REMARKS ON THE 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”? (old ideas stay around, but no longer shape the field)

WHAT WERE THE PARADIGM SHIFTS 1955 – 2023?

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 2nd – 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

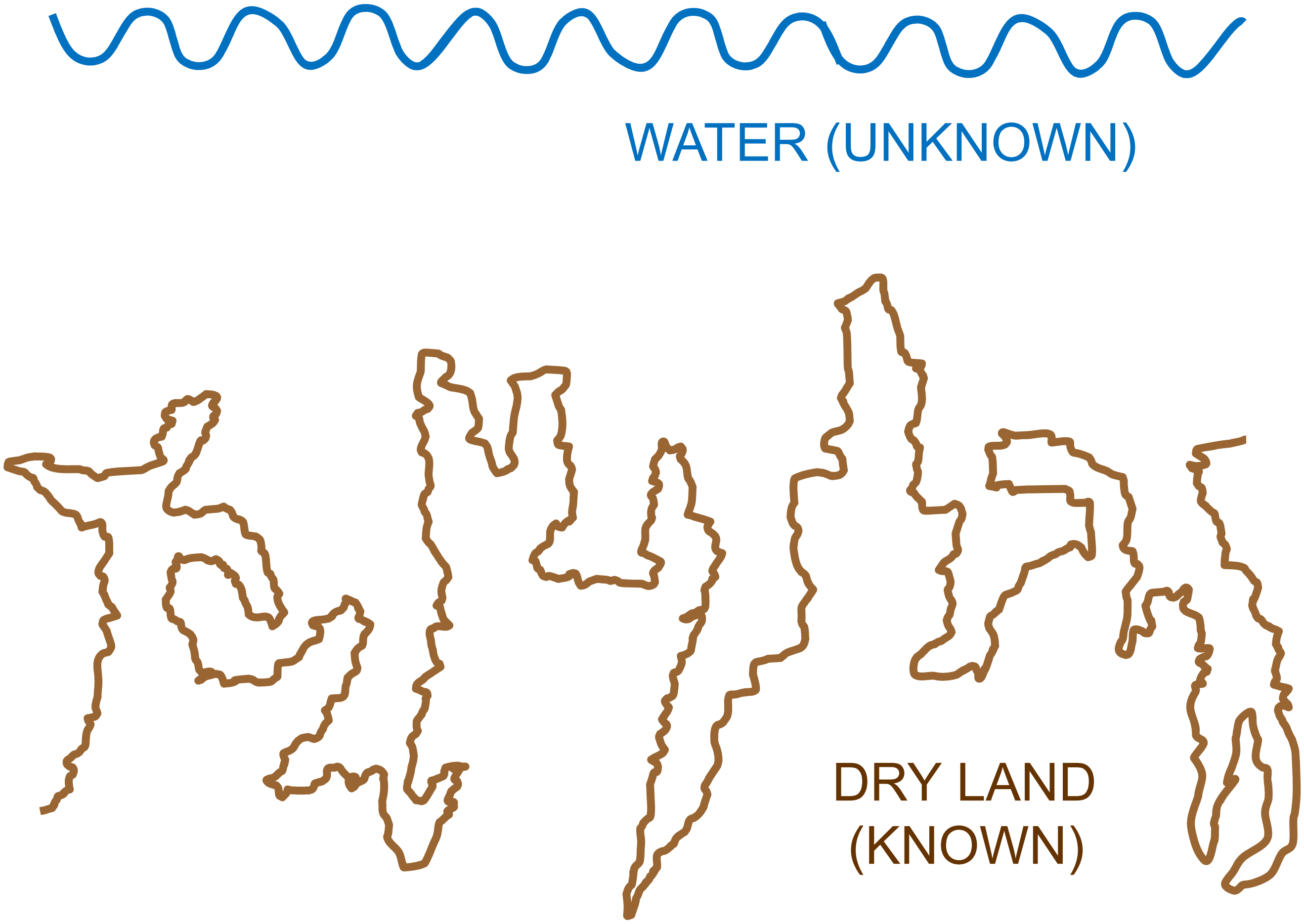
5. Quantum information (2002 -)
   need to take individual wave functions seriously: emphasis on entanglement.

