Emergent Physics and Micro-Ontology*

Margaret Morrison†‡

This article examines ontological/dynamical aspects of emergence, specifically the micro-macro relation in cases of universal behavior. I discuss superconductivity as an emergent phenomenon, showing why microphysical features such as Cooper pairing are not necessary for deriving characteristic properties such as infinite conductivity. I claim that the difficulties surrounding the thermodynamic limit in explaining phase transitions can be countered by showing how renormalization group techniques facilitate an understanding of the physics behind the mathematics, enabling us to clarify epistemic and ontological aspects of emergence. I close with a discussion of the impact of these issues for questions concerning natural kinds.

1. Introduction. An emergent property or phenomenon is usually defined as one that arises out of lower-level constituents but is neither reducible, explainable, nor predictable from them. Emergence is sometimes associated with nonreductive physicalism, a view that advocates the physical nature of all concrete entities while acknowledging that some entities/properties that arise from this physical base cannot be reduced to it. The philosophical challenge is how to understand the relation between these various ontological and explanatory levels, especially since emergentists claim a distinct status for emergent phenomena/properties, distinguishing them from straightforward aggregates of constituents. To use Anderson's (1972, 395) words, the whole is not only greater than but very different from the sum of the parts.

When one is dealing with emergence in physics, physicalism is not an issue. No one denies that condensed matter phenomena such as super-

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†To contact the author, please write to: Philosophy Department, University of Toronto, Trinity College, Toronto, ON M5S 1H8, Canada; e-mail: mmorris@chass.utoronto.ca.

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conductivity, phenomena often described as emergent, comprise elementary particles or are physical in nature. Rather, the concern is whether some variant of reduction is really at work in contexts typically associated with emergence. An advocate of reduction could easily claim that because the macro level is composed of micro constituents, there is no physical difference between different levels; instead what is lacking is an appropriate type of explanatory relation. Consequently, appeals to emergence indicate insufficient knowledge of the relevant explanatory connections between different theoretical levels, not a physical difference.

But this response is not unproblematic. Because we do not have the requisite explanatory or predictive abilities where emergent phenomena are concerned, it is not obvious that the physical relations characteristic of reduction hold in these cases. There are methods in place for understanding how micro-macro levels are connected to each other and how emergent phenomena arise; but as we shall see below, these methods speak against a general reductionist strategy. More specifically, the framework provided by renormalization group (RG; Wilson 1983) techniques has shown that while emergent phenomena, especially the "universal" phenomena in condensed matter physics, are certainly composed of micro constituents, they are nevertheless largely insensitive to changes in their microphysical base.[1] Prima facie, this seems odd since we intuitively think that what happens at the micro level will influence, at least in some significant way, phenomena at larger scales. But that is exactly what is so puzzling about emergence. It is not that condensed matter physics is emergent with respect to particle physics, tout court, but rather that there are certain kinds of phenomena, both in condensed matter and indeed in high-energy physics itself, whose explanation can be understood only from within the emergentist picture.

My discussion here will focus on the ontological aspects of emergent behavior, specifically why cases of universal behavior violate the reductionist picture typically used to characterize physical phenomena. In order to substantiate the "more is different" claim, the ontological problem of how to construe the physical relation between the micro and macro levels needs to be addressed. Retaining emergence simply as an epistemic category is not philosophically viable because it fails to sufficiently differ-

1. Universality refers to the fact that phase transitions arising in different systems often possess the same set of critical exponents. For instance, the critical exponents at the liquid gas critical point are independent of the chemical composition of the fluid and share the same critical exponents as the ferromagnetic phase transition in uniaxial magnets. These systems belong to the same universality class, and it is shown by the RG that the thermodynamic properties of a system near a phase transition depend only on a small number of features, such as dimensionality and symmetry, and are insensitive to the underlying microphysics.

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entiate emergent phenomena from straightforward aggregates. As we shall see below, the ontological and epistemic issues surrounding emergence are deeply intertwined, making it all the more important that these various relations are made more explicit.

The relation between ontological and epistemic independence is especially important since the latter is a necessary but not a sufficient condition for emergence; the fact that we need not appeal to micro phenomena to explain macro processes is a common feature of physical explanation across many systems and levels. Instead, what is truly significant about emergent phenomena is that we cannot appeal to microstructures in explaining or predicting these phenomena even though they are constituted by them. Although this seems counterintuitive, RG methods reveal the nature of this ontological independence by demonstrating (1) how systems with completely different microstructures exhibit the same behavior, (2) how successive transformations give you a Hamiltonian for an ensemble that contains very different couplings from those that governed the initial ensemble, and (3) the importance of the physics behind the notion of an infinite spatial extension for establishing long-range order. So, although a phase transition is connected with a symmetry breaking that involves microphysical constituents (e.g., spin directions and Cooper pairing), it also involves a topology that extends over an infinite region of space; it is the latter that is relevant for determining the type of cooperative behavior that characterizes the universality of emergent phenomena. RG reveals why the micro details of symmetry breaking are neither ontologically nor epistemically necessary for emergence; the information is simply lost as the length scale changes.

I begin by reviewing some arguments that do mention ontological aspects of emergence (e.g., Humphreys 1997a, 1997b; Howard 2007) and discuss why none seems to capture the features necessary for a general characterization of emergent phenomena in physics. From there I go on to discuss superconductivity as an example of emergence and show why microphysical aspects such as Cooper pairing are not necessary for deriving its characteristic features (e.g., infinite conductivity, flux quantization). My discussion is largely sympathetic to many of the claims about emergence presented by Batterman (2002) but differs in that it stresses the ontological/dynamical features of emergence via its connection with the physics of symmetry breaking associated with phase transitions and how that picture fits into the framework of RG.[2] Although this approach

2. I characterize Batterman's account as explanatory insofar as the main argument centers on how asymptotic methods (via the RG) allow us to explain features of universal phenomena that are not explainable using either intertheoretic reduction or traditional causal mechanical accounts presented by RG. Although he has recently

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brings its own problems related to the thermodynamic limit, those difficulties can be countered by showing how RG techniques facilitate an understanding of the physics behind the mathematics. In other words, I claim that renormalization techniques extend beyond their role as predictive tools by providing us with new physical information that can help clarify both the epistemic and ontological aspects of emergent phenomena. I close with a discussion of the relevance of these issues for our notion of natural kinds.

Emphasizing the importance of emergence in physics is not to deny that reductionism has been successful in producing knowledge of physical systems. Rather, my claim is that as a global strategy, it is not always capable of delivering the information necessary for understanding the relation between different levels and kinds of physical phenomena.

