COMPLEXITY, SYMMETRY AND STRONG CORRELATIONS

Jak Chakhalian

Solid State Physics 601
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Phenomena Emerging from Complexity

APPROACH TO COMPLEX PHENOMENA

reductionism and emergence

WHAT IS 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.

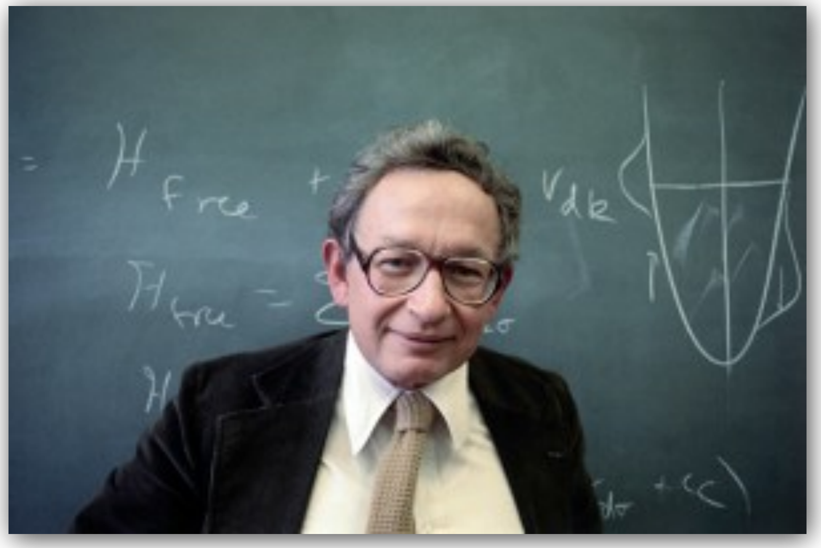
Condensed Matter and Materials Physics: The Science of the World Around Us, NAS, National Academies Press (2007).

More Is Different

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

P. W. Anderson

SCIENCE
4 August 1972, Volume 177, Number 4047



Nobel prize, 1977

More is the Same; Phase Transitions and Mean Field Theories

Leo P. Kadanoff

J Stat Phys (2009) 137: 777–797

"Infinitely more is different."

Summary of the paper:
A dialog in Paris in 1920

FITZGERALD: The rich are different from us.

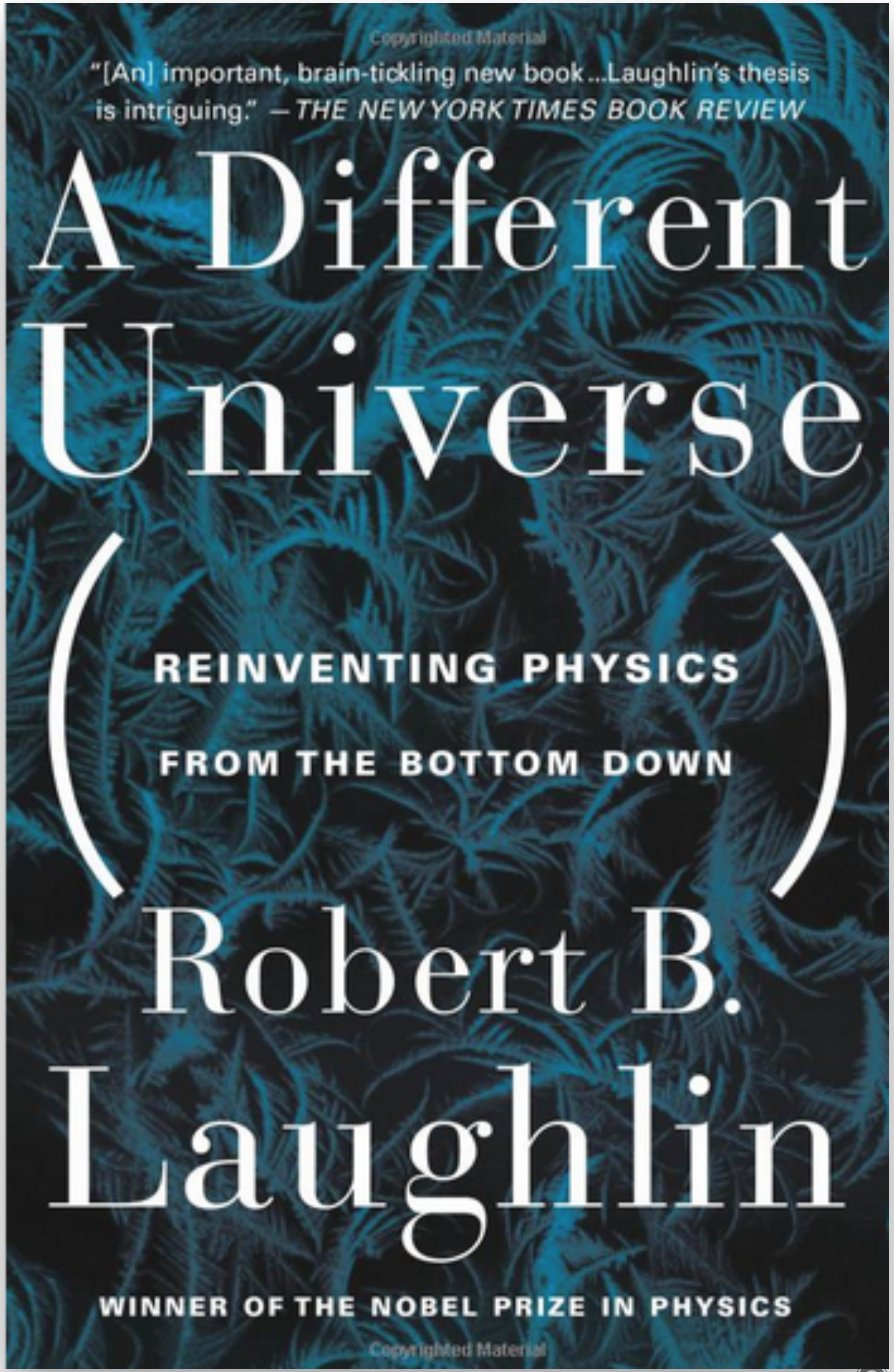
HEMINGWAY: Yes, they have more money.

