Chapter 2
Toppling the Pyramids: Physics Without Physical State Monism

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Abstract In this paper, we challenge a wide-spread assumption among philosophers that contemporary physics supports *physical state monism*. This is the claim that the causal powers of a system supervene upon the ‘lower-level’ laws and the lower-level state of the cosmos (as represented by our ‘best physics’). On this view, it makes sense to ignore a macroscopic system’s higher-level properties in determining its causal powers, since any higher-level powers are merely artifacts of our special interests. We argue that this assumption is common both to *microphysicalism*, which carves the cosmos into a set of microscopic constituents, and *priority monism*, which posits a single cosmic substance, but is incompatible with any form of *physical pluralism* that attributes irreducibly higher-level powers to entities of intermediate scales. We consider a number of case studies in contemporary physics which fail to support the thesis of state monism. We argue that the causal powers of many systems are (determined by) higher-level, macroscopic properties that are neither reducible nor weakly emergent, and that contemporary physics is compatible with some kind of pluralism that affirms that these entities are robustly real. A pluralist ontology is likely to have implications for discussions of free will and agency.

Keywords Scientific pluralism · Quantum mechanics · Causal powers

2.1 Introduction

In contemporary metaphysics, macroscopic objects are not ordinarily counted among nature’s building blocks, particularly among philosophers who are seeking to put forward a scientifically respectable account of nature’s fundamental ontology.

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C. J. Austin et al. (eds.), *Powers, Time and Free Will*, Synthese Library 451,
https://doi.org/10.1007/978-3-030-92486-7_2

Although various forms of scientific pluralism are being actively explored by philosophers of science (Chang, 2017), it is more common for metaphysicians to endorse microphysicalism, in which the fundamental constituents are very small (such as particles), or even to adopt priority monism (Schaffer, 2010), in which there is only one fundamental entity (namely, the cosmos). In contrast, pluralist perspectives of nature that admit fundamental objects at different scales are typically taken to involve some form of 'folk mereology' that lacks scientific respectability (Rose & Schaffer, 2017), since they fail to accord with what we have good reason to believe about nature on account of the success of our 'best physics'.

In this paper, we are concerned with removing this impediment to the construction of pluralist accounts. An example of such an account is Inman's (2017) recent proposal for a 'neo-Aristotelian' mereology that admits 'ordinary, macroscopic composite objects' (ibid, p.4) within its fundamental ontology. Our concern is not to establish any particular ontology of nature, however, but to argue that there is reason to think quantum physics admits an ontological reading that is compatible with some kind of physical pluralism, in which there are fundamental objects that exist between the microscopic and the cosmic scale.

A good reason for adopting some kind of physical pluralism is the existence of macroscopic objects with top-down causal powers. Such objects have 'higher-level' physical properties that make a causal difference to the temporal development of their lower-level physical properties. Conversely, a good reason to reject physical pluralism is the supposed reducibility of any higher-level powers to (or their weak emergence from) some lower-level substrate described by our best physical theory, whose physical content is (supposedly) the set of worlds possible according to its laws. We argue that neither microphysicalism nor priority monism should be regarded as more scientifically respectable than physical pluralism, however, because there is good reason to think that physics is compatible with a form of strong emergence that admits irreducible, higher-level causal powers. Our paper is divided as follows.

In Sect. 2.2, we claim that microphysicalists and priority monists presuppose the truth of *physical state monism*. This is the assumption that the causal powers of a system which bring about change supervene upon the lower-level state of the cosmos and the lower-level laws that govern this state. In Sect. 2.3, we discuss the role played by higher-level, macroscopic boundary conditions in physics in determining the physical content of a theory, in addition to any lower-level laws, observing that the reduction of the higher-level to the lower-level never goes all the way in practice. In Sect. 2.4, we consider the role of different representations in fulfilling the explanatory virtues of quantum physics, observing that our best physical theories fail to disclose a unique microphysical structure which evolves according to one set of lower-level laws.

In Sect. 2.5, we discuss three physics-based arguments against pluralism: first, Schaffer's argument from quantum entanglement, which claims the whole of nature is reducible to a single substance; secondly, the Quantum Darwinist's argument for the weak emergence of the classical world from a purely quantum substrate, which appeals to the process of decoherence; thirdly, the argument from the causal closure of the microphysical world, which claims that strong emergence demands the existence of 'spooky' forces. We show how each of these arguments begs the question against physical pluralism. In Sect. 2.6, we offer some concluding remarks on the prospects of physical pluralism.

2.2 Bricks Without Straw

2.2.1 Microphysicalism and Priority Monism

Microphysicalism remains a popular position among analytic philosophers. Hüttemann (2015) distinguishes three forms that it may take: micro-determination, micro-government and micro-causation. According to micro-determinists, 'the behaviour or the properties of compound systems are determined by the behaviour or the properties of their constituents and the relations among them but not vice versa' (ibid., p. 7). For philosophers who uphold micro-government, 'the laws of the micro-level govern the systems on the macro-levels' (ibid.). Among those who are micro-causalists, it is claimed that 'all causation takes place in virtue of the causation on the level of the (ultimate) parts – or the micro-level. Macro-causation, on this view, is entirely derivative and piggybacks on the causation of the microconstituents' (ibid., pp. 7–8).

Microphysicalism exerted a powerful influence over the philosophy of science of the last century. In Oppenheim and Putnam's (1958) influential paper, "The Unity of Science as a Working Hypothesis", nature is conceived as a hierarchy in which cells are composed of molecules, molecules of atoms, and atoms of whatever microscopic constituents are identified by physics at the 'unique lower level' (ibid., p. 9), which have to be described solely in terms of the language of our best physics. Likewise, microphysicalism has proven a hard taskmaster in the philosophy of mind. Kim (1997) famously argued that mental properties must be reduced to microphysical properties if they are to be considered causally efficacious,[1] which raises doubts about free will given the alleged causal completeness of the lower-level physics. The background conception of nature that shapes these metaphysical theories about how the world is put together can be pictorially represented as a giant pyramid, in which everything rests upon a comprehensive lower-level of microscopic constituents.

It is perhaps not so controversial these days, even among card-carrying physicalists, to confess to having doubts about microphysicalism in the light of contemporary physics (Papineau, 2008). In his comments on Hüttemann's (2015) case against microphysicalism, Schaffer (2008, p. 256) identifies three reasons to think microphysicalism false: against micro-determinists, he notes that, 'the properties of subsystems are determined by the properties of systems and not vice versa', appealing to the 'argument from quantum entanglement'; against the concept of

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[1] As Kim (1984, p. 100) puts it, the world is as it is 'because the micro-world is the way it is'.

micro-government, he observes that ‘the laws of the macro-physical govern the microphysical systems’, appealing to the ‘argument from the universe being the only isolated system’ (ibid.); against micro-causation, he urges that ‘all causation takes place in virtue of the causation on the macro-physical level’, appealing to the ‘argument from macro-government plus cause-law connection’ (ibid.).

As Schaffer points out, however, these arguments against microphysicalism do not uniquely favour the kind of physical pluralism that Hüttemann espouses, in which physical systems of all scales are regarded as interdependent equals. They also count as evidence in favour of priority monism, in which the *only* fundamental thing in existence is the cosmos, and everything else is grounded in the cosmic whole (Schaffer, 2010). The picture of nature, in this case, is of an inverted pyramid, in which everything rests on a single point.

Yet there is another reason for favouring some kind of physical pluralism over priority monism: namely, the existence of systems of an intermediate scale, between the microscopic and the cosmic, that possess higher-level causal powers. According to the physicist George Ellis, such higher-level powers act ‘top-down’ on the lower-level properties of their environments, and are not reducible to (nor weakly emerge from) a system’s lower-level powers (Bishop & Ellis, 2020). However, microphysicalism and priority monism are themselves manifestations of a more entrenched orthodoxy concerning the relation between physics and metaphysics that characterises contemporary philosophy, which rules *a priori* against the existence of macroscopic entities with higher-level causal powers. To put the point more accusingly: the orthodox way of interpreting physical theories among philosophers seems to be rigged in favour of reductionism.

2.2.2 Physical State Monism

It is widely supposed among analytic philosophers that to offer a metaphysical interpretation of a physical theory is to identify the set of worlds that are possible according to that theory. On this view, a possible world is a complete and internally consistent possible state of affairs, and a physical theory contributes to our knowledge of nature by declaring some of these states permissible whilst excluding others. It is also widely supposed that the laws specified by a physical theory determine the set of possible worlds that it permits: they are those complete states of affairs that are consistent with its laws.

For many philosophers, the task of interpreting a physical theory, such as quantum mechanics, is a matter of fixing upon some set of lower-level constituents and picking out their possible arrangements according to its lower-level laws (Dorr, 2011, p. 139).[2] The basic lower-level constituents described by our ‘best physics’ may be conceived as a set of microscopic entities or as modifications of one

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[2] Button (2013, p. 12) has described this recipe as ‘orthodoxy for post-Quinean metaphysics’.

underlying cosmic substance. Either way, the total set of possible arrangements of the world's lower-level constituents determines the *state space* within which the state of the cosmos evolves. Having identified these basic constituents, propositions about the world may be evaluated as true or false just in case they can be understood as referring to their possible arrangements. On this view, 'everything that is physically possible must be possible in the same way' (Ruetsche, 2011, p. 3). Ruetsche (2011) calls this the *unimodal* conception of physical possibility, which is embodied in the standard conception of physical content:

> *Unimodal physical content*
>
> The physical content of some theory T is determined by the set of physically possible worlds W in which the laws of T are true.