2. Problems for Reduction. Perhaps the most famous of the reductionist debates in philosophy of science involves the reduction of thermodynamics (TD) to statistical mechanics (SM) and whether chemistry can be reduced to quantum mechanics (QM). The kind of reduction at issue here deals with theories and laws. In other words, are the theoretical frameworks of the so-called reducing theory (SM and QM) capable of capturing the essential features of the reduced theory (TD and chemistry)? While this notion of intertheoretic reduction is important for identifying the concepts in one domain with those in another, it is by and large an epistemic concern. In other words, even if we possessed a theory that could successfully identify or correlate these concepts (e.g., temperature and mean kinetic energy), nothing follows as to whether the properties or entities in each domain are ontologically the same (e.g., that phenomenon produced in a phase transition can be identified with its microconstituents prior to the transition). And, once we focus on ontological aspects of the relation, some serious problems arise.

Supervenience is a common way for philosophers to retain the appealing aspects of reduction without embracing its difficulties, in particular the

emphasized the "physical" aspects of RG explanations, symmetry breaking does not function in a significant way (Batterman 2011). My account attempts to integrate symmetry breaking and RG explanations into an overall dynamical picture. For criticisms of the explanatory role of the thermodynamic limit, a crucial aspect of RG methods, see Callender (2001) and Earman (2004). Bangu (2009) has shown how utilizing the data/phenomena distinction enables us to avoid those types of criticisms.

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most appealing aspect—physicalism.[3] There are several accounts of how this works, but most involve some type of dependency relation. Since we can assume, for the context of this discussion, that physicalism is unproblematic, the pros and cons of supervenience need not concern us at this point.[4] Instead I want to briefly look at some ontological accounts of emergence, each of which respects the "autonomy" of emergent phenomena by showing why the identity claims characteristic of reductions fail. Despite this, I want to claim that they are largely unsuccessful in capturing features typically associated with the large class of emergent phenomena in physics, particularly condensed matter.

Humphreys (1997a, 1997b) defines emergence in terms of a fusion relation operating between different levels of entities and properties.[5] He characterizes the fusion relation (1997b, 8) by defining a class of *i*-level properties and entities, P_m^i and x_r^i, respectively, as the first level at which instances of P_m^i (x_r^i) occur. The fusion operation [$*$] results in the following: if $P_m^i(x_r^i)(t_1)$ and $P_n^i(x_s^i)(t_1)$ are *i*-level property instances, then $[P_m^i(x_r^i)(t_1) * P_n^i(x_s^i)(t_1)]$ is an $i + 1$–level property instance, the result of fusing $P_m^i(x_r^i)(t_1)$ and $P_n^i(x_s^i)(t_1)$. According to Humphreys, it is the physical interactions represented by the fusion operation that lead to the transition from the i to $i + 1$ level that is responsible for emergent features. The fused $[P_m^i * P_n^i][(x_r^i) + (x_s^i)](t_1')$ is a unified whole in that its causal effects cannot be correctly represented in terms of the separate causal effects of $P_m^i(x_r^i)(t_1)$ and $P_n^i(x_r^i)(t_1)$. Moreover, within the fusion $[P_m^i * P_n^i][(x_r^i) + (x_s^i)](t_1')$, the original property instances $P_m^i(x_r^i)(t_1)$ and $P_n^i(x_s^i)(t_1)$ no longer exist as separate entities and do not possess all their *i*-level causal powers available for use at the $i + 1$ level. In other words, these *i*-level property instances no longer have independent existence within the fusion; they simply go out of existence in producing the higher-level emergent instances.

Hence, the subvenient base cannot be the reason the emergent property

3. Rueger's (2000) account of emergence involves a notion of supervenience defined in terms of stability or robustness. An emergent phenomenon/property is produced when a change in the subvenient base produces new behavior that is both novel and irreducible. The causal powers that emergent phenomena have are simply those that "structural properties have in virtue of being configurations of their lower level constituents" (317). My difficulty with this view is that even if the emergent properties are novel and irreducible, they are still the result of the system configured in a certain way. Consequently, the causal powers of the whole are no different from those of the parts, making emergent properties similar to resultant properties.

4. See Beckermann, Flohr, and Kim (1992) for various discussions.

5. If we identify emergent properties as resulting from the interaction of the constituents, then it is not immediately clear how to motivate the "more is different" claim characteristic of emergent phenomena.

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is instantiated since the $i + 1$–level property instances do not supervene upon the i-level property instances. Humphreys (1997b, 15) cites the example of quantum entanglement as a case of emergence resulting from the kind of fusion he describes. The composite system can be in a pure state when the component systems are not, and the state of one component cannot be completely specified without reference to the state of the other component. He sees the interactions that give rise to the entangled states as having the features required for fusion because the relational interactions between the constituents can no longer be separately individuated within the entangled pair.[6]

Silberstein and McGeever (1999, 187) claim that "QM provides the most conclusive evidence for ontological emergence," and their discussion of entanglement (189) appears to endorse the appropriateness of fusion for describing the whole-part relation in this context. In Howard (2007, 12), the paradigm case of emergence is also quantum entanglement, and he claims that in areas of condensed matter physics where there is a reasonably successful theory (superconductivity and superfluidity), there is also a clear connection to microphysical entanglement. As an example he cites the role of Bose-Einstein condensates (BEC) in superfluidity and the way that Cooper pairs in superconductivity are, in effect, BECs.[7] Consequently, condensed matter theory (CMT) supervenes on the most basic property of the micro realm—entanglement (17). Howard states that "while condensed matter physics does not obviously reduce to particle physics, phenomena . . . such as superfluidity and superconductivity do supervene on physical properties at the particle physics level and hence are not emergent with respect to particle physics" (6). In other words, "the physical structure that [does] the explaining in condensed matter physics . . . is entanglement . . . the micro-world upon which condensed matter physics is said not to supervene" (22).

While these various claims about entanglement as an example of emergence are certainly plausible, the converse is less convincing; in other words, phenomena such as superconductivity, crystallization, magnetization, and superfluidity are neither explained by nor ontologically iden-

6. Humphreys (1997a, 342) also discusses examples of emergent phenomena that are not of this sort, namely, those that occur in ideal macroscopic systems containing an infinite number of particles. His point is that the emergent properties cannot be possessed by individuals at the lower level because they occur only with infinite levels of constituents. These are exactly the sorts of examples I will have more to say about below.

7. A BEC is a state of matter formed by bosons confined in an external potential and cooled to 0 kelvin or −273.15°C. This causes a large fraction of the atoms to collapse into the lowest quantum state of the external potential.

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tified with quantum entanglement.[8] Nor can the latter account for the stability associated with these phenomena and the ability to make very accurate predictions about their behavior. Humphreys is explicit that emergence does not require supervenience insofar as the fused properties cease to exist once the emergent phenomenon is present. But how can this enable us to retain the ontological independence of the micro level in contexts like CMT and particle physics? Howard's solution is to understand these relations as supervenient, but this is of little help if we understand supervenience in the typical way, where the connection between the two levels requires a covariance relation to be maintained.[9] While Howard acknowledges that supervenience does not imply reduction, we shall see below that the kind of phenomena considered emergent in CMT are not actually explained in terms of microphysical properties in the way he suggests. The characteristic behaviors that identify phenomena as emergent (e.g., infinite conductivity) are neither explained nor identified with microphysical constituents.[10] But because emergent phenomena "arise out" of their microphysical base, we need some account of the ontological connection between the levels to fully explain the exact nature of the emergence relation.

