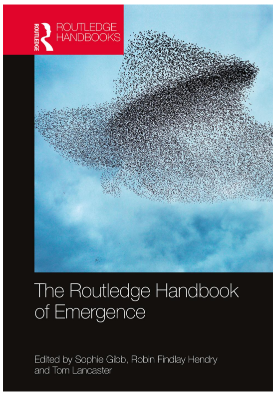

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COMPLEXITY AND FEEDBACK

Robert Bishop and Michael Silberstein

Introduction

Complexity is a multifarious concept; different researchers focus on different aspects. For instance, a system can be considered complex because it has many interacting parts, yet its behavior can be relatively simple, that is, easy to predict, control and manipulate: car engines and watches would be examples. On the other hand, a system with few interacting parts can exhibit behavior considered complex, that is, hard to predict: three billiard balls on a torus would be an example (Krámli, Simányi, and Szász 1991). Also note that both the terms "complexity" and "emergence" often are used for two seemingly different cases. One case involves simple rules governing uniform elements that generate unpredictable ("complex") behavior such as strikingly stable patterns in finite automata. Another case involves "complex," seemingly random, often nonlinear interactions of uniform elements that generate robust and stable large-scale patterns that are therefore, at least from a particular level of analysis, largely predictable, for example, Rayleigh-Bénard convection (RBC). The idea is that in the first kind of case we have complexity from relative simplicity, while in the second kind of case we have simplicity from relative complexity.

Of course, this all depends on how those terms are defined, so this way of putting things is often misleading. For example, if RBC is just the result of *simple laws* of more fundamental physics, then these two cases are seemingly really not so different after all. That is, given that they both involve macroscopic stable patterns generated from the temporal evolution of more basic microscopic constituents, what, if anything, makes these cases different? Notice that this way of putting the problem immediately ties together the concepts of complexity and emergence, because it defines complex processes as those that *emerge* from more basic processes, and remain stable across time and across changes in the more basic constituents. There are a number of different ways that macroscopic stable patterns apparently can arise in different kinds of systems. This is just to say that such stable patterns per se are, in some sense, multiply realizable.

People often point to a lack of central control as at least a necessary condition for complex behavior (Ladyman, Lambert, and Wiesner 2013). Does that condition hold in both the previous cases? If lack of central control means the absence of a designer or central decision-maker (e.g. a CEO), then both cases meet the condition. Or if a lack of central control means the organization of the system is such that even given different initial conditions or disruptions/deletions of the basic parts, the macroscopic patterns will remain stable, then again, both cases meet that condition. Nevertheless, assuming reality is not actually a finite automaton, then, in the case of RBC and the like, there is no purely computational account for the large-scale stable patterns (i.e., no account in which the program/algorithm itself is a kind of centralized control). Rather, there are various temporal and length scales of physical/chemical processes/elements that actually *interact* to generate the large-scale patterns, where the latter patterns become crucial for how the system components behave.

Ladyman, Lambert, and Wiesner (2013) point out that when the nature of hierarchical physical processes is compositional, one gets a lack of centralized control for free, at least in the sense of no central controller and distributed order. That is true as far as it goes, but doesn't help much with the case of RBC and other actual-world complex systems: How do stable, large-scale patterns arise and maintain themselves, given only the seemingly random interactions of uniform parts governed by nothing but basic physical laws of nature? Certainly, appealing primarily to initial conditions to answer that question in all such cases is inadequate because it ignores the important roles of contingency and context. Moreover, depending on how one thinks of physical laws and physical elements, such as atoms, the mystery only gets more profound. For instance, if laws of nature are not like algorithms that "govern" processes and physical elements are not like digital or information-based processes, then the computational metaphor, the analogy with finite automata, becomes less useful. Put differently, the actual world involves genuine physics and chemistry. It's the physical properties and their physical relations in concrete contexts that make the difference for system behaviors.