The notion of laws, in this case, is to be understood in the narrow sense of the lower-level laws specified by some physical theory T, rather than the broad sense of laws that govern physical entities in general. Likewise, the notion of possibility is to be understood in the narrow sense of what is possible regarding the arrangements of the lower-level constituents to which T refers, rather than the broad sense of what is considered to be possible in nature. This characterisation is narrowly concerned with the *causal closure* of the lower-level constituents of a system within the state space in which they evolve.

The unimodal conception of physical content is affirmed by microphysicalists, who favour the ontological priority of the microscopic, and priority monists, who believe microscopic reality is grounded in the cosmos as a whole. Microphysicalists and priority monists are divided concerning the number of fundamental entities, but united in excluding from the fundamental ontology any entities that exist between the microscopic or the cosmic scale. In their hierarchical picture of physics, higher levels are supposed to be related to lower levels in such a way that the physical content of a higher level-theory can be derived from the physical content of a lower-level theory (Leggett, 1992).

Such a claim has been supported by appealing to some version of Nagel's (1961, pp. 353-354) account of how this reduction is supposed to take place, in which higher-level and more specialised theories are reduced to lower-level and more comprehensive theories by *deducing* the higher-level laws from the lower-level laws (plus boundary conditions). Whilst the Nagel-Schaffner model is not without critics, it has been staunchly defended as offering the best account of a successful reduction, and it qualifies Nagel's original account in a number of helpful and significant ways.[3] Consider the following two theories: T_f, is some candidate fundamental theory, such as our 'best physics', and T_t is a more specialised theory targeted for reduction. According to this model:

> *Nagelian-Schaffner reduction*
>
> T_t is reduced by T_f just in case the laws of T_t^* are derivable from the laws of T_f^*, and the terms of T_t^* are associated via bridge laws with terms of T_f^*,

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[3] For a recent exposition and defence, see Dizadji-Bahmani et al. (2010).

where (a) T_t^* is an analogous (or approximate) version of T_t, and (b) T_f^* is derivable from T_f by means of auxiliary assumptions. The Nagel-Schaffner model recognises that exact derivability is an unrealistic requirement: it suffices that the laws deduced from the fundamental theory should be analogous to, or approximate, the laws of the targeted theory. Likewise, the auxiliary assumptions required to derive T_f^* from T_f are typically taken to be idealisations and boundary conditions that have no ultimate significance concerning what is possible according to the reducing theory. Having obtained T_t^* as an analogous version of T_t, and T_f^* from T_f by appropriate idealisations and boundary conditions, they can be connected by bridge laws. The bridge laws that enable the derivation of T_t^* from T_f^* constitute rules of translation which connect the vocabulary of T_t^* to that of T_f^*. For Schaffner, a bridge law can be characterised as a 'reduction function', which offers a statement to the effect that some term w_e of T_t^* is coextensional with some term w_f of T_f^*, and specifies the functional relationship between the magnitudes of the terms.

We shall classify philosophers who adopt a hierarchical conception of physics, in which the physical content of higher-level theories is derivable from lower-level theories, as *physical state monists*, whether they are microphysicalists or priority monists. Physical state monism can be distinguished from the kind of physical pluralism whose scientific respectability we wish to defend by the way in which it determines the causal powers of a physical system:

> *Physical state monism*
> Let S be a physical system (smaller than the whole cosmos), with boundary conditions B delineating S from its environment.
>
> 1. The causal powers of S to change its physical properties supervene upon lower-level laws and the boundary conditions B.
> 2. The lower-level laws govern the lower-level state of the cosmos, and the boundary conditions B supervene upon this lower-level cosmic state.

We shall understand B to include the initial conditions of S. To accommodate the possibility of indeterminism, we may consider the powers of S to be *probabilistic powers* to bring about changes in the lower-properties of its components, which are weighted by a certain probability. Both a microphysicalist and a priority monist can affirm 1 and 2, although they conceive the lower-level differently. Both regard the higher-level properties of macroscopic objects as supervening upon lower-level properties. State monism entails the following:

> *Physical state monism: corollary*
> The higher-level properties of a physical system have no irreducible causal powers to change the lower-level physical properties of a physical system.

Our aim in this paper is to raise doubts about this claim. In doing so, we mean to call into question the wide-spread assumption that contemporary physics straightforwardly supports physical state monism, in which the world is pictured hierarchically as a pyramid (or an inverted pyramid) that rests upon a lower-level that is composed of one or more entities that exist at the same physical scale, over some more egalitarian form of physical pluralism, in which the world contains fundamental entities at different physical scales that exercise higher-level causal powers. We think the evidence from physics can be parsed in a pluralistic way that is scientifically respectable, and that philosophers should feel free to adopt a pluralistic approach to physics in constructing their metaphysical models of nature. We will begin by considering how higher-level, macroscopic properties are invoked by physicists in practice.

2.3 The Role of Boundary Conditions in Physics

We live in a world in which macroscopic entities seem to play a role in settling how nature unfolds. Animals, for example, have causal powers to engage freely in a variety of different activities, such as nutrition and locomotion, which do not seem to be explicable without appealing to their inherent agency (Steward, 2012). According to physical state monism, however, the whole course of nature is settled by the lower-level state of the cosmos and the laws that govern the temporal development of this physical state. Yet what reasons might one have for thinking that physical state monism is true or scientifically respectable? One might try to support such a position on the historical premise that progress in physics involves the stripping away of macroscopic quantities, with physical state monism occupying the triumphant limit of this march; a position whose scientific respectability is *justified by inductive reasoning*. We shall argue that this 'historical' premise, however, is difficult to square with scientific practice.

2.3.1 A Question of Scale

In physics, it is commonplace to use microscopic phenomenological quantities that are experimentally measured, such as mass, charge, or spin, whose values are not themselves determined by the physical theory, in defining the physical state of a system. These are often assumed to come from a more fundamental and comprehensive theory of the physical world that we do not yet know. An example of this practice can be found in quantum electrodynamics. In this theory, the electric charge is 'renormalized' (Hollowood, 2013), where the experimentally measured value of the charge is understood to be the result of an infinite series of interactions between charge and field, which in turn rescales the measured strength of the charge compared to its 'bare' value. Summing this series of interactions predicts an infinite rescaling, revealing an incompleteness in our understanding of electric charge. It is hoped by some physicists that a microscopic theory such as string theory will one day eliminate this problem, providing some kind of fundamental basis for the number we call 'charge' (Wen & Witten, 1985).

Yet there are also many cases where physical theories contain *macroscopic* phenomenological quantities. These are also not determined by the theory, but by contrast, depend upon large scale properties of the physical system. The ubiquity of such quantities in physical models has to be squared with the hierarchical view of physics as a tower with different levels of description that sequentially ‘zoom in’ on some fundamental level of reality. In the hierarchical view, each lower level replaces the parochial and phenomenological description of the level above with an improved and more comprehensive lower-level description. One day, it is presumed, we will reach the ground floor and possess the language of Nature. There is a complication, however, in the way in which laws are applied to explain phenomena in practice: physicists typically use theories that contains quantities from levels ‘above’ whatever happens to be the level of interest, not merely from ‘below’ the level of interest. Such mixed-level approaches to scientific explanation occur in physical descriptions of

(i) *the boundary conditions of a system*. Most physical theories are written in terms of differential equations, but a physical model of a system only offers testable predictions once boundary conditions for these equations have been specified. Yet these boundary conditions often have a higher-level, *macroscopic* origin. A simple example is a quantum particle incident onto a reflecting barrier (see Sect. 2.3.2). According to microphysicalists, the barrier is made of many microscopic constituents. The physical theory, however, instead of adopting a many-particle description of the barrier, deploys a single number that represents a macroscopic property of the multitude of particles (Harrison & Valavanis, 2016).

(ii) *systems in, or close to, thermodynamic equilibrium*. Take a small collection of particles (positions $\mathbf{x}_n \in \mathcal{P}$) in equilibrium with a much larger system $\mathcal{S}$ ($\mathcal{P} \subset \mathcal{S}$) (see Sect. 2.4.3). The coarsest level of description would use classical thermodynamics, treating the whole system $\mathcal{S}$ using only the macroscopic variables of volume V and temperature T. To describe the particles in $\mathcal{P}$, however, we require the theory of open quantum systems (Breuer & Petruccione, 2007), which is several levels of description more detailed than classical thermodynamics. A naïve supporter of the hierarchical view of physics might expect macroscopic variables such as temperature simply to be eliminated in such a quantum description. However, to capture the interaction between the particles $\mathcal{P}$ and the rest of the system it is essential to retain the temperature variable (ibid.), which must be experimentally measured at the macroscopic level.

(iii) *multi scale phenomena.* The theory of Quantum Optics, for example, describes the behaviour of individual quanta of light (photons) inside transparent materials such as glass (Loudon, 2000). In this theory, light is treated microscopically and fully quantum mechanically, but the material enters the theory through the value of the refractive index, *not* as the collection of atoms making up the glass. This description arises due to a separation of scales: the wavelength of photons in the material is much larger than the size of an atom. Since the hierarchical reading of physics suggests that quantum mechanics is a ‘zoomed in’ account of reality, concerned with atomic scale phenomena, one might therefore expect macroscopic quantities such as the optical refractive index – a property of solid objects made up of many billions of atoms – to disappear from the representation. However, this is not how quantum mechanics works in practice. Let us consider a couple of more detailed examples to illustrate how common such mixed scale quantities are in physics.