The point I want to argue is that acknowledging an ontological relation between emergent phenomena and their microscopic constituents does not constitute a claim about reduction or supervenience. Why? In the case of ontological reduction, there exists a type of identity that cannot be upheld in cases of emergence. Reductionism assumes, among other things, that because a particular macro phenomenon is a collection of micro entities/properties, the latter not only explains the behavior of the former, giving us some insight as to why it behaves as it does, but also constitutes it. Emergence shows us that the opposite is true. Initially this appears somewhat confusing because, for example, we typically understand the causal foundation of superconductivity in terms of Cooper pairing; so to claim

8. Although entanglement is undoubtedly operating here, my use of the term "identified" is meant to indicate that I do not subscribe to the view that emergent phenomena are explained via an ontological identification with entangled states, nor does the association with entanglement serve as an example of the supervenience relation where the basal property is associated with the higher-level property.

9. Howard cites Davidson's (1970) definition in which supervenience is described as an ontic relationship between structures construed as a set of entities. The higher-level (B) entities supervene on the lower-level (A) ones if and only if the former are wholly determined by the latter such that any change in (B) requires a corresponding change in (A).

10. Infinite conductivity is one of the properties, along with flux quantization and the Meissner effect, that are exact regardless of the type of metal that is contained in the superconductor.

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that there is no reduction to or identification with this microphysical base requires a clarification of the exact nature of these ontological relations.

In what follows I argue that understanding emergent phenomena in terms of symmetry breaking—a structural dynamical feature of physical systems (about which I will have more to say below)—clarifies both how and why emergent phenomena are independent of any specific configuration of their microphysical base. An important advantage of this strategy is that the microphysical entities and properties remain intact and autonomous, unlike Humphreys's fusion relation or accounts that appeal to quantum entanglement. As we shall see below, this relative independence from the underlying microphysics is crucial for understanding the difference between emergent and resultant properties and for highlighting the similarities and differences between emergence and multiple realizability.

3. Why Emergence? When evaluating the merits of reductionist explanation, it is also important to inquire about its limits and how far this kind of explanation extends. Specifically, what actually counts as "reduction" and at what point does the addition of free parameters undermine reductionist claims? The nonrelativistic Schrodinger equation presents a nice illustration of the kind of reduction we typically associate with explanation in physics:

$$i\hbar \frac{\partial}{\partial t} |\Psi\rangle = \mathcal{H}|\Psi\rangle. \tag{1}$$

It describes, in fairly accurate terms, a large number of physical phenomena and can be completely specified by a few quantities such as the charges and masses of the electron and atomic nuclei, as well as Planck's constant. It can be solved accurately for small numbers of particles (isolated atoms and small molecules) and agrees in minute detail with the experiment. However, as Laughlin and Pines (2000) point out, when the number of particles exceeds around 10, this is no longer the case. It is possible to perform approximate calculations for larger systems that yield knowledge of atomic sizes and the elastic properties of solid matter and so forth, but the use of approximation techniques means that these are no longer deductions from first principles or fundamental theory; instead they require experimental input and specific, local details. What this indicates is a breakdown of the reductionist ideal of deriving explanations of a large number of phenomena from a few simple equations or laws.

But does this really undermine reduction as an explanatory strategy? The answer depends, in part, on how many free parameters one is willing to accept into the explanation; in other words, at what point does it no longer make sense to call an explanation reductive when the explanatory

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information comes via the free parameters rather than fundamental features of theories/laws? Regardless of one's take on this particular matter, there is a related problem raised by Laughlin and Pines that speaks more pointedly to the emergence issue; namely, what accounts for the stability and accuracy of measurements of parameters e, $\hbar$, and m in the Hamiltonian for the Schrodinger equation when their values cannot be derived or predicted by direct calculation? These measurement experiments involve phenomena such as the Josephson and quantum Hall effects, which, taken together, provide the most accurate measurement of Planck's constant h. Laughlin and Pines claim that these types of experiments work because "there are higher organizing principles in nature that make them work" (2000, 28). Examples of such principles are continuous symmetry breaking, which renders exact the Josephson quantum, and localization, which is responsible for the quantum Hall effect.[11] They claim that both effects are "transcendent" in that neither can be deduced from the microphysics and would continue to be true even if the theory of everything were changed. These are classified as emergent phenomena or "protectorates."

In Laughlin and Pines's discussion of continuous symmetry breaking, they do not elaborate on the notion of "transcendence" or the status of organizing principles; but in the latter case, independence from specific theoretical content is going to be necessary if emergent phenomena are to be properly autonomous from the microphysical domain. While many physical theories/phenomena incorporate or involve various types of symmetry breaking, the notion itself is not linked to any specific theoretical framework. Rather, it functions as a structural constraint on many different kinds of systems in both high-energy physics and condensed matter physics.

I refer to symmetry breaking as a "structural/dynamical feature of physical systems" because of the way order and structure emerge as a result of the phase transitions associated with symmetry breaking. In fluid dynamics the emergence of new order and structure occurs when a dynamical system is driven further and further away from thermal equilibrium. By increasing control parameters such as temperature and fluid velocity, old equilibria become unstable at critical points and break down, and new branches of local equilibria with new order emerge. Spontaneous symmetry breaking (SSB) is manifest in, among other things, the acquisition of rigidity and the existence of low-energy excitations in condensed matter

11. Localization involves the absence of diffusion of waves in a random medium caused by a high concentration of defects or disorder in crystals or solids. In the case of electric properties in disordered solids, we get electron localization, which turns good conductors into insulators.

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physics; superconductivity incorporates symmetry breaking via Cooper pairing as a basic feature in the Bardeen-Cooper-Schrieffer (BCS) theory. Particle masses in high-energy physics are also thought to be generated by SSB. In each of these cases we have dynamical processes that produce specific effects. Because these processes involve a connection with microphysics, the challenge for the emergentist is to explain how and why we should think of symmetry breaking as distinct from the type of fundamental physics associated with reduction. We will see why this is the case below.

When Laughlin does speak of organizational principles, he seems to have in mind the kind of order that is produced as a result of some type of collective action that is essentially independent of the details of the underlying microphysics. For example, he mentions principles governing atomic spectra that can be understood without any reference to the quark structure of nucleons and the laws of hydrodynamics, which would be roughly the same regardless of variations in detailed intermolecular interactions. However, in both of these cases we need to differentiate explanatory from ontological claims since emergence is not simply about different organizational principles being important at different scales or laws not requiring specific micro details. More is required.