40 YEARS LATER …

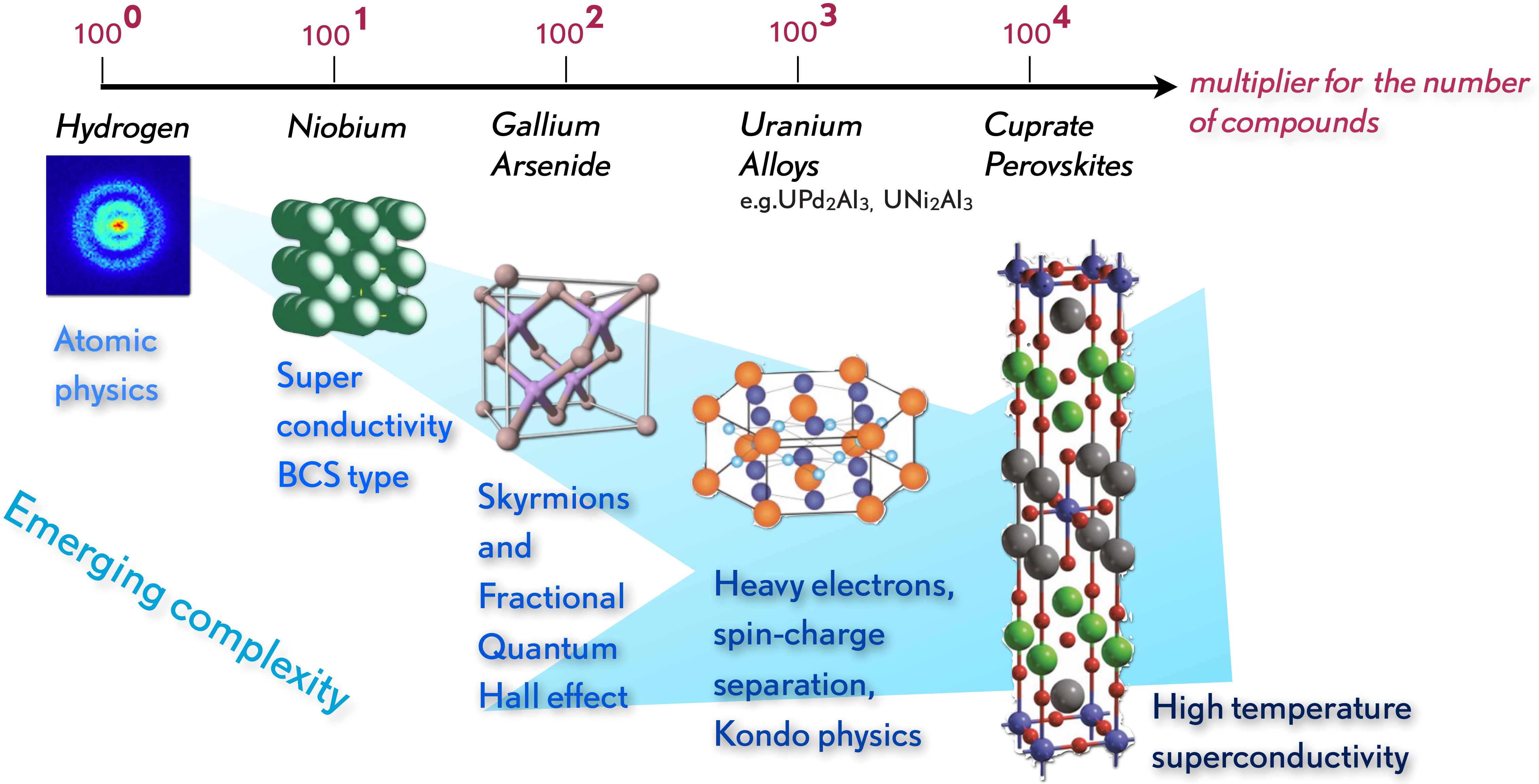
Robert B. Laughlin

Nobel prize 1986

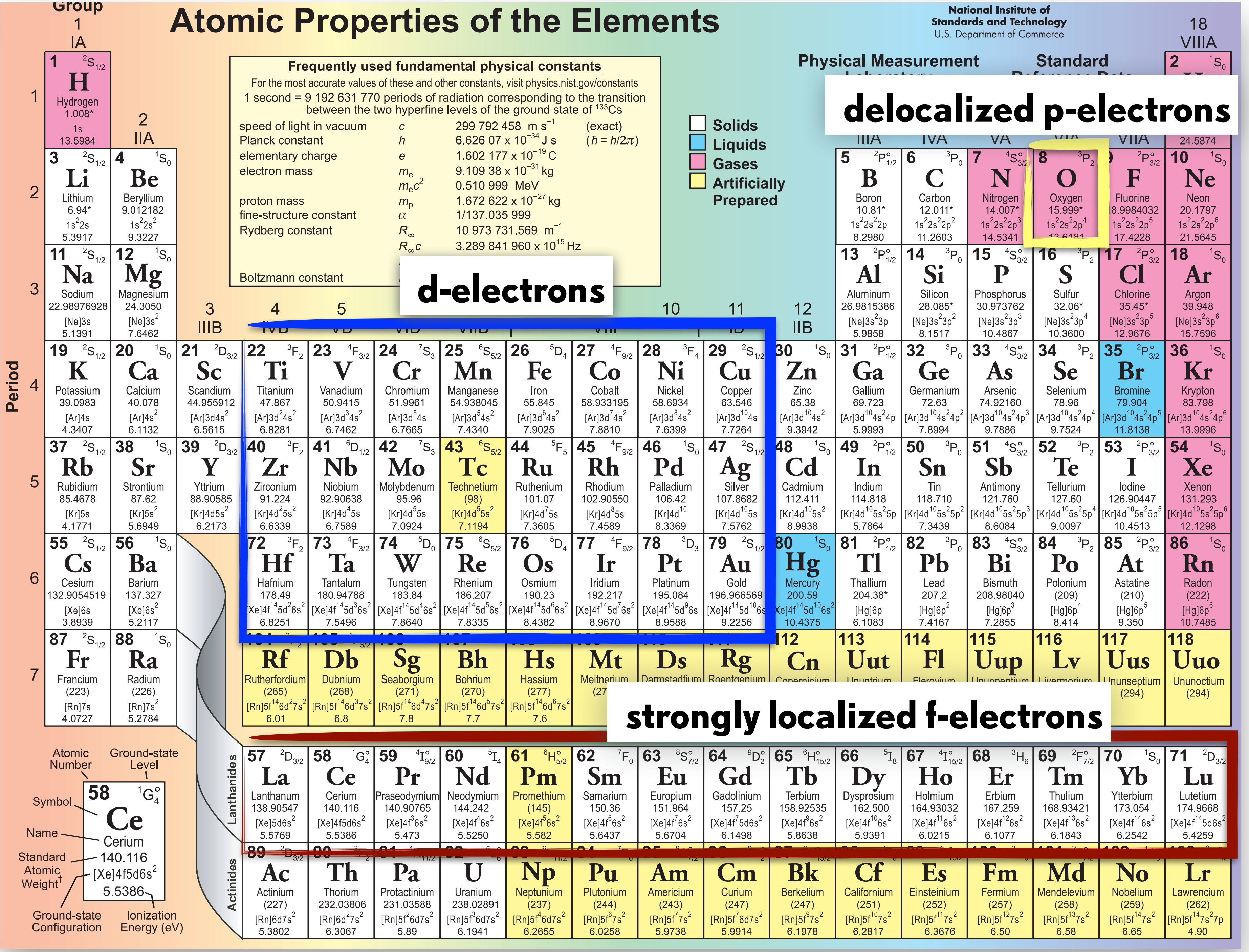
The low-energy excited quantum states of these systems [crystalline solids] are particles in exactly the same sense that the electron in the vacuum of quantum electrodynamics is a particle … Yet they