Title: Concepts of Emergence Appropriate for Effective Field Theories

Date: Oct 26, 2011 11:30 AM

URL: http://pirsa.org/11100054

Abstract: This talk considers the extent to which the intertheoretic relation between an EFT and its (possibly hypothetical) high-energy theory supports a notion of emergence. When a high-energy theory exists, this relation is based on a process that involves the elimination of high-energy degrees of freedom. This elimination results in an EFT that formally bears little resemblance to the high-energy theory. I investigate the extent to which this lack of formal resemblance underwrites notions of novelty and autonomy that may be appropriately associated with emergence. I'll begin by reviewing the method by which an EFT is constructed from a high-energy theory by means of integrating out high-energy degrees of freedom from the latter. I'll then review a number of attempts in the philosophical literature to explicate the notion of emergence. I'll first consider general phillosophical accounts that identify emergence as supervienience without reduction, or as associated with various notions of autonomy (reductive, predictive, causal, and/or explanatory). I'll then consider more specific accounts related to physics in particular, including Batterman's (2002) notion of the failure of a limiting relation, and Mainwood's (2006)description of the concept of emergence associated with the claims of condensed matter physicists (e.g., Anderson 1972). This account conceives emergence as microphysicalism (the claim that emergent properties/entities are ultimately composed of microphysical properties/entities) coupled with novelty cashed out in terms of a mechanism (in this case spontaneous symmetry breaking) that produces a reduced phase space supporting (emergent) properties that are not explicitly defined on the initial phase space. A similar account is given by Wilson (2010), who explicates novelty in terms of an elimination of degrees of freedom. I'll suggest that Batterman's account does not quite succeed in the context of EFTs (simply put, the relation between an EFT and its high-energy theory cannot be described in terms of the failure of a limiting relation), and while the elimination of degrees of freedom does occur in EFTs, this process is different from the process described by Mainwood and Wilson (in particular, the phase space of an EFT is not, in general, a reduced phase space of a high-energy theory). This suggests that a notion of emergence as microphysicalism coupled with novelty can be applicable to the EFT context, as long as an appropriate mechanism that underwrites novelty, other than spontaneous symmetry breaking, can be identified. This mechanism perhaps can be identified simply as the particular approximation scheme employed in the construction of an EFT.

A Concept of Emergence for EFTs

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Brooklyn, New York

1. How to Construct an EFT.
2. The EFT Intertheoretic Relation.
3. Emergence in EFTs.
4. Other Notions of Emergence.
5. Conclusion.

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1. How to Construct an EFT

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Given a "high-energy" Lagrangian $\mathcal{L}[\phi(x)]$:

(I) Identify and eliminate high-energy degrees of freedom.

- Choose a cutoff Λ and decompose $\phi(x) = \phi_H(x) + \phi_L(x)$.
- Perform integration over $\phi_H(x)$:

$$Z = \int \mathcal{D}\phi_L \mathcal{D}\phi_H e^{i\int d^D x \mathcal{L}[\phi_L, \phi_H]} = \int \mathcal{D}\phi_L e^{i\int d^D x \mathcal{L}_{eff}[\phi_L]}$$

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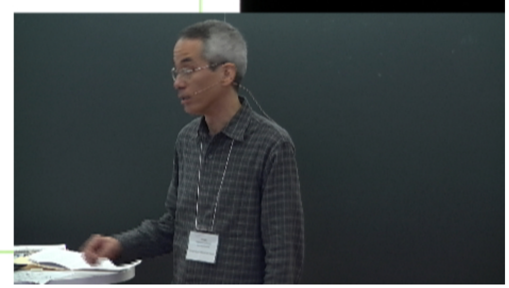
(1) $\mathcal{L}[\phi(x)]$ has ∞DOF, $\mathcal{L}_{eff}[\phi_L(x)]$ has finite DOF.

(2) $\mathcal{L}_{eff}[\phi_L]$ is formally distinct from $\mathcal{L}[\phi]$.