When symmetries are spontaneously broken, the result is the occurrence of ordered states of the sort Laughlin refers to. For example, magnetization results from broken spin rotation symmetry, and massive particles break a phase rotation symmetry. These symmetries impose structural constraints on the physical world in that they give rise to and explain certain forms of dynamical interactions. As we shall see below, these constraints are general structural features of physical systems that can apply in a variety of theoretical contexts. By contrast, fundamental theory is concerned with details, expressed via laws and models, of specific physical systems and how they behave. It is these general features rather than specific details of micro processes that prove important for emergence. In order to clarify the ontological relations among emergence, symmetry breaking, and microphysics, let me turn to the example of superconductivity, which nicely illustrates these features.

4. Emergent Phenomena, Dynamics, and Ontology. Many of the physical properties of superconductors such as heat capacity and critical temperature (where superconducting properties are no longer present) vary depending on the type of metal. However, there is a class of properties that are independent of the specific material and are exact for all superconductors, properties such as infinite conductivity (very low electrical resistance and currents that can circulate for years without perceptible decay),

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flux quantization, and the Meissner effect.[12] These can be predicted with extraordinary accuracy; but in deriving them and other phenomena associated with superconductors, one typically uses models that are just reasonably good approximations. There are macroscopic models such as Ginzburg-Landau, in which cooperative states of electrons are represented using a complex scalar field, and the microscopic model(s) of the BCS theory, in which electrons appear explicitly and are assumed to interact only by single phonon exchange. The latter is the widely accepted account that explains the superconducting phase of a metal as involving many pairs of electrons (Cooper pairs) bound together at low temperatures. This pairing in a superconductor is a collective phenomenon analogous to magnetization in a magnet and, as with magnetism, involves symmetry breaking and a phase transition. The essence of the BCS theory is the appearance of a pair field that is the order parameter of the superconducting state, just as magnetization is the order parameter of the ferromagnet.[13] Exactly how this pairing occurs is the subject of different model explanations, one of which was provided by Bardeen, Cooper, and Schrieffer themselves in their original (1957) paper.[14]

It is tempting to see the story about Cooper pairing as a reductive, microcausal explanation insofar as the electron pairs seem to be the defining characteristic of superconductivity. However, the story is more complicated than might first appear. Recall the discussion above of the Josephson effect and the problem of deriving exact results from approximations. The same situation arises with superconductivity, where the properties (infinite conductivity, flux quantization, etc.) are exact and are the same for all superconductors. Since they are exact results, they must follow from general principles rather than simply be derived using approximations. So, while highly precise predictions about superconductors follow from the models, they do so because the models embody a symmetry principle—the spontaneous breakdown of electromagnetic gauge invariance (Weinberg 1986, 1996). One needs detailed models like BCS to explain the specifics of how the SSB occurs, at what temperature superconductivity is produced, and as a basis for approximate quantitative calculations, but not to derive the most important exact consequences of

12. The former is a quantum phenomenon in which the magnetic field is quantized in the unit of $h/2e$, and the latter simply refers to the expulsion of a magnetic field from a superconductor.

13. The order parameter is a variable that describes the state of the system when a symmetry is broken; its mean value is zero in the symmetric state and nonzero in the nonsymmetric state.

14. For more on the topic of superconductivity, theories, and models, see Morrison (2007, 2008).

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this breakdown—infinite conductivity, flux quantization, and the Meissner effect—properties that define superconductors.[15]

This fact is crucial for our account of emergence because it shows that the microphysical details about how Cooper pairing takes place are not important in deriving and explaining fundamental features of superconductivity. Put differently, it is not that instances of superconductivity in metals do not involve micro processes; rather the characteristics that define the superconducting state are not explained or predicted from those processes and are independent of them in the sense that changes to the microphysical base would not affect the emergence of (universal) superconducting properties. Although the breakdown of gauge invariance involves the formation of Cooper pairs—a dynamical process—the micro story figures simply as the foundation from which superconductivity emerges.

The key to understanding this relationship involves the connection between phase transitions and symmetries. Symmetry breaking is reflected in the behavior of an order parameter that describes both the nature and magnitude of a broken symmetry. In the ferromagnetic state, the order parameter is represented by the vector describing the orientation and size of the material's magnetization and the resulting field. In the superconducting case, the order parameter is the amplitude $\langle\varphi\rangle$ of the macroscopic ground state wave function of the Cooper pairs. The electromagnetic properties in a superconductor are dominated by Cooper pairs, whereas electrons in a metal normally behave as free particles that are repelled from other electrons because of a negative charge. Because Cooper pairs appear only at T_c (their presence indicates that the system has undergone a phase transition), they give rise to the order parameter, which involves the Cooper pairs forming a single wave function. In general, the order parameter can be thought of as an extra variable required to specify the macroscopic state of a system after the occurrence of a phase transition. In nonsuperconducting metals, gauge invariance ensures that $\langle\varphi\rangle = 0$. It should be noted here that an order parameter can have a well-defined phase in addition to an amplitude, and it is the phase that governs the macroscopic properties of superconductors and superfluids.

Given this picture, we now need to disentangle the relation between the order parameter and the emergent nature of superconductivity. Recall that the symmetry breaking associated with the order parameter in superconductivity is electromagnetic gauge invariance. The electromagnetic properties are dominated by Cooper pairs, with each pair j having a wave function

$$\psi_c^j(\boldsymbol{r}) = V^{-1/2} a_j(\boldsymbol{r}) \exp i\varphi_j(\boldsymbol{r}), \tag{2}$$

15. See Weinberg (1986, 1996) for details.

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where $a_j(\boldsymbol{r})$ and $\varphi_j(\boldsymbol{r})$ represent the amplitudes and phases, respectively. The mean separation at which pair correlation becomes effective is between 100 and 1,000 nanometers and is referred to as the coherence length, $\boldsymbol{\xi}$, which is large compared with the mean separation between conduction electrons in a metal. In between one pair there may be up to 10^7 other electrons that are themselves bound as pairs. The coherence volume $\boldsymbol{\xi}^3$ contains a large number of indistinguishable Cooper pairs, so one must define a density of wave functions averaged over the volume. The average will be nonzero only if the phases $\varphi_j(\boldsymbol{r})$ are close together; that is, the neighboring Cooper pairs are coherent. In the case of the ground state wave function density,

$$\psi(\boldsymbol{r}) = 1/\boldsymbol{\xi}^3 \sum_{j\in\xi}^{3} \psi_j(\boldsymbol{r}_j) \propto \sqrt{n_s} \exp i\varphi(\boldsymbol{r}), \tag{3}$$

we can identify $|\psi(\boldsymbol{r})|^2$ with the density of Cooper pairs at point $\boldsymbol{r}$ and then define creation and annihilation operators for particles at $\boldsymbol{r}$. In a normal conducting metal the expectation value for these operators takes a value zero, but in superconductors the operator $\psi(\boldsymbol{r})$ acquires a nonzero expectation $\langle\psi(\boldsymbol{r})\rangle$. So, at zero temperature,

$$\langle\psi^\dagger(\boldsymbol{r})\psi(\boldsymbol{r})\rangle = \langle\psi^\dagger(\boldsymbol{r})\rangle\langle\psi(\boldsymbol{r})\rangle. \tag{4}$$

The order parameter is then defined as the expectation value of operator $\psi(\boldsymbol{r})$.