are not elementary, and, as in the case of sound, simply do not exist outside the context of the stable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



COMPLEXITY IN SOLIDS



A masterplan for designing complex materials

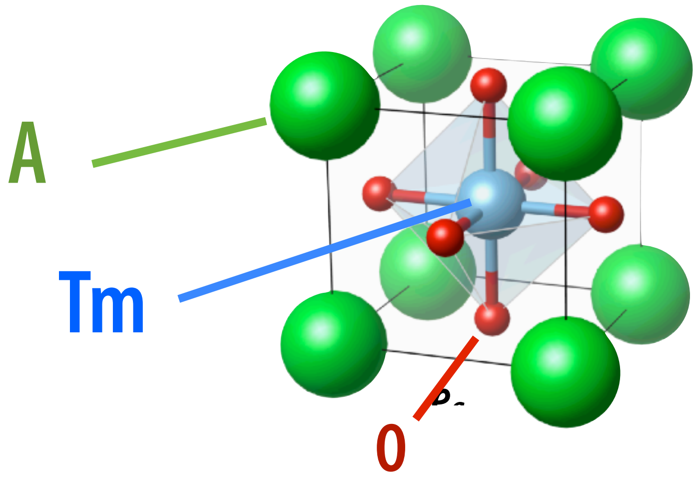


PEROVSKITE COMPLEX OXIDES

A =La, Ce, Pr …. Tm =Fe, Ru, Ir ..