2.3.2 Quantum Mechanics of a Particle in a Box

The case of the ‘particle in a box’ is an elementary problem in basic quantum mechanics (Griffiths & Schroeter, 2018). This problem concerns a microscopic point particle, such as an electron, that can move in only one direction, x. It is represented as a wavefunction $\psi(x)$, the square magnitude of which tells us the probability of finding it at the point x. The wavefunction obeys the differential equation,

$$-\frac{\hbar^2}{2m}\frac{d^2\psi(x)}{dx^2} = E\psi(x), \tag{2.1}$$

which is the time-independent Schrödinger equation. Here $\hbar$ is the reduced Planck’s constant, m is the particle mass, and E is the particle energy. These quantities are concerned with either the microscopic properties of the electron (m and E), or the quantum scale ($\hbar$). At first sight it seems we are dealing with a microscopic theory of a point particle; the energy, mass, and reduced Planck’s constant may be phenomenological quantities, but if they are, they arise from a more ‘zoomed in’ theory of the electron.

The problem is to find the allowed wave functions $\psi(x)$ and energies E of the particle. Significantly, Eq. (2.1) has no physical content, on its own. There are an infinite number of solutions: propagating waves (positive energy)

$$E > 0: \qquad \psi(x) = \exp\left(\pm i\frac{\sqrt{2mE}}{\hbar}x\right), \tag{2.2}$$

and exponentially diverging solutions (negative energy)

$$E < 0: \qquad \psi(x) = \exp\left(\pm\frac{\sqrt{2m|E|}}{\hbar}x\right), \tag{2.3}$$

neither of which can be normalized so that all probabilities sum to unity. Eq. (2.1) only tells us that a system has energy and a wavefunction that either oscillates or diverges as $|x| \to \infty$. To obtain any predictions, we must specify *boundary conditions*, in addition to the differential Eq. (2.1). These boundary conditions are an essential part of the theory. Suppose we now assume the boundary conditions of a particle confined in a box of size L, by setting the wave function to zero everywhere outside the region between $x = 0$ and $x = L$:

$$\psi(x < 0) = 0, \qquad \psi(x > L) = 0, \tag{2.4}$$

In this example, it is known with certainty that the particle is somewhere between $x = 0$ and L. Imposing the boundary condition (2.4) restricts the energy to be both positive, and quantized: $E = n^2\pi^2\hbar^2/2mL^2$ (n is an integer), and constrains the wavefunction to be of the form

$$\psi(x) = \sqrt{\frac{2}{L}}\sin\left(\frac{n\pi x}{L}\right), \tag{2.5}$$

which is now normalized so that all probabilities add to unity $\int_0^L |\psi(x)|^2 dx = 1$. It is only now that we are in a position to make any predictions that concern actual experiments: the quantized energy levels tell us the possible energies (frequencies) of light that can be emitted when the particle makes a transition between energy states, and the wave functions (2.5) tells us where the particle is likely to be found if the system is experimentally probed.

The boundary conditions (2.4), however, are a proxy for an interaction between the microscopic particle and another macroscopic system. This other system is not treated using a lower-level theory like quantum mechanics, which is evident from the absence of any probabilistic aspect to Eq. (2.4). A reasonable approximation to the boundary conditions (2.4) could be realised by applying a spatially varying electric field to an electron (zero field between $x = 0$ and L, rapidly increasing to a very large value at the edges). But this electric field would have to be produced by a large number of charges for it to be treated as a classical (non-probabilistic) charge density distribution, and thus give rise to these definite boundary conditions (2.4). Moreover, it is doubtful whether there is a self-consistently quantum mechanical way of explaining how classical properties emerge from a purely quantum substrate (see Sect. 2.5.2).

From a naïve perspective, it may seem obvious that the time-independent Schrödinger Eq. (2.1) represents a microscopic theory of small objects, which does not depend upon any quantities from higher-level, macroscopic physics. However, in order to use Eq. (2.1) in any scientific practice that makes predictions we have to supplement it with additional boundary conditions, and in even the simplest of quantum systems these boundary conditions are specified by *macroscopic*, classical variables. It is far from obvious that these classical properties are governed by the unitary Schrödinger equation (Drossel, 2017, 2020).

2.3.3 The Arrow of Time in Electromagnetism

Let us consider another example from physics where macroscopic boundary conditions are essential to the physical content of a model. This example concerns the problem of the arrow of time in electromagnetism. Maxwell's equations are perhaps the most successful set of laws in physics. They govern the behaviour of the electric **E** and magnetic **B** fields in space and time. These fields are produced by distributions of electric charge density ρ, or current density $\mathbf{j}$. In the case of an oscillating current $\mathbf{j}_\omega$ (oscillating at frequency ω radians per second), the electric field is governed by the differential equation

$$\nabla \times \nabla \times \mathbf{E} - k_0^2 \mathbf{E} = i\omega\mu_0 \mathbf{j}_\omega, \tag{2.6}$$

where $i = \sqrt{-1}$, $k_0 = \omega/c$, μ_0 is the permeability of free space, and c is the speed of light. Equation (2.6) governs the emission and reception of electromagnetic waves of a fixed frequency; be that radio wave reception, or the emission of light from an atom. Suppose someone with mathematical ability, but no knowledge of physics, attempts to solve this equation. They will find that the field produced by the current can be written as the following set of integrals:

$$\boldsymbol{E}(\boldsymbol{x}) = \frac{\mu_0 c^2}{i\omega} \int_{\mathbb{R}^3} d^3\boldsymbol{x}' \int_{\mathbb{R}^3} \frac{d^3\boldsymbol{k}}{(2\pi)^3} \frac{k_0^2 \boldsymbol{j}_\omega(\boldsymbol{x}') - \boldsymbol{k}(\boldsymbol{k} \cdot \boldsymbol{j}_\omega(\boldsymbol{x}'))}{k_0^2 - \boldsymbol{k}^2} e^{i\boldsymbol{k}\cdot(\boldsymbol{x}-\boldsymbol{x}')}. \tag{2.7}$$

Although this formula appears to be a precise, analytic equation for the electric field, it fails to determine *any* quantity for the field at *any* position $\mathbf{x}$. In the denominator of the second integral, which ranges over all possible real values of the vector $\mathbf{k}$, there is a division by the quantity $k_0^2 - \mathbf{k}^2$, and since somewhere in the integral $k_0^2 - \mathbf{k}^2 = 0$, formula (2.7) thus involves division by zero. This renders the whole expression *indeterminate*. The resolution of this problem is the same as in Sect. 2.3.2. Equation (2.6) is not enough for the theory to have physical content; we must impose boundary conditions (Jackson, 1998). To do this, we can make the following replacement in the denominator of Eq. (2.7):

$$\begin{aligned}\left(k_0^2 - \mathbf{k}^2\right) &= (k_0 - |\mathbf{k}|)(k_0 + |\mathbf{k}|) \\ &\to (k_0 - |\mathbf{k}| + i\eta_1)(k_0 + |\mathbf{k}| + i\eta_2),\end{aligned} \tag{2.8}$$

where η_1 and η_2 are infinitely small real numbers that are taken to zero at the end of the calculation, thus recovering a solution to Eq. (2.6). With this modification we no longer end up dividing by zero when we evaluate (2.7). In principle these real numbers $\eta_{1,2}$ could be different, but to simplify the discusson we assume that $\eta_1 = \eta_2 = \eta$.

The number η serves to specify the behaviour of the field at infinite distances, which in turn also specifies *the arrow of time*. It picks out one of several possible solutions to (2.6). For instance, if $\eta > 0$ then (2.7) predicts that the oscillating current density $\mathbf{j}_\omega$ produces electromagnetic waves which travel *outwards* from the source to infinity. This is the behaviour of nature with which we are familiar. Meanwhile, if $\eta < 0$ then the time reverse of this behaviour is predicted, in which every source of waves becomes a sink. In this unfamiliar picture of nature, electromagnetic waves are continually arriving from infinity to focus onto electric currents and disappear (Weinstein, 2011). In such a world, mobile phone would receive calls from infinity, which would be transformed into the sound of your voice and absorbed by your vocal chords.

A model that deploys the laws of electromagnetism is thus incomplete without the specification of a boundary condition. This boundary condition sets the arrow of time, which is observed to be such that the universe as a whole is evolving towards an ever more probable configuration. Just as a gas spreads out to fill a box rather than localising to one region of it, the electromagnetic field spreads out to fill space rather than concentrating in particular regions. This is the thermodynamic arrow of time, which accords with our observation of entropy increasing with time. The origin of this boundary condition remains unclear (see discussion in Earman, 2011a) and at present has no agreed derivation from a microscopic theory. What is evident is that the boundary condition is essential to the theory of electromagnetism (quantum or otherwise), whilst representing macroscopic behaviour described by classical thermodynamics. We are again using *macroscopic* parameters to constrain a microscopic theory of physics. The naïve induction argument for state monism proceeds upon a false premise.

2.4 The Role of Representations in Physics

The more sophisticated apologist for physical state monism may downplay the role of higher-level properties in specifying boundary conditions because they believe the physical state of a system, however large, can be *uniquely represented* by our best theory of the properties of matter (quantum physics), and that the complete physical content of this theory concerning some parochial system $\mathcal{P}$ can be derived in principle from its representation of a larger system that includes it $\mathcal{S}$ ($\mathcal{P} \subset \mathcal{S}$). According to this argument, the need for boundary conditions in defining the physical state of a system is just a practical concern that has no bearing upon the interpretation of a theory in terms of a set of possible worlds, since the set of possible worlds for the smaller subsystem $\mathcal{P}$ is merely a subset of the set of possible worlds for the larger system $\mathcal{S}$. From this perspective, the macroscopic boundary conditions for the particle in a box could be replaced in principle with a theory of a many-particle system that includes the walls of the box (Fetter & Walecka, 2003). Of course, this more inclusive physical model would also require boundary conditions, but we can reiterate this process in principle until we arrive at the state of the entire cosmos and the complete set of physically possible worlds. This uniqueness premise, however, is also difficult to square with scientific practice, as we shall now explain (Glick, 2016).

