Reflections on the Past, Present and Future of Condensed Matter Physics

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THE PROGRESS OF CONDENSED-MATTER PHYSICS: A SERIES OF (MINI-) PARADIGM SHIFTS?

T. S. Kuhn (The Structure of Scientific Revolutions, 1962):

old paradigm	⟶	paradigm shift	⟶	new paradigm
(“normal” science)		(scientific revolution)		(“normal” science)

(examples: Copernicus, SR, QM ...)

Dictionary definition of Paradigm Shift:

(Merriam-Webster): an important change that happens when the usual way of thinking about or doing something is replaced by a new and different way.

(Cambridge): a time when the usual and accepted way of doing or thinking about something changes completely.

in a scientific context, the paradigm determines

- what are the legitimate/interesting questions
- what kinds of answers to them are allowed
- what kinds of evidence may be adduced

Revolutions in CMP: mostly “velvet”?

CONDENSED MATTER ("SOLID STATE") PHYSICS, C. 1955

- rather detailed understanding of fairly narrow range of topics, mostly related to crystalline solids (liquid He excluded, almost nothing on glasses or "soft matter")

- mostly based on single-electron picture
  (but no topological insulators!)
  exceptions:
  phonons (of course!)
  magnetism (mostly mean-field)
  Landau-Lifshitz theory of 2nd order phase transitions
  ↓
  London-Ginzburg-Landau theory of superconductivity
  Bohm-Pines theory of electron gas

  most theory "first-principles" (exceptions: LGL, Pippard...)

  "computational" physics in infancy

- little connection with e.g. astrophysics, biology, …

- interest in (e.g.) QM foundations not quite "respectable"

- sociologically, U.S. (and U.K.) CMP community relatively non-diverse.

All in all, typical Kuhnian "normal science"!
[cf: Phys. Rev. **79**, 352 (1950)]

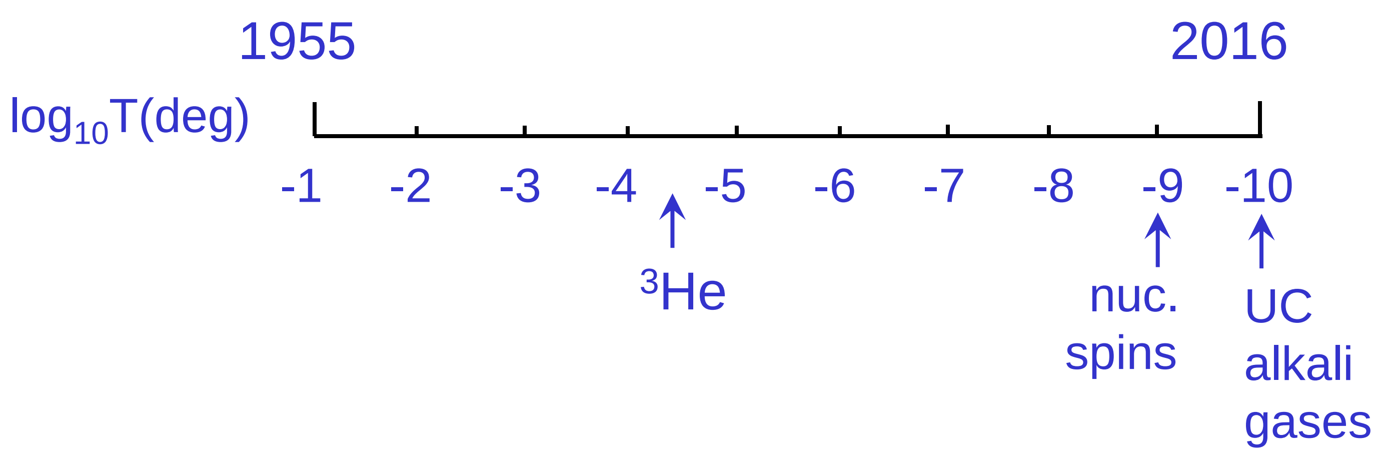
What Changed in 60 Years?