e.g. $CaTiO_3$. $NdNiO_3$, $SrMnO_3$

AMO_3 perovskite unit cell



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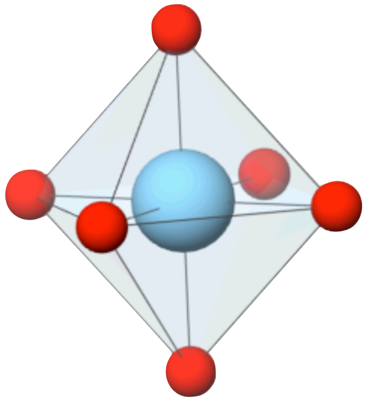

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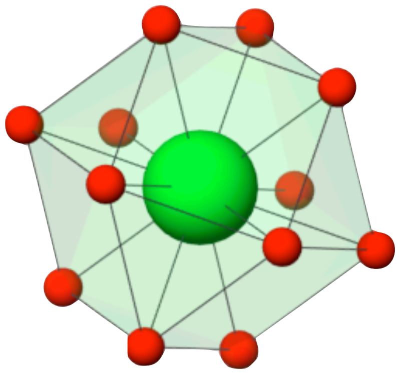
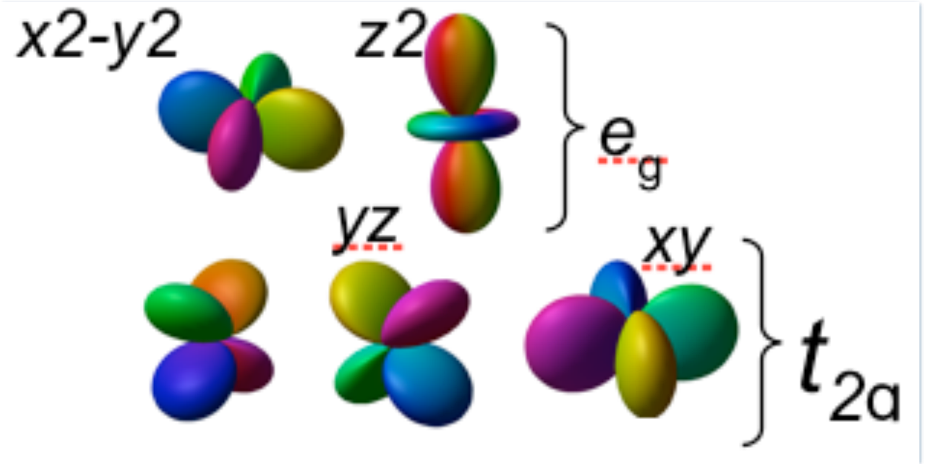
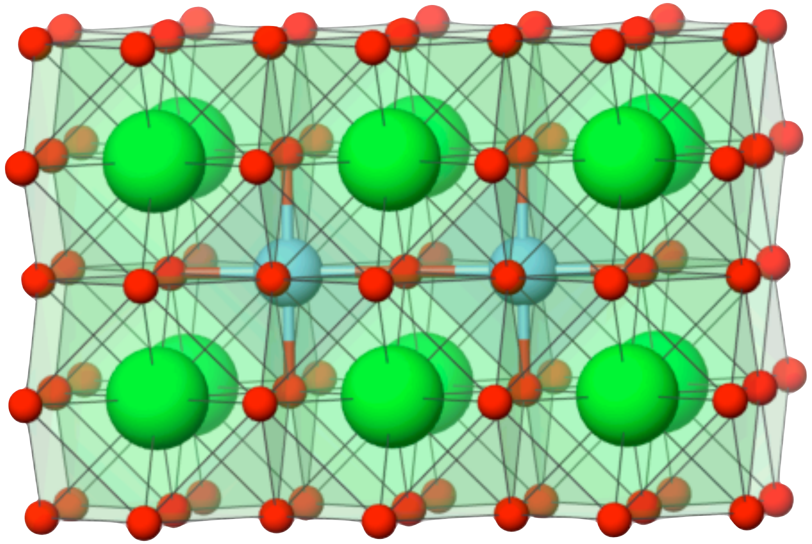