Some other developments:

superfluid ^{3}He (1972)
integral quantum Hall effect (1980)
cuprate superconductivity (1986)
topological insulators (2004)
room-temperature superconductivity (2022)(?)

$\Big\}$ exciting, but didn't shift paradigm.

Condensed-Matter Physics in 2023: The "Rugged-Seashore" Analogy



WATER (UNKNOWN)

DRY LAND
(KNOWN)

Examples:

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

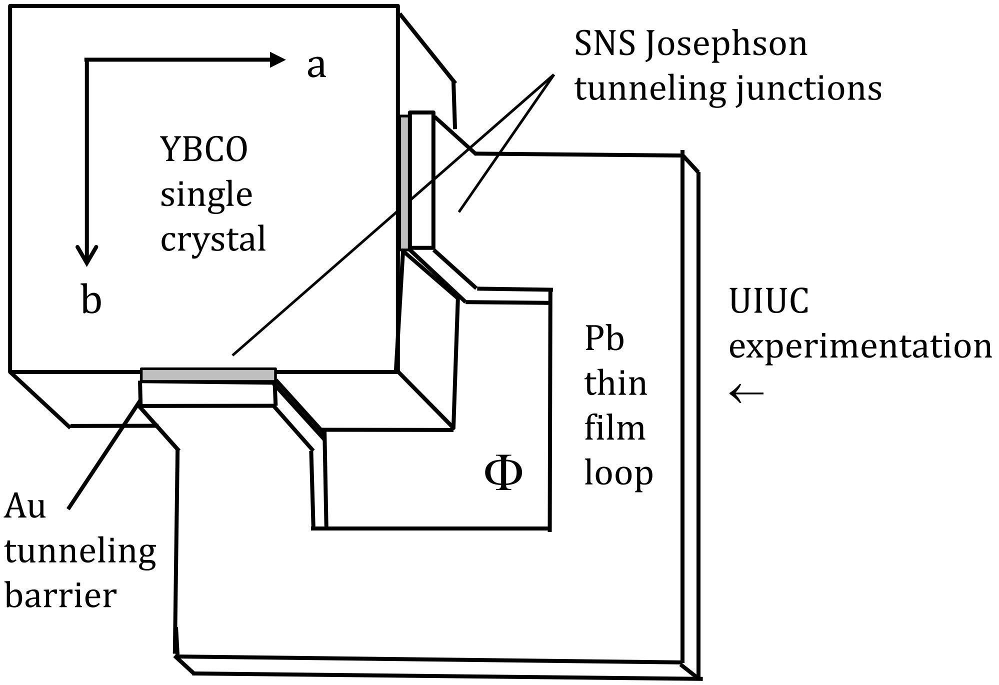
Given that CMP (like most other areas of physics) seems to be overall in a Kuhnian "normal" phase, how can we make "interesting" progress?

A possible answer: think up new questions (ideally yes/no ones)which we can answer by experiment, with only minimal reliance on microscopic theory.

Some examples from specific subfields:

(a) Cuprate superconductivity:

i) Can we understand the macroscopic properties without a detailed microscopic theory?
A: Yes, use generalized Ginzburg-Landau theory



ii) What is the symmetry of the Cooper-pair wave function (order parameter)? (s/d)
A: Use Josephson circuit*

↑: in case of (non-cuprate) Sr_2RuO_4, appears to give answer inconsistent with Knight-shift (+ neutron) data

*Geshkenbein, Larkin, Barone 1985 (for heavy-fermion superconductors)

iii) Where in the space of (q, ω) is the inter-conduction electron Coulomb energy saved (or expended) in the $\mathrm{N} \rightarrow S$ transition?

A: EELS / optical experiments

iv) Are we “spoiled” by success of BCS? Is it always possible to discuss low-T ($\mathrm{T} \lesssim \mathrm{T}_0$) behavior in terms of low-ε ($\varepsilon \lesssim k\mathrm{T}_o$) states?

