Title: Why is More Different?

Date: Oct 28, 2011 10:00 AM

URL: http://pirsa.org/11100062

Abstract: Emergent phenomena are typically described as those that cannot be reduced, explained nor predicted from their microphysical base. However, this characterization can be fully satisfied on purely epistemological grounds, leaving open the possibility that emergence may simply point to a gap in our knowledge of these phenomena. By contrast, Anderson

ISSUES:

1. What's the relation between micro and macro?

2. What's the role of symmetry?

3. What's the nature of prediction in emergent phenomena?

OUTLINE

1. INTRODUCTION – DIFFERENT ACCOUNTS OF EMERGENCE
2. EMERGENCE AND QUANTUM PROTECTORATES
3. EFFECTIVE THEORIES AND SSB
4. SSB AND THE ORDER PARAMETER
5. CONCLUSIONS

1. INTRODUCTION

TWO DIFFERENT CONCEPTIONS OF EMERGENCE:

Philosophical Definition of Emergent Phenomena: Those that cannot be reduced, explained nor predicted from their microphysical base (using first principles).

- This characterization can be fully satisfied on purely **epistemological** grounds, suggesting that emergence may simply point to a gap in our knowledge of these phenomena .

- Also relates to notions of novelty and su

Anderson's (1972) claim that the whole in not only greater than but very "*different from*" its parts suggests an **ontological** dimension to emergence.

QUESTION: How can we explain superconductivity as an emergent phenomenon in a way that captures an element of ontological distinctness from the micro-ontology of Cooper pairing?

What's the "*difference*" that characterizes emergence (as opposed to resultants or aggregates)?

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QUESTION: How can we explain superconductivity as an emergent phenomenon in a way that captures an element of ontological distinctness from the micro-ontology of Cooper pairing?

What's the "*difference*" that characterizes emergence (as opposed to resultants or aggregates)?

- RG methods that show how critical point behaviour is insensitive to the Hamiltonian governing the microphysical base

But is this really sufficient??

- It is possible to claim that the independence simply reflects the fact that different 'levels' are appropriate when explaining physical behavior, e.g. we needn't appeal to micro properties in explaining fluid behavior.

- Is emergence simply an appeal to novelty and "levels of explanation"?
- So, how can we characterize emergence such that the ontological independence is preserved in a way that reflects an ontological/physical difference?

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Need to distinguish properties of superconductors:

- Infinite conductivity, flux quantization and the Meissner effect are exact properties of all superconductors that can be derived from the breakdown of electromagnetic gauge invariance.

- These are different from transition temperatures, coherence lengths, etc. which require a microphysical explanation via approximations; these aren't emergent in the QP sense.

- But we also think of emergent phenomena as the result of collective excitations – the collective dynamics of the system's components.

- What is the connection between the higher organizing principles and the micro level?

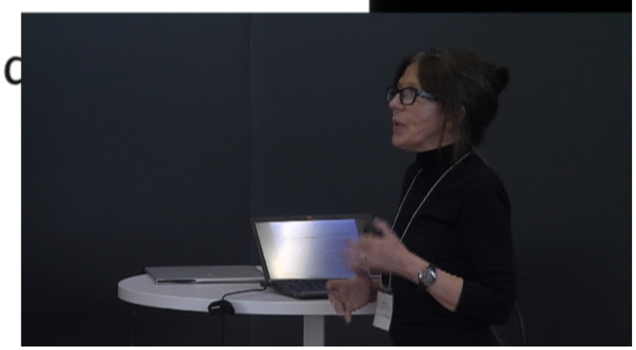
3. Effective Theories and SSB

- Emergent Phenomena are often associated with Effective Theories that focus on appropriate degrees of freedom to describe phenomena at a given length scale, while ignoring those at shorter distances (or higher energies).

- RG is a systematic method for integrating out short distance degrees of freedom.

- EFTs are approximate theories: **E.G.** BCS theory of superconductivity.

- BCS involves electrons in a metal interacting with lattice vibrations (phonons).
- Phonons cause attractive interactions between electrons causing them to form Cooper Pairs.
- Length scale of the pairs is much larger than the wavelength of the phonons.
- Possible to neglect the phonon dynamics and construct a theory (BCS) with two electrons effectively interacting at a point.
- Cooper pairing is the micro causal story c superconductivity.