(3) $\phi_L(x)$ is "dynamically" distinct from $\phi(x)$.

(4) Relation between $\mathcal{L}_{eff}$ and $\mathcal{L}$ *cannot* be presented as a formal derivation.



2. The EFT Intertheoretic Relation

Example 1: Superfluid Helium 3-A

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- With respect to T_c, low-energy degrees of freedom are bosonic hydrodynamical sound waves $\varphi(x)$:

$$\mathcal{L}_{eff} = -n[\partial_t\varphi + \tfrac{1}{2m}(\partial_i\varphi)^2] + \rho[\partial_t\varphi + \tfrac{1}{2m}(\partial_i\varphi)^2]^2 \qquad (2)$$

- *Non-relativistic* Lagrangian density. (Schakel 1998)
- φ encodes phase of order parameter.
- n and ρ are the fermion number density and density of states.

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- With respect to ground state, low-energy degrees of freedom are massless fermions coupled to a Maxwell field:

$$\mathcal{L}_{eff} = \bar{\Psi}\gamma^{\mu}(\partial_{\mu} - qA_{\mu})\Psi + \mathcal{L}_{Max} \qquad (3)$$

- *Relativistic* Lagrangian density. (Volovik 2003)

2. The EFT Intertheoretic Relation

Comparison

$$\mathcal{L} = \Psi^\dagger\{i\partial_t - (\partial_i^2/2m + \mu)\}\tau_3\Psi + \mathcal{L}_{int}[\Psi, \Delta] \quad (1)$$

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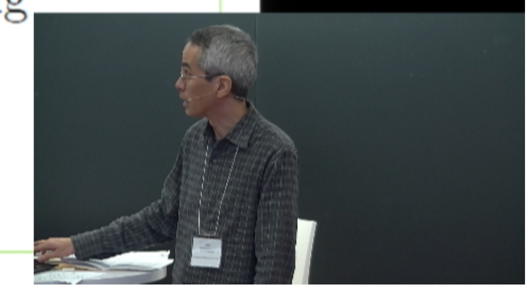
a. High-energy theory (1) is formally and dynamically distinct from low-energy EFTs (2) and (3).

- High-energy theory (1) is a non-relativistic QFT describing *fermionic* degrees of freedom.
- EFT of T_c (2) is a non-relativsitic QFT describing *bosonic* degrees of freedom.
- EFT of ground state (3) is a *relativistic* QFT.



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b. (1), (2) and (3) describe distinct physical systems:

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Suggests:

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2. *Ontological distinctness*: Degrees of freedom of $\mathcal{L}_{eff}$ are (typically) associated with physical systems that are distinct from the physical systems associated with the DOF of $\mathcal{L}$.

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Suggests:

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3. *Ontological dependence*: DOF of $\mathcal{L}_{eff}$ are exactly the low-energy DOF of $\mathcal{L}$. (Physical systems described by an EFT do not "float free" of those described by its high-energy theory.)

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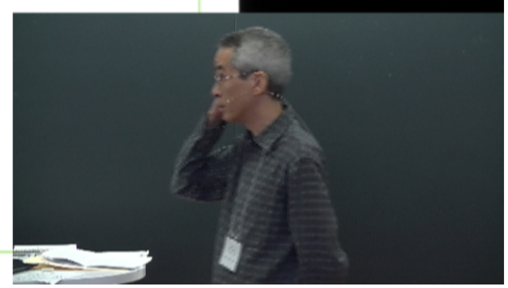
- *Non-relativistic* Lagrangian density. (Schakel 1998)



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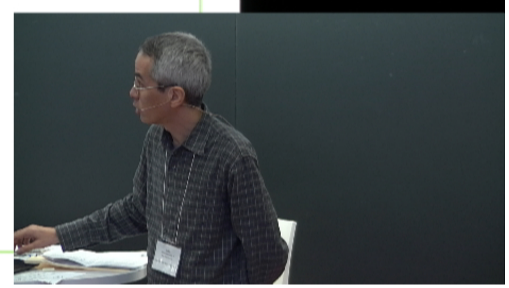

