Fluid Convection, Constraint and Causation

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Abstract
Complexity–nonlinear dynamics for my purposes in this essay–is rich with metaphysical and epistemological implications but is only recently receiving sustained philosophical analysis. I will explore some of the subtleties of causation and constraint in Rayleigh-Bénard convection as an example of a complex phenomenon, and extract some lessons for further philosophical reflection on top-down constraint and causation particularly with respect to causal foundationalism.

1. Complexity: Nonlinear Dynamics

Quintessential examples of complexity resulting from nonlinear dynamics are (i) the butterfly effect, where the flapping of a butterfly's wings in Argentina can influence the formation of a tornado in Texas three weeks later, and (ii) 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. Complex systems typically are analyzed as *dynamical systems*, mathematical models where time can be either a continuous or a discrete variable. Many complex systems involve nonlinear interactions, my focus here, but others might involve intricate networks (1). 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).

A dynamical system is characterized as linear or nonlinear depending on whether the *principle of linear superposition holds*. For linear systems, the principle holds if any multiplicative change in a variable, by a factor α say, implies a change of its output proportional to α. A dynamical system is nonlinear if linear superposition fails. Physically, this failure corresponds to a system's output *not* changing proportionally to any change in input. The phenomenon of *sensitive dependence*–the smallest change in the initial conditions can issue forth in a drastic change in a system's behavior–registers this non-proportional response. The most cited measure of sensitive dependence involves an exponential parameterized by the largest *global Lyapunov exponent*. Such exponents are derived through a linear stability analysis of the trajectories of nonlinear equations in a suitable state space, but turn out to be of limited pragmatic value (2).

Dynamical systems typically are analyzed in a *state space*, an abstract mathematical space of points where each point is assumed to represent a possible state of the target system. It is then possible to study a mathematical model of the target system by following the model's trajectory–the history of state transitions–in state space. These trajectories are governed by the model equations and represent the model's behavior in terms of its state transitions from the initial state to some chosen final state. Using these mathematical tools, complex phenomena such as convection can be analyzed precisely.

2. Complexity: Hierarchies

In some simple, non-complex systems, a hierarchy of physical forces can be readily distinguished epistemically into what appears to be clear levels of structure (e.g., elementary particles, molecules, crystals). In some cases the constituents may provide both necessary and sufficient conditions for the existence and behavior of the higher-level structures (here, and throughout I am using necessary and sufficient conditions in the sense typically found in physics, e.g., the necessary and sufficient conditions for the equilibrium of a single particle is that the resultant of all applied forces vanishes). For complex systems, however, levels of structure may only be distinguishable, if at all, in terms of dynamical time scales (e.g., time scales associated with diffusive vs. convective processes in fluids). Talk of levels is largely pragmatic and descriptive, hence, we often speak of "levels of description" (2). Different descriptive levels can give us some guidance for focusing on ontological features of different domains (e.g., physical, chemical or biological) such as 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 constituent molecules.

Properties in different domains of complex systems are coupled to each other in nontrivial 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 can even influence and constrain, the behavior of constituents composing these structures (2, 3). That is, the constituents composing large-scale structures provide necessary but *not* sufficient conditions for the existence and behavior of those structures, an example of *contextual emergence* (4, 5, 6, 7; see below). Moreover, the system constituents do not provide necessary and sufficient conditions for their own behavior when larger-scale structures and dynamics constrain or otherwise influence the behavior of constituents (6). This latter kind of hierarchy is called a *control hierarchy* (8, 9) even if the "levels" can only be identified pragmatically.

In complex systems (e.g., convection), control hierarchies affect their constituents primarily through *constraints*. A constraint is some form of limitation or modification of the degrees of freedom of some processes and/or constituents in a system. Constraints shape or influence the behavior of constituents without removing all the latter's degrees of freedom (in contrast to simple crystals, for instance). These 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. When the behaviors of the constituents of a system are highly coherent and correlated, the system cannot be treated even approximately as an aggregation. Rather, some particular global or nonlocal description is required where individual constituents cannot be fully characterized without reference to larger-scale structures or the system as a whole. A nonlocal description in nonlinear dynamics is a description that necessarily must refer to larger-scale system and environmental features in addition to local interactions of individual constituents with one another. 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).