Despite the role of the order parameter in characterizing the symmetry breaking in a superconductor, we will now go on to show that it is possible to derive the exact (emergent) properties of superconductors simply from the assumption of broken electromagnetic gauge invariance without relying on the microphysics of Cooper pairing. To demonstrate this, we consider how the consequences of broken gauge invariance for superconductors can be derived from a formalism that deals solely with the general properties of the Goldstone mode, which is a long-wavelength fluctuation of the corresponding order parameter.[16] The general framework is set up in the following way: The electromagnetic gauge group $U(1)$ is the group of multiplication of fields $\psi(x)$ of charge q with the phases $\psi(x) \rightarrow \exp(i\Lambda q/\hbar)\psi(x)$. Because the q are integer multiples of $-e$, the phases Λ and $\Lambda + 2\pi\hbar/e$ are taken to be identical. The group $U(1)$ is spontaneously broken to Z_2, the subgroup consisting of $U(1)$ transformations with $\Lambda = 0$ and $\Lambda = \pi\hbar/e$. According to the general understanding of SSB, the system described by a Lagrangian with symmetry group G when in a phase in which G is broken to a subgroup H will possess a set of Nambu-Goldstone excitations described by fields that transform under the sym-

16. My discussion follows Weinberg (1986).

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metry group G like the coordinates of the coset space G/H. In this case there will be a single excitation described by a field $\varphi(x)$ that transforms under $G = U(1)$ like the phase Λ. The $U(1)$ group has the multiplication rule $g(\Lambda_1)g(\Lambda_2) = g(\Lambda_1 + \Lambda_2)$, so under a gauge transformation with parameter Λ, the field $\varphi(x)$ will undergo the transformation $\varphi(x) \rightarrow \varphi(x) + \Lambda$. Because $\varphi(x)$ parameterizes $U(1)/Z_2$ rather than $U(1)$, $\varphi(x)$ and $\varphi(x) + \pi\hbar/e$ are regarded as equivalent field values. The characteristic property of a system with broken symmetry is that the quantity $\varphi(x)$ behaves like a propagating field.

When one turns on the interaction of the superconductor with the electromagnetic fields **B** and **E**, their interaction is governed by the principle of local gauge invariance, where the Nambu-Goldstone field $\varphi(x)$ transforms under $U(1)$ with a space-time-dependent phase $\varphi(x) \rightarrow \varphi(x) + \Lambda(x)$. The potentials transform as usual, and all the other field operators are gauge invariant. The Lagrangian for the superconductor plus electromagnetic field is

$$L = \tfrac{1}{2} \int d^3x(\mathbf{E}^2 - \mathbf{B}^2) + L_m[\nabla\varphi - A,\ \varphi + A^0,\ \bar{\psi}], \tag{5}$$

where the matter Lagrangian is an unknown functional of the gauge-invariant combinations of $\partial_\mu\varphi$ and A_μ as well as the unspecified gauge invariants $\bar{\psi}$ representing the other excitations of the system. From L_m one obtains the electric current and charge density as variational derivatives

$$J(x) = \delta L_m/\delta A(x), \tag{6}$$

$$\varepsilon(x) = -\delta L_m/\delta A^0(x) = -\delta L_m/\delta\dot{\varphi}(x). \tag{7}$$

Because $\varphi(x)$ is the only non-gauge-invariant matter field, we can use just the Lagrangian equations of motion for $\varphi(x)$ to derive the equation for charge conservation. The structure of the functional matter Lagrangian need not be specified; instead one need only assume that in the absence of external electromagnetic fields the superconductor has a stable equilibrium configuration with vanishing fields

$$\nabla\dot{\varphi} - A = \dot{\varphi} + A^0 = 0. \tag{8}$$

The assumption that electromagnetic gauge invariance is spontaneously broken is equivalent to the claim that the coefficients of the terms in L_m of second order in $\nabla\dot{\varphi} - A$ and $\dot{\varphi} + A^0$ have nonvanishing expectation values, which makes φ behave like an ordinary physical excitation. As we shall see in deriving the consequences of these assumptions, the important point is that $\varphi(x)$ is not understood as the phase of a complex wave function used in an "approximate" model/treatment of electron pairing

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but, rather, a Nambu-Goldstone field that accompanies the breakdown of SSB. Put differently, we do not need a microscopic story about electron pairing and the approximations that go with it to derive the exact consequences that define a superconductor. Planck's constant $\hbar$ simply does not appear in the differential equations governing φ.

From this framework one can derive fundamental properties of superconductors such as the Meissner effect, flux quantization, and infinite conductivity. For example, in the case of flux quantization we have a current flowing through a superconducting loop in thick closed rings that is not affected by ordinary electrical resistance. It cannot decay smoothly but only in jumps. However, when dealing with infinite conductivity, one needs to take account of time-dependent effects. We saw above (7) that charge density is given by $-\varepsilon(x) = \delta L_m/\delta\dot{\varphi}(x)$, where $-\varepsilon(x)$ is the dynamical variable canonically conjugate to $\varphi(x)$. In the Hamiltonian formalism, H_m is a functional of $\varphi(x)$ and $\varepsilon(x)$ with the time dependence of φ given by

$$\dot{\varphi}(x) = \delta H_m/\delta(-\varepsilon(x)). \tag{9}$$

The voltage at any point is defined as the change in the energy density per change in the charge density at that point:

$$V(x) \equiv \delta H_m/\delta\varepsilon(x). \tag{10}$$

Consequently, the time dependence of the Nambu-Goldstone field at any point is given by the voltage $\dot{\varphi}(x) = -V(x)$. From this it follows that a piece of superconducting wire that carries a steady current with time-independent fields must have zero voltage difference between its ends, which is just what is meant by infinite conductivity. Without this zero voltage the gradient $\nabla\varphi(x)$ would have to be time dependent, leading to time-dependent currents or fields.

A crucial part of the story, which is significant for emergence, is the relation between infinite conductivity and the presence of an energy gap in the spectrum of the Cooper pairs. Typically it is the presence of an energy gap that distinguishes superconductivity from ordinary conductivity by separating the Fermi sea of paired electrons from their excited unpaired states. The process is thought to be due, essentially, to quantum mechanics, and it implies that there is a minimum amount of energy ΔE required for the electrons to be excited. As temperature increases to T_c, Δ goes to zero. Although some accounts of superconductors relate infinite conductivity directly to the existence of the gap, the treatment above shows that infinite conductivity depends only on the spontaneous breakdown of electromagnetic gauge invariance and would occur regardless of whether the particles producing the pairing were fermions instead of bosons. This is further evidenced by the fact that there are known examples of superconductors without gaps.