We will ultimately argue that while both cases can be said to involve complexity and emergence in *some sense*, the case of RBC involves *ontological* emergence and complexity in an interesting sense. This is in large part because we think the best explanation for the existence of the robust large-scale patterns in RBC involves global or systemic features of such systems that do not reduce to either the basic dynamics of the parts or to the initial conditions of the elements. We call this *ontological contextual emergence*, and we think it is often the best explanatory framework for complexity defined as the emergence of stable and self-maintaining patterns from more basic interactions. Before we get there, we need to say more about the various concepts of complexity and emergence.

Sometimes it is particular properties of systems or dynamical processes that are considered complex: noncomputability such as algorithmic complexity, nonpredictability, nonderivability, inherent statistical complexity (e.g., systems which are neither completely random nor completely ordered), information theoretic limits (e.g., the no-cloning theorem in quantum information theory), stochasticity, multiple realizability, nonlinearity, self-organization, collective effects, feedback loops, hierarchies, interlevel or multiscale relations, phase changes, wholes or global properties constraining and modifying the behavior of their parts, robustness, plasticity and hysteresis would be examples discussed in the literature. One or more of these various aspects have been identified as a signature of complexity in physics, chemistry, biology, geology and computer science, just to name a few disciplines.

However, the fact is neither scientists nor philosophers have made any compelling case for which aspects should be considered necessary or sufficient for a system or dynamics to be classified as complex (e.g., Ladyman, Lambert, and Wiesner 2013). Scientists in many disciplines tend to treat the various aspects of complexity phenomenologically (see later). Furthermore, in the physics literature, where some of the most sustained attention to measures for complexity has been given, there is no agreed-upon measure (e.g., Grassberger 1989; Sporns 2007; Wackerbauer et al. 1994). One possible explanation for the lack of agreement on complexity measures is the alleged observer-relativity of at least some forms of complexity: measures of complexity are not independent of the observer or the observer's choice of measurement apparatus (Crutchfield 1994; Grassberger 1989).

The situation for emergence is very similar to that for complexity in that there is no agreed-upon universal definition of emergence. Both emergence and complexity can be defined in ways that are relatively more epistemic or relatively more ontic, with some definitions straddling both (Silberstein 2012). Likewise, definitions of both can be more or less formal/computational/information theoretic versus physical. There are those who try to define emergence in terms of complexity and vice versa. For example, formal measures of complexity, whether they pertain to computational limits, correlational or causal connections of various sorts that can only be understood statistically or in network terms, say, are often invoked when defining epistemic forms of emergence that focus on failure of predictability and derivability (Silberstein 2012; Ladyman, Lambert, and Wiesner 2013). Clearly, one has to specify exactly what one means by complexity or emergence for any meaningful discussion to take place.

While some might take all of this as reason to be skeptical about either emergence or complexity, we think the pluralism exhibited in the scientific literature about these concepts is perfectly reasonable. Therefore, we accept that emergence and complexity are only contingently related. This means that one has to spell out the particulars of how complexity and emergence relate in some specific case.

If anything passes for a kind of agreement in multidisciplinary "complexity studies," it's that complex systems or dynamics often involve some form of feedback, connecting processes across differing length and time scales. Feedback loops are particular kinds of relations between systems and environment, between system and subsystems or between subsystems. In engineering and design contexts, feedback loops are used as control mechanisms based on goals. For instance, a heating and air conditioning control is set to maintain a particular room temperature. A feedback loop involves a thermometer measuring the temperature and feeding this information back to the control unit, which then turns the heating or air conditioning on or off depending on a comparison of the temperature with the set goal.

Feedback loops relating multiple subsystems with the overall system and/or environment are an example of a more general phenomenon – nonseparability (see later) – that seems to be a characteristic of many systems that are regarded as complex and as possessing emergent properties. For brevity's sake, we will focus on aspects of complexity and feedback that give rise to nonseparable properties and processes in classical physics. It should be noted that nonseparability is often characterized in both formal/mathematical and physical terms. And it should also be noted that complex, nonseparable systems often exhibit both ontic and epistemic features of emergence. In any case, nonseparability often counts as a marker of both complexity and/or emergence of one sort or another.

