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Reference:

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3. Rayleigh–Bénard convection

The fluid equations governing Rayleigh–Bénard convection are the heat transport equation,

$$\frac{\partial T}{\partial t} + (\mathbf{v} \cdot \nabla)T = \kappa \nabla^2 T, \tag{1}$$

the Navier–Stokes equation,

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{v} + g, \tag{2}$$

and the continuity equation (conservation of mass),

$$\frac{\partial \rho}{\partial t} + \mathbf{v} \cdot \nabla \rho + \rho \nabla \cdot \mathbf{v} = 0. \tag{3}$$

In (1)–(3), T is the temperature, v is the velocity, ρ is the density, κ is the thermal diffusivity, ν is the kinematic viscosity and g is gravity. The velocity, temperature and density are coupled, the fluid flow inducing temperature variations, while changes in fluid density due to temperature induce changes in the fluid flow. Except for a fluid initially at rest, where the initial pressure p0 is related to ρ through p0 = ρg, the pressure is determined implicitly and, hence, is not an independent variable. Note that this means the pressure is not a dynamic variable. For an incompressible fluid, such as water, the pressure is not fixed locally but depends on distant parts of the fluid dynamics (e.g., Paul, Chiam, Cross, & Greenside, 2003).

3.1 Some system-wide properties of fluids

Before discussing Rayleigh–Bénard convection proper, I want to provide some context by quickly reviewing a few basic properties of fluids involved in various global or system-wide interactions in fluid dynamics. As Batchelor points out (1967, p. 2), the cohesive force among molecules is long-ranged relative to molecular length scales,

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[4] Note that typically fundamental forces (e.g., gravity, electromagnetism) are not explicitly identified with constraints.

falling off as r−7 in the case of nonpolar molecules (where the overall molecular charge is neutral), although it can be larger for polar molecules (e.g., Feynman et al. 1963, pp. 12–16). This force provides a means for large collections of molecules to interact with each other through continuous complex interactions of all the electrons in one molecule with all the electrons in several other molecules, not merely through nearest neighbor interactions. This continuous interaction of a molecule with the cohesive forces of several other molecules is a distinguishing features of liquids in stark contrast to an ideal gas, where molecules are roughly dynamically independent (Batchelor, 1967, p. 53).

Although the basis for why fluid elements cohere, cohesive forces are usually ignored in detailed treatments of fluid dynamics as they are relatively weak. Instead such forces form the background for those treatments in the following way. Cohesive forces in fluids cause the molecules to be packed as closely together as repulsive forces of quantum origin allow. This means that when fluid dynamicists speak of 'fluid particles' or 'fluid molecules,' they do not mean individual chemical molecules (e.g., an individual H_2O molecule in a stream of water). Rather, these 'particles' or 'molecules' refer to collections of roughly 10^{22}–10^{23} chemical molecules. In order to avoid terminological confusion, I will refer to these collections as fluid elements, volumes of a large number of chemical molecules that are small when compared with the size of the fluid system, but large when compared with the size of individual chemical molecules. Cohesive forces play a major role in defining the size and contents of these fluid elements.

Considering a fluid at the level of fluid elements motivates what is known as the continuum hypothesis: even though properties such as the mass or velocity of a fluid are ultimately concentrated in the nuclei of individual chemical molecules, and, hence, are not "smeared" uniformly over the volume of the fluid system, nevertheless such quantities can be treated as if they are continuous and can be regarded as being spread uniformly over the volume of a fluid element (Batchelor, 1967, p. 4).This assumption turns out to be well justified (Batchelor, 1967, Mareschal, 1997). One can then define notions of local velocity, mass and such, where 'local' refers to individual fluid elements.

Moreover, there are two basic kinds of forces which act on fluids. The first group are long-range forces—such as gravity,[5] electromagnetism (when fluids also carry a charge), so-called fictitious forces like centrifugal forces (when fluid motion takes place with respect to an accelerating frame)—called body or volume forces. Such forces act on all elements of a fluid, such that these forces act equally on all matter within a given volume of fluid. The second group are short-range forces of molecular origin and are appreciable only at distances on the order of the separation of molecules in the fluid. These latter forces are called surface forces because they mainly act on a thin layer adjacent to the boundary of a fluid element, where the thickness of the layer is equal to the depth the forces penetrate. Examples of such forces would

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[5] For a fluid at rest, there are two interesting extreme cases. When the mass of the given fluid is much smaller than that of the surrounding matter, the external gravitational field is approximately uniform over the entire region occupied by the fluid (depending on the surrounding matter distribution).When the mass of the given fluid is large and isolated from other matter (e.g., a gaseous star), the volume force on a particular fluid element is due to the gravitational attraction of all other fluid elements. In the former case, gravity contributes to the global external constraints on the motions of fluid elements, while in the latter case, gravity generated by the fluid itself is the main nonlocal internal constraint on such motions.

be contact forces due to momentum transport across a common boundary between two fluid elements or forces arising from short-range interactions among molecules on the two sides of the common boundary.