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The advantage of thinking about emergence in this way is that it encompasses and clarifies both the ontological and epistemological aspects. Although superconductors are constituted by their microscopic properties, their defining features (infinite conductivity, flux quantization, the Meissner effect) are immune to changes in those properties (e.g., replacing fermions with bosons).[17] In other words, symmetry breaking (here the breakdown of electromagnetic gauge invariance) provides the dynamical explanation of emergent phenomena, but the specific microphysical details are irrelevant; how the symmetry is broken is not part of the account. In that sense the emergent phenomenon is not reducible to its microphysical constituents, yet both retain full physical status. This also allows us to see why supervenience, understood in terms of a dependency relation, is inapplicable in explaining the part-whole aspects of emergent phenomena; there is no determining linkage between the micro and macro levels. But this is exactly as it should be. What makes an emergent phenomenon emergent is that it satisfies certain conditions, one of which is that it cannot be captured using a supervenience relation.

Although we can explain emergent phenomena in terms of the symmetry breaking associated with phase transitions, the physics inherent in this explanation is not entirely unproblematic. A well-known fact about phase transitions is that even though they take place in finite systems, they can be accounted for only by invoking the thermodynamic limit $N \to \infty$. The link between assumptions about infinite systems and the physics of symmetry breaking/phase transitions is provided by RG methods, which function as a framework for explaining how certain types of phenomena associated with phase transitions arise, as well as the similarity in behavior of very different phenomena at a critical point (universality). RG provides the interconnection between mathematics and physics; fleshing out those details will further exemplify beyond the account of electromagnetic gauge invariance the ontological independence of the microphysics in accounting for emergent phenomena.

5. Infinite Systems, Wholes/Parts, and Natural Kinds. Batterman (2002) has provided an account of emergence that emphasizes, among other things, universality: how systems with different microstructures are capable of displaying identical behavior. An important feature of universality is the stability that is characterized by the fact that if certain basic features of the system were to change (substituting one type of magnetic material for another), the critical behavior (e.g., magnetization) would remain stable under these perturbations. Recall that this was the case with

17. This is the sense in which we can refer to the properties of a superconductor as "model independent" and not causally linked to a specific microphysical account.

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the superconducting properties: the microstructure of the superconducting material was irrelevant in accounting for features like infinite conductivity.

In his discussion of asymptotic behavior and its connection to universal phenomena, Batterman (2002, 38) claims that the RG arguments provide an explanation of stability by showing us why different phenomena can exhibit the same behavior. The RG transformation shows us how to eliminate degrees of freedom that are irrelevant and hence provides a method for "extracting just those features . . . that are stable under perturbation of their microscopic details" (38).[18] More recently, Batterman (2011, 1038) has criticized Laughlin and Pines's sole reliance on "higher organizing principles" as the explanation of protectorates/emergent phenomena. The main focus of the criticism is that appeals to symmetry breaking as "an organizing principle independent of microphysical details" are hardly satisfactory when the real explanation of why the microphysical details are irrelevant or independent is given by the RG. Batterman argues that the infinities and divergences characteristic of the thermodynamic limit at criticality are absolutely essential for explaining emergent protected states of matter. The RG exploits the divergences of the correlation length (loss of characteristic length scale) to facilitate the comparison of different systems and demonstrate similarities in their behavior, similarities that are the basis for universality. The RG methods do provide "principled physical reasons" grounded in the physics and mathematics of systems in the thermodynamic limit for ignoring explanatory details about microphysical structure.

While I agree with many of Batterman's claims, one cannot ignore the importance of symmetry breaking in grounding an ontological account of emergence. Although the RG provides an explanatory framework that shows why microphysical details can be ignored, it does not give us the kind of physical dynamics required for the production of emergent phenomena. For that we need symmetry breaking and the accompanying phase transitions. In fact, because symmetry breaking rather than specific microphysical processes is responsible for emergent phenomena, one gets the type of stable behavior characteristic of universality.[19] While Batterman is certainly right that RG methods explain the importance of diver-

18. In other words, the existence of structurally stable scaling solutions reflects the fact that the behavior in the asymptotic regime has stabilized, allowing us to infer that there are genuine physical effects present and allowing us to ignore most of the micro details that are irrelevant for understanding, explaining, or predicting this behavior.

19. Batterman (2002) claims that RG arguments are not epistemic and the structural stability is ultimately explained by "the underlying microscopic physics of the systems being investigated" (44). This seems at odds with the view presented in Batterman (2011), but it is exactly this structural stability that is explained by symmetry breaking.

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gences and singularities for representing the kinks in phenomena that indicate phase transitions, their importance also extends beyond that by providing the ontological foundation for the infinities associated with the thermodynamic limit. Part of the significance of the RG is that it does not just show that we can focus on the energies or levels we are interested in, leaving out the rest, as we sometimes do in idealization and model building; but, as we see below, it illustrates and explains the ontological and epistemic independence between different energy levels—the defining features of emergent phenomena.

5.1. Renormalization Group Methods: Physics in the Borderlands. One of the hallmarks of a phase transition is that it exhibits the effects of a singularity over the entire spatial extent of the system. Theory tells us that this happens only in infinite systems (particles, volume, or sometimes strong interactions), so phase transitions produce a variation over a vast range of length scales. As a mathematical technique, RG allows one to investigate the changes to a physical system as one views it at different distance scales. This is related to a scale invariance symmetry that enables us to see how and why the system appears the same at all scales (self-similarity). As we saw above, phase changes of matter are often accompanied by discontinuities such as magnetization in a ferromagnet. At a critical point the discontinuity vanishes, so for temperatures above T_c, the magnetization is zero. We also saw that the nonzero value of the order parameter is typically associated with this symmetry breaking, so the symmetry of the phase transition is reflected in the order parameter (a vector representing rotational symmetry in the magnetic case and a complex number representing the Cooper pair wave function in superconductivity).

In RG calculations the changes in length scale result from the multiplication of several small steps to produce a large change in length scale l. The physical phenomena that reflect this symmetry or scale transformation are expressed in terms of observed quantities—mathematical representations of the symmetry operation. For example, quantities that obey rotational symmetry are described by vectors, scalars, and so forth, and in the case of scale transformations, power laws reflect the symmetries in the multiplication operations. The physical quantities behave as powers l^x, where x can be rational, irrational, positive, and so on. Behavior near the critical point is described using power laws in which some critical property is written as a power of a quantity that might become very large or small. The behavior of the order parameter, the correlation length, and the correlation function are all associated with power laws in which the "power" refers to the critical exponent or index of the system. Diverse systems with the same critical exponents (exhibiting the same scaling be-

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havior as they approach the critical point) can be shown via RG to share the same dynamical behavior and hence belong to the same universality class.