2.4.1 A Question of Context

At the heart of any quantum theory are the canonical commutation relations between conjugate quantities such as position and momentum – or the anti-commutation relations which hold between the Pauli spin matrices – which encode the Heisenberg uncertainty principle. Any quantum theory which specifies a quantum state defined in a Hilbert space, and a set of bounded self-adjoint operators corresponding to observables $\left(\mathcal{H}, \widehat{O}_i\right)$ must realise the Weyl algebra associated with these relations. When the operators on a Hilbert space conform to these commutation relations, they are said to be a Hilbert-space representation (or 'representation', for short) of these quantum relations.

Suppose we believe that a physical theory delineates what is possible for a system to which it is applied, and agree that the possibilities for a quantum system are given by an expectation value assignment to its set of observables. Unitary equivalence is widely considered the standard of physical equivalence for representations of the commutation relations: if two representations are unitarily equivalent, there is some unitary operator $\widehat{U}$ that transforms one representation into the other $U : \mathcal{H} \rightarrow \mathcal{H}'$, such that both representations determine the same expectation values for the various observables which they define $U^{-1}\widehat{O}_i{}'U = \widehat{O}_i$. However, both quantum field theory and quantum statistical mechanics (in its thermodynamic limit) generate a continuum of unitarily inequivalent representations (Ruetsche, 2002, 2003, 2006, 2013).

The cause of this plurality of inequivalent representations is the necessity of using quantum models which have infinite degrees of freedom in order to describe many kinds of phenomena. Finite quantum systems admit only one concrete irreducible Hilbert-space representation. The *Stone-von Neumann Theorem* establishes that any pairs of distinct representations will be unitarily equivalent to the irreducible Schrödinger representation, since there is a unitary operator that transforms one into the other. Infinite quantum systems, however, admit infinitely many concrete Hilbert-space representations that fall outside of the scope of the Stone-von Neumann theorem (Ruetsche, 2011, chs. 2–3). The use of unitarily inequivalent representations is manifest in physical descriptions of:

(i) *relativistic effects in quantum field theory*. A non-interacting quantum field can be described in terms of a Fock space in which creation and annihilation operators are defined, which attributes different numbers of 'quanta' (or, different levels of 'excitation') to the various possible states of the quantum field. In the vacuum state of a quantum field, no quanta have been created. The Unruh Effect, however, predicts that an observer who is accelerating uniformly within a quantum field in the vacuum state of the Fock space associated with unaccelerated motion, would observe a thermal bath of Rindler quanta instead of a vacuum state (Earman, 2011b). The two representations of the quantum field that feature in this physically significant prediction are unitarily inequivalent. Likewise, unitarily inequivalent representations are also implicated in descriptions of interacting quantum fields and the interpretation of scattering theory (Earman & Fraser, 2006).

(ii) *symmetry breaking, and systems close to a critical point*. Quantum statistical mechanics provides a quantum mechanical underpinning for bulk properties associated with macroscopic physical systems, such as their temperature, pressure, and entropy. In the thermodynamic limit, a system with N particles and volume V is replaced by one in which the parameters N and V are taken to infinity, whilst the density N/V is kept constant. This procedure furnishes a model in which thermodynamic quantities, such as pressure and energy, can be represented as closed functions of thermodynamic variables, such as temperature and density, by treating the matter of the system as a continuum which has infinite degrees of freedom. Quantum theories that describe cases of spontaneous symmetry breaking and phase transitions in thermodynamic systems, however, deploy physically significant operators that are defined within unitarily inequivalent representations (see Sect. 2.4.2) (Ruetsche, 2011).

(iii) *systems in, or close to, thermodynamic equilibrium*. Consider two macroscopic systems which are in thermodynamic equilibrium with one another. Such materials both radiate and absorb electromagnetic energy, and can experience attractive (or repulsive) forces that are mediated by quantum fluctuations in the electromagnetic field (see Sect. 2.4.3). In order to represent the phenomenon of absorption within the theory of quantum electrodynamics, which occurs in any realistic physical system, a heat sink must be incorporated with uncountably many more degrees of freedom than the electromagnetic field (Philbin, 2010; Horsley & Philbin, 2014). Such systems do not admit a unique representation of the ground state of the electromagnetic field, and incorporate classical properties which have top-down causal powers: the temperature of the system, for example, affects both the amplitude of the field and the magnitude of the microscopic currents in the media.

Let us consider two examples of quantum systems in more detail in which the choice of physical representation is context-dependent.

2.4.2 Representing Phase Transitions

When a material undergoes a phase transition, certain classical properties of the material undergo change – typically, discontinuous change – due to some macroscopic change in their immediate external conditions. For example, an iron bar that is at thermal equilibrium, above a critical temperature $T \geq T_c$, exhibits a paramagnetic phase, in which it experiences no net magnetization, and below this critical temperature exhibits a ferromagnetic phase, in which it experiences spontaneous magnetization. In the presence of an external magnetic field, the ferromagnet admits two possible metastable states which are characterised by opposite magnetic polarisations.[4]

The statistical physics of finite systems, however, identifies equilibrium states with unique Gibbs states (Ruetsche, 2011, p. 3), implying that the phase available to a system at temperature T is unique for all T. This is contrary to what we observe in experiments. As Ruetsche (ibid.) points out, it is 'only in the thermodynamic limit [that] can one introduce a notion of equilibrium that allows what the Gibbs notion of equilibrium for finite systems disallows: the multiplicity of equilibrium states at a finite temperature implicated in phase structure'.

We may think of the simple ferromagnet in our example as consisting of magnetic moments arranged in a 1d lattice; eg. atoms with spin 1/2. To build a quantum theory for this composite system, we begin by assigning an atom at location k in the lattice a Pauli spin, $\sigma^k = \left(\sigma_x^k, \sigma_y^k, \sigma_z^k\right)$, where k ranges from $-N$ to N, which satisfies the canonical anti-commutation relations:

$$\left[\sigma_x^k, \sigma_y^{k\prime}\right] = i\delta_{kk'}\sigma_z^k, \text{etc.} \quad \sigma^k \cdot \sigma^k = 3I. \tag{2.9}$$

This expression evaluates as zero for $k \neq k'$, as measurements of different sites commute with one another. One way to set up a Hilbert space for a system in the thermodynamic limit $N \to \infty$, without departing from the tradition of using separable Hilbert spaces in quantum mechanics, is to begin with a ground state characterised by a sequence $s_k = +1$ for $k \in \mathbb{Z}$, then add all the sequences that can be obtained by making finitely many local modifications to this sequence which replace some of the entries with -1. Let us label this Hilbert space $\mathcal{H}^+$. A set of operators $\widehat{\sigma}_z^j$ may then be introduced such that sequences s_k whose j th entry is ± 1 correspond to the eigenvector in the Hilbert space associated with the eigenvalue ± 1. A magnetic polarisation observable for the composite system $\widehat{\mathbf{m}}$ can be defined with the components:

$$\widehat{m}_i^N = \frac{1}{2N+1} \sum_{k=-N}^{k=N} \widehat{\sigma}_i^k, \quad i \in \{x, y, z\}, \tag{2.10}$$

which has a limit $N \to \infty$ in the weak topology of $\mathcal{H}^+$, and is thus an element of the observable algebra of $\mathcal{H}^+$. Let $[s_k]_j \in \{-1, +1\}$ denote the j th entry in the sequence s_k. The expectation value of $\widehat{m}_z^N$, in the basis sequence s_k, is:

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[4] We mostly follow Ruetsche's (2003, 2006, 2013) philosophical discussion, but Schwabl's (2006) physics.

$$\frac{1}{2N+1}\sum_{k=-N}^{k=N}[s_k]_j. \tag{2.11}$$

For every state, the expectation value of $\widehat{\mathbf{m}}$ will be oriented along the z axis and will take the value of +1 in the thermodynamic limit, breaking the rotational symmetry of the system's dynamics, since only a finite number of spins take the value -1. But what about states that break this symmetry in the opposite direction? For these cases, we begin with a ground state characterised by a sequence $s_k = -1$ for $k \in \mathbb{Z}$, adding all the sequences that can be obtained by making finitely many local modifications which replace some of the entries with +1. Let us label this alternative Hilbert space $\mathcal{H}^-$. It is obvious that our two representations of the ground state of the ferromagnet are inequivalent.