Both kinds of forces are taken into account in the hydrodynamic equations above such that the dynamics of fluids is not merely that of nearest neighbor interactions among fluid elements. Furthermore, the volume and surface forces as well as their distribution throughout a fluid system are modified by the motions of fluid elements relative to each other.

Spatial correlations also play an important long-range role in the dynamics of fluid systems. The positions of fluid elements are not arbitrary given the fact that one element occupies some position centered around r1 prevents all other fluid elements from occupying that position. Due to fluid element interactions and the symmetry properties of the state vectors describing their positions, different values of the relative position (r2-r1) between two fluid elements do not appear with equal likelihood, hence the simultaneous positions r1 and r2 of the two elements are spatially correlated. It turns out that there is a simple relationship between the spatial integral of the correlation function representing spatial correlation and the mean square fluctuation of the density of elements composing a fluid (Pathria, 1972, pp. 447–450), meaning the spatial distribution of the elements is influenced by the presence of such correlations. This coupling due to correlations leads to collective behavior, contributing to the formation of coherent structures. When all fluid elements become so highly correlated with each other that the behavior of individual elements can be modified only by global changes (e.g., by changing the temperature gradient of the system), the system exhibits generalized rigidity.[6]

An important point regarding fluid systems is that there is a discernible hierarchy related to the kinds of dynamics taking place at different time scales. Focusing on (2), the $v \nabla^2 v$ term represents diffusive processes associated with the dynamics of individual fluid elements and their exchange of chemical molecules, while the $(v \cdot \nabla)v$ term represents convective processes associated with large scale fluid motions and structures. The Reynolds number is a dimensionless parameter that roughly characterizes the effectiveness of convective versus diffusive processes. For small values, the slower time scale (shorter length scale) diffusive processes are dominant, while at high values the faster time scale (longer length scale) convective processes are dominant. The interplay between these two sets of time and length scales is important. If the values of the Reynolds number is too small, coherent long-lived structures typically do not form. On the other hand, if the value is too large, turbulence dominates the flow and coherent short-lived structures only form intermittently. It is in a range in between the extremes where coherent long-lived structures form.

Lastly, I briefly mention that the velocity–time autocorrelation function has a longtime tail or memory effect (first observed by Alder & Wainwright, 1970): Through various interactions, a fluid element exchanges momentum with its surrounding neighbors, which, in turn, is transmitted throughout the fluid system (Pomeau & Résibois, 1975; Mareschal, 1997, 317–318). This means that information about the motion of an individual fluid element is communicated to other elements throughout the system over some time scale characteristic of the system.

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[6] For a summary of other possible correlation effects in nonlinear dynamical systems, see Bishop (2004).

3.2 Rayleigh–Bénard convection

Rayleigh–Bénard convection provides a concrete example of a complex nonlinear system. Initially 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. The fluid near the lower plate undergoes thermal expansion and is less dense than that above, creating an instability at a finite wavelength in the presence of gravity. This buoyancy force tends to lift the whole mass of fluid from the lower plate (a consequence of the conservation of mass), while the upper plate acts as an external constraint against such motion. As long as ΔT remains small enough, thermal conduction dissipates the temperature gradient sufficiently to maintain a stable state such that the fluid near the lower plate does not rise. In this state, the energy lost by the system due to dissipation balances the amount of potential energy available to be released by the system due to the density gradient in the direction opposite to gravity.[7]

To maintain this subtle balance, however, system boundaries and symmetries as well as conservation laws also play an important role acting as system-wide, global constraints on the motion of fluid elements (e.g., Busse, 1978, pp. 1932–1936). The system as a whole establishes the allowable states of motion accessible to fluid elements. If there were no such constraints, the fluid in the uniform state could in principle flow in an arbitrary number of directions and an infinite number of convection patterns would be possible. For example, conservation of mass imposes restrictions on the fluid velocity (Batchelor, 1967, pp. 73–75), while system geometries and symmetries strongly influence fluid flows and allowable pattern formation (Cross & Hohenberg, 1993).

In this globally stable conductive state, local variations in fluid density are the seeds leading to large-scale pattern formation. Typically these density variations are relatively small, but when ΔT passes a critical value ΔTc, the system becomes globally unstable and sensitive to small perturbations in fluid density. Now more potential energy is being released due to the temperature gradient than can be dissipated, and the relevant dynamics shifts from the slower diffusive timescale (small-scale effects) to the much faster convective timescale (large-scale effects). This extra energy drives instabilities[8] leading to a breakup of the stable conductive state and, eventually, to large-scale rotating structures resembling a series of parallel cylinders called Bénard cells, the simplest case of Rayleigh–Bénard convection. Associated with this new stable pattern is a large-scale, global constraint on the individual motions of fluid elements due to a balancing among effects owing to the structural relations of each fluid element to all other fluid elements, system boundaries and symmetries, and conservation laws.

