Phenomena Emerging from Complexity
reductionism and emergence
Emergent phenomena in condensed-matter and materials physics are those that cannot be understood with models that treat the motions of the individual particles within the material independently. Instead, the essence of emergent phenomena lies in the complex interactions between many particles that result in the diverse behavior and often unpredictable collective motion of many particles.
More Is Different

Broken symmetry and the nature of the hierarchical structure of science.

P. W. Anderson

More is the Same; Phase Transitions and Mean Field Theories

Leo P. Kadanoff


“Ininitely more is different.”

Summary of the paper: A dialog in Paris in 1920

FITZGERALD: The rich are different from us.

HEMINGWAY: Yes, they have more money.
The low-energy excited quantum states of these systems [crystalline solids] are particles in exactly the same sense that the electron in the vacuum of quantum electrodynamics is a particle ... Yet they are not elementary, and, as in the case of sound, simply do not exist outside the context of the stable state of matter in which they live.
Emerging complexity

COMPLEXITY IN SOLIDS

100^0
Hydrogen
Atomic physics

100^1
Niobium
Superconductivity BCS type

100^2
Gallium Arsenide
Skyrmions and Fractional Quantum Hall effect

100^3
Uranium Alloys
Heavy electrons, spin-charge separation, Kondo physics
  e.g. UPd_2Al_3, UNi_2Al_3

100^4
Cuprate Perovskites
High temperature superconductivity

Multiplier for the number of compounds
A masterplan for designing complex materials

**Frequently used fundamental physical constants**

- Speed of light in vacuum: $c = 299,792,458$ m/s
- Planck constant: $\hbar = 6.626 \times 10^{-34}$ Js
- Elementary charge: $e = 1.602 \times 10^{-19}$ C
- Electron mass: $m_e = 9.109383561 \times 10^{-31}$ kg
- Proton mass: $m_p = 1.67262199 \times 10^{-27}$ kg
- Fine-structure constant: $\alpha = 1/137.035999795$
- Rydberg constant: $R_h = 10,973.731,568$ m

**Ground-state configurations**

- **Strongly localized f-electrons**
- **Delocalized p-electrons**
- **d-electrons**

**Physical Measurement**

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<tr>
<th>Physical Measurement</th>
<th>Standard</th>
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<td>Liquids</td>
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**Atomic Properties of the Elements**

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PEROVSKITE COMPLEX OXIDES

$\text{AMO}_3$ perovskite unit cell

$A = \text{La, Ce, Pr \ldots}$

$\text{Tm} = \text{Fe, Ru, Ir \ldots}$

e.g. CaTiO$_3$, NdNiO$_3$, SrMnO$_3$

5 distinct atomic orbital shapes on $M$

$x^2-y^2$ \hspace{1cm} $z^2$

\{ $e_g$ \}

$yz$ \hspace{1cm} $xy$

\{ $t_{2g}$ \}
STRONG CORRELATIONS - MOTT INSULATORS

Electron counting

La$_2$CuO$_4$: 2 La (57x2)+Cu (29) + 4 O (4x8)=175 electrons

but La$_2$CuO$_4$ is a strong insulator!

For U >> t electrons localize: Mott insulator

Small U/t

Increasing U/t

Large U/t

Metal

Insulator

Electrostatics

Nevill Francis Mott

Nobel prize 1977

odd metal

even insulator

Metallic behavior expected

Fig: Pickett, RMP 61, 433 (1989)

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Insulator

Electrostatics

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odd metal

even insulator

Metallic behavior expected

Fig: Pickett, RMP 61, 433 (1989)
local entanglement of **lattice, charge, spin, and orbital degrees of freedom** defines multiple **closely spaced energy landscape** with meta-stable ground states.

Fig. J.M. Rondinelli and N.A. Spaldin, *Adv. Mater.* (2011)
Colossal magnetoresistance (CMR) manganites

High Tc superconducting cuprates e.g. $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$

Organic 1D salts e.g. $k$-(BEDT-TTF)$_2\text{Cu}[\text{N(CN)}_2]\text{Cl}$

Exciting physics but hard to realize in bulk materials
Broken Symmetry
and
Emerging Phases
Phase transitions usually involve symmetry breaking—a change in the symmetry of the constituents. For example, the molecules in a liquid are randomly arranged, and thus very symmetric. The molecules in an ice crystal are very orderly. Since disorder is more symmetric than order (you can look at a liquid from any angle and it will look the same), this is an example of symmetry breaking. Since symmetry breaking would not be predicted from fundamental laws, it is seen as a key aspect of systems that cannot be explained through reductionist means.

SYMMETRY IN SPACE - INVERSION, ROTATION, TRANSLATION

Most fundamental idea - central to many modern sciences

In antiquity synonymous with harmony and beauty
/ inversion symmetry, translational symmetry /

Symmetry in art
/ rotational symmetry /

Symmetry in biology

images from google.com
A canon "Quaerendo invenietis" based on retrogression

J.S. Bach, The Musical Offering, BWV 1079
BROKEN SYMMETRY

Left vs. Right

Arrow of time - past vs. future

images from google.com
"I am inclined to think that life, as manifested to us, must be a function of the dissymmetry of the universe and of the consequences it produces.... Life is dominated by dissymmetrical actions. I can even foresee that all living species are primordially, in their structure, in their external forms, functions of cosmic dissymmetry."
BROKEN SYMMETRY = EMERGENCE OF A NEW PHASE

Solid Argon melting

Solid Ar

Liquid Ar

gas

iron

A tri-critical point of Ar

Decreasing Temperature or Energy

\(<M\> \neq 0 \quad \text{and} \quad <M> = 0\)
**Broken symmetry** means the appearance of an ordered phase with a **non-zero order parameter**.
WHERE ARE THE NEW PHASES OF MATTER?

Landau “recipes” for getting new phases and states:

The sudden disappearance of a certain symmetry in the high-symmetry phase leads to the occurrence of a phase transition into a new phase with lower symmetry.

If we assume control over symmetry breaking, we may end up with new designer phases.