A relatively simple concrete example of a classical complex system with feedback where nonseparability arises is RBC. Therefore, we will focus on RBC as an example in the third section. In the next section, we will more fully characterize complexity in terms of nonseparability. We are not alone in focusing on RBC as a case study in the literature on complexity. Ladyman, Lambert and Wiesner, for instance, give RBC as an example of "robust order," and they conclude that such "robust order is a further necessary condition for a complex system" (2013, p. 27). While we agree that robust order is a condition for complex systems, we don't think Ladyman, Lambert and Wiesner fully capture what is important about such cases, namely, ontological contextual emergence.

Characterizing complexity

The clearest example in classical systems is when nonlinearity and feedback give rise to nonseparability, as opposed to quantum systems that are linear and also exhibit nonseparability (i.e., quantum entanglement). Here we will focus on such cases of nonlinearity to illustrate the basic concept of nonseparability. Let us be clear that nonlinearity in general is neither necessary nor sufficient for either complexity or emergence in any profound sense. Nonetheless, there are cases of nonlinearity that do exhibit ontological complexity and emergence, such as RBC.

Linear systems obey the principle of linear superposition and can be straightforwardly decomposed into and composed by subsystems. For instance, linear (harmonic) vibrations of a string can be analyzed as a superposition of normal modes, and these normal modes can be treated as uncoupled individual subsystems or parts. Classical linear systems can be thought of as aggregations of parts ("the whole is the sum of its parts"). The linear behavior of such systems is sometimes called *resultant* (as opposed to emergent).[1] Some nonlinear systems, by contrast, cannot be treated even approximately as a collection of uncoupled individual parts.

Some form of global description[2] is required, taking into account that individual constituents cannot be fully characterized without reference to larger-scale structures (e.g., processes, dynamics and constraints that may be system-wide or of even larger/higher scale). Rayleigh-Bénard convection is an example. It exhibits what is called *generalized rigidity*: 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, via so-called order parameters (Chemero and Silberstein 2008; Cross and Hohenberg 1993). This is an implication of generalized rigidity (e.g., convection cells in RBC systems are modified or disrupted through changing the temperature difference between the bottom and top plates of the confinement system [see Figure 11.1]). These globally constrained behaviors are often referred to as *emergent* (as opposed to resultant).

The intricate coupling between constituents or subsystems in some nonlinear systems is related to or described by the *nonseparability* of the Hamiltonian, a function describing the total energy of the system and characterizing its time evolution. A Hamiltonian is said to be separable if there exists a transformation carrying the Hamiltonian describing a system of *N* coupled constituents into *N* equations, each describing the behavior of one of the system's constituents. Otherwise, the Hamiltonian is nonseparable and the interactions within the system cannot be decomposed into interactions among only the individual components of the system (Goldstein 1980). When the constituents of a system are highly coherent, integrated and correlated such that their properties and behaviors are nonlinear functions of one another, the system cannot be treated as just a collection of uncoupled parts. The behavior of the parts is every bit as determined by the state of the whole as the other way around.

Systems in the biological domain often exhibit nonseparability: while there are component parts and processes, their individual behaviors systematically and continuously affect one another in a nonlinear fashion (Silberstein and Chemero 2013; Silberstein 2016). In such cases, mechanisms are not sequential but have a cyclic organization rife with oscillations, feedback loops or recurrent connections among components. In these instances, there is a high degree of interactivity among the components, and the system is nondecomposable, and therefore localization, as expressed by separability, will fail (Bechtel and Richardson 2010, p. 24). Furthermore, if the nonlinearity affecting component operations also affects the behavior of the system as a whole, such that the component states and properties are dependent on a total state-independent characterization of the system (i.e., one sufficient to determine the state and the dynamics of the system as a whole), then the behavior of the system can be called "emergent" (Ibid, 25). Bechtel and Richardson emphasize that when the feedback is system-wide such that almost all "the operations of component parts in the system will depend on the actual behavior and the capacities of its other components" (Ibid, 24), the following features result. First, the behavior of the component parts considered within the system as a whole are not predictable in principle from their behavior in isolation. Second, the behavior of the system as a whole cannot be predicted, even in principle, from the separable Hamiltonians of the component parts (Ibid, 24). All of this applies equally to other systems exhibiting strong forms of nonlinearity.