MO_6 rigid

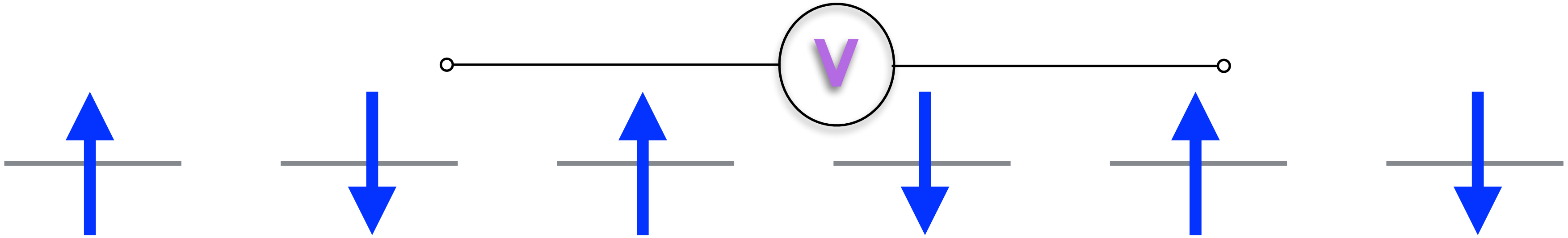
AO_{12} soft

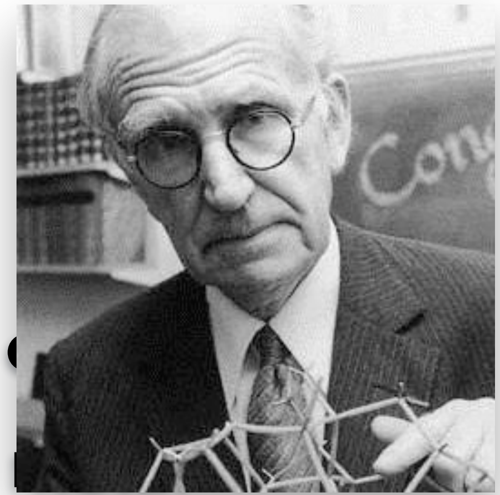
5 distinct atomic orbital shapes on **M**





STRONG CORRELATIONS - MOTT INSULATORS





Nevill Francis Mott

Nobel prize 1977

Electron counting

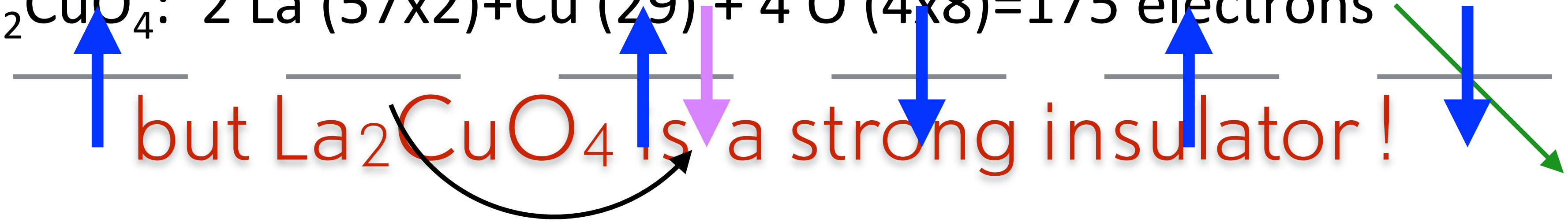
La_2CuO_4: 2 La (57x2)+Cu (29) + 4 O (4x8)=175 electrons

loses coulomb energy, U

even

insulator

but La_2CuO_4 is a strong insulator !



gains kinetic energy, t

For U >> t electrons localize: Mott insulator

Small U/t	Increasing U/t	Large U/t
Metal	→	Insulator

COMPLEXITY IN CORRELATED MATERIALS

local entanglement of ***lattice, charge, spin,*** and ***orbital degrees of freedom*** defines multiple *closely spaced energy landscape* with meta-stable ground states