The proof may proceed by contradiction. Suppose there is some unitary transformation, $U : \mathcal{H}^+ \rightarrow \mathcal{H}^-$, such that $U\widehat{\sigma}_n^+U^{-1} = \widehat{\sigma}_n^-$ for all n, which implies that $\widehat{m}^{N-} = U\widehat{m}^{N+}U^{-1}$, and suppose that $|\psi^+\rangle$ and $|\psi^-\rangle$ are unit vectors in the Hilbert spaces $\mathcal{H}^+$ and $\mathcal{H}^-$ respectively. Assuming that these two vectors are related by the transformation $|\psi^+\rangle = U \mid \psi^-\rangle$, it follows that

$$\langle\psi^+|m_z^{N+}|\psi^+\rangle = \langle\psi^-|m_z^{N-}|\psi^-\rangle. \tag{2.12}$$

However, this identity does not hold in the thermodynamic limit $N \rightarrow \infty$, since the right hand side evaluates as +1 and the lefthand side as -1. These representations are not physically equivalent, and Hamiltonians defined on these two models describe physically different dynamical situations. Nonetheless, both of these states are physically significant. In the 1d Ising model of ferromagnetism, the pairwise interactions between the different spin sites contribute to the total Hamiltonian (energy) of the system (Schwabl, 2006, pp. 287–307):

$$H = -J\sum_{k,k'}\sigma^k \cdot \sigma^{k'}, \tag{2.13}$$

where J is a positive real number that depends on the distance between the spins. This model can be extended to include an external magnetic field B, which is directed along the preferred axis of the uniaxial magnet:

$$H' = -J\sum_{k,k'}\sigma^k \cdot \sigma^{k'} - b\sum_{k}\sigma^k, \qquad b = \frac{1}{2}g\mu_B B, \tag{2.14}$$

where μ_B is the Bohr magneton, which expresses the magnetic moment of an electron caused by its spin, and g is a dimensionless factor. Such a system energetically favours states in which the spins are all aligned with the field. In the $\mathcal{H}^+$ representation, this is the ground state that corresponds to the sequence $s_k = +1$ for all k. Likewise, in the $\mathcal{H}^-$ representation, this is the ground state corresponding to

$s_k = -1$ for all k. Both the state in which the magnetic polarisation of the composite system is aligned in the positive direction +1, captured by the $\mathcal{H}^+$ representation, and the state in which it is aligned in the opposite direction -1, included in $\mathcal{H}^-$, are available to the system as metastable states below the critical temperature.

If the physical content of a theory is simply the set of possible worlds determined *en bloc* by its laws, then these two quantisations of the system constitute rival theories that contradict one another about what is physically possible. In practice, however, physicists frequently deploy inequivalent representations in their models of a system where the correct choice is *context-dependent*. It does not follow that they take seriously the infinite number of particles apparently introduced in the thermodynamic limit $N \to \infty$ (Ruetsche, 2003). Rather, it is the plurality of equilibrium states implicated in phase structure that matters. Significantly, in cases like these, we find ourselves relying upon *macroscopic* properties to determine the appropriate representation $(\mathcal{H}^+, \mathcal{H}^-)$.

2.4.3 Representing Chemical Forces

Let us now consider the case of the van der Waals force between two dipoles at positions r_1 and r_2, where each dipole is comprised of electrons in motion around a positive ion, and each has an overall neutral charge. The chemical bonds between molecules have sometimes been described as being nothing but a sum of van der Waals forces that is too large to compute in practice, but is explicable in principle in terms of a microscopic quantum field theory. This reductionist claim, however, glosses over some highly significant details. The Casimir-Polder expression for the energy of a dipole-dipole system, derived using normal-mode quantum electrodynamics, is of the form

$$U \propto \frac{\alpha_1 \alpha_2}{d^7}, \tag{2.15}$$

which depends upon the microscopic polarisabilities of the two dipoles, α_1 and α_2, that describe their linear response to the electromagnetic field, and upon the distance d between them (Casimir & Polder, 1948). It is sufficient for our purposes to note that this interaction energy can be derived using a quantum mechanical model of the system whose dynamics is characterised by a Hamiltonian function, and that it determines a mechanical force which arises from quantum fluctuations that occur within the system even at zero temperature. These fluctuations polarise the otherwise neutral dipoles and cause them to attract one another.[5]

However, standard text-book expressions of the van der Waals force, which are highly idealised, tacitly depend upon assumptions about the macroscopic

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[5] For an introduction to quantum fluctuation forces, see Simpson and Leonhardt (2015).

environment of the system, which are made explicit in models that make more realistic predictions. For example, the Casimir-Polder expression assumes the idealised geometry of free space, but a more general expression can be derived for an environment with an arbitrary geometry, from which the Casimir-Polder expression may be recovered as a limiting case. In reality, the electromagnetic field is not free but is scattered by materials comprising the surrounding environment. This scattering affects the micro-forces experienced at a given point in space, which determines the strength of the dipole-dipole interaction.

In addition to scattering the fields, the surrounding materials serve as a heat sink that absorbs the fields, and are characterised by thermal, macroscopic properties. As electromagnetic waves propagate through these materials, they displace electromagnetic charges, and in so doing, they induce electric currents in the materials. Significantly, the dispersive (scattering) properties of a material are directly related to its dissipative (absorbing) properties:[6] for macroscopic media they are typically modelled by complex-valued electric permittivity $\epsilon(\omega)$ and magnetic permeability $\mu(\omega)$ functions, in which the real part of the function quantifies the way the field is dispersed by the medium, and the imaginary part the rate at which it is absorbed.

Let's consider this absorption mechanism in a little more detail. It is convenient to build the quantum model for such a system by beginning with a classical Lagrangian density broken up into a sum of three parts:

$$\mathcal{L} = \mathcal{L}_F + \mathcal{L}_H + \mathcal{L}_I, \tag{2.16}$$

where $\mathcal{L}_F$ is a contribution due to the electromagnetic field, $\mathcal{L}_H$ is a contribution due to the surrounding materials, and $\mathcal{L}_I$ accounts for the interaction between the matter and the fields. The part due to the field is the same as in empty space. In order to represent the phenomenon of absorption within the theory of quantum electrodynamics, physicists have modelled the heat sink of the materials as an infinite continuum of oscillators (see Philbin, 2010, then Horsley & Philbin, 2014). For a one-dimensional system:

$$\mathcal{L}_H = \frac{1}{2}\int_0^\infty \left[\left(\frac{\partial X_\omega(x,t)}{\partial t}\right)^2 - \omega^2 X_\omega^2(x,t)\right] d\omega. \tag{2.17}$$

This is a system with uncountably many more degrees of freedom than the field: at each point in space there is a continuum of oscillators of amplitude X_ω. Even after the quantised field has been 'renormalised' to remove the divergences familiar to conventional quantum field theory, the thermalised system retains infinitely many degrees of freedom. Nonetheless, the inclusion of every possible natural frequency of oscillation at each point in space (2.17) is necessary to reproduce the wave equation in an absorbing material. Each oscillator in the heat sink contributes an

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[6] The real and imaginary parts are connected by the Kramers-Kronig relations.

amount $\alpha(\omega)\widehat{X}_{\omega}$ to the total polarisation of the medium, where $\alpha(\omega)$ is a function that is related to the electric permittivity of the medium $\epsilon(\omega)$. For a system in which $\mu = 1$ and the electric field is E_z, the interaction of the medium and the field is given by Simpson and Leonhardt (2015, ch. 4):

$$\mathcal{L}_I = E_z \int_0^{\infty} \alpha(\omega) X_{\omega}(x, t) d\omega. \tag{2.18}$$

The equation of motion for the oscillators in the heat sink is:

$$\left[\frac{\partial^2}{\partial t} + \omega^2\right] X_{\omega} = \alpha(\omega) E_z, \quad \alpha(\omega) = \sqrt{\frac{2\omega\epsilon_0 \mathrm{Im}[\epsilon(\omega)]}{\pi}}. \tag{2.19}$$

This results in a current in the medium:

$$J_z = \frac{\partial}{\partial t} \int_0^{\infty} \alpha(\omega) X_{\omega} d\omega. \tag{2.20}$$

Energy does not flow out of the electromagnetic field and into the materials without coming back again. In fact, the materials heat up due to the current generated by the field, then radiate the energy they have absorbed, thus contributing to the surrounding field. In this environment, the quantum energy levels of the microscopic molecules comprising the dipole-dipole system are thus permanently 'dressed' by the thermalised electromagnetic field, due to their interaction with their immediate environment. In the general theory, the assumption of thermodynamic equilibrium is made explicit, in which the temperature of the total system is introduced as a 'classical' variable that affects both the amplitude of the fields and currents.

Even for the case of fluctuation-induced forces at *zero temperature*, however, such as the van der Waals force between two dipoles in a vacuum, which can be recovered from the general theory as a limiting case, the ground state of the total system remains one in which the thermal properties of the materials and the electromagnetic properties of the fields are inextricably coupled. The ground state of the thermalised field in the general description is *not* the ground state of the free field, but belongs to a unitarily inequivalent representation. Fundamentally, it is the ground state of a polariton field, in which the thermalised matter and the electromagnetic fields are mixed (Simpson, 2014, 2015).

It would be question-begging, then, to infer the reduction of thermalised chemical systems to aggregates of microscopic physical constituents by appealing to the reducibility of intermolecular forces to quantum fluctuation forces, when our best description of any of the forces that we can measure is one in which macroscopic features of the system are already implicated. To accomplish such a reduction, we would have to demonstrate how to remove these background features, by showing that higher-level properties like temperature can be consistently represented within a quantum mechanical model that admits a unique microphysical representation, which applies to physical systems whether or not they are in thermodynamic equilibrium.

2.5 Saving the Macroscopic

According to physical state monists, the content of a physical theory is simply the set of worlds that are possible according to that theory's laws, whilst our best physical theory is typically taken to describe some fundamental set of lower-level constituents which compose the whole cosmos. Since the arrangements of these lower-level constituents are determined solely by lower-level laws, the causal powers of any physical system to change its physical properties, however large or small, are supposed to supervene upon the lower-level laws and the lower-level state of the cosmos, as described by our best physics.