The Hamiltonian framework provides a useful formal way for understanding the basis for many of the nonseparable phenomena of complexity.[3] Typical definitions of complexity are formalized in terms of probabilities with no explicit reference to physical system variables, though physical variables are required to define the state space over which probability measures are defined (e.g., various forms of algorithmic or statistical complexity – Grassberger 1989; Wackerbauer et al. 1994). Usually, in scientific contexts, complex systems are characterized by phenomenological features that shape our intuitions about complexity. Complex systems are typically many-bodied; they exhibit broken symmetry; there are a number of distinguishable, interdependent scales or nested structures; the hierarchies in complex systems typically are associated with irreversible processes; system constituents are coupled to each other via various relations; constituent properties and dynamics depend upon the structures in which they are embedded as well as the environment of the system as a whole; such systems display an organic unity of function which is absent if one of the constituents or internal structures is absent or if relational coordination among the structures and constituents is lacking; several components are tightly interconnected through feedback loops and other forms of structural/functional relations crucial to maintaining the integrity of the system; system behavior is often situated somewhere between simple order and total disorder; the organizational/relational unity of the system is resilient under small perturbations and adaptive under moderate changes in its environment; and the degree of complexity of systems is relative to how we observe and describe them. Such qualitative features are found in theory and experiments on complex physical systems such as RBC (e.g., Cross and Hohenberg 1993).

The concept of hierarchy is of central importance in complex systems. For noncomplex systems, there is a distinguishable ordering of scales of structure due to the hierarchy of physical forces and dynamical time scales (e.g., elementary particles, molecules, solids).[4] In some of these cases the so-called lower-level constituents may provide both necessary and sufficient conditions for the existence and behavior of the larger-scale structures.

By contrast, in complex systems scales of structure are often only distinguishable in terms of dynamical time scales and are coupled to each other in such a way that at least some of the larger structures are not fully determined by, and even influence and constrain, the behavior of constituents at the smaller scale. That is, these constituents provide some necessary but *no* sufficient conditions for the existence and behavior of some of the larger-scale structures (Bishop and Atmanspacher 2006; Bishop 2012, sec. 3.4). Moreover, the micro-scale constituents may not even provide necessary and sufficient conditions for their own behavior if the larger-scale structures can influence constituent behavior (see later). That is, the laws and properties of the constituents at the smaller scale are not sufficient for their own behavior if large-scale constraints play a role in what behaviors such constituents can exhibit. This latter kind of hierarchy is called a *control hierarchy* to distinguish such cases from systems such as sand grain piles and simple crystals (Pattee 1973, pp. 75–79; Primas 1983, pp. 314–323).

The control exercised in complex systems takes place through constraints and feedback loops. The interesting types of constraints actively change the rate of reactions or other processes of constituents relative to the unconstrained situation (e.g., catalysts). Moreover, these constraints control constituents without removing too many of their configurational degrees of freedom (contrast with simple crystals). Such constraints may be external, due to the environment interacting with the system, and/or internal, arising within the system due to the collective effects of its constituents or large-scale dynamics. Positive feedback loops, for example, push a system further in a particular direction, reinforcing and amplifying the initial change; negative feedback loops push the system in the opposite direction, counteracting the effected change. Obviously in engineering and design contexts there is central control.

An example of a feedback loop without central control would be the Belousov-Zhabotinsky (BZ) reactions (e.g., malonic acid–bromate–cerium catalyst in sulfuric acid medium) in chemical kinetics, where autocatalysis forms a positive feedback loop, while negative feedback loops block unbounded growth and return the system back towards its original state. These complex reactions produce the startling oscillations between two equilibrium states signaled by a series of changes in color from yellow to clear to yellow repeating the pattern. Most self-organizing phenomena, such as these BZ patterns, are due to the interaction of positive and negative feedback loops (Érdi 2008).