If ΔT is increased beyond a second threshold $\Delta T\alpha$, the cells begin to oscillate transversely in complicated ways. Further increases in ΔT lead to destruction of the

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[7] Typically the Reynolds number is used to characterize behavior in convection systems. Since this parameter is proportional to ΔT, I have chosen to focus on the temperature gradient as this is more physically perspicuous for the current description.

[8] The growth rate of instabilities depends only on the wave number; that is, 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 & Hohenberg, 1993, Sects. VI and VIII; Haken, 1983b, chap. 7). For Rayleigh–Bénard convection, the most unstable mode scales as the distance of plate separation.

cells and to chaotic behavior in the fluid, where spatial correlations persist. When ΔT is sufficiently large, fluid motion becomes turbulent and uncorrelated at any two points in the fluid.

Rayleigh–Bénard convection under increasing ΔT exhibits typical phenomena associated with nonlinear systems such as period-doubling cascades, phase locking between distinct oscillatory modes and sensitive dependence on initial conditions. For small aspect ratios (ratio of plate separation to plate length), the critical dynamics is characterized by a strange attractor of less than five dimensions in state space. Since a fluid continuum has an infinite number of dynamical variables in general, the fact that so few control the dynamical behavior of Rayleigh–Bénard convection is remarkable. For large aspect ratios, the number of degrees of freedom involved appears to increase greatly.

The Rayleigh–Bénard system clearly exhibits the features listed in Sect. 2.2 As ΔT exceeds ΔTc, the homogeneity of the distribution of the fluid elements and some of the spatial symmetries of the container are broken and the fluid elements self-organize into distinguishable Bénard cells. There is a hierarchy distinguished by dynamical time scales (molecules, fluid elements, Bénard cells) with complex interactions taking place among the different levels. Fluid elements are situated in that they participate in particular Bénard cells within the confines of the container walls. The system as a whole displays integrity as the constituents of various hierarchic levels exhibit highly coordinated, cohesive behavior. Additionally, the organizational unity of the system is stable to small perturbations in temperature and adapts to larger changes within a particular range.

Furthermore, Bénard cells act as a control hierarchy, constraining the motion of fluid elements. Bénard cells emerge out of the motion of fluid elements as ΔT exceeds ΔTc, but these large-scale structures determine modifications of the configurational degrees of freedom of fluid elements such that some motions possible in the equilibrium state are no longer available. In the original uniform state, the fluid elements can exhibit a particular range of motions constrained by the system symmetries and boundaries, by body forces such as gravity, and so forth. In particular, as long as $\Delta T < \Delta Tc$, fluid elements cannot access rotational states of motion characteristic of Rayleigh–Bénard convection. In the new nonequilibrium steady state, the fluid elements exhibit coherent motion (Bénard cells), but most of the states of motion characteristic of the original uniform state are no longer accessible (e.g., fluid elements cannot sit motionless). It can be shown that the uniform and damped modes follow—or are enslaved by—the unstable growing mode leading to cell formation. Basically, the variables characterizing steady and damped modes come to be systematically replaced by variables characterizing the growingmode; consequently there is a corresponding reduction in the degrees of freedom characterizing the system's behavior (e.g., Haken, 1983a, chaps. 7–8; 1983b, chap. 7). Such a reduction of the degrees of freedom is crucial to the large-scale behavior of convection systems (Greenside, Coughran, & Schryer, 1982, Malraison, Atten, Bergé, & Dubois, 1983).[9]

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[9] Some have complained that these reductions are ultimately epistemological in the sense that they are simplified descriptions of physical systems in terms of a reduced number of variables so that these variables should not be considered as causal (e.g., Walter, 2001, p. 177 and references therein). However, this complaint ignores the experimental support for the causal role of these variables (e.g., Malraison et al., 1983). One could justify the causal effectiveness of such variables along the lines of entity realism (e.g., Hacking, 1983, 1984): if an entity can be used in manipulations and interventions

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There is an alternative analysis of the development of the instability, where the fluid velocity is locked onto the evolution of the temperature field. Under reasonable conditions, the timescale is governed by the diffusion of the temperature (a nonlinear process) and the velocity field responds instantaneously to changes in the fluid density induced by the temperature field (e.g., Guyon, Hulin, Petit,&Mitescu, 2001, chap. 10). Changes in the fluid velocity then act back on and drive the temperature field.

4. Downward causation and Rayleigh–Bénard convection

How are we to understand the causal interplay between fluid elements and Bénard cells? The fluid elements are necessary for the existence of Bénard cells (no fluid elements, no cells). But the dynamics of fluid elements themselves are not sufficient on their own to bring about such structure; temperature gradients, gravity, long-range forces and correlations, physical boundaries and symmetries, conservation laws among other things are also involved (recall the degeneracies in fluid motion mentioned earlier). Context, then, plays a crucial role in pattern formation. Indeed, in the absence of gravity, Rayleigh–Bénard convection would never arise because there would be no buoyancy force. Cell formation means the fluid elements are correlated with each other through myriad physical relations,[10] reflecting large-scale structural constraints on the dynamics of the fluid elements through these emergent relations (e.g., enslavement, bulk flow[11]). Bénard cells even modulate their fluid element and energy intake to maintain cohesion within a range of variations in ΔT.