We have considered a number of case studies in contemporary physics, however, in which *macroscopic properties* are seen to play an essential role in specifying the boundary conditions of a system and in characterising its environment in a way that is relevant to determining a theory's physical content. Instead of progressively 'zooming in' upon some lower level of reality that admits a unique microphysical representation, physicists deploy physically inequivalent representations of a system's states and observables in order to capture a wide variety of phenomena in different *macroscopic contexts*.

This raises an important question for standard philosophical approaches to the interpretation of physics: if we cannot specify the physical content of a theory without invoking macroscopic properties of the system it describes, and if the dynamics that governs the micro-physics depends upon its macroscopic context, why should we be obliged to choose between microphysicalism or priority monism in carving up nature? We suggest that this lack of independence of the microscopic world from the macroscopic world, and this element of context-dependence, should encourage rather the development of *a* pluralistic parsing of physics, which admits the existence of fundamental entities at intermediate physical scales, and where the physical possibilities of nature are not determined *en bloc* by lower-level laws. In what follows, we consider three arguments against physical pluralism, each of which begs the question in what it sets out to prove. We argue that contemporary physics is compatible with a strong form of emergence that affirms the existence of higher-level properties and top-down causal powers.

2.5.1 Quantum Entanglement and Reductionism

A key part of the apologetic for priority monism in contemporary metaphysics, which claims that the whole of physical reality is reducible to modifications of a single cosmic substance, is the argument offered by Schaffer (2010, section 2.2) that appeals to the phenomenon of quantum entanglement. Since this claim is logically inconsistent with physical pluralism, such an argument counts as a reason for rejecting pluralism. It can be reconstructed as follows:

1. Quantum-entangled systems that evolve unitarily according to lower-level quantum mechanical laws are fundamental physical wholes.
2. The cosmos is a quantum-entangled system that evolves unitarily according to lower-level quantum mechanical laws.
3. Therefore, the cosmos is a fundamental physical whole.

An entangled system of particles is one in which the outcomes of measurements of the particles are correlated in such a way that the quantum state describing this system cannot be decomposed into the product of spatially separate states associated with each particle (Bell, 1964). The fact of their 'non-separability' offers a *prima facie* reason for considering the entangled system to form an irreducible whole. Let us accept the first premise, for the sake of argument.

Regarding the argument's second premise, Schaffer (2010, p. 52) claims that 'one gets initial entanglement from the assumption that the world begins in one explosion (the Big Bang) in which everything interacts. This initial entanglement is then preserved thereafter on the assumption that the world evolves via Schrödinger's equation'. In other words, to get from the fact that some particles are quantum entangled in some situations to the inference that *everything* is mutually entangled and comprises an irreducible whole, the cosmos must have a universal wave function defined in a single Hilbert space that evolves unitarily according to lower-level laws, and must therefore admit a single unique representation. Every higher-level system must be reducible to this lower-level system. The reduction relation, in this case, is cashed out in terms of *metaphysical grounding*. Schaffer admits macroscopic objects within his ontology, but such objects are not *fundamental*, being grounded in the cosmos as a whole. The conclusion of his argument is inconsistent with the kind of physical pluralism whose scientific respectability we are seeking to defend.

But why should we suppose the physical cosmos to be reducible to a single quantum-entangled system? Presumably, because any higher-level theory's laws are said to be reducible to a lower-level theory's laws. The Nagelian-Schaffner model of reduction, however, implicitly assumes the truth of physical state monism, by trivialising the role of higher-level properties that we find indispensable for generating physical models that make testable predictions.

There are two problems with this claim. First, there is reason to doubt that there is a cosmic state that evolves unitarily according to Schrödinger's equation, because of the role that macroscopic, classical properties appear to play in modifying the behaviour of quantum systems. We shall discuss this difficulty concerning the quantum dynamics in Sects. 2.5.2 and 2.5.3. Secondly, it is not sufficient to establish a nomological translation between two physical theories to show that one theory can capture all of the physical possibilities described by the other theory, and hence derive all of its physical content.

The physical possibilities of a quantum system are supposed to be given by assignments of expectation values to sets of observables. Yet thermal systems, as we have seen, require unitarily inequivalent Hilbert-space representations of the canonical commutation relations, which are disjoint in their assignments of expectation values (see Sect. 2.4.2), and two quantum states that belong to unitarily inequivalent representations are *ipso facto* not quantum-entangled. Yet if quantum states of physical systems are properly represented by Hilbert space representations, and if there is no unique representation in which a universal wave function for the cosmos can be defined, then the cosmos is *not* a single quantum-entangled system which evolves unitarily according to lower-level laws. In that case, the second premise of the argument for priority monism is false, and the conclusion that the cosmos is the only fundamental entity in existence has not been established.

There is no obvious way to dismiss this troubling element of pluralism in the heart of our best quantum theories. On the one hand, to privilege the physical content of one particular Hilbert space representation – a move that Ruetsche (2011) calls 'Hilbert space conservatism' – would be to reduce the number of physically significant states to a subset of those that are generally accepted by scientific practices. On the other hand, to confine the physical content of a quantum theory to the algebraic structure shared by different Hilbert space representations – 'algebraic imperialism' – would be to reduce the number of physically significant observables, since only a proper subset of the bounded self-adjoint operators that are deployed in quantum mechanical explanations instantiate the Weyl algebra. Either move fails to support the explanatory agenda of our best quantum theories and is inconsistent with adopting a realist stance toward theories in virtue of their explanatory successes.

Suppose instead of relying upon the algebraic approach to quantum field theory that is typically invoked by philosophers to discuss questions of interpretation, we focus on the 'conventional' Lagrangian version deployed by working physicists. According to Wallace (2011), the problem of unitarily inequivalent representations is circumvented in conventional quantum field theory by the introduction of cutoffs which limit its application to systems with only finite degrees of freedom. In this context, we might try to interpret the thermodynamic limit as merely a bridging law between a higher-level theory that describes thermal quantum systems, and a lower-level theory that describes a system in terms of a many-particle wave function with only finitely many degrees of freedom (Butterfield, 2011) (see Sect. 2.5.2). However, as Fraser (2009) points out, for a quantum field in spacetime to be considered to have only finite degrees of freedom, it would have to model spacetime as both finite and discrete. To waive this theoretical cost, conventional quantum field theory would have to be viewed as an *effective* field theory that is limited in its application within a specific energy scale, and thus unsuited to specifying the fundamental lower-level laws of nature, much less to determining all the physical possibilities.

In trivialising the role of boundary conditions in determining physical possibilities, it seems the Nagelian-Schaffner theory of reduction is not only insensitive to scientific practices, but undermines scientific realism. As Ruetsche (2011, p. 5) observes: 'there often isn't a single interpretation under which a theory enjoys the full range of virtues realists are wont to cite as reasons for believing that theory'.

Yet perhaps the decisive factor in determining whether there are macroscopic features of the world which are on an ontological par with its microscopic features is the impossibility of recovering certain macroscopic features of the manifest image upon which we depend for the possibility of scientific inquiry from a lower-level quantum mechanical description. We consider this element of top-down dependency further in the following two sections.

2.5.2 Quantum Darwinism and Weak Emergence

A second argument against physical pluralism could be based on the ‘Quantum Darwinist’s’ claim that the higher-level classical properties of a physical system only *weakly emerge* from a lower-level quantum substrate which evolves according to lower-level laws. For *weak emergentists*, the causal powers conferred by the higher-level properties of a system are a subset of the causal powers of the lower-level properties comprising the emergence base. These powers are generated by abstracting from the details of the lower-level physics, rather than something over and above the lower-level (Bedau, 1997). Since the conclusion of this argument undermines one of the key reasons for admitting higher-level entities into the fundamental ontology, in virtue of their possessing top-down causal powers, it counts as a reason for rejecting the kind of physical pluralism we are defending. The argument might be formulated as follows:

1. If higher-level properties weakly emerge from a lower-level substrate, their powers are subsets of the powers conferred by the lower-level properties.
2. If the powers of higher-level properties are subsets of the powers of lower-level properties, they do not confer top-down causal powers.
3. Higher-level properties weakly emerge from a lower-level substrate.
4. Therefore, higher-level properties do not confer top-down causal powers.

We take the first premise to be true by definition: according to weak emergentists, ‘less is different’ (Butterfield, 2011).[7] In other words, the novel behaviour that is associated with the phenomenon of emergence is to be explained in terms of what we have left out of the description and our own epistemic limitations, rather than in terms of an expanded ontology. In support of the second premise, it may be argued that, if the causal powers conferred by a system’s higher-level properties are only a subset of the system’s lower-level powers, generated by a coarse-grained description of the system in question, then ‘top-down causation’ is merely part of a phenomenological description of nature, and should not be part of any fundamental description.

In defence of the third premise, Quantum Darwinists claim that one can eliminate any element of context-dependence by treating a thermal system as an open quantum system embedded in a cosmic environment, and the combined system that includes

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[7] To be contrasted with regard to the characterisation of emergence famously offered by Anderson (1972), for whom ‘more is different’.

its environment as an isolated, non-thermal quantum system. On this view, the universal reality underlying the quantum statistical mechanics of thermalised systems admits a unique physical representation in the form of a many-particle wave function, which evolves unitarily according to the Schrödinger equation, whilst the macroscopic property of temperature weakly emerges as part of a coarse-grained representation of the environment with which the open system is interacting. The quantum substrate from which macroscopic systems are said to emerge is described solely in terms of lower-level quantal properties. Nothing more is needed. The conclusion of the argument logically follows from the premises.