The correlation function $\mathbf{\Gamma}(r)$ measures how the value of the order parameter at one point is correlated to its value at some other point. If $\mathbf{\Gamma}$ decreases very fast with distance, then faraway points are relatively uncorrelated and the system is dominated by its microscopic structure and short-ranged forces. A slow decrease of $\mathbf{\Gamma}$ implies that faraway points have a large degree of correlation or influence on each other, and the system thus becomes organized at a macroscopic level. Usually, near the critical point ($T \to T_c$), the correlation function can be written in the form

$$\mathbf{\Gamma}(r) \to r^{-p} \exp(-r/\xi),$$

where ξ is the correlation length. This is a measure of the range over which fluctuations in one region of space are correlated with or influence those in another region. Two points separated by a distance larger than the correlation length will each have fluctuations that are relatively independent. Experimentally, the correlation length is found to diverge at the critical point, which means that distant points become correlated and long-wavelength fluctuations dominate. The system "loses memory" of its microscopic structure and begins to display new long-range macroscopic correlations.

The iterative procedure associated with RG results in the system's Hamiltonian becoming more and more insensitive to what happens on smaller length scales. As the length scale changes, so do the values of the different parameters describing the system. Each transformation increases the size of the length scale so that the transformation eventually extends to information about the parts of the system that are infinitely far away. Hence, the infinite spatial extent of the system becomes part of the calculation, and this behavior at the far reaches of the system determines the thermodynamic singularities included in the calculation. The change in the parameters is implemented by a beta function

$$\{\tilde{J}_k\} = \beta(\{J_k\}),$$

which induces what is known as an RG flow on the J space. The values of J under the flow are called running coupling constants. The phase transition is identified as the place where the RG transformations bring the couplings to a fixed point, with further iterations producing no changes in either the couplings or the correlation length. The fixed points give the possible macroscopic states of the system at a large scale. So, although the correlation length diverges at the critical point, using the RG equations reduces the degrees of freedom, which, in effect, reduces the correlation length.

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The important point that distinguishes RG from previous renormalization methods is that the number and type of relevant parameters are determined by the outcome of the renormalization calculation.[20] After a sufficient number of successive renormalizations, all the irrelevant combinations have effectively disappeared, leaving a unique fixed point independent of the value of all the irrelevant couplings. Assuming that a fixed point is reached, one can find the value that defines the critical temperature, and the series expansions near the critical point provide the values of the critical indices.[21] The fixed point is identified with the critical point of a phase transition, and its properties determine the critical exponents. The latter characterize the fluctuations at the critical point, with the same fixed-point interactions describing a number of different types of systems. In that sense RG methods provide us with physical information concerning how and why different systems exhibit the same behavior near the critical point (universality).

The basis of the idea of universality is that the fixed points are a property of transformations that are not particularly sensitive to the original Hamiltonian. What the fixed points do is determine the kinds of cooperative behavior that are possible, with each type defining a universality class. The important issue here is not just the elimination of irrelevant degrees of freedom; rather it is the existence or emergence of cooperative behavior and the nature of the order parameter (associated with symmetry breaking) that characterizes the different kinds of systems. The coincidence of the critical indices in very different phenomena was inexplicable prior to RG methods. Part of the success of RG was showing that the differences were related to irrelevant observables—those that are "forgotten" as the scaling process is iterated. Another significant feature of RG is that it showed how, in the long-wavelength/large-space-scale limit, the scaling process in fact leads to a fixed point when the system is at a critical point, with very different microscopic structures giving rise to the same long-range behavior.

20. In earlier versions, parameters like mass, charge, etc. were specified at the beginning, and changes in length scale simply changed the values from the bare values appearing in the basic Hamiltonian to renormalized values. The old renormalization theory was a mathematical technique used to rid quantum electrodynamics of divergences but involved no "physics."

21. The equivalence of power laws with a particular scaling exponent can have a deeper origin in the dynamical processes that generate the power-law relation. Phase transitions in thermodynamic systems are associated with the emergence of power-law distributions of certain quantities, whose exponents are referred to as the critical exponents of the system. Diverse systems with the same critical exponents—those that display identical scaling behavior as they approach criticality—can be shown, via RG, to share the same fundamental dynamics.

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What this means for our purposes is that RG equations illustrate that phenomena at the critical point have an underlying order. Indeed what makes the behavior of critical point phenomena predictable, even in a limited way, is the existence of certain scaling properties that exhibit universal behavior. The problem of calculating the critical indices for these different systems was simplified using the RG because it showed why the different kinds of transitions such as liquid gas, magnetic, alloy, and so forth share the same critical exponents experimentally and can be understood in terms of the same fixed-point interaction.

What, then, are the implications of this story for emergence? Although fundamental properties of superconductors can be derived from the assumption of broken electromagnetic gauge invariance, a full explanation involves the RG framework. If we consider how RG explains the behavior of phenomena at the critical point, we see that it furnishes a physical understanding of the relation between the dynamics of the system and assumptions about $T \to \infty$. It shows us how phase transitions are connected not only to symmetry operations that are part of the microscopic features of the system (as in the case of spin directions in a ferromagnet) but also to the topology of an infinite spatial region and why the latter is crucial for determining, within the RG calculations, that a phase transition has taken place. RG equations provide us with further elucidation as to why the dynamical details are unimportant for critical point behavior such as the emergence of the universal properties of superconductors.

Consequently, RG aptly illustrates the nature of the ontological relation between an emergent phenomenon/property and its microphysical constituents. As I noted above, epistemic independence—the fact that we need not appeal to micro phenomena to explain macro processes—is not sufficient for emergence since it is also a common feature of physical explanation across many systems and levels. Emergence is characterized by the fact that we cannot appeal to microstructures in explaining or predicting these phenomena despite their microphysical base. RG methods reveal the nature of this ontological independence by demonstrating the features of universality and how successive transformations give you a Hamiltonian for an ensemble that contains very different couplings from those that governed the initial ensemble. Finally, and perhaps most importantly from a philosophical perspective, we can understand the importance of the physics behind the notion of an infinite spatial extension for establishing long-range order. What this means is that although phase transitions are connected with symmetry breaking that involves microphysical constituents (e.g., spin directions and Cooper pairing), it also involves a topology that extends over an infinite region of space; it is the latter that is relevant in determining the type of cooperative behavior that

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characterizes the universal nature of emergent phenomena. RG reveals how the details are lost as the length scale changes.

Before turning to the final part of the argument, I should mention some pertinent objections to the account presented above.[22] Most of the worries surrounding emergence are related to the issue of reduction and whether the former presents a telling case against the latter. Why, for example, should universality be considered more effective against reduction than multiple realizability arguments? Moreover, one could also claim that universality and symmetry breaking are part of fundamental physics, and hence the emergentist story actually incorporates elements of reduction. Since the multiple realizability arguments in the literature (e.g., Kim 1992) bear on the issue of natural kinds, the answer is perhaps best left until the next subsection, where that issue is specifically addressed. The objection concerning symmetry breaking and fundamental physics can be answered as follows: Although what defines fundamental physics is not rigidly designated, it unequivocally includes explanations that invoke microphysical entities and theories/laws that govern them. When symmetry breaking features in microphysical theories, its role requires specific details of the "breaking," that is, an account that appeals to microstructures as in the case of the Higgs mechanism. The point of the superconductivity example was to illustrate that details of symmetry breaking were not necessary for the derivation of infinite conductivity; all that was required was an assumption that electromagnetic gauge invariance was spontaneously broken. So, while SSB bears some relation to microphysical explanation, as a general process it does not qualify as "fundamental" in the way the term is typically understood. The existence of universal phenomena further bears this out. Because we witness identical behavior at the critical point from phenomena that have completely different microstructures, and the explanation ignores those microstructures, the notion of fundamental physics is rendered inapplicable.