The relationship between fluid elements and cells is not a simple matter of a feedback mechanism, at least during the process of pattern formation. A feedback mechanism typically involves a reference state and a number of feedback-regulated set points so that comparisons between the evolving and reference states can be made and adjustments effected (e.g., a thermostat). But during pattern formation in Rayleigh–Bénard convection the appropriate reference states do not exist: the original uniform state is destroyed and a new nonequilibrium steady state forms (Bénard cells). This new steady state can function as a new reference state, but it is at the level of large-scale structure, where self-regulation of the cells takes place (e.g., responses to changes in ΔT), further modifying the behavior of the fluid elements.

The fact that all fluid elements in the nonequilibrium state are correlated with each other indicates that these constraints on the fluid elements' states of motion is enforced globally (i.e., beyond mere nearest neighbor interactions). One mechanism through which this arises is stable bulk shear flow of the Bénard cells acting on fluid elements. Shear flow occurs when adjacent layers of fluid slide over one another. So, for example, different layers of Bénard cells rotate differentially—inner layers rotate faster than outer layers—about the cell center in a steady bulk shear flow. Such steady shear flow acts to constrain/modify the dynamics of fluid elements in the following way. Consider a fluid eddy, a coherently rotating system of fluid elements. The eddy

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Footnote 9 continued
then it should count experimentally as real. The reduced variables in question fulfil the appropriate causal roles.

[10] Each fluid element is correlated with all other elements. When considering an idealized fluid system of infinite extent, the correlation length would become infinite. However, given a finite geometry and boundaries, the correlation length is the length of the largest dimension of the system.

[11] That is, the overall motion of a large volume of fluid.

is characterized by the distance over which it remains coherent, the eddy coherence length le, which is roughly the distance between two adjacent eddies of comparable scale. In the presence of a random background flow, fluid elements of a given eddy, which move a distance le, are subjected to the effects of adjacent eddies and are no longer identifiable with their original eddy. In other words the original eddy will decohere—the coherently rotating fluid elements will break up—as the fluid elements originally associated with it are carried away by other eddies (a form of the process know as advection). This process takes place over a time scale known as the eddy lifetime, te. This loss of correlation arises because the random background flow acts both to scramble the original eddy's motion and to spread the latter's energy from one scale to another (generally cascading downward to smaller scales). Such processes can lead to the rapid destruction of large-scale structures, or prevent such structures from forming, and play an important role in turbulence.

In the presence of a stable bulk shear flow, however, te—a measure of the eddy's coherence time—is modified because the background shear flow tends to stretch the eddy due to the fact that its different fluid elements are carried along at different speeds by the shear flow. In effect, te is lengthened as the advective effects of other eddies and the destructive effects of random flows are suppressed by the larger-scale shear flow. Those elements of fluid flow that are random get carried along with and enslaved by the bulk shear flow before disruption of local- and medium-scale patterns can occur.[12]

This is an important process by which Bénard cells maintain themselves and limit the range of motions accessible to fluid elements. Such stability is due to the collective effects of steady, large-scale, shear fluid motion suppressing local deviations. So although the fluid elements 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 governing influence constraining the local dynamics of the fluid elements (again, recall the fluid degeneracies and their curtailment discussed previously).[13] The fluid elements, 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 elements.[14]

4.1 The proposal by Thompson and Varela

Element (a) in TV reads "E is a global process that instantiates P and arises from the nonlinear dynamics, D, of the local interactions of N's components." The term "global process" here should be understood in a relationally dynamic sense, meaning that the process E arises from the interactions of the components and functions as a (quasi) stable unit, but what acts as a unit is strongly dependent on the relations that develop among the components of N (the evolutionary history and context play a key role

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12 For mathematical and experimental details, along with other examples of similar processes, see (Terry, 2000).

13 See Bishop (2004) for examples in nonequilibrium statistical mechanics, where collective effects not reducible to local interactions contribute to the dynamics of systems.

14 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 Paul et al., 2003). 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, for example.

here). The relations that develop among the components are driven by the dynamical evolution such that multiple possibilities for various processes to be manifested exist (e.g., different possible convection patterns in Rayleigh–Bénard Convection).[15] Referring only to "nonlinear dynamics" in (a) may also be insufficient as it appears that more needs to be specified. The couplings among system constituents as suggested by many of the features characterizing complex systems (Sect. 2.2)—implying that nonseparability of the Hamiltonian may be an important issue (cf., Kronz, 1998)—as well as the values of system parameters are crucial to pattern formation. In addition, external constraints play an important role in the formation and maintenance of Bénard cells, so these must be part of the characterization of the processes instantiating emergent properties. Emphasizing the contextual features of the dynamics is also important.