It is the third premise that we wish to challenge. A difficulty arises in specifying the boundary between a microscopic quantum system that is to be measured by a macroscopic system from any macroscopic system that is used to measure it. According to advocates of the Quantum Darwinism programme, the macroscopic objects with higher-level classical features that scientists depend upon for making measurements are supposed to emerge from a lower-level quantum substrate that can be characterised without invoking macroscopic properties, due to the physical process of decoherence (Zurek, 1982, 2003).[8]

The theory of decoherence is supposed to explain how the reduced density matrix of a quantum system, which encodes all of the statistical information that can be extracted from the system by an observer, evolves from being a superposition of components that can 'interfere' with one another in a non-local way (due to the well-defined phase relations between these components), to a 'mixed state' in which the effects of interference between any of these components becomes negligible (due to the leakage of this phase coherence into the environment). The reduced density matrix represents the state of a system $\mathbb{S}$ obtained from the composite state of a system and its environment $\mathbb{S} + \mathbb{E}$ by 'tracing out' the environment $\mathbb{E}$ of the system (that is, by averaging over the environmental degrees of freedom). The goal of decoherence theory is to explain the vanishing of the 'off-diagonal' terms in the reduced density matrix, which corresponds to the vanishing of interference.

According to the theory of environmentally induced superselection (also known as einselection), a large system such as a measuring device is steered towards having those sensible and determinate 'pointer observables' that are familiar to ordinary experience due to its continual interaction with an environment with many more degrees of freedom than itself. Such interactions are typically modelled as scattering processes, in which the system interacts with a swarm of surrounding particles, and they favour states that are well localised in position, since the interaction Hamiltonians describing such processes typically embody a force law that is a function of position. In the case of such a composite system $\mathbb{S} + \mathbb{E}$, the off-diagonals in the reduced density matrix of $\mathbb{S}$ are periodic functions that oscillate as a function of time. To secure the disappearance of interference, for all practical purposes, the off-diagonal function will have to be small in value, and have a long recurrence time before the process of recoherence is allowed to take place.

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[8] For a more complete account of QD see Zurek (2009).

Technically speaking, the diagonalised reduced density matrix of a system that has ‘decohered’ is an *improper* mixture, since the system that it describes remains quantum-entangled with its environment. It is simply that the phase coherence between its components that endangers classical behaviour at the macroscopic level has ‘leaked’ into the environment through the process of decoherence in such a way that there are no local observations that can reveal it. Whilst the reduced density matrix of a system (in which the off-diagonals have effectively vanished) predicts the correct measurement statistics, quantum events are not always averaged when considering the behaviour of macroscopic systems, and individual events can change the behaviour of macroscopic systems (consider, for example, the case of an atom undergoing radioactive decay). Consequently, decoherence theory does not obviate the need for an interpretation of quantum mechanics that can explain the existence of measurement outcomes. This fact is generally acknowledged. Nonetheless, decoherence theory remains the linchpin of the Quantum Darwinist programme, which seeks to offer an observer-independent explanation of the emergence of a ‘classical’ world of objects from the unitary quantum dynamics. These macroscopic objects mirror, for the most part, the behaviour predicted by classical Newton-Maxwell physics.

Yet there is good reason to think that the process of decoherence depends upon the existence of a fundamental division between the microscopic and macroscopic (Kastner, 2014), and thus the theory of decoherence presupposes what the Quantum Darwinist programme sets out to derive. Specifically, in order for the off-diagonal elements in the reduced density matrix of the system to vanish, and for the recoherence time of the system to be sufficiently long to justify neglecting non-local effects, we must assume the initial states of the subsystems comprising its environment and their associated couplings with the system to be *random*. Yet the assumption of randomness is *inconsistent* with any purely quantum mechanical framework in which the universe is modelled as a closed system with a universal wave function that evolves unitarily according to Schrödinger’s dynamics.

Of course, no observed system is *really* closed, and the assumption of randomness is consistent with what we observe. Every system that scientists probe in their experiments is interacting with a much larger environment that *appears* to be random. However, as Kastner (2014, p. 57) points out, ‘the “openness” of the system is not actually available in the… unitary-only picture’ of the Quantum Darwinist. In the case of the composite system, $\mathbb{S} + P + \mathbb{E}$, in which P is a macroscopic system corresponding to a measuring device that is monitoring a microscopic system S, the total system $\mathbb{S} + P + \mathbb{E}$ is a closed system that is characterised by a single quantum state which evolves *deterministically*, however things may otherwise appear. In such a picture everything is always coherently entangled. Thus the Quantum Darwinist ‘can only make an arbitrary division into system+pointer+environment’ (ibid.), since there is no objective division that can be supported self-consistently from within the unitary-only picture.

In the absence of any natural division of the world into microscopic systems, their measuring devices, and their environments, however, Quantum Darwinists cannot appeal to the *appearance* of randomness – as if the environment were in fact objectively carved up into largely uncorrelated classical systems – without crucially begging the question. Hence the appeal to decoherence in this context is viciously circular, as Kastner and others have argued (see also Fields, 2010, 2011). Kastner (2014, p. 58) writes: ‘The problem is not so much a lack of observer-independence as it is failure to account for the initial independence of the environment from the system’, which is assumed by the adoption of random phases between the sub-systems of the environment.

2.5.3 Causal Closure and Strong Emergence

There is a third misgiving a modern philosopher may entertain about admitting pluralist parsings of physics, which concerns the violation of the causal closure of the microphysical world entailed by stronger forms of emergence. *Strong emergentists* can be distinguished from weak emergentists by their denial of the unimodal conception of physical content that unites physical state monists, in which the laws of our best physics determine the set of physically possible worlds *en bloc*. According to strong emergentists, there are systems with higher-level causal powers that influence the temporal development of lower-level properties, which do not merely supervene upon lower-level laws and the lower-level state of the cosmos, and the physical content of higher-level theories often is not derivable from the content of lower-level theories (Noble, 2011).

According to contemporary physics, however, there are only four physical ‘forces’ in nature: gravitation, electromagnetism, the weak interaction, and the strong interaction. If there are higher-level properties which are neither reducible to lower-level properties, nor weakly emergent, then how are higher-level properties supposed to make a causal difference to the lower-level physics without introducing ‘spooky’ forces into nature – such as the discredited notion of vital forces in biology – in addition to the four physical forces? An argument against strong emergence might be formulated as follows:

1. There are no more than four basic forces in nature.
2. If top-down causation occurs, then the lower-level is not causally closed.
3. If the lower-level is not causally closed, then there are more than four basic forces in nature.
4. Therefore, top-down causation does not occur.

The first premise can be taken as a methodological assumption governing the practice of physics, and as reflective of the confidence of scientists in the power of physical models to explain and predict natural phenomena. Philosophers should not posit more physical forces than are admitted by our best physics. We take the second premise to be a statement of the obvious: the lower-level physics cannot be causally closed if there are higher-level properties in nature which have causal powers to change lower-level properties, and if these higher-level properties are not ultimately reducible to lower-level properties. The third premise makes a claim about the conditions under which the lower-level physics might fail to be causally closed. If we reject the causal closure of the lower-level, then we must appeal to the existence of additional and mysterious forces that are unknown to our best physics, such as the discredited notion of 'vital forces' in biology, to accommodate the causal powers of macroscopic entities such as plants and animals. The conclusion follows from the premises.

The third premise of the argument is false, however, since the consequent is a *non sequitur*. There is another way in which higher-level properties can make a causal difference to lower-level properties. According to Ellis (2012, p. 1896): 'the upper levels exercise crucial influences on lower level events by setting the context and boundary conditions for the lower level actions'. This *context-dependence* can be secured by adopting an appropriate quantum dynamics, in response to the measurement problem of quantum mechanics.

The measurement problem is an open problem in the interpretation of quantum mechanics precisely because of the role that macroscopic measurements play in modifying microscopic behaviour (Schlosshauer, 2005). As we discussed in Sect. 2.3.2, the fundamental mathematical object within quantum theory is the wave function; or, more properly, the quantum state.[9] This mathematical object encodes the probability of an arbitrarily complicated system having any particular configuration that can be specified in whatever way we choose. Prior to any measurement – or any other collapse-inducing event – the wave function evolves according to the time-dependent Schrödinger equation

$$\widehat{H} \mid \psi\rangle = i\hbar \frac{\partial \mid \psi\rangle}{\partial t}, \tag{2.21}$$

where $\widehat{H}$ is the Hamiltonian of the system, representing its energy. Equation (2.9) has a formal solution in terms of a unitary operator $\widehat{U}$,

$$\mid \psi(t)\rangle = \widehat{U}(t) \mid \psi(0)\rangle, \tag{2.22}$$

i.e. the wave function at some arbitrary time t can be obtained from the wave function at time $t = 0$ through the action of this unitary 'time evolution' operator $\widehat{U}$.[10] The theory tells us how to start from a given state of a system, perhaps a configuration of particles or a field, and evolve the probability amplitudes for all the possible configurations of the system in time. But now suppose we perform a 'non-demolition' measurement on the system – perhaps the number of photons in an electromagnetic wave (Xiao et al., 2008) – which does not destroy the quantum

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[9] Here we write the wave function as $|\psi\rangle$, to indicate that this object is not necessarily a function of position.

[10] The meaning of 'unitarity' is that the probabilities computed from $|\psi\rangle$ always sum to unity; the operator $\widehat{U}$ simply re-distributes the probabilities between different possibilities as time goes on.

system being measured. After this measurement we know more about the state of the system than the wave function (2.22) lets on.