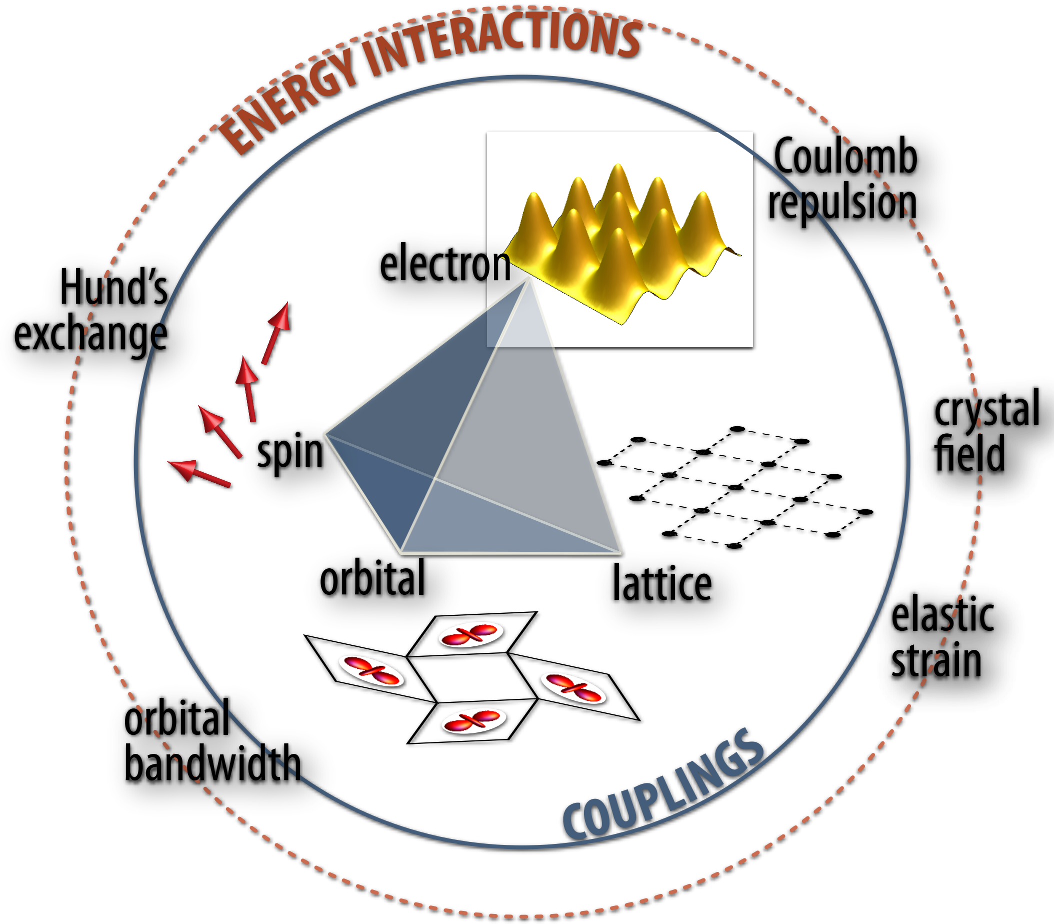


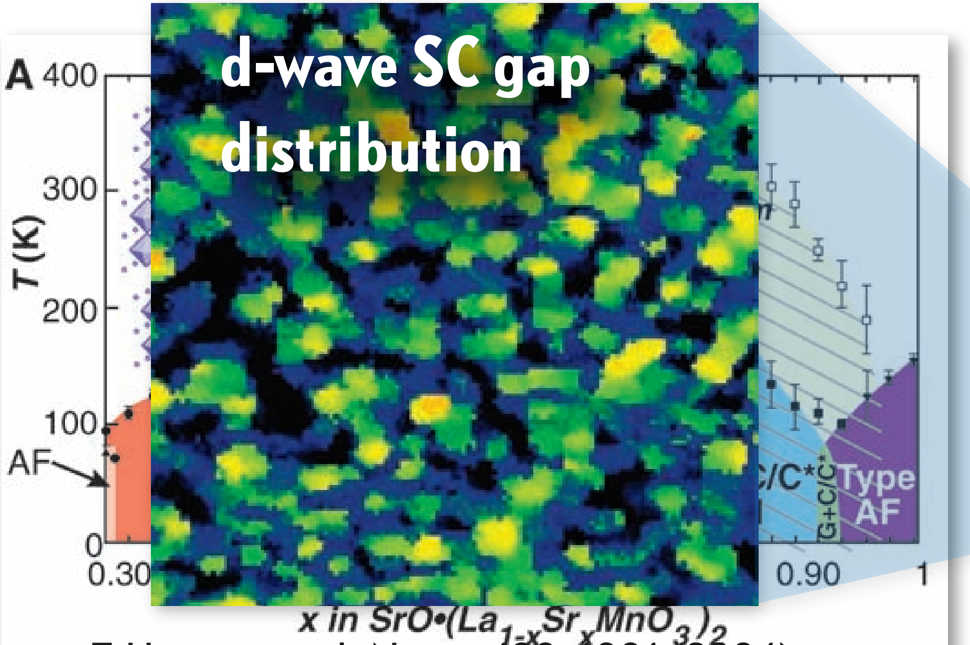
Fig. J.M. Rondinelli and N.A. Spaldin, *Adv. Mater.* (2011)