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- *Non-relativistic* Lagrangian density. (Schakel 1998)
- ϑ chosen so that electrons ψ have an even number of magnetic fluxes ("composite" fermions).
- Quantum Hall Effect: $\sigma = \nu(e^2/h)$,

$$\nu = \frac{(\#\, electrons)}{(\#\, states\ per\ energy\ level)} = \text{integer or fraction}$$

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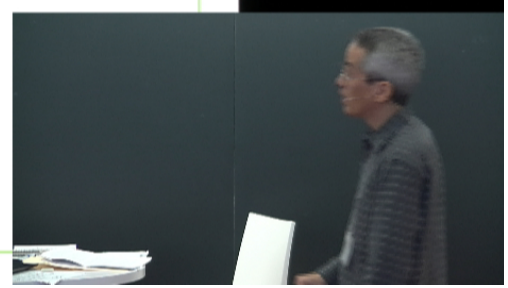

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- *Topological quantum field theory.* (Schakel 1998)
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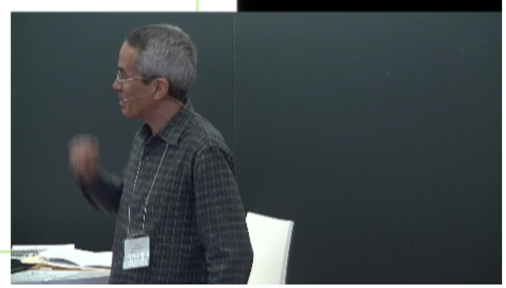
- An EFT of the Fractional QHE, but not a *low-energy* EFT.



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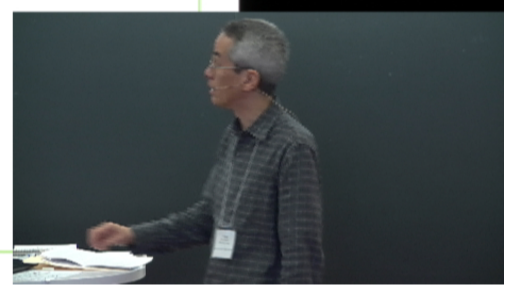
- Low-energy degrees of freedom of edge are bosonic hydrodynamical sound waves $\phi(x)$:

$$\mathcal{L}_{eff\text{-}edge} = (1/8\pi)\{(\partial_t\phi)^2 - (\partial_x\phi)^2\} \quad (6)$$

- *Relativistic* (1+1)-dim Lagrangian density. (Wenn 1990)



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(a) *Emergence as descriptive of the ontology (entities, properties) associated with a physical system with respect to another.*

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(b) *Emergence as a relation between theories.*

- To say phenomena associated with an EFT are emergent is to say the EFT stands in a certain relation to a high-energy theory.

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My Approach:

- Use the (informal) intertheoretic relation between an EFT and its high-energy theory to inform an ontological notion of emergence appropriate for EFTs.

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- Use the (informal) intertheoretic relation between an EFT and its high-energy theory to inform an ontological notion of emergence appropriate for EFTs.

- *Thus*: Emergence (under this view) is not a formal characteristic of theories; but rather an interpretation-dependent characteristic.

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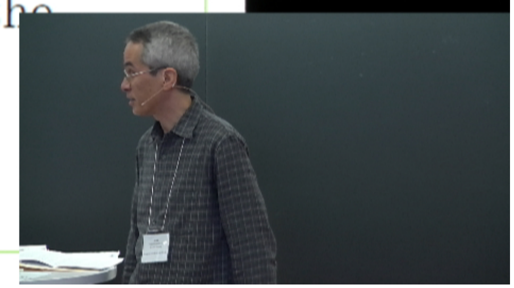
- (i) and (ii) are underwritten in the EFT context by the elimination of degrees of freedom (DOF)...