Rayleigh-Bénard convection and complexity

As a detailed case study, consider RBC (Figure 11.1). A layer of fluid is sandwiched between two thermally conducting plates, where the lower plate is heated while the upper one is maintained at a fixed temperature. This establishes a temperature gradient, ΔT, in the vertical direction. Being warmer, the fluid near the lower plate undergoes thermal expansion and 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. 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 parcels are actually collections of an Avogadro's number of individual molecules acting as a unit (e.g., individual H_2O molecules in a parcel of water). It's the fluid parcels as a whole bulk that have this tendency to start moving vertically.

The upper plate acts as an external constraint against this upward motion. System-wide, global constraints on the motion of parcels due to container boundaries and symmetries, as well as conservation laws, also contribute to this subtle balance in the fluid (Busse 1978). The allowable states of motion accessible to fluid parcels are established by the system as a whole. This includes the so-called body or volume forces acting equally on all matter within a given volume of fluid, such as gravity. In the absence of constraints and body forces, 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. Restrictions on the fluid velocity are imposed by conservation of mass (Batchelor 1967), while fluid flows and allowable pattern formation are strongly influenced by system geometries and symmetries (Cross and Hohenberg 1993). In addition, due to long-range

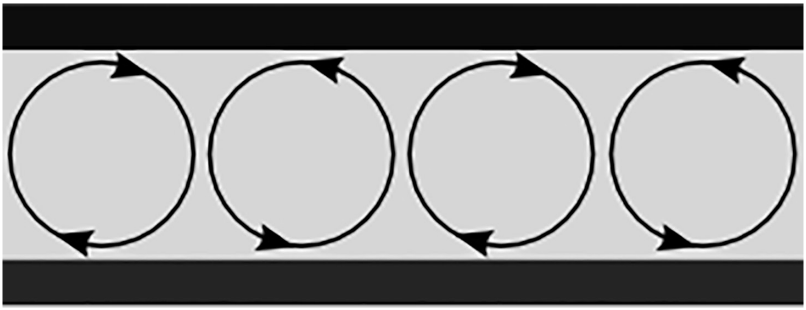

Figure 11.1 Basic Rayleigh-Bénard convection system. The lower plate is held at a warmer temperature than the top plate creating convective cells rotating in the directions indicated by the arrows.

interactions and the symmetry properties of the state vectors describing fluid parcel positions, different values of the relative positions between parcels are correlated. The spatial distribution of parcels is influenced by the presence of such correlations, and this coupling due to correlations leads to collective behavior contributing to the formation of coherent large-scale structures. As the temperature difference surpasses a critical value, the correlation lengths among fluid parcels become the size of the container. It's when all fluid parcels become so highly correlated with each other that the behavior of individual parcels can be modified only by global changes (e.g., by changing ΔT) that the fluid system exhibits the generalized rigidity referred to earlier.

Typically, fluid density variations are relatively small and are rapidly damped out in the initial globally stable conductive state. Nevertheless, when ΔT passes a critical value ΔT_c, the system becomes globally sensitive to small perturbations in fluid density. Eventually, some of the spatial symmetries of the initial stable state of the fluid induced by the container are broken along with the homogeneity of this state of the fluid parcels. The growth rate of perturbations depends only on the wave number, meaning that although the fluctuations in combination with the system geometry and symmetries lead to a selection of one growing mode, its growth rate is determined solely by global system properties (Cross and Hohenberg 1993). The most unstable mode scales are the distance of plate separation. The result is distinguishable large-scale structures: Bénard cells. This new stable pattern is a large-scale, dynamical constraint on the individual motions of fluid parcels due to a balancing among effects due to the dynamics, the structural relations of each fluid parcel to all other fluid parcels, bulk motion of the fluid as a whole, system boundaries and symmetries and conservation laws. In particular, important effects in this balance are the positive feedback in the coupling between the convective flows and the deformation of the isotherms, on the one hand, and the countering of this feedback by the fluid's viscosity tending to slow the convection and the thermal conductivity tending to suppress perturbations to the convective flows due to temperature, on the other hand. This balancing keeps the Rayleigh-Bénard instability in check and produces an organizational unity within the large-scale dynamical and container constraints that is remarkably stable in the face of small perturbations.