EMERGING COMPLEXITY FROM STRONG CORRELATIONS

Complexity in Strongly Correlated Electronic Systems

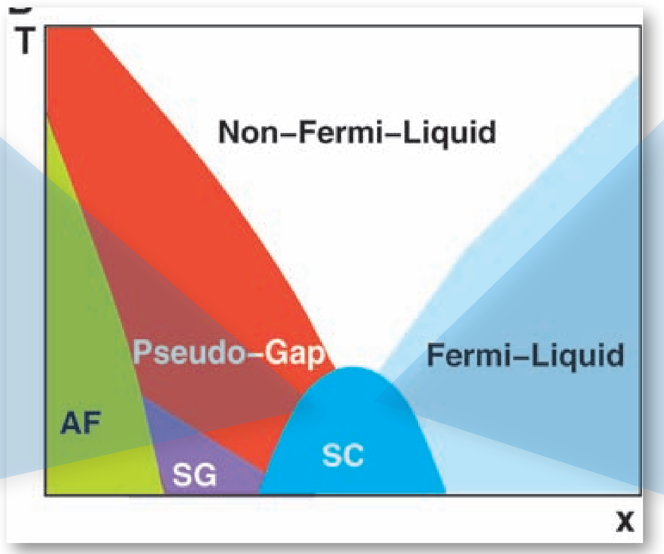
Elbio Dagotto

SCIENCE VOL 309 8 JULY 2005

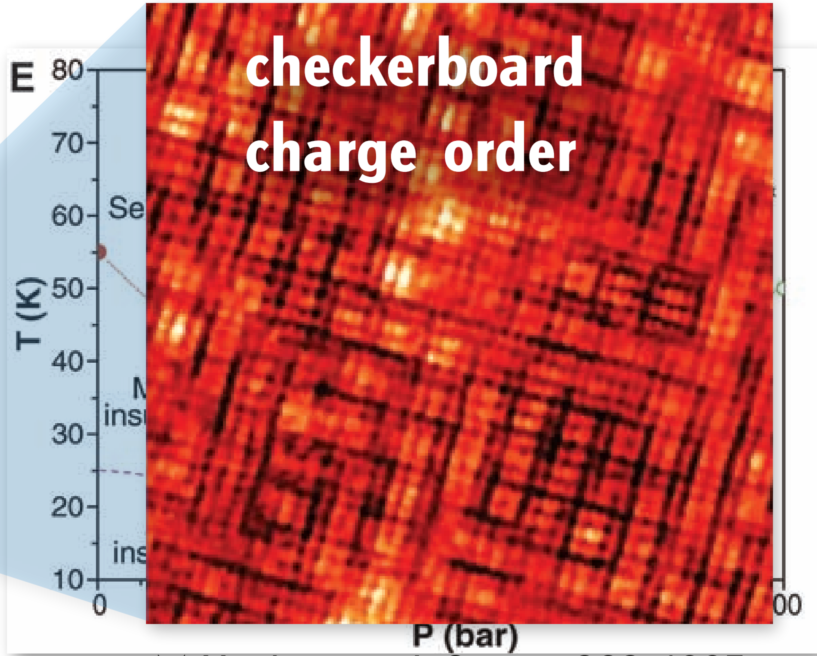


T. Hanaguri et al., Nature 430, 1001 (2004)

Colossal magnetoresistance (CMR) manganites



High Tc superconducting cuprates e.g. $YBa_2Cu_3O_{7-x}$



M. Vershinin et al., Science 303, 1995 (2004)

Orga[illegible] 1D salts e.g. k-(BEDT-TTF)$_2$Cu[N(CN)$_2$]Cl

Exciting physics but hard to realize in bulk materials

Broken Symmetry

and

Emerging Phases

SIGNS OF EMERGENT BEHAVIOR

Phase transitions usually involve *symmetry breaking*—a change in the symmetry of the constituents. For example, the molecules in a liquid are randomly

Condensed Matter and Materials Physics: The Science of the World Around Us, National Academies Press (2007).

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

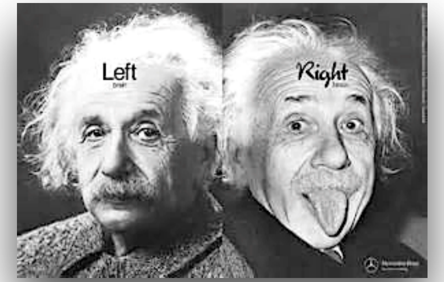
SYMMETRY IN TIME OR TIME INVERSION

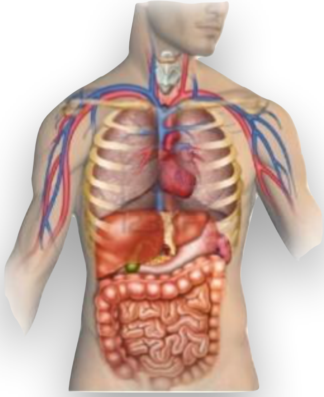
A canon "Quaerendo invenietis" based on **retrogression**

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

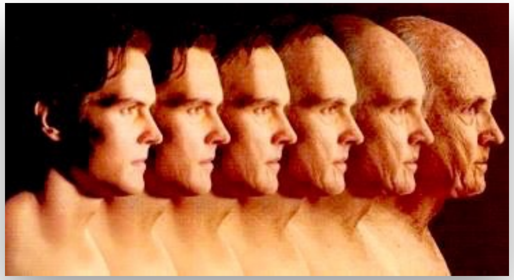
BROKEN SYMMETRY

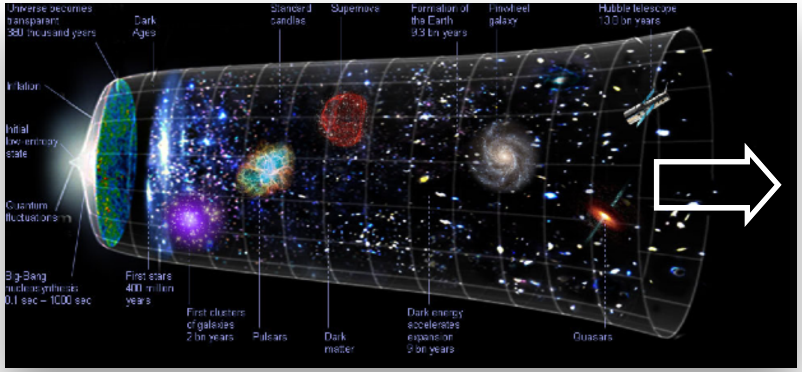
Left vs. Right





Arrow of time - past vs. future





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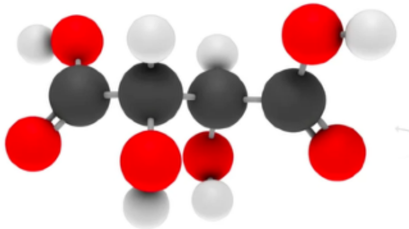
CHIRALITY OR BROKEN SYMMETRY OF LIFE