Bénard cells arise from the dynamics of fluid elements in the Rayleigh–Bénard system as ΔT exceeds ΔTc, where each fluid element becomes coupled with every other fluid element (element (a) of TV).More importantly, Bénard cells act as a control hierarchy, constraining and modifying the trajectories of fluid elements; that is, Bénard cells have a "determinative influence" on the dynamics of the fluid elements as lower-level system components (element (b) of TV). Moreover, although the fluid elements are necessary for the existence of Bénard cells, the former are insufficient to totally determine the behavior of the latter. This relationship between necessary and sufficient conditions seems implicit in (b), but due to its importance in issues surrounding reduction and emergence, this relationship should be brought out explicitly (e.g., Bishop, 2006b; Bishop & Atmanspacher, 2006).

This relationship is a nonquantum kind of "relational holism" understood in Teller's (1986) sense, where, the relations among constituents are not determined solely by the constituents' intrinsic properties. The properties of integrity, integration and stability exhibited by Bénard cells are relationally dynamic properties involving the nonlocal relation of all fluid elements to each other (element (c) of TV). Such global interactions along with evolutionary history and context all play a role in the determination of which convection patterns arise; the intrinsic properties of fluid elements alone plus the force laws underdetermine these outcomes. However, the behavior of Bénard cells as units differs from holistic entanglement in quantum mechanics in the sense that fluid elements may be distinguished from each other while they are simultaneously identified as members of particular Bénard cells and participate in interaction with fluid elements throughout the system. In this context focusing on the nonseparability of the Hamiltonian may also prove appropriate because, in contrast to the quantum case, classical states are always separable even when the Hamiltonian is nonseparable (cf. Kronz, 1998; Kronz & Tiehen, 2002).

4.2 Is downward causation coherent?

Among metaphysicians, downward causation has not enjoyed a positive reputation of late. One reason is the suspicion that downward causation entails a violation of the "causal closure of the physical." For example, according to Kim, the causal closure

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[15] These considerations lie at the heart of self-organization and pattern formation. Given the same dynamics, changes in experimental setup can favor the formation of one form of Bénard cell over others. Due to sensitive dependence, given identical experimental setups, fluctuations at the level of fluid elements can lead to different pattern formation on multiple runs of an experiment (e.g., the direction of rotation of cells). The dynamics makes possible a number of different ways in which the fluid elements can organize themselves into coherent large-scale patterns (i.e., a number of different ways in which the nonlocal relations among fluid elements can arise).

principle (CP)means that "Any physical event that has a cause at time t has a physical cause at t" (1993, p. 280). There are two possible readings of this principle based on the ambiguity carried by the notion of 'physical.' The first, or weaker, reading is the sense of 'physical' as in elements of the physical sciences broadly construed (sometimes encompassing biology as well). On this reading, there are no possible "nonphysical" causes capable of influencing physical systems. The second, or stronger, reading is the sense of 'physical' as in elements of physics. On this reading, there are no causes outside the purview of physics that can influence events in the domain of physics.[16]

Worries about CP normally arise in the context of philosophy of mind, but in the context of Rayleigh–Bénard convection, higher-level physical structures (Bénard cells) constrain and modify the behaviors of the lower-level system constituents (fluid elements). In this case downward causation does not entail any violation of CP in either a strong or weak sense—nothing outside of physics influences the behavior of the physical system in question. Van Gulick articulates a related worry that if some kind of "system-wide powers" or forces arise at the system level that are not determined by the laws governing the system constituents, then such forces "could override or violate the laws governing the powers of the parts" (2001, p. 18). Such a "violation" could be seen to "threaten the view of the physical world as a closed causal system" (p. 19).Without debating the coherence of the metaphysical assumption of the world as a "closed causal system," the constraining/modifying effects Bénard cells have on the motions of fluid elements is an example of a large-scale, nonlocal influence acting on the fluid elements, but this influence is consistent with the laws governing the motion of fluid elements, even though these laws and the properties of fluid elements underdetermine the behavior of the cells (recall the degeneracies in the fluid equations).[17] It is not clear why such large-scale, nonlocal influences should not be viewed as cooperating with the laws governing the system constituents, filling the gaps left by the underdetermination of these forces, as opposed to viewing such influences as somehow overruling these forces.[18]

Downward causation has also been considered as possibly involving an absurdity if it is reflexive; that is to say, if there is a "global-to-local" influence for which the local dynamics provide no sufficient account. In this case there is an apparent absurdity in that downward causation implies "a kind of self-causation, or self-determination" (Kim, 1999, 28). Admittedly, self-causation in general is a problematic concept, but the self-causation involved in Rayleigh–Bénard convection is of a type where the

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[16] I have argued elsewhere (Bishop, 2006a) that this latter reading of 'physical' renders CP invalid and question begging.