- How does this approximate theory allow us to derive the *exact* properties of a superconductor (infinite conductivity, zero resistance etc)?
- How do we get exact results from approximations?
- They follow from the fact that a superconductor is a material in which electromagnetic gauge invariance is spontaneously broken.

- The relevant symmetry group U(1) is the group of two dimensional rotations.
- These act of the two dimensional vector whose components are the real and imaginary parts of the electron field (the QM operator that in matter QFTs destroys electrons).
- The symmetry breaking leaves unbroken a rotation by 180 degrees which changes the sign of the electron field.

- As a result, products of an even number of electron fields have non-vanishing expectation values in a superconductor (but a single electron field doesn't).

- All of the exact properties of the superconductor (infinite conductivity, quantization of magnetic flux, etc.) follow from the assumption that em gauge invariance is broken in exactly this way.

- Consequences of broken gauge invariance for superconductors can be derived from a formalism that deals solely with the general properties of the Goldstone mode (a long-wavelength fluctuation of the corresponding order parameter).

Weinberg, "Superconductivity for Particular Theorists", *Prog. Theor. Phys*. 86 (1986)

Weinberg, *Quantum Theory of Fields.* Vol.2 Modern Applications CUP (1996)

The characteristic property of a system with broken symmetry is:

(1) the quantity $\phi(x)$ (N–G field) behaves like a propagating field.

(2) the second variational derivative of L with respect to $\phi\,(x)$ has non–vanishing expectation value.

- In deriving the consequences of these assumptions (QPs), the important point is that $\phi(x)$ is not understood as the phase of a complex wave function used in an "approximate" model/treatment of electron pairing, but rather, a Nambu–Goldstone field that accompanies the breakdown of SSB.

- **Put differently**: we don't 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.

- In this case the effective theory BCS is not the source of the explanation of emergent phenomena.
- Although some accounts of superconductors relate infinite conductivity directly to the existence of the gap, if infinite conductivity depends only on the spontaneous breakdown of electromagnetic gauge invariance then the micro explanation of the gap doesn't matter.
- So, what about the micro physics and Cooper pairing?
- What's the role of the order parameter in this framework?

4. SSB, Order Parameter & RG

- Symmetry breaking is typically reflected in the behaviour of an order parameter – a thermodynamic variable that describes both the nature and magnitude of a broken symmetry.

- In the superconducting case the order parameter is the amplitude $\langle \phi \rangle$ of the macroscopic ground state wave function of the Cooper pairs (a complex number).

- The Nambu–Goldstone mode is identified with a long wave–length fluctuation of the order parameter.
- The correlation function $\Gamma(r)$ measures how the value of the order parameter at one point is correlated to its value at some other point.

- As the correlation length (the distance over which fluctuations in one region of space are correlated with those in another) diverges at the critical point 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.

- As the length scale changes, so do the values of the different parameters describing the system with each transformation increasing the size of the length scale so 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 behaviour at the far reaches of the system determines the thermodynamic singularities included in the calculation.
- The phase transition is identified as the place where the RG transformations bring the couplings to a fix

- 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.

- Fixed points determine the kinds of cooperative behaviour that are possible.

- The important issue here isn't just the elimination of irrelevant degrees of freedom, rather it is the *existence or emergence of cooperative behaviour* and the nature of the order parameter (associated with symmetry breaking) that characterizes the different kinds of systems.

- 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.

RE: ONTOLOGICAL INDEPENDENCE

- 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.

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- Showing the independent derivation from symmetry principles isn't enough, you need to also show the micro–macro relation which is what the RG explanation does.
- What this means for our purposes is that RG equations illustrate that phenomena at critical point have an underlying order.
- What makes the behaviour of critical point phenomena predictable, even in a limited way, is the existence of certain scaling properties that exhibit 'universal' behaviour.

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CONCLUSIONS:

How and why is more different?

- Because the collective long range behaviour allows for micro-independence in specific systems and universality across systems.
- 2 different routes to show micro independence – SSB and RG (info is lost as length scale changes). Top down and bottom up.

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