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Emergence and mechanism in the fractional quantum Hall effect

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ABSTRACT

For some authors, an adequate notion of emergence must include an account of a mechanism by means of which emergent behavior is realized. This appeal to mechanism is problematic in the case of the fractional quantum Hall effect (FQHE). There is a consensus among physicists that the FQHE exhibits emergent phenomena, but there are at least four alternative explanations of the latter that, arguably, appeal to ontologically distinct mechanisms, both at the microphysics level and at the level of general organizing principles. In light of this underdetermination of mechanism, one is faced with the following options: (I) deny that emergence is present in the FQHE; (II) argue for the priority of one mechanistic explanation over the others; or (III) temper the desire for a mechanism-centric account of emergence. I will argue that there are good reasons to reject (I) and (II) and accept (III). In particular, I will suggest that a law-centric account of emergence does just fine in explaining the emergent phenomena associated with the FQHE.

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1. Introduction

For some authors, an adequate notion of emergence must include an account of a mechanism by means of which emergent behavior is realized. These authors maintain that without such an account, emergence risks becoming a trivial concept that is appealed to whenever we lack epistemic access to a physical phenomenon, or the technical skill required to provide a complete description of it. According to Mainwood (2006, 284), for instance, "…emergent properties are not a panacea, to be appealed to whenever we are puzzled by the properties of large systems. In each case, we must produce a detailed physical mechanism for emergence, which rigorously explains the qualitative difference that we see with the microphysical". The mechanism of most interest to Mainwood in the context of condensed matter physics is spontaneous symmetry breaking (SSB). Morrison (2012, 160) similarly claims that emergence in condensed matter systems must be underwritten by a physical mechanism, and in particular SSB: "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." Finally, Lancaster and Pexton (2015) note that while the fractional quantum Hall effect (FQHE) cannot be explained in terms of SSB, nevertheless a physical mechanism can be associated with it; namely, what Wen (2013) refers to as "long-range entanglement", and it is in terms of this mechanism that emergence in the FQHE should be understood.

The aim of this essay is to question this mechanism-centric view of emergence by considering Lancaster and Pexton's example of the FQHE in a bit more detail.[1] The consensus among physicists is that this effect exhibits emergence, but there are at least four alternative explanations of it that, arguably, appeal to distinct ontological mechanisms, at both the microphysical level and the level of what have been called higher organizing principles. These explanations include (1) the Laughlin ground state account, (2) the composite fermion account, (3) the composite boson account, and (4) the topological order account. The FQHE is described by these accounts as (i) a many-body Coulomb effect of electrons, (ii) a one-body effect of composite fermions, (iii) a many-body effect of composite bosons, and (iv) a many-body entangled effect of electrons, respectively. These ontologically distinct microphysical

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[1] In addition to Lancaster and Pexton (2015), recent philosophical discussions of the FQHE include Shech (2015), and Lederer (2015).

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mechanistic accounts are underwritten by the following ontologically distinct high-level mechanistic accounts: (a) localization (accounts 1 and 2); (b) spontaneous symmetry breaking (account 3), and (c) long-range entanglement (account 4).

In light of this underdetermination of mechanism, one is faced with the following options: (I) deny that emergence is present in the FQHE; (II) argue for the priority of one mechanistic explanation over the others; or (III) temper the desire for a mechanism-centric account of emergence. I will argue that there are good reasons to reject (I) and (II) and accept (III). In particular, I will suggest that emergence in the FQHE is best described in terms of a law-centric view of emergence. According to this view, emergence is characterized, in part, by novelty, and novelty is underwritten by an appeal to distinct laws, cashed out as the equations of motion associated with formally distinct Lagrangian densities.

Section 2 contrasts mechanism-centric and law-centric views by means of a particular notion of emergence relevant to the FQHE. Sections 3 and 4 describe the quantum Hall effect and alternative mechanistic accounts of the FQHE. Section 5 makes the case for a law-centric view of emergence in the FQHE.

2. Two versions of emergence

I will make the distinction between the mechanism-centric and law-centric views of emergence in terms of a particular ontological account of emergence. The intent is to capture a sense of emergence that is relevant to the FQHE, on the one hand, and yet general enough to underwrite the mechanism-centric/law-centric distinction, on the other. The account I will consider is based on two conditions, inspired by Mainwood (2006, 20):

(a) *Microphysicalism*: An emergent system is composed of microphysical systems that comprise the fundamental system and that obey the fundamental system's laws.
(b) *Novelty*: The properties of the emergent system are *dynamically independent* of, and *dynamically robust* with respect to, the properties of the fundamental system.

Microphysicalism is intended to capture the intuition that an emergent system does not “float free” of the fundamental system from which it emerges; rather, there must be a sense in which the fundamental system ontologically determines the properties of the emergent system. This sense cannot be too strong, however, and this is the motivation for *novelty*. To say an emergent property is *dynamically independent* of a fundamental property is to say the former is independent of the dynamics that governs the latter. To say an emergent property is *dynamically robust* with respect to a fundamental property is to say the former is dynamically independent of the latter, and remains so, despite changes in the dynamics of the latter.