(in reality, $\mathrm{E} \sim \mathrm{N}\varepsilon$ is played off against $\mathrm{N}k_\mathrm{B}\mathrm{T}$)

Amorphous systems (“glasses”)

General observation: the overall properties of glasses are much more universal than those of erysrals, yet we have a much worse understanding of them!

A. particularly striking quantitative universality*

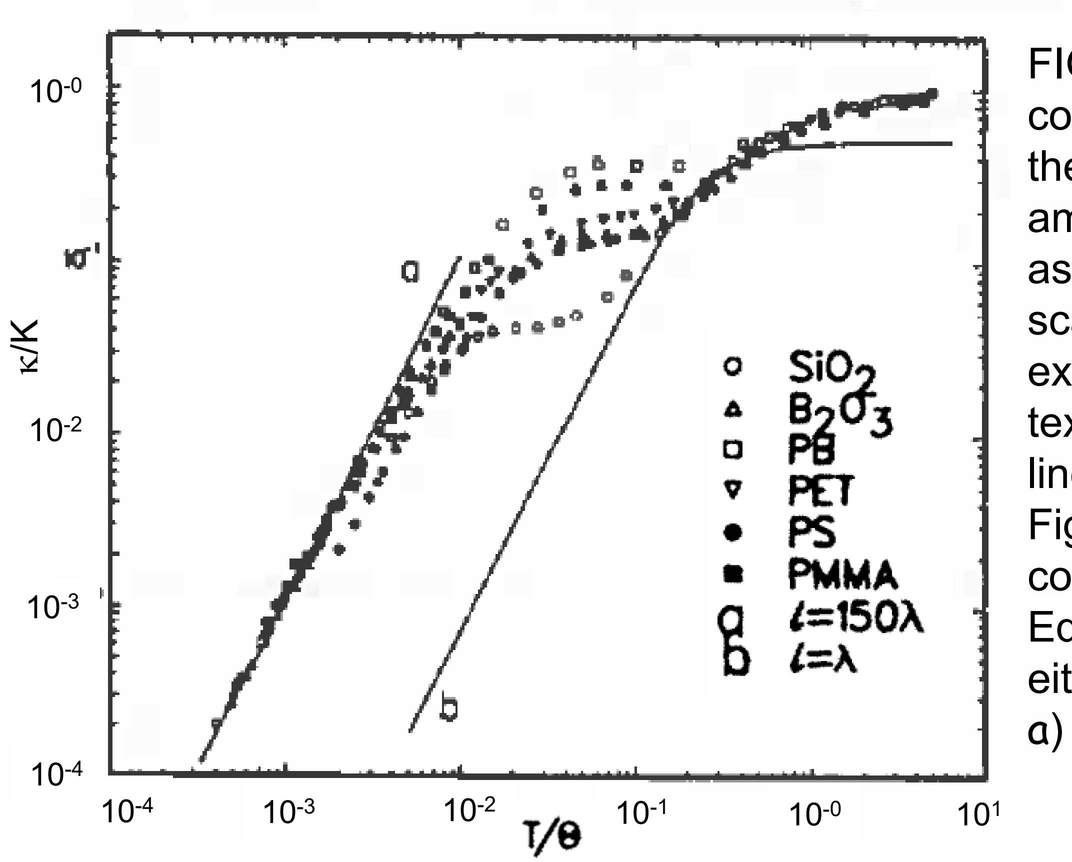


FIG. 2. Thermal conductivities for the same six amorphous solids as in Fig. 1, scaled as explained in the text. The solid lines here and in Figs. 3-5 were computed from Eq. (2) using either ℓ=150λ (line a) or ℓ=λ (line b).

This is essentially a graph of phonon mean free path (ℓ) versus to de Broglie wavelenth (λ) of thermally dominant phonons. We see ℓ / λ is constant and ~ 150 for $T \lesssim 1\mathrm{K} (\lambda \gtrsim 300\text{Å})$ and constant and ~1 at $T \gtrsim 10\mathrm{K}$ ($\lambda \lesssim 30$Å) , irrespective of microscopic nature of system.

*Freeman & Anderson, Phys. Rev. B 34, 5684 (1986)

The standard tunnelling two-level system (TTLS) model = noninteracting two-level systems with energy E: density of states $P(E)$~ const. for $E \to 0$. Couple to phonons & thereby determine ℓ.

