, the stability conditions in the domain of statistical mechanics can be used to pick out an appropriate coarse graining to transition from the domain of classical point mechanics to the domain of statistical ensembles of particles. There are other ways, however, for the stability conditions of the target domain to enter. For example, the Born-Oppenheim procedure institutes the stability conditions existent in the chemical domain for the stable molecular configurations presupposed by quantum chemistry. The crucial point is that, except for trivial cases, the stability conditions making appropriate target domain states possible don't exist in the presumed underlying domain.

Defending causal foundationalism via an appeal to fundamental dynamical laws–construed as causal laws–always appeals to these fundamental laws in a context-free

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[12]A topology is a mathematical space of elements possessing a definable distance measure (metric). A contextual topology is a mathematical space of elements that has been suitably enriched by incorporating information from the target domain and its context (e.g., states and symmetries of the target domain) to contain observables appropriate to the states of the target domain. For example, the contextual information necessary to produce a suitably enriched topology for observables in statistical mechanics is not given by the finer topology of the underlying domain of classical particle mechanics (Primas 1998; Bishop and Atmanspacher 2006).

[13]For example, a spacetime manifold making spatial and temporal properties of particles possible, conditions (given by a combination of quantum mechanical and chemical domains) for material bodies with particular properties, etc.

manner (e.g., first principles approaches to explanation). The difficulty, here, is that except for simple cases the bare context of the fundamental laws–whatever is considered to be "more fundamental" with respect to the target domain–never contains the stability necessary for the appropriate states (and observables) appropriate to their own domain let alone the target domain's stability conditions. These conditions are always presupposed (and contextual emergence teaches us to look to an enriched domain for the required information). Even the most fundamental laws of physics must come to expression in particular contexts to have any bearing on some set of states.

The second difficulty with appealing to the supposed necessitating character of fundamental laws is that this move presupposes the causal closure of physics, namely that no other law-like features from domains outside those of the fundamental laws constrain or otherwise affect the fundamental laws and properties of the supposed underlying domain. However, this is more presumption than what one can demonstrate by argument. What an examination of physics shows us is that the presumed causal completeness of physics is actually a typicality condition (Bishop 2006). What this means is that the fundamental laws of physics tells us only what typically will happen in the absence of any intervening causes or constraints from outside of the domain of physics. Quantum mechanics is one of the most successful and strenuously tested theories of physics. Nevertheless, the domain of quantum mechanics doesn't contain the laws, properties and conditions necessary to fully govern the motions of the molecules in my fingers as I type these words. This failure of causal closure isn't an artifact of mixing microstates (quantum mechanics) and coarse-grained macrostates–a mixture that can lead to problems when trying to analyze causation (Kutach 2007)–as the relationship between the domains of physics and chemistry isn't one of coarse graining, but is much more complex (e.g., Bishop 2010a; Hendry 2010).[14]

Whatever the plausibility of the necessitarian view of fundamental laws, it is a metaphysical doctrine. After all, physics doesn't need a necessitarian view of fundamental laws for its theories and practices. Moreover, one can make reasonable sense of our physical theories and practices using either a necessitarian or a contingent construal of fundamental laws, though the contextual nature of physics is less plausibly understood on the necessitarian account. Likewise, metaphysical doctrines like atomistic physicalism are also less plausible in the face of the contextual nature of physics. Here, there is an immediate implication for causal fundamentalism, where evolution equations are construed as causal laws. The laws and properties in a domain like classical particle mechanics are insufficient by themselves to completely determine the behavior of systems in another domain like statistical mechanics. And, the laws and properties of a domain like quantum mechanics are insufficient by themselves to completely determine molecular shape in the domain of chemistry. Hence, the extent to which it is wedded to atomistic physicalism is the extent to which causal foundationalism is an inadequate

[14]One should be careful not to confuse the ubiquity of fundamental laws with a causal closure thesis that the fundamental laws determine all behaviors. The fact that the fundamental laws of physics probably are involved in the typing of my fingers at the keyboard in no way implies that these laws are determining the precise motions of my fingers. It isn't uncommon for the ubiquity claim to become confused with the causal closure claim.

analysis for any domains related by contextual emergence (e.g, complex systems). Consequently, our causal explanations for such situations will be inadequate to the extent that they adhere to this kind of foundationalism.