1. Sociologically, CMP community much more diverse

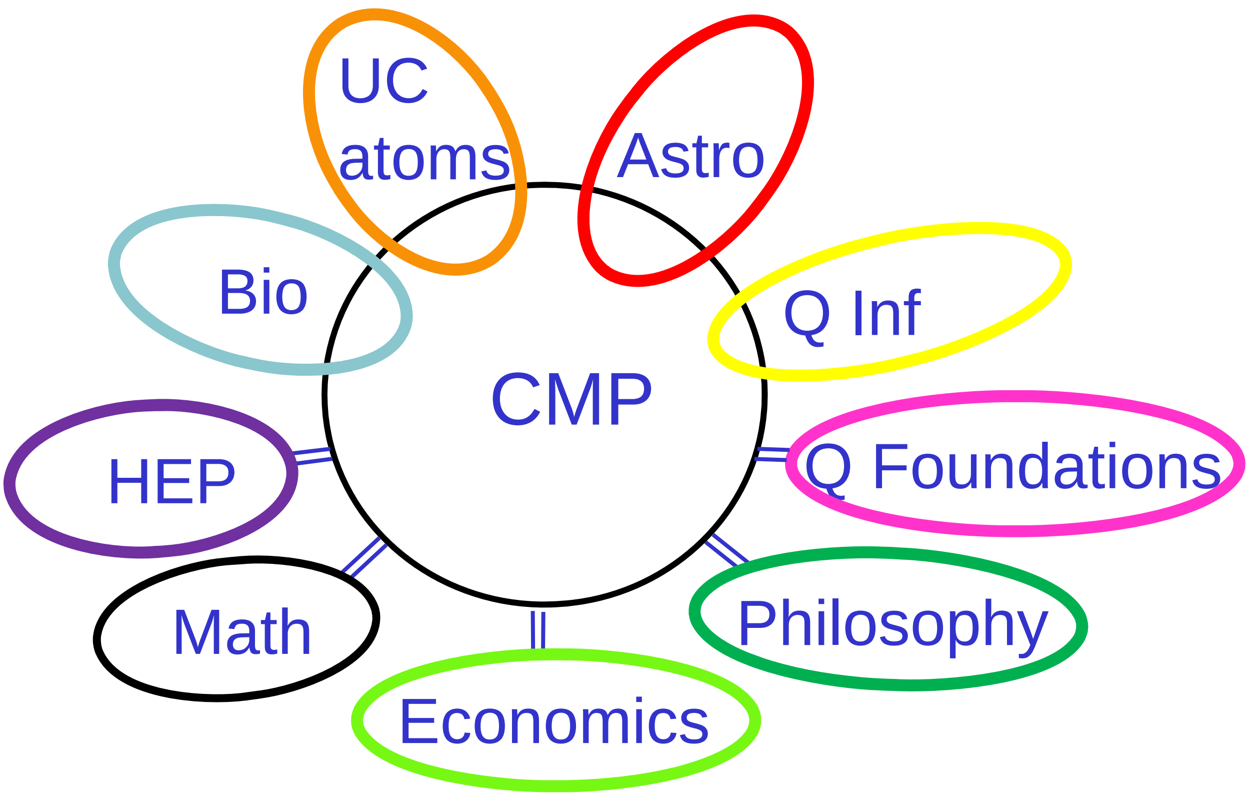
2. Rise of "computational physics"

3. Huge advances in cryogenics, materials science, diagnostic techniques…

   e.g.



4. "Outreach" to other disciplines



How has CMP itself changed? (↑: a theorist's view....)

WHAT WERE THE PARADIGM SHIFTS 1955 – 2016?

1. Landau Fermi-liquid theory (1956)
   don't even try to calculate from first principles, rather try to relate different physical properties of given system.

2. BCS theory (1957)
   try to identify crucial physical effect (in this case, phonon-induced attraction) and encapsulate in effective low-energy Hamiltonian

3. Renormalization group approach to 2^{nd} – order phase transitions (1963-71)
   universality, broken symmetry
   (L. P. Kadanoff: "The practice of physics has changed… going from solving problems to discussing the relationship between problems")

4. Fractional quantum Hall effect (1983)
   quasiparticles (e.g. anyons) whose character bears no relation to underlying particles or waves