[17] This amounts to a denial of one of the core principles of atomistic physicalism as identified by van Gulick: "The only law-like regularities needed for the determination of macro features by micro features are those that govern the interactions of those micro features in all contexts, systemic or otherwise" (2001, p. 18). However, the degeneracies in fluid motion make it clear that specific global and/or system-wide contexts (e.g., symmetries and boundaries, collective effects, history of development) are crucial to determining fluid behavior in convection; hence, the denial of this principle is well justified in the case of fluids because the contributions that the laws and microfeatures make to Bénard cells are conditioned by context.

[18] This latter possibility is a metaphysician's worry if CP is taken in the strong sense, i.e., that physics is causally closed. But there is every reason to think that the weak construal of CP is more reasonable given that physics—as with all sciences—is highly idealized and given that there appear to be clear examples where chemical and biological structures constrain or modify the behavior of electrons, molecules and such (Bishop, 2006a). That is, these structures fill the underdetermination left by the fundamental forces of physics via context (e.g., Bishop, 2006b; Bishop & Atmanspacher, 2006).

dynamics of the fluid elements, under particular conditions, give rise to large-scale patterns in the form of Bénard cells. In turn these cells constrain and modify the local dynamics of the fluid elements as the cells form and maintain themselves including managing their own material and energy intake. So Bénard cells arise out of the local dynamics of the fluid elements. But they are also causes in that these cells constrain and modify the dynamics of fluid elements by limiting (allowing) access to states of motion that were previously accessible (inaccessible). Such constraint and maintenance functions of Bénard cells are not absurd in any obvious sense though they act more as formal or structuring causes.

Still, the intelligibility of downward causation has been questioned. Kim has argued that synchronic or simultaneous downward causation is incoherent.[19] He considers the following situation:

> At a certain time t, a whole, W, has emergent property M, where M emerges from the following configuration of conditions: W has a complete decomposition into parts a1, ..., an; each ai has property Pi; and relation R holds for the sequence a1, ..., an. For some aj, W's having M at t causes aj to have Pj at t (1999, p. 28).

Kim begins his analysis by supposing that W has a particular emergent property M, at the given time t, and that M's emergence at t is dependent on a particular micro configuration at t, namely that the micro constituents ai have the particular properties Pi. This means, on Kim's analysis, that W has M at t only because each ai has the particular property Pi. Although not explicitly stated, this analysis assumes a general supervenience relation: "causal relations among macroevents and macroproperties must hold in virtue of (and therefore be explicable in terms of) causal relations holding for events and properties at a more basic level. This is only a special case of the general thesis that all the facts in the world supervene on the microphysical facts" (Kim, 1993, pp. 358–359). In other words, the macro property M obtains in W only in virtue of the particular microphysical facts (each ai having the particular property Pi). According to Kim, "it makes one feel uncomfortable to be told also that aj is caused to have Pj at the very time, t, by the whole's having M at t" (Kim, 1999, p. 28). Kim then seeks to diagnose the source of this "metaphysical discomfort."

It is clear that Kim's discomfort derives from the fact that each ai having Pi at t is what gives rise to M, while M is considered to be the cause of each ai having the particular property Pi at t. In other words, the Pi are both cause of and caused by M. The claim on which Kim focuses in his diagnosis is that synchronic downward causation involves an incoherence because W having M at t causes aj to have Pj at t, implying that prior to t, aj does not already have Pj at t (hence, how could M have emerged in the first place). To get the implication, however, one must also invoke what Kim calls the causal-power actuality principle (CPAP):

> For an object, x, to exercise, at time t, the causal/determinative powers it has in virtue of having property P, x must already possess P at t. When x is caused to

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[19] Kim notes that this situation "involves the controversial idea of simultaneous causation (where a cause and its effect occur at the same time)" (1999, p. 36, fn. 34). I take it that Kim's worry about simultaneous causation is whether it can be made metaphysically coherent, not physically coherent. There are physically coherent expressions of synchronic effects in physics as in relativistically consistent instantaneous action-at-a-distance theories (Dirac, 1949, Hill, 1967). Regarding the latter, there is an empirical question whether such simultaneous influences exist, but they are physically intelligible. See Taylor (1963, 1966), Brand (1980), and Huemer and Kovitz (2003) for defenses of the metaphysical coherence of simultaneous causation

acquire P at t, it does not already possess P at t and is not capable of exercising the causal/determinative powers inherent in P (1999, p. 29).

This is a metaphysical principle offered to answer Kim's metaphysical worry. One point to note is that Kim's analysis presupposes the ai and W are wholly distinct entities. In the case of convection, the fluid elements (ai) and the Bénard cells (W) are not wholly distinct entities though the two levels can be distinguished via dynamical time scales (Sect. 2.3). There is no "complete decomposition into parts," so one key assumption underlying Kim's metaphysical worry does not hold in the case of Rayleigh–Bénard convection.