Here the reductionist might respond that surely it is possible in principle to derive macro phenomena from micro properties given the Schrodinger equation and the appropriate initial conditions (i.e., God could do it). But again, universality speaks against this possibility. If we suppose that micro properties could determine macro properties in cases of emergence, then we have no explanation of how universal phenomena are even possible. Because the latter originate from vastly different micro properties, there is no obvious ontological or explanatory link between the micro and macro levels. More specifically, while fluids and magnets both arise out of microphysical constituents, their behavioral similarity at crit-

22. I am grateful to the anonymous referees for raising these points.

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icality is independent of and immune to changes in those micro constituents. This is what separates emergent phenomena from resultant properties and aggregates. In the latter cases there is a direct physical link between the micro and macro that is absent in cases of emergence. The fact that God might be able to do it offers us no useful information for understanding the differences between emergence and reduction and to that extent represents an irrelevant variable.

5.2. Emergence and Natural Kinds. The final piece of the puzzle concerns how to identify phenomena as truly emergent as opposed to just a different form or state of its basic underlying constituents. In other words, we need some way of characterizing similarities and differences between different *kinds* as opposed to *states* of matter, especially given the importance of micro-macro independence for emergence. Identifying natural kinds and similarity relations is a well-worn philosophical problem. However, because emergent phenomena are not determined by their microphysical constituents, we have no basis for an account of natural kinds as they are typically understood; some other method of identification is required.

Here again the physics of phase transitions provides a possible solution by appealing to the reversible adiabatic map. In many physical systems, changes in the underlying equations of motion require a check at each stage to ensure that the ground state and low-lying excitations have evolved in a one-to-one way.[23] If the system contains a small number of particles, this is not necessary since the mapping is guaranteed to be one-to-one by the adiabatic principle. However, if the system contains a thermodynamically large number of particles, a small change to the equations of motion can result in a violent rearrangement of the ground state and low-lying excitations, causing a breakdown of the one-to-one mapping. In such cases we have a quantum phase transition that functions as the criterion for individuation. In other words, the relevant distinction is between different phases of matter rather than different types or kinds. Two states are the same phase of matter if they can be slowly transformed into each other without encountering a quantum phase transition and are different if they cannot. On this definition, metals, insulators, and superconductors are all different whereas two metals with slightly different electron-electron repulsion strength are the same.

This notion of sameness is rather counterintuitive from the point of view of fundamental physics, but that is exactly the point. When thinking in terms of reduction and derivation from first principles, our concern is

23. For a complete discussion, see Laughlin (1999).

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to differentiate matter into specific kinds according to its defining properties, as in the case of classifying elementary particles according to their quantum number, charge, and so forth. Elements are differentiated on the basis of their atomic number and substances like water according to their chemical composition and molecular/atomic structure. This process, whereby phenomena are thought to have essential features, presupposes an underlying microphysical structure that underwrites and justifies the classification. Moreover, an explanation of these properties can supposedly be deduced from first principles. But in the case of emergent phenomena, this relation to microphysics is absent, so our classification scheme must rely on a different strategy when grouping phenomena according to their universality class. The relevant issue when dealing with the different "levels" characteristic of emergence is not simply that phenomena at different scales obey different fundamental laws. While general relativity is required on the cosmological scale and quantum mechanics on the atomic, these differences do not involve emergent behavior in the sense discussed above.

The final objection to consider concerns the relation between universality and multiple realizability (MR) and whether the former presents us with stronger arguments against reduction than the latter. Initially one might think that universality is simply a type of MR, and to some extent this is true. The possibility that macro-level regularities are heterogeneously multiply realized is evidenced by the fact that liquids and gases exhibit the same type of behavior at the critical point while having radically different microstructures. Critics of MR, notably Kim (1992), invoke the claim that proper scientific "kinds" are individuated on the basis of causal powers, so the causal properties of the macro phenomenon are determined by their micro realizers; hence mental properties, if they are multiply realized, cannot be scientific kinds. These arguments from philosophy of mind are disanalogous in an important sense: the physical or scientific nature of emergent phenomena is not in question; so the issue is whether examples of universal behavior fall prey to some form of reduction in virtue of a supervenient relation to their microphysical base.[24]

Here again the answer is "no." The dependence relation required for supervenience is clearly lacking in cases of universal behavior since fixing the subvenient properties in no way fixes the supervenient ones and vice versa: the whole is substantially different from the sum of its parts. In cases of supervenience, any change in higher-level properties requires a difference in lower-level properties, something that fails to occur in cases

24. Although there are arguments for the claim that supervenience need not entail reduction, my argument rests on the fact that even the requirements of supervenience fail in the case of universal phenomena.

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of emergence. For example, superconducting metals that constitute different natural kinds will have different transition temperatures, but they exhibit the same properties as a consequence of broken electromagnetic gauge invariance. The claim so often associated with supervenience—there can be no A difference without a B difference (where A properties supervene on B properties)—is irrelevant here since once the system reaches the critical point and universal behavior (A properties) is dominant, information about micro-level structure (B properties) is simply lost. Natural kind behavior that appeals to the micro properties invoked by Kim is inapplicable in cases of emergence.

Again, this is not simply a matter of ignoring irrelevant details as one does in the formulation of laws or levels of explanation. In those cases, changes in macrostructure are determined by changes in microstructure and vice versa. In emergence the important physical relationships involve long wavelengths and cooperative behavior that results from spontaneous symmetry breaking. We saw above that emergent properties that define superconductors are a consequence of broken electromagnetic gauge invariance and can be derived from a formalism that deals solely with the general properties of the Nambu-Goldstone mode. In deriving these properties the important point is that $\varphi(x)$ is not understood as the phase of a complex wave function describing the microphysics of electron pairing but rather a Nambu-Goldstone field that accompanies the breakdown of SSB. We also know that the Goldstone mode is identified as a long-wavelength fluctuation of the corresponding order parameter. It is these fluctuations that are responsible for the collective dynamics that occur at the critical point, giving rise to emergent phenomena. We have also seen how RG incorporates these long-wavelength fluctuations in terms of the infinite spatial extension of the system and how the scaling process leads to fixed points that identify and define the emergent cooperative behavior. In that sense, we have two different but related routes to explaining micro independence, the top-down approach exemplified by SSB and the bottom-up approach illustrated by RG methods. The systematic treatment provided by RG enables us to see behind the abstract mathematics of the thermodynamic limit and divergence of the correlation length to fully illustrate the physical processes involved in emergent universal phenomena.

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