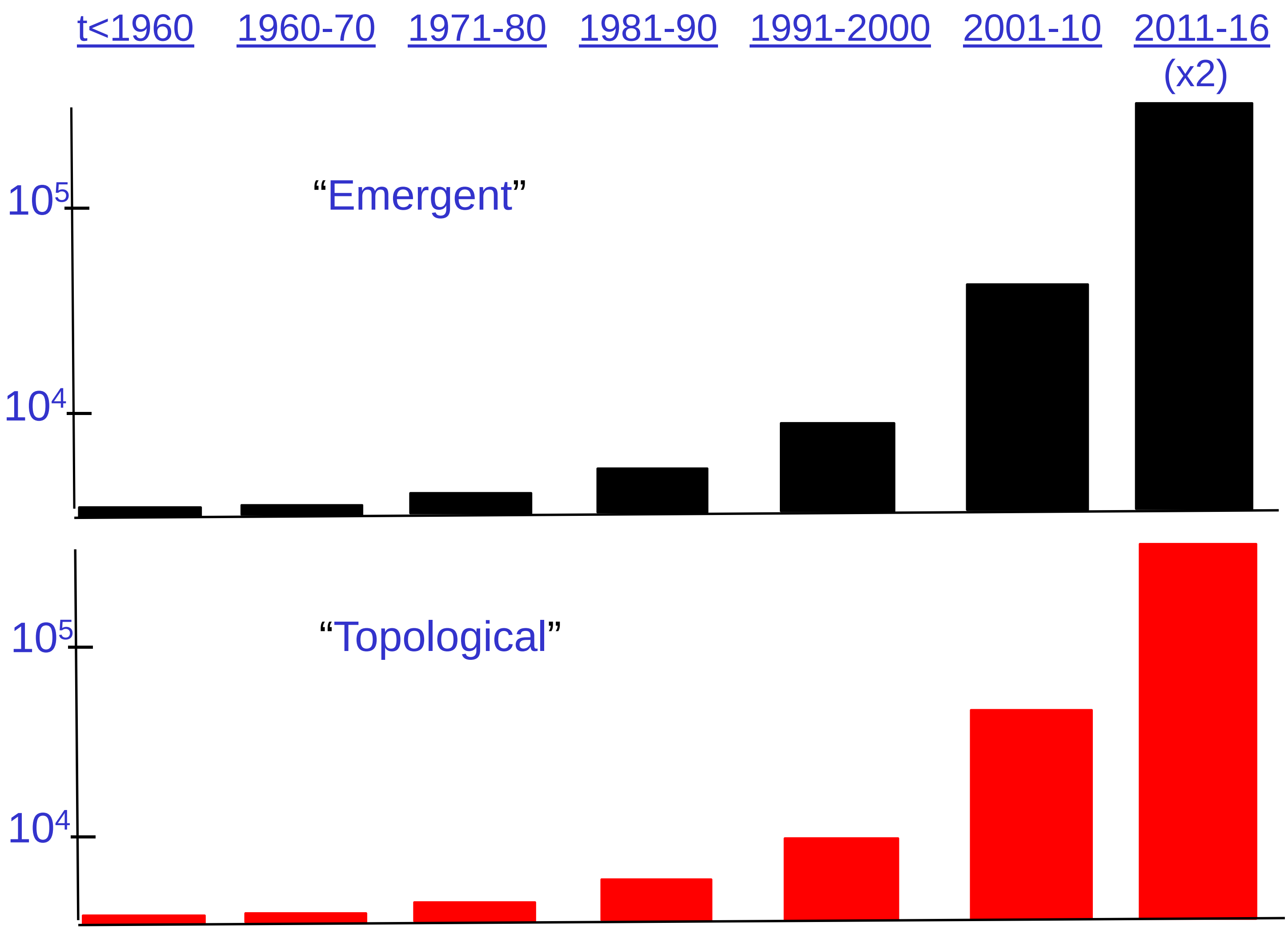
5. Quantum information (2002 -   )
   need to take individual wave functions seriously

Some other developments:

superfluid ^3He (1972) integral quantum Hall effect (1980) cuprate superconductivity (1986) topological insulators (2004)	} exciting, but didn't shift paradigm.

A TALE OF TWO BUZZWORDS

Entries in INSPEC index under “subject, title, abstract”
(↑ : of course, not all CMP)