3. Complexity: Identity and Individuation

The complex dynamics in nonlinear systems blurs distinctions like part-whole, system-environment, constituent-hierarchy and so forth (e.g., cases where hierarchies are only distinguishable by differing time scales). Mathematical modeling of physical systems typically distinguishes between variables and parameters as well as between systems and their environments. However, when nonlinearities are significant, 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 by making the difference between whether the system exhibits chaotic behavior or not, for example. Parameters such as the heat distribution on a Rayleigh-Bénard 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. The distinction between model variables and parameters becomes less clear when temporal parameter variation can move a model in and out of extreme sensitivity to the smallest of changes drastically altering model behavior as much if not more than temporal changes in variables. 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 (10), so the system/environment distinction becomes more a matter of pragmatically cutting up the 'system' and 'environment' in ways useful for our analysis.

We have no clear-cut ontology for systems in these cases raising questions about identity and individuation for complex systems. Traditional metaphysical concerns with identity and individuation revolve around numerical identity and the criteria for individuation and identity through time. For example, 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 distinct entities can be identified (and re-identified through time) and individuated. Consider the so-called butterfly effect. Earth's weather is a complex system, but its potential sensitivity to the slightest perturbations leave its boundaries ill-defined if butterfly wing flappings 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 regions 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 (e.g., through affecting convection patterns)–a distinct system or a qualitatively different extension of the Earth's weather system?

Some amount of idealization and choice are always involved in distinguishing systems from boundaries even in simple textbook cases such as an ideal gas in a container with an external heat source. Complex systems such as the weather significantly complicate the individuation task underlying the choice of system/environment boundary. It seems plausible to consider butterflies, storm fronts and 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 and involve serious rather than mild idealizations. Similar issues arise in other domains such as biology (e.g., Love, this issue).

4. Complexity: Reduction and Contextual Emergence

The issues of identity and individuation in complex systems lead naturally to a discussion of reduction and emergence. In rough outline, reductionist lore maintains that properties and behaviors of systems as a whole are nothing other than the states and properties of their parts (ontological reductionism) or are ultimately 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 presence of nonlinearities and the possibilities for holism and nonlocal constraint lead to the need to consider an alternative to the standard lore.

For instance, against reductionist lore, the lack of necessary and sufficient conditions for the behavior of underlying constituents in complex systems (e.g., control hierarchies) directly challenges reductive atomism: "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" (11). However, in complex systems, such as Rayleigh-Bénard convection, control hierarchies and other inter-level/inter-domain relations are crucial to determining the behavior of system constituents (6, 12, 13). The behavior of constituents in such systems is *conditioned* by contexts in which the constituents are situated and is not merely the result of the context-free, law-like regularities envisioned in reductive atomism.

Linear systems typically can be described using models involving decomposable constituent parts where the behavior of each component is independent of the other components (e.g., linear harmonic vibrations of a string). The effects of system components can be "summed" and hierarchies distinguished. Reductionist lore tends to work well for such systems. In contrast, when nonlinearities are important individual system components are not independent of each other. Moreover, the behavior of individual system components is 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 some possibilities while constraining others for component behavior relative to what would be possible for the components if these effects were absent. 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 (14).

The interplay between parts and wholes in complex systems and their environments typically leads to the self-organization observed in such systems. Sensitivity to minute changes at the component level in such systems is partly shaped by the 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 (4, 5):

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

For example, think of the domain of H_2O molecules as the putative realizers of the convection cells in a Rayleigh-Bénard system. 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 H_2O molecules alone do not offer sufficient conditions for the properties and behaviors of convective cells (6). Contingent conditions specifying the context for the transition from the molecular domain to the properties and behaviors of fluids and 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 (see sec. 6).