Another point to note is that because the entities involved are not wholly distinct, the causal relations are not all temporal: the large-scale structures determine/constrain some of the causal properties the fluid elements contribute at the time such contributions are made. One way to see this is via the metaphysical concept of realization. The core idea of realization is that higher-level properties ("macrophysical") are realized by lower-level entities and properties ("microphysical") such that the causal efficacy of the former properties is nothing but the causal efficacy contributed by the latter (e.g., Kim, 1998, 1999, Gillett, 2002, pp. 98–101). However, in the case of Rayleigh–Bénard convection, the contributions individual fluid elements make to the Bénard cells is conditioned by the cells: The properties individual fluid elements contribute to the cells are conditioned upon the properties instantiated by the cells. Furthermore, this downward determination is instantaneous; that is, the properties of the fluid elements only contribute when they realize particular other properties such as those associated with the collective motion and large-scale structure of Bénard cells. Hence, CPAP is not applicable to the case of Rayleigh–Bénard convection, nor is there any apparent incoherence involved in this simultaneous upward/downward co-determination.

The physical picture is the following. Bénard cells emerge out of the local dynamics of fluid elements as a large-scale, nonlocal process with the property that this structure constrains/modifies the states of motion accessible to fluid elements. This is because the Bénard cells act as a control hierarchy. When the cells are established at time t, this governing property is established at t; it did not exist prior to t. Likewise, prior to t, the trajectories of fluid elements had the property of accessing various states of motion, a property they loose at t due to the large-scale, nonlocal governing effects of Bénard cells. The causal constraints/modifications on the motion of the fluid elements in this case is synchronic: the emergence of the self-regulating large-scale pattern is simultaneous with the modifications of/constraints on the accessible states of motion. If it were not synchronic, the pattern would not arise.[20] Because of the long-range correlations, an individual fluid element can only execute motions allowed to it by all other fluid elements (e.g., all the Bénard cells will determine whether or not a particular fluid element will stay in formation with its current cell or migrate to a neighboring cell).

On Kim's picture, the Bénard cells (or the ever-growing pattern) can have no causal influence at time t on the fluid elements. Any influence large-scale structures have

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[20] This is somewhat oversimplified. In reality Bénard cells form over some finite, but short (at least for small systems) time period. However, at each instant during this period of pattern formation, the corresponding large-scale, nonlocal constraints appear modifying the accessible states of fluid element motion. Downward constraint or determination is still synchronic as the large-scale, nonlocal processes alter the states of motion accessible by the fluid elements instant by instant.

on fluid elements can only occur at some delay $t + \tau$, where τ is some small positive number (set aside the fact that on his view the constraining influence of the cells must be a chimera). This would be the physical import of CPAP, the idea being that the fluid elements contribute all the casual properties had by the large-scale structures, hence the need for whatever causal influences the latter have to lag the contributions of the fluid elements. However, this misses out the notion of control hierarchy at work here, namely the constraining function the (developing) large-scale structures exert on the fluid elements. As the patterns form, they exhibit a downward determinative influence on the fluid elements, making the contribution of the latter at t to the large-scale conditional on the pattern at t. That is to say, large-scale structures arise out of fluid elements, but they also condition or constrain the contributions the fluid elements can make, namely by modifying or selecting which states of motion are accessible to the fluid elements (e.g., due to enslavement; see Haken, 1983b). Hence, if there was no synchronic relationship between the constraints and the fluid elements, 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.

4.3 Comparison with Sperry cases

Is the candidate for downward causation proposed here, Rayleigh–Bénard convection, different from Sperry cases? In his example of the wheel rolling down a hill, the structural properties of the wheel supposedly constrain the movement of the molecules composing the wheel, carrying them down the hill. Kim has argued (1999, pp. 29–31) that such cases as the motion of the whole wheel can be analyzed as the summed motion of parts[21] (and, hence, is a diachronic effect). In contrast, the kind of governing influence, which Bénard cells have on the fluid elements, cannot be so analyzed (it is synchronic).

Perhaps the constraining/modifying behavior of the Bénard cells is merely an artifact of our explanation like that of Sperry's wheel (hence, only epistemological at best), or perhaps the ascription of ontological status to downward causation in Rayleigh–Bénard convection is misguided because such large-scale, nonlocal processes are not really causal since all 'proper' causation in physical systems has to be local, efficient causation (e.g., as is often assumed to be the case in analyzing examples like Sperry's wheel). Although space does not permit a full response, such objections overlook the close interplay between experiment and theory regarding the contextual factors involved in convection (e.g., symmetries, long-range forces, spatial correlations involving all fluid elements, dynamical history) and also beg the question about how such large-scale, nonlocal structuring factors operate.