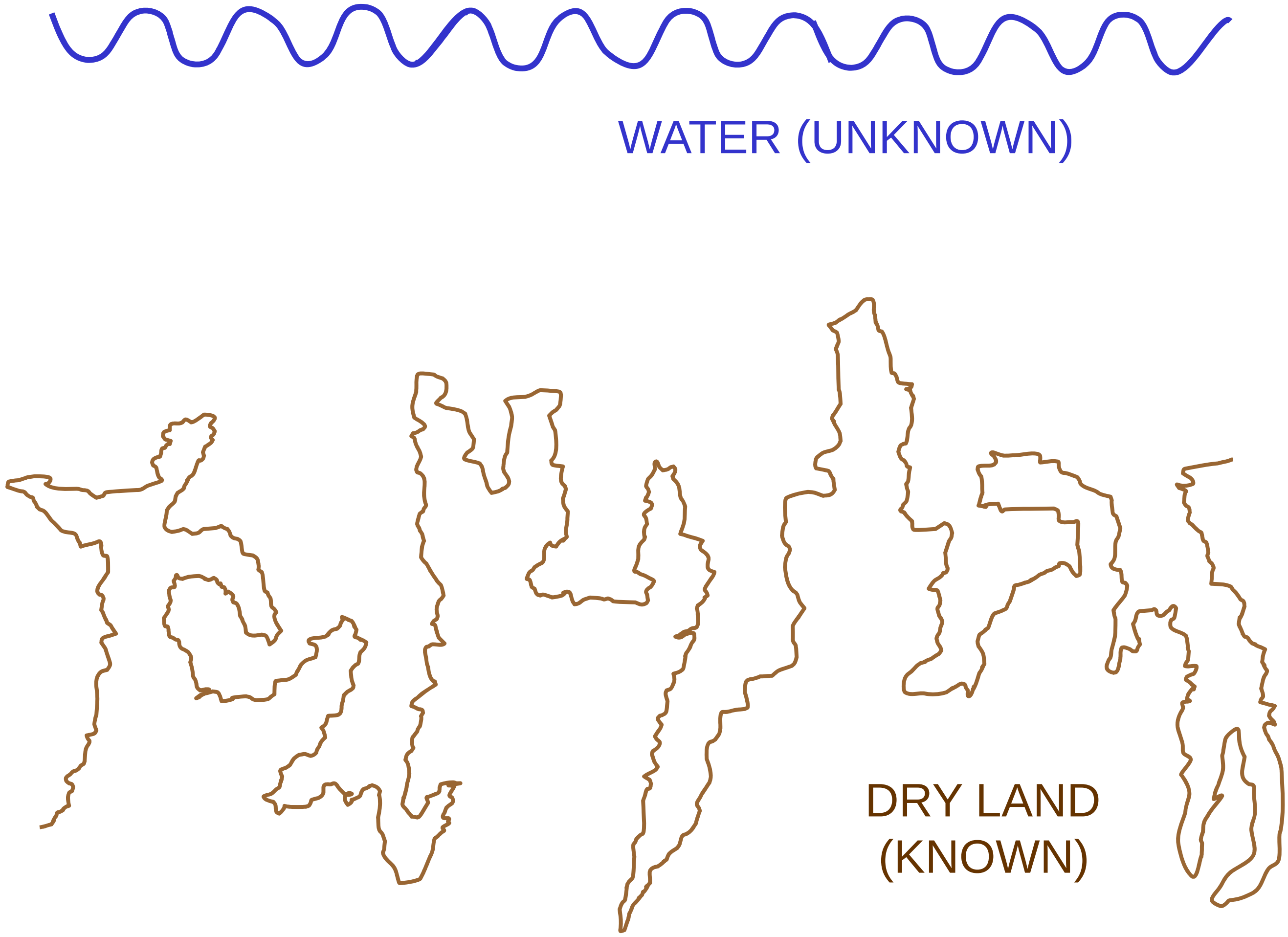
Which (interesting) properties of condensed-matter systems are not emergent/topological?

Non-emergent: can be explained as sum of “single-particle” behavior, e.g. IQHE, topological insulators...

Non-topological: problem is that in last resort all uniquely QM behavior is based on single-valuedness of wave function (Takabayashi, Nelson...) i.e. “topological”!

So, “non-topological” = “insensitive to single-valuedness of wave function over macroscopic distances”?

Condensed-Matter Physics in 2016: The "Rugged-Seashore" Analogy



Examples:

"KNOWN"	versus	"UNKNOWN"
crystalline solids		glasses (amorphous materials)
"classical" superconductivity		high-temperature superconductivity
laboratory photovoltaics		natural photosynthesis

CONDENSED-MATTER PHYSICS IN 2016: SOME MISCELLANEOUS THOUGHTS

Different kinds of problems, e.g.

ultracold atomic gases	Hamiltonian known and tractable (at least computationally)
high-temperature superconductivity	Hamiltonian partially known but intractable
amorphous materials	Hamiltonian not even known

Are we "spoiled" by BCS? Does an "effective" low-energy Hamiltonian always exist?

Are particle-physics/gravitational analogies useful?

(a) for theory: yes! (broken symmetry, RG, AdS/CFT...)

(b) for experiment: maybe (but what exactly is one testing?)

mathematical convenience vs. physical insight (P. Nozières: "only simple qualitative arguments can reveal the underlying physics")

Impact of quantum information (e.g. re-examination of BdG equations and their interpretation)

The scourge of bibliometrics and "high-impact" journals.

CONDENSED MATTER PHYSICS: THE FUTURE

(would I encourage my grandchildren to go into CMP?)

(a) further in the existing mould:

- more "sophisticated" ordered phases
- far-off-equilibrium phenomena
- more strongly and "delicately" entangled states...

(b) The really slippery issues in science: where we don't know what questions to ask! by definition, not found in periods of "normal science", so may need to actively push borders of CMP

one direction: biological organization, brain, consciousness...

another possible one: foundations of quantum mechanics and/or statistical mechanics.

e.g.

- how do we (can we?) describe the preparation of an experiment entirely in quantum-mechanical terms?
- is the "arrow of time" a spontaneously broken symmetry?

modest step in this general direction: use of CMP to test QM of a macroscopic variable ("invisible" paradigm shift!)