In this sense, complex systems seem to validate intuitions many emergentists have that some form of holism plays an ineliminable role in the determination of the behavior of complex systems that cannot 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 such as that exemplified in 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 of the target domain not given by the reduction domain allow for the (in principle) prediction or explanation of properties and behaviors of the target domain in many cases (4, 5, 15). This specification of information from the target domain occurs through constructing a *contextual topology*, a topology of a mathematical state space of fluid molecules that has been suitably enriched to correspond to a state space on which the relevant algebra of observables of the fluid flow can be well-defined. This enrichment is due to incorporating conditions from the target domain–the fluid–and its context. The stability conditions associated with the fluid dynamics domain allow a contextual topology to be introduced by picking out particular reference states and defining the appropriate observables for these states. These observables will form an algebra with an associated weak topology. This coarser topology characterizes an algebra containing observables not definable under the finer topology of the algebra associated with the observables of the fluid molecule state space.

5. Complexity: Rayleigh-Bénard convection

Rayleigh-Bénard convection illustrates important themes of complexity outlined above. A layer of fluid is sandwiched between two horizontal thermally conducting plates. The lower plate is heated while the upper one is maintained at a fixed temperature, establishing a temperature gradient ΔT in the vertical direction. As the fluid near the lower plate undergoes thermal expansion it becomes less dense than that above. In the presence of gravity, this creates an instability resulting in a buoyancy force tending to lift the whole mass of fluid from the lower plate. The upper plate acts as an external constraint against such motion.

Boundaries and symmetries as well as conservation laws also play important roles acting as system-wide, global constraints on the motion of fluid molecules contributing to this subtle balance (12). The system as a whole establishes the allowable states of motion accessible to fluid molecules. If there were no such constraints, the fluid in the uniform state in principle could flow in an arbitrary number of directions and an infinite number of convection patterns would be possible. Conservation of mass, for instance, imposes restrictions on the fluid velocity (16), while system geometries and symmetries strongly influence fluid flows and allowable pattern formation (13).

Typically, fluid density variations in the initial globally stable conductive state are relatively small and are rapidly damped out. When ΔT passes a critical value ΔT_c, however, the system becomes globally sensitive to small perturbations in fluid density. Eventually, the homogeneity of the stable conductive state of the fluid molecules along with some of the spatial symmetries induced by the container are broken enabling the fluid molecules to self-organize into distinguishable large-scale structures (Bénard cells). This new stable pattern is a large-scale, global constraint on the individual motions of fluid molecules due to a balancing among effects owing to the dynamics, the structural relations of each fluid molecule to all other fluid molecules, bulk motion of the fluid as a whole, system boundaries and symmetries, and conservation laws.

Although, Bénard cells emerge out of the motion of fluid molecules after ΔT exceeds $\Delta T_{c,}$ these large-scale structures determine modifications of the configurational degrees of freedom of fluid molecules such that some motions possible in the equilibrium state are restricted. In the original uniform state, fluid molecules can exhibit a particular range of motions constrained by the system symmetries and boundaries, by body forces such as gravity, and so forth. For instance, while $\Delta T < \Delta T_c$, fluid molecules cannot access rotational states of motion characteristic of Rayleigh-Bénard convection. In the new nonequilibrium steady state, the fluid molecules exhibit coherent convective motion, but most of the states of motion characteristic of the original uniform state are no longer accessible (e.g., fluid molecules cannot sit motionless). New system behaviors and new patterns of constraint emerge over time.

The new patterns of constraint that arise are due to the collective effects of steady, large-scale, shear fluid motion suppressing local deviations. This is to say that although body forces such as gravity and container boundaries play a role, the key constraints arise dynamically to shape constituent behavior. So although the fluid molecules are necessary to the existence and dynamics of Bénard cells, they are not sufficient to determine that dynamics, nor are they sufficient to fully determine their own motions. Rather, the large-scale structure supplies a shaping or structuring influence constraining the local dynamics of the fluid molecules. This is contextual emergence in action. The fluid molecules, the dynamics, the large-scale structures and the system-wide forces and symmetries together form necessary and sufficient conditions for the behavior of the convection system and its constituents. Note that this influence does not involve qualitatively new forces, but the collective effects of the action of the Bénard cells on the fluid molecules. The bulk flow of fluids also plays an important role in the formation and dynamics of patterns by contributing nonlocal effects (e.g., acting over many roll widths in Rayleigh-Bénard convection; see [17]). Bulk flow of the entire convecting system gives rise to an additional slow time dependence as it advects the pattern, which can contribute to pattern stability.