Dynamical independence is supposed to guarantee that, while the emergent system is ontologically determined in a minimal sense by the fundamental system, insofar as it is ultimately composed of microphysical systems that comprise the fundamental system and that obey the fundamental system’s laws, it is not completely determined by the fundamental system, insofar as, even though its *microphysical constituents* obey the fundamental system's laws, it does not; hence the dynamics of the fundamental system fails to specify how the emergent system behaves. One way (but perhaps not the only way) to cash out the notion of dynamical independence is in terms of a mathematical distinction between equations of motion. Thus if the equations of motion that govern the properties of a given system are distinct from those that govern the properties of another system, the former properties can be said to be dynamically independent of the latter properties.

Dynamical robustness is supposed to guarantee that this independence is persistent; it is not just due to a particular realization of the fundamental system’s dynamics, but rather persists under slight perturbations of the latter. Suppose, for instance that the dynamics of systems S and $S^{'}$ are encoded in equations of motion that differ only in an interaction term (suppose $S^{'}$ is a relativistic scalar field with an interaction described by a potential $V^{'}(\varphi)$, and S is a relativistic scalar field with an interaction described by a potential $V(\varphi) \neq V^{'}(\varphi)$. Then $S^{'}$ is dynamically independent of S, insofar as the behavior of (the properties of) $S^{'}$ will not be determined by the dynamics of (the properties of) S. But $S^{'}$ is not dynamically robust with respect to S, insofar as a change in the dynamics of S that maps $V(\varphi)$ onto $V^{'}(\varphi)$ will result in a dynamics that completely determines the behavior of $S^{'}$. The failure of dynamical robustness in this example suggests that $S^{'}$ is not dynamically independent of S in an essential way. Rather, $S'$and S seem better understood as the same system undergoing different interactions.

Note that when the dynamics of S' and S are sufficiently distinct, dynamical robustness is somewhat trivial. For instance, if $S^{'}$ is a scalar field and S is a Maxwell field, then $S^{'}$ is dynamically independent of, and dynamically robust with respect to, S. Changes to the dynamics of the Maxwell field obviously will not map its dynamics onto the dynamics of the scalar field, simply because the dynamics of a Maxwell field is unrelated in any way to the dynamics of a scalar field. Dynamical robustness becomes more interesting when the dynamics of $S^{'}$ and S are related in a way that does not affect their independence. On the surface, this may seem strange: how can two types of dynamics be *independent* of each other yet still be *related*. Arguably, this is the case when the dynamics of $S^{'}$ encodes the low-energy dynamics of S; i.e., when the theory $T^{'}$ that describes $S^{'}$ is a low-energy effective theory of a high-energy theory T that describes S. In this case, $S^{'}$ is dynamically independent of S, insofar as $T^{'}$ and T are formally distinct (at the level of equations of motion, say). Moreover, more than one high-energy theory can be associated with the same low-energy effective theory $T^{'}$: any theory T^{*} that differs from T only in its high-energy degrees of freedom will have the same low-energy effective theory T' as T. In other words, changes to the high-energy degrees of freedom of T will not affect its relation to $T^{'}$. This suggests that, in such cases, S' is “non-trivially” dynamically robust with respect to S.[2]

Dynamical independence and dynamical robustness are intended to be instances of Butterfield (2011, 921) more general concepts of “novelty” and “robustness”, which are defined relative to a comparison class as “not definable from the comparison class”, and “the same for various choices of, or assumptions about, the comparison class”, respectively. Note that the above account emphasizes the role that dynamics plays in underwriting these concepts, but remains agnostic about how dynamics is to be understood (i.e., whether in terms of causes, mechanisms, dynamical

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[2] To make this a bit more precise would require fleshing out some of the details involved in the construction of an effective field theory (EFT) (see, e.g., Bain, 2013, 258–61). For EFT aficionados, dynamical independence of $S^{'}$ from S holds insofar as the effective Lagrangian density $\mathcal{L}_{T^{'}}[\theta]$ that encodes T' is formally distinct from the high-energy Lagrangian density $\mathcal{L}_{T}[\phi]$ that encodes T, where ϕ are the degrees of freedom of S and θ are the degrees of freedom of $S^{'}$. The construction of $\mathcal{L}_{T'}$ assumes that there is a characteristic energy Λ with respect to which ϕ can be split into a high-energy regime and a low energy regime θ. Dynamical robustness of $S^{'}$ with respect to S holds insofar as, (a) we assume that T is “realistic” in the sense of being 4-dim, and this entails that $T^{'}$ is characterized by a finite number of “marginal” and “relevant” couplings (i.e., couplings that are significant for energies $E < < \Lambda$), which encode the contributions from T; and (b) this finite number only depends on the dimension of spacetime and the symmetries at low-energies; in particular, the effects of any other high-energy theory T^{*} that differs from T only in its high-energy degrees of freedom with respect to Λ can be encoded in the same finite number of relevant and marginal couplings in $T^{'}$.