Although Bénard cells emerge out of the motion of fluid parcels after ΔT exceeds ΔT_c, these large-scale structures determine modifications of the configurational degrees of freedom of fluid parcels such that some motions possible in the initial uniform state are restricted while other motions not available in the uniform state are now accessible. For instance, while $\Delta T < \Delta T_c$, fluid parcels cannot access rotational states of motion characteristic of RBC. In the new nonequilibrium steady state, the fluid parcels exhibit coherent convective motion, while most of the states of motion characteristic of the uniform state are no longer accessible (e.g., fluid parcels cannot sit motionless).

As $\Delta T > \Delta T_c$, there is a hierarchy distinguished by dynamical time and spatial scales (individual molecules, fluid parcels, Bénard cells) with complex interactions taking place among the different scales. The system as a whole displays integrity as the constituents of various hierarchic scales exhibit highly correlated, cohesive behavior. In particular, Bénard cells act as a control hierarchy, constraining the motion of fluid parcels. These cells not only modify the allowable states of motion for the fluid parcels but also determine which fluid parcels will stay with which cell and which parcels will migrate to a different cell.

The stability of the new patterns of constraint that arise is due to the collective effects and feedback loops of steady, large-scale, shear fluid motion suppressing local deviations within a particular system geometry. Although body forces such as gravity and container boundaries play a role, here, the key constraints and feedback loops arise dynamically to shape constituent behavior within the particular system geometry. 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 RBC; see Paul et al. 2003). So although the fluid parcels and their properties provide some necessary conditions for the existence and dynamics of Bénard cells, they are neither sufficient to determine that dynamics nor sufficient to fully determine their own motions.

Complexity and emergence

Reductionist accounts maintain that properties and behaviors of systems are nothing other than the resultant product of the states and intrinsic properties of their parts (ontological reductionism) or are ultimately explainable in terms of the states and intrinsic properties of their parts (epistemological reductionism). Emergence accounts deny one or both of these claims. The various cases of nonseparability in the form of strong nonlinearity, constraints, feedback loops acting across spatial scales, etc., and the "holism" exhibited by such complex systems have proved fruitful for understanding more about how emergence works in complex phenomena.

For instance, reductive atomism or "mereological supervenience" maintains that "[t]he 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" (Van Gulick 2001, p. 18). Control hierarchies with feedback loops operating across length scales are crucial to determining the behavior of system constituents in many complex systems such that underlying constituents in complex systems lack the necessary and sufficient conditions for their own behavior, let alone the system's behavior. Constituent behavior in such systems (e.g., RBC) is *conditioned* by the contexts in which the constituents are situated and is not merely the result of the context-free, law-like regularities envisioned in reductive atomism. When nonlinearities are important, the failure of separability is clearly on display: individual system components are not independent of each other, and the behavior of individual system components is not independent of the wholes and various scales in between wholes and parts. Feedback loops and constraints acting across various length scales, as well as constraints associated with the whole system, enable some possibilities for constituent behavior while restricting other possibilities relative to what would be possible for the constituents if the effects of feedback loops and constraints were absent.

This is a form of *mereological emergence*, wherein the behavior of the whole isn't determined (either synchronically or diachronically) by the intrinsic properties of the most basic parts or even their relations (Silberstein 2002, pp. 91, 96–98, 2012). But there is more to the story than this. The interplay between parts and wholes in complex systems and their environments mediated by positive and negative feedback loops typically leads to the self-organization observed in such systems. Sensitivity to minute changes at the component scale in these systems is partly determined by the relations acting at different scales in such systems. This kind of behavior is indicative of the framework of ontological contextual emergence (Bishop 2005, 2010, 2012; Bishop forthcoming):

> The properties and behaviors of an underlying domain (including its laws) of a system offer some necessary but no sufficient conditions for the properties and behaviors at a larger scales or target system domain.