The physical picture is the following. Bénard cells emerge out of the local dynamics of fluid molecules as a large-scale, nonlocal process with the property that this structure constrains or shapes the states of motion accessible to fluid molecules. This is because the Bénard cells act to provide functional organization and coherence to fluid molecule behavior. Bénard cells form over some finite time period. At each instant during this period of pattern formation, a corresponding large-scale, evolving nonlocal constraint modifies the accessible states of fluid molecule motion. Prior to the establishment of this dynamically evolving constraint, the trajectories of fluid molecules had the property of accessing various states of motion (e.g., various motions accessible in the initial quiescent state), a property they lose due to the large-scale, nonlocal constraining effects of the forming Bénard cells. The downward constraints on the motion of the fluid molecules in this case are synchronic (6). The emergence of the self-regulating large-scale pattern is simultaneous with the instant-by-instant modifications of the accessible states of motion for fluid molecules. As the patterns form, they exhibit a downward determinative influence on the fluid molecules, making the contribution of the latter at an instant *t* to the large-scale conditional *on the pattern at t*. That is to say, large-scale structures arise out of fluid molecules, but they also dynamically condition or constrain the contributions the fluid molecules can make, namely by modifying or selecting which states of motion are accessible to the fluid molecules. Hence, if there was no synchronic relationship between the constraints and the fluid molecules, there would be no pattern.

There are no "new forces" coming out of nowhere; rather, the fluid is governing itself in a complex set of interactions among parts and wholes in a particular context. Because of the long-range correlations, an individual fluid molecule can only execute motions allowed to it by *all other fluid molecules and the dynamics*. For example, all the Bénard cells will determine whether or not a particular fluid molecule will stay in formation with its current cell or migrate to a neighboring cell (13).

An important point to note is that in the case of convection, while the fluid molecules and the Bénard cells are not wholly distinct entities, the former can multiply realize the latter similar to the way gas molecules in a room can multiply realize temperature. For instance, the fluid molecules of a homogeneous fluid can be freely rearranged without changing the macroscopic properties of the fluid such as temperature, density and pressure. Whereas in the case of gases, individual molecules move independently of their neighbors except for occasional collisions, in fluids due to long-range cohesive forces individual molecules are packed as closely together as quantum repulsion forces will allow. This means that fluid molecules are actually collections of roughly an Avogadro's number of individual molecules acting as a unit (e.g., individual H_2O molecules in a fluid molecule of water). The different arrangements of these fluid molecules corresponding to the same macroscopic fluid properties form equivalence classes with respect to these fluid properties.

In situations where such equivalence classes exist, an important procedure for constructing contextually emergent observables can be implemented (18): Identify a proper partition of the fluid molecule state space into equivalence classes of individual states indistinguishable with respect to some ensemble property such as the mean kinetic energy (a momentum distribution of an ensemble of fluid molecules). Equivalence classes of individual states multiply realize these statistical states and each cell in the partition can be viewed as the support for the distribution representing the statistical state. Next, identify individual states in the fluid dynamics state space (where Bénard cells are found) that are co-extensional with these statistical states in the partition over the fluid molecule state space. To carry out this second step requires a particular choice of the context of the fluid dynamics state space. This determines the set of emergent variables that are constructed from the statistical states defined in the partition over the fluid molecule state space. The context of the fluid dynamics state space serves as a *stability condition* implemented in the partition over the fluid molecule state space ensuring not only that the emergent observables are stable under temporal evolution, but also endowing the fluid molecule state space with a new contextual topology. Note that the contextual conditions specifying the stability condition are only found in the fluid dynamics domain. Examples of such conditions would be thermodynamic equilibrium needed to specify temperature (19) and both thermodynamic equilibrium and temperature needed to specify the chemical potential (20). This construction procedure is not only applicable to physics (e.g., thermodynamics, fluid dynamics), but to neuroscience as well (Atmanspacher, this issue).

The other known procedure for constructing contextually emergent observables involves using contextual conditions from the target domain state space–molecules and molecular structure, say–to enrich the realizing domain state space–protons, neutrons and electrons, say–so that an asymptotic series in the latter domain may be regularized producing new contextually emergent observables not given in the original topology of the latter state space as is the case in the relationship between quantum mechanics and molecular structure (4, 7).