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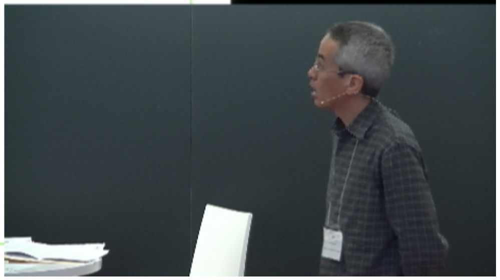
How the properties of a system described by $\mathcal{L}_{eff}$ emerge from a fundamental system described by $\mathcal{L}$:

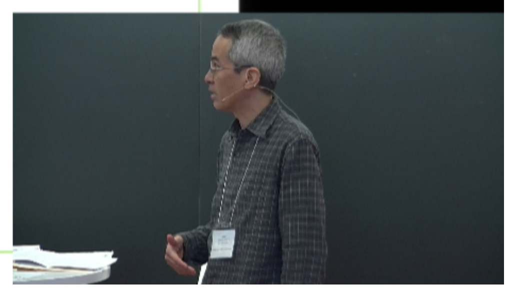


3. Emergence in EFTs

How the properties of a system described by $\mathcal{L}_{eff}$ emerge from a fundamental system described by $\mathcal{L}$:

(i) *Microphysicalism*: High-energy DOF are integrated out of $\mathcal{L}$, which entails that the DOF of $\mathcal{L}_{eff}$ are exactly the low-energy DOF of $\mathcal{L}$.

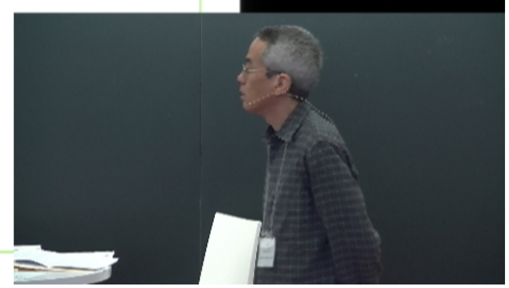
(ii) *Novelty*: $\mathcal{L}_{eff}$ is expanded in a local operator expansion. The result is dynamically distinct from $\mathcal{L}$ in the sense of a failure of lawlike deducibility from $\mathcal{L}$ of the properties described by $\mathcal{L}_{eff}$.



4. Other Notions of Emergence

(A) *New Emergentism.*

- <u>*Claim (Mainwood 2006)*</u>: *Microphysicalism* and *novelty* characterize the "New Emergentism" of Anderson (1972) and Laughlin and Pines (2000).



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- *But*: The mechanisms that underwrite New Emergentism are spontaneous symmetry breaking and universality.
- *And*: These mechanisms are typically *not* present in EFTs:
  - Present in EFTs for superfluid ^{3}He-A.
  - Not present in EFTs for quantum Hall liquids.

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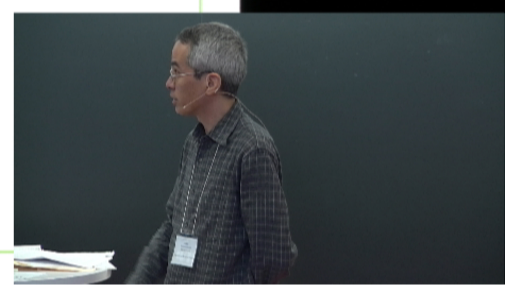

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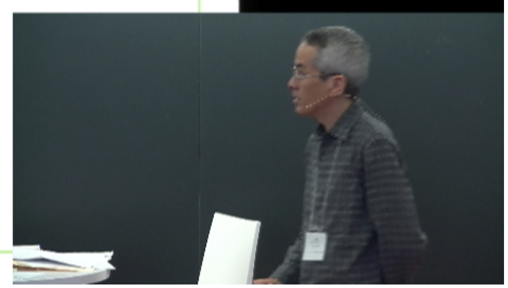
- Applicable to EFTs?
- *No*: DOF elimination in an EFT is characterized by:



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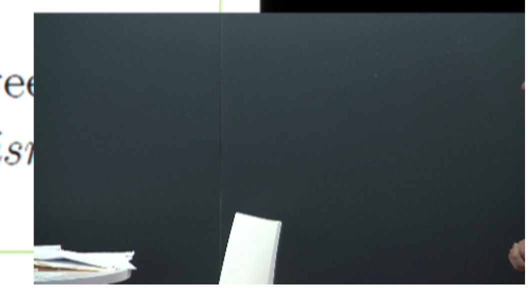

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- Necessary conditions for the existence of an emergent property described by a theory T' with respect to a more fundamental theory T (Batterman 2000):

(i) There must be a limiting relation between T and T'.

(ii) The limiting relation must fail in the context in which the emergent property is identified; in particular, there must be a *physical singularity* associated with the emergent property.

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Example (i): Properties associated with phase transitions involving spontaneously broken symmetries.
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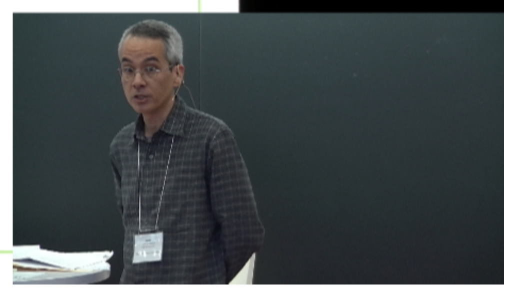

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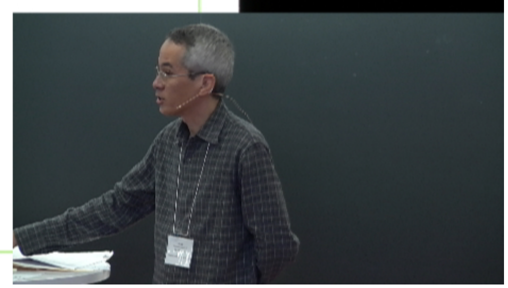
- Limiting relation fails at a critical point/fixed point.
- Physical singularity $=$ divergence in correlation length.
- Emergent properties $=$ properties associated with the phase transition.



4. Other Notions of Emergence

(C) *The Failure of a Limiting Relation.*

Example (ii): Properties associated with a cutoff-regulated theory.
T = renormalizable continuum theory.
T' = cutoff-regulated theory.
Limiting relation = $\Lambda(s) \to \infty$, $[\textit{bare parameters}] \to \infty$,
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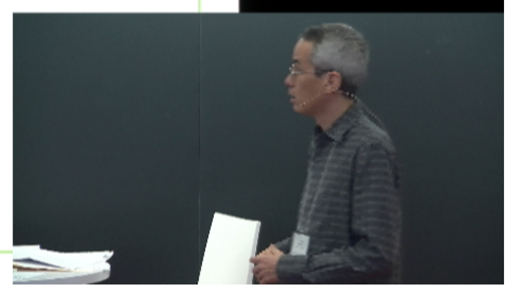

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- T = high-energy theory; T' = EFT?
- *No*: Not all EFTs are obtained from renormalizable high-energy theories.
- *Moveover*: T and T' are formally identical in Example (ii), whereas an EFT and its high-energy theory are not.

5. Conclusion

- Emergence in an EFT can be characterized by the elimination of DOF from a high-energy theory.

- This results in an EFT that can be interpreted as describing *novel* entities or properties in the sense of being dynamically independent of, and thus not deducible from, the entities or properties associated with a high-energy theory.

- These novel entities or properties can be said to ultimately be composed of the entities or properties that are constitutive of a high-energy theory (*microphysicalism*), insofar as the DOF exhibited by the former are exactly the low-energy DOF exhibited by the latter.