One might respond that although no reductive analysis of these effects can be given currently, some future better theory will be able to explain, from the point of view of the fluid elements, the necessary and sufficient conditions for the behavior of the cells (hence, blocking epistemological emergence and, presumably, ontological emergence as well[22]). Such a reply presupposes metaphysical reductionism, but there is not much evidence for this as a general assumption, at least not in any of our sciences (Bishop, 2006a, b; Bishop & Atmanspacher, 2006). On the other hand, there are a

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[21] Presumably there is a limit to how far down such a reductive analysis can go before it becomes nonsensical, but this has to do with the transition from classical mechanics to quantum mechanics.

[22] See Van Gulick (2001) for a lucid discussion of these distinctions.

number of cases, for example in chemistry and thermodynamics, where reductionism of this type fails (Bishop, 2004, 2006b; Bishop & Atmanspacher, 2006). After all, the fact that a system is composed of constituents does not imply that all the system's behaviors are caused by the behaviors of its constituents in a resultant fashion (that is to confuse analysis of systems with reductionism of systems to their components). To presume that a future better theory will be reductionist is simply to beg the question.

Furthermore, although there is a microscopic approach to the fundamental conserved quantities of fluid systems (e.g., particle number, energy and momentum) analogous to the hydrodynamic approach discussed in Sect. 3, this kinetic approach still makes irremovable references to such nonlocal and system-wide features as conservation laws, symmetries and dynamical modes of the system as a whole in order to understand the behavior of a test particle (Pomeau & Résibois, 1975).[23] Collective features of the system still play an ineliminable, crucial determinating role in the dynamics of system constituents even from the kinetic perspective.

5 Concluding remarks

There are several lines of evidence, including molecular dynamics simulations aimed at giving a microscopic view of fluid dynamics, indicating that the hydrodynamic description is valid, even at molecular length and time scales (Mareschal, 1997, pp. 317–320). This is to say, the hydrodynamic description of fluids is not valid because it "averages over" individual interactions of fluid elements, a misleading characterization ignoring the role nonlocal and system-wide features play in the derivation, closure and solution of the fluid equations. Rather, the description is valid because it includes effects that are absent from considering just the local (nearest-neighbor) interactions of individual fluid elements. For instance, hydrodynamics includes the evolving relations that develop among all fluid elements with each other and their constraining influence on the dynamics of individual fluid elements and possible nearest-neighbor interactions.

Rayleigh–Bénard convection, then, looks to be a promising candidate for studying inter-level causation, flowing from the fluid elements upward and from the large scale structures downward. The tight integration between the effects of the dynamics in these different hierarchies—representing different length and time scales—with the Bénard cells acting as a control hierarchy, can be an important source of insight for enriching and extending our understanding of causation. For example, typical philosophical accounts of causation—e.g., counterfactual, logical, probabilistic, process, regularity, structural—were developed within the context of a "linear worldview" heavily influenced by a nearly exclusive focus on linear models of Newtonian mechanics. In the context of nonlinear systems, such as convection, there are many additional channels of interaction not envisioned in such a linear framework (e.g., open systems exchanging matter and energy with their environments (a form of situatedness), nonlinear feedback loops, inter-level interactions, self-organization, whole-part relations, memory effects). Dealing with these additional forms of interaction appears difficult without modifying or extending typical causal accounts. For instance, process theories lack an adequate account of the structural influence of large-scale, global influences on parts, while structural theories lack an adequate account of large-scale nonlocal

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[23] Note that even the definitions of conservation laws for local quantities in a fluid make irremovable references to system-wide properties (e.g., Guyon et al., 2001, chaps. 3 and 5).

processes. Counterfactual approaches maintain (roughly) that a cause is some event in the absence of which the effect would not occur; the applicability of this approach, however, is substantially limited by the multiple realizability exhibited by many of the nonlinear behaviors in complex systems (regularity accounts suffer similar limitations).

In particular, as proposed in this essay, fluid convection can serve as a model for further study of causal accounts. More to the point, such a model is well suited for exploring emergence and downward constraint, clearly going beyond Sperry's examples in these respects. Furthermore, convection processes can serve to test the applicability and generality of many of the assumptions and arguments invoked in philosophical discussions of reduction, emergence and downward causation (e.g., Kim's CPAP). Getting clearer about the applicability of such assumptions as well as about emergence and downward causation in the context of concrete examples like convection might also shed light on how to think about these concepts in terms of cognitive function and broader issues in philosophy of mind. For example, TV was originally proposed in the context of an embodied cognitive science, where consciousness might be viewed as an emergent feature of the nonlinear neural dynamics constrained and modified by its presence in a body ecologically situated in a wider environment (Thompson & Varela, 2001). Sharpening our understanding of emergence and downward determination using concrete examples from nonlinear dynamics—with all the features listed in Sect. 2.2—should prove useful in understanding and evaluating the evidence for the downward determination of mental activities on, for example, the dynamics of epileptic activity (e.g., changes in the patterns of the neural dynamics; Le Van Quyen, 1997a, b; Thompson & Varela, 2001).

So it appears that classical physics still holds many philosophical lessons for us to learn.

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