Can explain $T \lesssim 1K$ data (only), but at the cost of near-unbelievable degree of coincidence in parameters:

$$\ell / \lambda = \text{const.} \frac{\rho c^2}{g^2 P(E)}$$

← each factor fluctuates by ~6-10

An old idea* which may still have some merit:

At short distances ($r \lesssim 30$Å) phonon-induced interaction $g^2/\rho c^2 r^3$ dominates over original ("bare") TLS energy. On dimensional grounds, if resulting P(0) is constant then it must $\propto \rho\, c^2/g^2$:

$$P(0) = \text{const.}\frac{\rho c^2}{g^2} \qquad \text{with const.} \sim 1$$

But then

$$\ell / \lambda = \text{const. } \rho c^2 / g^2 \; P(0) = \text{const.} \sim 1!$$

Hence can explain high-temperature (short-distance) behavior.

But what about universal low-temperature behavior? (argt. would require const. ~ 150). No obvious reason for that …

What are we missing?

*e.g. AJL, Physica B **169**, 322 (1991)

3) Ultracold atomic gases

Legitimately a part of CMP, but untypical in that “Nature is doing exactly what the textbooks tell her to!”
So … what is the (exciting) future?

i) testing conjectures made about more traditional systems, but untestable there (ex: (non)-metastability of supercurrent in superfluid with internal degrees of freedom).

ii) analog computing (e.g. 2D Hubbard model)

iii) instantiation of various quantum-information ideas e.g. new “phases” generated by continuous “measurement”.
one problem: surfeit of possibilities!

e.g. for 100 qubits, Hilbert space is 2^{100}–dimensional: how do we know which parts of it to explore? (traditionally, lowest-energy sector: but are there other “unique” regions, e.g. super-highly-entangled ones)?)

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But, quite generically, the $64K question for the future of condensed matter physics (CMP):

WILL ARTIFICIAL INTELLIGENCE PUT (HUMAN) CONDENSED-MATTER PHYSICISTS OUT OF BUSINESS?

Don’t laugh: look over your shoulder!

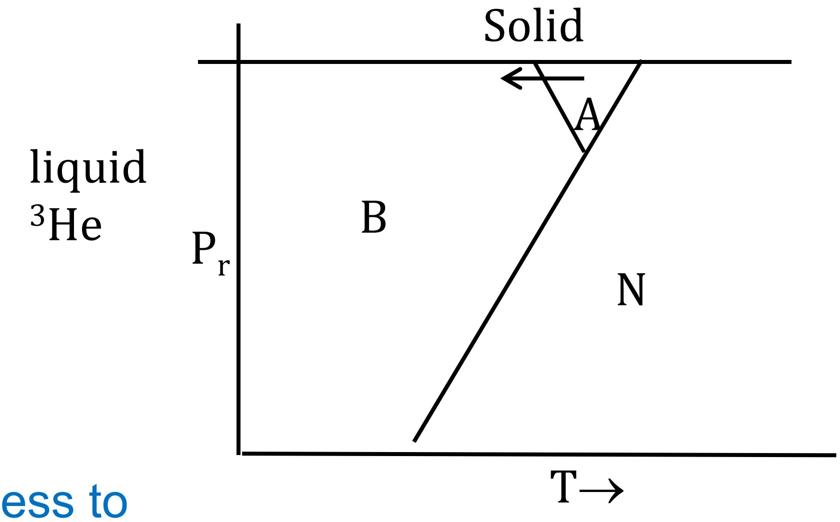
Protein folding: > 17K papers in literature
Alphafold program* (2021) may make >50% of them obsolete!

This and similar programs use machine learning to generalize from existing examples, so:

V. likely to be good for materials-genome type operations; may well find robust RT superconductors

but …

can it e.g. calculate A →B nucleation rate in liquid ^{3}He?
(why interesting?)



A. allow program access to “all we know” about liquid ^{3}He
B. allow it access to “all we know” about physics
C. tell it to concentrate on cosmic rays

*E. Callaway, Nature Intl. Weekly Journal of Science **604**, 234 (2022)