6. Complexity and Causation

Causation in complex systems has received very little sustained analysis in the philosophy literature though (21) is a notable exception. Yet, complexity raises difficult questions for thinking about causation when nonlinear relationships, sensitive dependence, and concrete contexts can be so important in determining system behavior.

6.1 Identifying Causal Difference Makers

How are we to identify the causes at work in systems where nonlinearities are important? What to do if quantum effects possibly can influence macroscopic complex systems (22) or electrons dancing about elsewhere in our galaxy possibly can play a role in such systems here on Earth? How far down do we have to go to identify the relevant factors 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 influences (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 by exacerbating the problem of specifying the relevant 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" changes are not insignificant. 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. Nonlinearity 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 or lowered 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. The nonlinear nature of complex systems threatens to turn the insight of difference-making into a triviality. The nonlinearity of the dynamics makes discriminating relevant difference-makers difficult because such dynamics enables even the seemingly most insignificant factors to play a role in influencing system behavior.

6.2 Upward Determination and Downward Constraint

Typical metaphysical analyses cash out causal difference-making as "bottom up," 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. But what about situations where larger scale structures or control hierarchies act to constrain, shape or organize the behavior of system components? Cases such as fluid convection, where the molecular domain provides necessary but insufficient conditions for the total behavior of convection cells, and where the convection cells constrain the behaviors of fluid molecules, are rather typical 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 determining 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 (6, 22). Typical metaphysical analyses of causation focus on logical and formal relationships among efficient causes in bottom-up constructions. In contrast, convection patterns are examples of downward constraint due to dynamics and emerging dynamical relations.

While most metaphysicians focus on the "upward" flow of efficient causation from system components to system behavior as a whole, complex systems such as convecting fluids present plausible examples of a "downward" flow of influence and constraint on the behavior of system components. Such behaviors clearly raise questions for a program of discovering the factors influencing complex systems' behavior in the fundamental laws alone, an approach to causation championed by those who favor physical accounts of causation. For a good comparison of difference-making and physical accounts of causation, see ([23]).

Nonlinear dynamics teaches us that the contexts into which fundamental laws come to expression are at least as important as the laws themselves, so the strategy of looking exclusively to fundamental laws and theories for our causal cues, as *causal foundationalism* does, will likely miss much of what is going on in complex systems. A similar anti-causal foundationalist point can be made in interventionist accounts of causation ([24]). The dynamically emerging convection patterns constraining or shaping fluid constituents influence or intervene in ways that are not captured in traditional efficient causation accounts.

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 is shaped by an important assumption that is questionable in nonlinear dynamics (and other contexts as well; see Love, this issue): Natural laws are universal in the sense of being context free (as in the characterization of reductive atomism given 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, 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 come 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 connected with contextual emergence (sec. 4): While fundamental laws establish some necessary conditions for the possible behaviors of objects, contingent contexts must be added to establish jointly necessary and sufficient conditions for actual behaviors. Fundamental laws clearly 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 (2). Concrete contexts into which laws come to expression are at least as important as the laws. We should, then, resist the tendency to focus exclusively on fundamental laws for developing accounts of the influences determining complex systems' behaviors. Sound accounts of 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 being exhibited at different scales within the system ([25] and [26] have some discussion of how these two features might be brought together fruitfully in the service of explanation).

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 possibility spaces 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 influence and constraint. Dynamics at different spatial/temporal scales as well as that of wholes in complex systems act to constrain or shape the possibilities made available by fundamental laws. Note there is no reason to suspect that such constraining effects would somehow lead to violations of fundamental laws–cooperation rules the day.

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 spaces for emergent nonlinear laws, though particular features of contexts might be required for nonlinear dynamical laws to arise.

6.3 Laws, States and Context

The interest in causal laws among philosophers stems from construing laws as governors or specifiers of the history of state transitions of a system 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 some time t_a plus the fundamental laws necessitate the state $s(t_b)$ at some later time t_b ([27]).

