Strong emergence, top-down causation, and irreversibility
The hierarchical structure of nature

Reduction

Atoms → Molecules → Cells → Individuals → Society

Emergence:
The whole has properties that the parts don't have
The question that divides physicists

Partial reduction; Top-down causation

Atoms → Molecules → Cells → Individuals → Society

Strong emergence; Bottom-up causation
Focus of this talk: strong emergence within physics

Atomic Physics

Condensed Matter Physics, Statistical Physics

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Arguments for strong emergence

• The parts have never existed without the whole
The parts have never existed without the whole
Arguments for strong emergence

- The parts have never existed without the whole
- Full reduction to QM of $10^{23}$ particles is never done in condensed matter physics
Reduction is never really done

"On the nature of research in condensed-state physics" (Foundations of Physics, 1992)

No significant advance in the theory of matter in bulk has ever come about through derivation from microscopic principles. (...) The so-called derivations (...) from microscopic principles alone are almost all bogus.

Tony Leggett
Reduction is never really done

„The many-electron wave function is not a legitimate scientific concept for \( N > 1000 \) … because the wave function can neither be calculated nor recorded with sufficient accuracy“ (Nobel lecture 1999)

Walter Kohn
Arguments for strong emergence

- The parts have never existed without the whole
- Full reduction to QM is never done in condensed matter physics
- Emergent phenomena are determined by higher-order principles which are independent of many microscopic details
Higher-order principles

„The Josephson quantum is exact because of … continuous symmetry breaking. The quantum Hall effect is exact because of localization. Neither of these things can be deduced from microscopics, and both ... would continue to lead to exact results even if the Theory of Everything were changed.“

Bob Laughlin

Higher-order principles

Broken symmetries!

(“More is different”, Science, 1972)

Phil Anderson
Arguments for strong emergence

• The parts have never existed without the whole
• Full reduction to QM is never done in condensed matter physics
• Emergent phenomena are determined by higher-order principles
• “Higher-level” theories require new fundamental laws
New law in statistical mechanics

Classical mechanics
Quantum mechanics (Schrödinger equation)

Additional rule of equal probability/statistical independence

Statistical mechanics

Deterministic
time reversible

Stochastic
irreversible
Arguments for strong emergence

• The parts have never existed without the whole
• Full reduction to QM is never done in condensed matter physics
• Emergent phenomena are determined by higher-order principles
• “Higher-level” theories require new basic laws
• “Lower-level” theories are neither exact nor complete
Not exact

We should have learned this from the history of classical mechanics

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Not complete

The context determines what can happen

Quantum-mechanical chance is a top-down effect!
Not complete

The context determines what can happen

Quantum-mechanical chance is a top-down effect!