A helpful way to think of how necessary and sufficient conditions work in contextual emergence is as an INUS condition – an Insufficient though Necessary contributor to a condition that is Unnecessary but Sufficient for the effect. For example, a short-circuit by itself is neither necessary nor sufficient for causing a fire, but can be a necessary contributor to a contingent sufficient condition that started a fire. In contextual emergence, the underlying domain contributes a necessary but insufficient part of a contingent sufficient condition for properties and behaviors in that domain or in other domains or at larger scale. An important set of the sufficient conditions for the contextual emergence of properties and entities are *stability conditions*. Stability conditions represent those conditions guaranteeing the existence and persistence of relevant states and observables for a system, perhaps even for the persisting existence of the system in question. These conditions are never given by "elementary" or underlying domains alone.[5]

To illustrate, think of the domain of H_2O parcels as the putative realizers of the convection cells in RBC. The reference to necessary conditions of the parcels means that properties and behaviors of the convective cells may imply the behaviors of these parcels. Nevertheless, the converse is not true, as the properties and behaviors of the fluid parcels alone do not offer the set of necessary and sufficient conditions for the properties and behaviors of convective cells (Bishop 2012; Bishop forthcoming). Contingent conditions specifying the context for the transition from the fluid parcels 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.

In this sense, RBC illustrates how large-scale constraints play an ineliminable role in the determination of the behavior of complex systems. Yet care is needed with typical emergentist intuitions such as that the existence and behavior of wholes cannot be predicted from parts, or that wholes cannot be explained from parts in complex systems. With ontological contextual emergence, relevant information about the properties and behaviors of constituents in the underlying domain *plus* the specification of an appropriate contingent context of the target system not given by the underlying domain allow for the (in principle) prediction or explanation of properties and behaviors of the larger scales in many cases (Bishop forthcoming; Bishop and Atmanspacher 2006; Primas 1998). Stability conditions provided by the large-scale fluid dynamics allow the existence of particular reference states and observables for RBC. States, observables and stability conditions are important ontological features of physical systems, so ontological forms of emergence are the most interesting to explore here.

Rayleigh-Bénard convection and contextual emergence

The Bénard cells emerge out of the local dynamics of fluid parcels as a large-scale, nonlocal, dynamical process that, in turn, constrains or shapes the states of motion accessible to fluid parcels. Bénard cells act to provide functional organization and coherence to fluid parcel behavior. Instant by instant during pattern formation, a corresponding large-scale, evolving, nonlocal constraint modifies the accessible states of fluid parcel motion. Prior to the establishment of this dynamically evolving constraint, fluid parcels' trajectories had the property of accessing various states of motion (e.g., those accessible in the initial uniform state). But they lose this property due to the large-scale, nonlocal, constraining effects of the forming Bénard cells. The large-scale constraints on the motion of the fluid parcels in this case are synchronic: 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 parcels. The forming patterns exhibit a large-scale constraint on the fluid parcels, making the contribution of the latter at an instant t to the large-scale conditional *on the pattern at t*. Large-scale structures arise out of fluid parcels, but they also dynamically condition or constrain the contributions the fluid parcels can make, namely by modifying or selecting which states of motion are accessible to the fluid parcels. Hence, if there was no synchronic relationship between the constraints and the fluid parcels, there would be no pattern.

This is indicative of contextual emergence. There are no "new forces" coming out of nowhere, so no radical emergence. Instead, the fluid is governing itself in a complex set of interactions among parts and wholes, where the collective effects of the action of the Bénard cells on the fluid parcels is the new influence. The jointly necessary and sufficient conditions for the behavior of the convection system and its constituents are provided by the fluid parcels, the dynamics, the large-scale structures and the body forces, the system-wide geometry and the symmetries. An individual fluid parcel can only execute motions allowed to it by *all other fluid parcels and the large-scale dynamics*.