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 a particular 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 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 evolve 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 fluid domain), and allow a contextual topology 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 do not include the conditions necessary for the existence, stability and identity of such states (e.g., 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.). As another example, the dynamical equations for quantum chemistry presuppose appropriate molecular configuration states but do not include the conditions necessary for the existence, stability and identity of such states ([4], [7]).

It is typically the case in physical sciences that the laws and properties of the presumed underlying domains *do not* 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 the 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. In the case of quantum chemistry, adiabatic procedures such as the Born-Oppenheim procedure implement 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 do not exist in the presumed underlying or realizing domain.

Defending causal foundationalism via an appeal to fundamental dynamical laws–construed as causal laws–typically treats to these fundamental laws in a context-free manner (e.g., first principles approaches to explanation). However, 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 conditions necessary for the 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 of physics constrain or otherwise affect the fundamental laws and properties of the fundamental domain. However, this is more presumption than what one can demonstrate by argument. The presumed causal completeness of physics is actually a typicality condition (28). What this means is that the fundamental laws of physics tell us only what typically will happen in the absence of any intervening influences or constraints from outside of the domain of physics (i.e., in relatively context-free situations). Quantum mechanics is one of the most successful and strenuously tested theories of physics. Nevertheless, the domain of quantum mechanics does not contain the laws, properties and conditions necessary to fully determine the motions of the molecules in my fingers as I type these words. This failure of causal closure is not an artifact of mixing microstates (quantum mechanics) and coarse-grained macrostates (27)–a mixture that can lead to problems when trying to analyze causation–as the relationship between the domains of physics and chemistry is not one of coarse graining, but is much more complex (4, 7). 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 are involved in the my fingers' typing in no way implies that these laws are determining the precise motions of my fingers. It is not uncommon for the ubiquity claim to become confused with the causal closure claim in philosophical literature.

Whatever the plausibility of the necessitarian view of fundamental laws, it is a metaphysical interpretation. After all, physics does not 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 interpretations such as reductive atomism are also less plausible in the face of the contextual nature of physics. Here, there is an immediate implication for causal foundationalism, where evolution equations are construed as causal laws: The laws and properties in a domain of fluid molecules, say, are insufficient by themselves to completely determine the behavior of systems in another domain, fluid dynamics, say. 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 reductive atomism is the extent to which causal foundationalism is an inadequate 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.

7. Discussion

In the context of nonlinear dynamics, the intuitions underlying physical accounts of causation disappear while those underlying difference-making accounts become complicated to say the least. Of course there are physical causes and of course causes make a difference, but these intuitions and approaches to causation do not give us much purchase on the factors at work in complex systems. When complex systems are not 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 characterizing systems are likely far more limited than their proponents realize. Possibly interventionist accounts of causation (e.g. [24]), may fair better in such contexts, but the key point is that the language of efficient causation is wholly inappropriate for characterizing inter-level, part-whole and downward forms of constraint.

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 questions of identifying the relevant causes and the determination of the system's boundaries remain unanswered. We still have stable patterns where the dynamics shapes the outcomes; our philosophical analyses of causation come up short in characterizing that dynamics and its influence.

Moreover, many formulations of causal foundationalism (23, 27) 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 influencing behaviors 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 as dictators. Although this necessitarian reading of fundamental laws has been popular since the beginning of the 18th century, though always having significant objections raised against this reading over the centuries, 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 is not a lesson of nonlinear dynamics alone, though it shows up particularly clearly there. For instance, from first principles we can determine 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 particles–provided that this length is much longer than any other length scale in the system (29, 30). 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 of particle interactions. Or moving closer to our lived experience, the position and timing of quantum events that are partly constitutive of my knee cap do not determine the position and motion of my knee cap when walking. Instead, the location and motion of my knee cap partly constrain–*condition*–the position and timing of those quantum events. One might object that if the examples in this paragraph as well as the complex systems examples above were subjected to a complete quantum mechanical treatment that these kinds of dynamical and contextual sensitivities would vanish or be "properly" explained from first principles. The plausibility of this objection fades once it is realized that such an analysis comes up short for molecules because of irreducible reference to chemical contexts (4, 7).

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. The usual metaphysical interest in logical and formal relationships among efficient causes suffers from missing both the character and context of dynamics. There is much we have to learn about the influences at work in complex systems.

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