For example, the measurement outcome of the experiment may, with certainty, have ruled out some of the states to which $|\psi\rangle$ assigns non–zero probability. To obtain the correct results for future experiments, we must therefore *update* the wave function with the empirical knowledge we have gained. Yet this updating is not performed by the time evolution operator $\widehat{U}$. For instance suppose at time t we find an electromagnetic field has n photons in it, $|\psi\rangle{=}|n\rangle$. The wave function has to undergo the following discontinuous modification:

$$\begin{aligned} |\psi(t-\delta t)\rangle &= \widehat{U}(t-\delta t)|\psi(0)\rangle, \\ |\psi(t+\delta t)\rangle &= |n\rangle. \end{aligned} \tag{2.23}$$

This discontinuous change of the wave function (from $\widehat{U}(t-\delta t)\mid\psi(0)\rangle$, to $|n\rangle$) is known as the 'collapse of the wave function', and it is necessary to properly account for any non-demolition experiment. There is no agreed understanding of this process (Omnès, 1994). Even if the phenomenon of decoherence is taken into account (as suggested in e.g. Omnès, 1994), the time evolution operator must still be supplemented with a discontinuous change of state.

According to Bell (1987), any realist approach to quantum mechanics that seeks to explain the existence of determinate measurement outcomes, such as the number of photons in an electromagnetic field, must come to terms with a dilemma: either the dynamics of standard quantum mechanics is wrong, and the wave function evolves according to a non-linear Schrödinger equation that permits the wave function to collapse, or standard quantum mechanics is incomplete, and there are 'hidden variables' (ibid, p.1), in addition to the wave function, that evolve according to some non-linear dynamics of their own.

Maudlin (1995) has argued that the choice comes down to two possibilities: either we should adopt something like the GRW theory, or something like the theory of Bohmian mechanics. The GRW theory seizes the first horn of the dilemma by incorporating a stochastic mechanism which produces random hits on the wave function that occur universally for microscopic particles and result in an objective collapse of the wave function (Ghirardi et al., 1986). The effects of this non-linear modification to the Schrödinger equation become significant when a large number of quantum-entangled particles are involved, such as the particles that compose a macroscopic instrument of measurement.

The theory of Bohmian mechanics seizes the second horn of the nomological dilemma by positing a global configuration of particles whose trajectories are choreographed by the universal wave function (de Broglie, 1928; Bohm, 1951, 1952). The guiding equation for the particles depends in a non-linear way upon the universal wave function, which evolves according to the standard Schrödinger equation. The collapse of the wave function, according to Bohmians, is not an objective event, but merely an artifact of using an effective wave function to model a system, instead of the universal wave function. The only relevant part of the universal wave function is the part that supports the particle configuration.

An alternative ‘contextual’ model of the quantum dynamics is available, however, proposed by Drossel and Ellis (2018), in which the interaction of a quantum system with the intrinsic heat bath of a measuring instrument plays a key role in solving the measurement problem. In this system, the macroscopic, thermal properties of an instrument have the power to collapse the wave function of a microscopic system. The *CWC model* (contextual wave function collapse) drops the assumption of physical state monism that underpins Maudlin’s ultimatum, by incorporating the notion of top-down causal powers.

As in the GRW modification of quantum mechanics, the CWC model seizes the first horn of Bell’s dilemma, allowing the wave function to become localised with respect to position. It also distinguishes measurements from localisation events. Unlike GRW theory, however, the stochastic corrections that achieve these localisations depend upon the local *macroscopic context* of a system, which includes the measuring device. In short, the CWC model incorporates a feedback loop – from a particle, via the intrinsic heat bath of the measuring device, back to the particle – which introduces non-linear terms in the Schrödinger equation. These terms are physically motivated: they can be accounted for in terms of thermodynamics and solid-state physics (Drossel & Ellis, 2018, pp. 13–19).

As in Bohmian mechanics, the CWC model relies upon the effects of the environment upon the measuring process to explain why the outcomes of quantum experiments conform to standard quantum statistics and Born’s rule for quantum observables. Unlike Bohmian mechanics, the CWC model does not conceive any part of the environment that is relevant to the measuring process as a many-particle quantum system that is subject to unitary and reversible time evolution. Rather, the heat bath of an instrument is characterised as having non-zero temperature and only a limited ‘memory’, since it radiates irreversibly into the heat sink of its surroundings.

Consequently, the CWC model does not leave the quantum system entangled with any part of its environment beyond the usual time scale of decoherence. According to the CWC model, the heat bath of the measuring instrument can serve as a bridge between quantum systems and their ‘classical’ environment, just so long as we are willing to reject ‘the untestable and implausible claim that the environmental heat bath can be described by an infinite-precision wave function that is subject to unitary time evolution’ (Drossel & Ellis, 2018, p. 4).

The CWC model does not introduce any spooky new forces in nature, nor does it assume state monism by postulating the existence of a universal wave function defined in a single Hilbert space. According to Ellis (ibid., p.25): ‘Quantum theory *per se* does not tell us what Hilbert spaces to use. This requires the classical, macroscopic context’. In this model, the higher-level classical properties derive their causal powers from the role they play in specifying the boundary conditions within which the micro-evolution of a system takes place.[11]

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[11] Simpson (2021) has proposed an ontology of thermal substances for the CWC model.

2.6 Concluding Remarks

Microphysicalism and priority monism are often regarded as antagonistic positions in contemporary philosophy. In this paper, however, we have argued that they are both manifestations of a more entrenched orthodoxy that rules against fundamental ontologies that admit macroscopic entities. According to *physical state monists*, the causal powers of a physical system supervene upon the lower-level laws and lower-level state of the cosmos, as they are represented by our best physics, because the physical content of a theory is assumed to be specified by a set of possible worlds which are determined by its laws (Sect. 2.2). This presumption is widely in evidence in philosophy – in discussions of free will, for example, and mental causation.

Against this orthodoxy, we have argued that there is a striking inconsistency between the pretensions of state monism and scientific practices. We considered models of quantum systems in which the boundary conditions are specified by higher-level, macroscopic properties (Sect. 2.3). It is far from evident that our best physics 'zooms in' upon a basic level that can be described solely in terms of lower-level laws and properties. We also considered models which apply physically inequivalent representation to the same system to explain their behaviour (Sect. 2.4). It is highly doubtful that physics provides a unique microphysical representation of a lower-level cosmic state, which evolves according to one set of physical laws, from which the physical content of any model of a macroscopic system could be derived. Rather, physical laws seem to be patchy and context dependent, as Cartwright (1999) has famously argued.

We broached the possibility of some kind of physical pluralism instead, which admits fundamental entities between the microscopic and cosmic scales, and refuted three arguments that attempt to impugn the scientific respectability of pluralism (Sect. 2.5): an argument in favour of priority monism, on the basis of quantum entanglement; an argument in favour of weak emergence, which appealed to the phenomenon of decoherence; and an argument in favour of the causal closure of the lower-level world, which invoked the bogeyman of mysterious forces. Each of these arguments presupposes a unimodal conception of physical possibilty and begs the question against physical pluralism.

There is good reason to think that the physical possibilities encompassed by our best physical theories are not specified *en bloc* by lower-level laws, and hence to reject a unimodal conception of physical content. The framework of algebraic quantum mechanics, as we have seen, admits two levels in specifying the content of theory: at the level of the algebra, which is common to different microscopic systems, and at the level of the Hilbert space representation, which takes into account macroscopic contingencies of particular systems, such as equilibrium temperature (Ruetsche, 2003). A more nuanced conception of content is therefore needed to capture the full range of explanatory virtues realists typically cite as reasons for believing this theory. There is also good reason to abandon the orthodox belief that the lower-level physics is causally closed. The measurement problem in quantum mechanics admits a well-motivated solution in which higher-level properties set the context and boundary conditions for the lower-level behaviour, which is consistent with actual scientific practices (Drossel & Ellis, 2018). This contextual model of the quantum dynamics opens the conceptual space for a fundamental ontology that includes macroscopic entities with top-down causal powers.

We note in closing that there are other ways of interpreting the concept of physical possibility than in terms of a flat set of possible worlds. In Inman's (2017) neo-Aristotelian mereology, for example, possibilities are understood rather in terms of things' *natures*. According to Koons (2021) and Simpson (2021), the fundamental entities are 'thermal substances', which have both quantal and classical properties, whose natures are defined at the *macroscopic* level. Our object in this paper has not been to argue for any particular fundamental ontology, however, but rather to question the scientifically privileged status of microphysicalism and priority monism, which has been taken for granted by many philosophers, and to question the view that the laws specified by our best physics determine a set of possible worlds, rather than simply constraining the possibilities. In the absence of any good reason for believing state monism to be the default position endorsed by our best physics, we think it is reasonable for philosophers to construct ontologies that include physical entities at a variety of scales, which have the freedom to exercise top-down causal powers. Such ontologies are likely to have far-reaching implications for our understanding of free will and agency (topics which Helen Steward and Daniel De Haan explore in their own chapters in this volume), as well as for artificial intelligence (Ellis, 2016; Ellis & Drossel, 2019).

Acknowledgements The authors would like to thank (in alphabetical order) Barbara Drossel, George Ellis, Robert Koons, and Jonathan Schaffer for their critical feedback on this paper. William Simpson would like to acknowledge the support of the John Templeton Foundation via the international project, *God and the Book of Nature*, Grant Id: 61507, and to thank Marcus Ackermann for his assistance in reformatting the final version of this paper.

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