While the fluid parcels and the Bénard cells are not wholly distinct entities – nonseparability – the former can multiply realize the latter, similar to the way gas molecules in a room can multiply realize temperature. The fluid parcels of a homogeneous fluid can be freely rearranged without changing the macroscopic properties of the fluid such as temperature, density and pressure. The different arrangements of these fluid parcels corresponding to the same macroscopic fluid properties form equivalence classes with respect to these fluid properties. Such multiple realizability is typical of emergence in complex systems.

Situating complexity and emergence in context

The literature typically discusses two categories of emergence: 1) Strong or radical emergence, where emergent entities or properties are thought to be the result of irreducible bridge laws or causal powers to produce qualitatively new phenomena. Such strongly emergent phenomena are also said by some to possess novel "downward" causal powers that constrain the behavior of other phenomena at smaller spatial and temporal scales. And 2) weak emergence, where emergent entities or properties fail to be predictable, derivable, explainable or characterizable in terms of the "more basic" entities and properties out of which the emergents arise. Weak emergence has no necessary ontological implications, whereas strong emergence does (Silberstein 2012) – indeed, weak emergence is consistent with ontological reduction and the failure of epistemic reduction. Strong emergence is suspicious to most participants in the reduction/emergence debates, as it's often characterized as inexplicable magic or otherwise impossible (Ibid). As we have seen in the case of RBC, forms of large-scale determination arise that do not involve new brute bridge laws or forces. On the other hand, weak emergence is ubiquitous but does not illuminate the ontological contextual emergence illustrated by RBC. Ontological contextual emergence provides a framework where the emergence of new entities, such as Bénard cells, and their properties, are predictable, derivable or explainable once the jointly necessary and sufficient conditions are understood.

If strong and weak accounts of emergence were the only options, it's easy to see why there is so much skepticism about emergence. Without a credible alternative for ontological (strong) emergence, it can appear that ontological reduction is the only viable option. A diagnosis of this unhappy situation is that the different sides of the reduction-emergence debate seem to share the same metaphysical picture: reality as analogous to an axiomatic system. Just as there are axioms in geometry and derived theorems, so the world has some fundamental features, and all other features are logical or metaphysically necessary consequences of these fundamentals. The finite automata known as the Game of Life can serve as an analogy: There is a small set of rules, and all behaviors of the entities that arise in the game are consequences of these rules plus their initial conditions.

Particular ontological forms of emergence, such as mereological emergence or ontological contextual emergence, are viable alternatives for robust forms of emergence that are not brute, mysterious or merely weak. There is good scientific evidence for these forms of ontological emergence. In the case of classical systems, we have RBC, some types of networks, etc., and in the case of quantum systems, we have molecular structure and entanglement (Bishop 2005, 2010; Silberstein 2002, 2012, 2017).

Unlike the Game of Life, the emergence of large-scale structures, such as Bénard cells and their constraint on fluid parcels' degrees of freedom, is not the logical or necessary consequences of a set of fundamental axioms or laws simpliciter, but rather involve stability conditions not given by the base axioms or laws. In complex systems, context plays as fundamental a role as do physical laws. The relationship between complexity and emergence may be contingent, but ontological contextual emergence is an example of a framework allowing a middle path between weak and strong emergence that illuminates this contingence.

Notes

1 See (McLaughlin 1992) for a discussion of the origin and history of the terms "resultant" and "emergent."

2 Global descriptions in nonlinear dynamics are descriptions that necessarily must refer to irreducible, system-wide and environmental features in addition to local interactions of individual constituents with one another.

3 Any case of quantum entanglement represents an example of a nonseparable Hamiltonian. And although one usually does not write down a Hamiltonian for networks generated by linear matrices, some of these exhibit nonseparability as well (Silberstein 2016).

4 There is no assumption that there are ontologically pre-given levels. We assume that whatever levels there are in the physical world arise over time, contingently as it were.

5 Some contextual information appears in boundary conditions, but note from the description of RBC earlier that concrete contexts and their stability conditions are not captured in boundary conditions.

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