6. Discussion

In the context of nonlinear dynamics, the intuitions underlying physical and difference-making accounts of causation do not disappear so much as they are shown to be rather trivial. Of course there are physical causes and of course causes make a difference, but these intuitions and approaches to causation don't give us much purchase on the fine-grained features of causation in complex systems.[15] Rather, physicists and others who study complex systems tend to be rather pragmatic in their selection of the features they deem relevant. For example, the fluid equations governing Rayleigh-Bernard convection require the imposition of a constant temperature along the bottom plate of a container holding fluid so that a temperature difference can be established. In an idealized mathematical model of this situation, there is a very serviceable pragmatic choice to make for where to draw the boundary and what factors to consider as relevant to the model. However, when these same fluid equations are applied to model atmospheric weather there is no obvious choice for where to place the cut between weather system and other systems as well as for what the relevant vs. irrelevant factors are. Operationally it is fine that we can make pragmatic choices that give us well-posed equations to solve on a computer, but the foundational questions of identifying the relevant causes and the determination of the system's boundaries remains unanswered. While we still have stable patterns where the dynamics governs the outcomes, our philosophical analyses of causation come up short in characterizing that dynamics.

Moreover, many formulations of causal foundationalism (e.g., Ney 2009) share a deep similarity with reductionism: seeking genuine physical causal efficacy at the most fundamental levels of nature as revealed in the fundamental laws and properties of physics. Complex systems raise significant challenges for such foundationalism just like they do for reductionism. Detailed examination of nonlinear dynamical systems reveals that there is more to causal efficacy than fundamental physics' laws and constituents. One crucial intuition behind causal foundationalism, and reductionism in general, seems to be that the fundamental laws of physics necessitate the states they govern. Although this necessitarian reading of fundamental laws has been popular since the end of the 17th century, the discussion of nonlinear dynamics above indicates that the necessitarian view is an *interpretation* of the laws of physics. Whatever necessity the laws of physics carry it is always conditioned by the context into which the laws come to expression.

However, this isn't a lesson of nonlinear dynamics alone, though it shows up particularly clearly there. For instance, from first principles we can determine that for three particle interactions in quantum mechanics that the binding of three particle states will depend only on the scattering length–the distance over which the interaction takes place between pairs of

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[15]When complex systems aren't involved, perhaps physical and/or difference-making causal accounts can do the jobs their proponents have advertised, but given that nonlinearities are rather pervasive in nature, these approaches to causation are likely far more limited than their proponents realize.

particles–provided that this length is much longer than any other length scale in the system (Efimov 1970; Pollack, Dries and Hulet 2009). But no first principles can tell us what length scales are to be expected in the concrete contexts into which such principles come into expression. The behavior of three-particle binding states turns out to be as dependent on the actual context as the laws governing particle interactions. Or moving closer to our lived experience, the position and timing of quantum events that are partly constituitive of my knee cap don't determine the position and motion of my knee cap. Instead, the location and motion of my knee cap partly constrain–*condition*–the position and timing of those quantum events.[16]

The systems of interest in physics and most natural sciences are largely dynamical, so a scientific metaphysics suitable for natural science needs to be sensitive to dynamics and context. There is much we have to learn about analyzing causation in complex systems. The usual metaphysical interest in logical and formal relationships among efficient causes suffers from missing both the character and context of dynamics.

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[16]One might object that if the examples in this paragraph as well as the complex systems examples were subjected to a complete quantum mechanical treatment that kinds of dynamical and contextual sensitivity to which I'm pointing would vanish or be "properly" explained from first principles. The plausibility of this objection begins to fade once it's realized that such an analysis comes up short for molecules (e.g., Bishop 2010a; Hendry 2010).

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