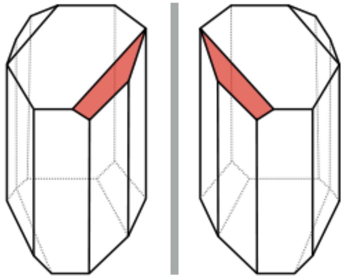
molecules of life are chiral !

Louis Pasteur

1822-1895

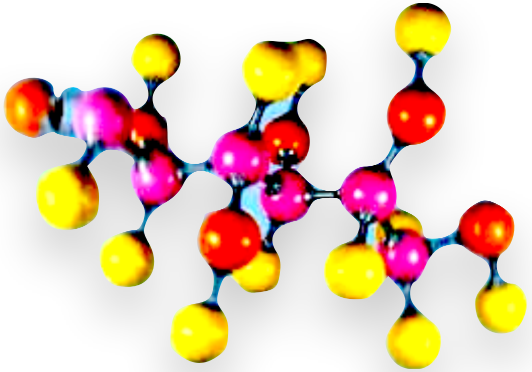


tartaric acid in old wine



DNA

sugars



"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."

c.1850

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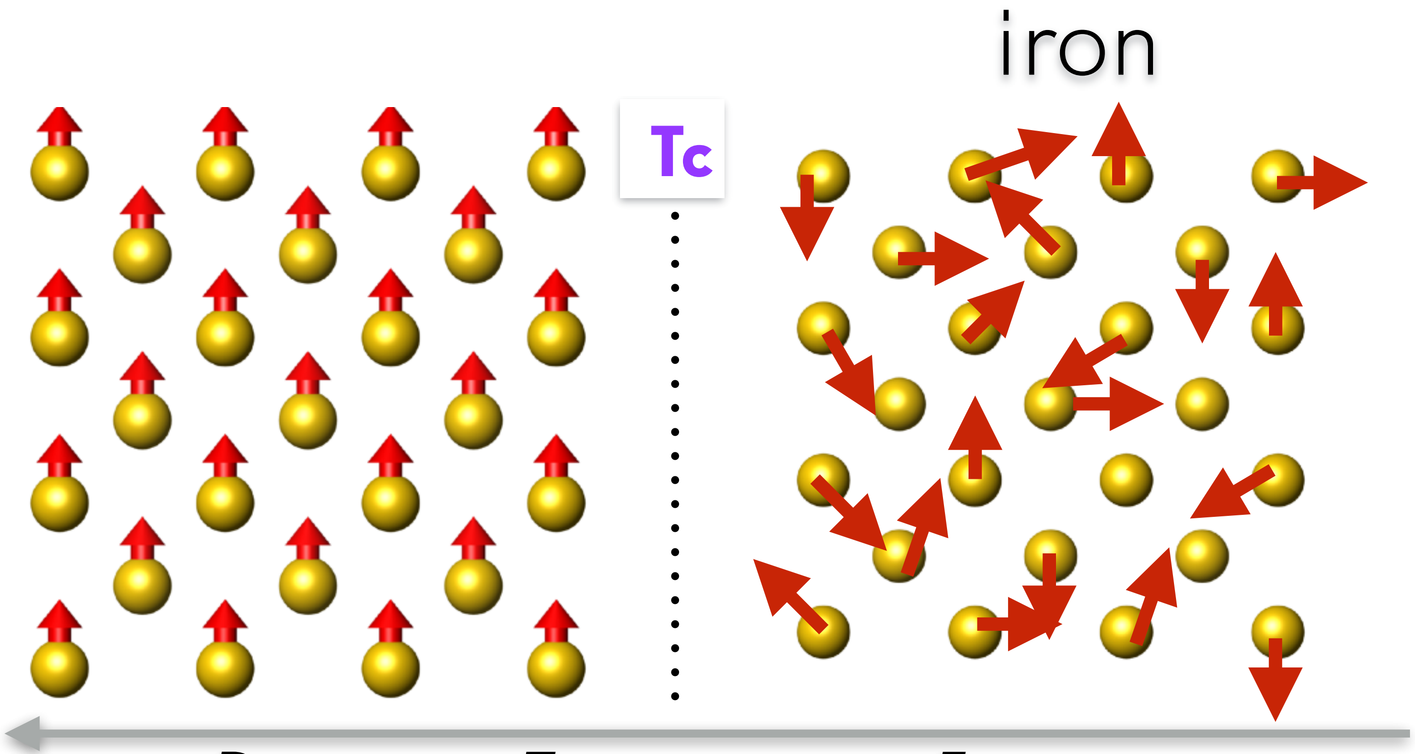
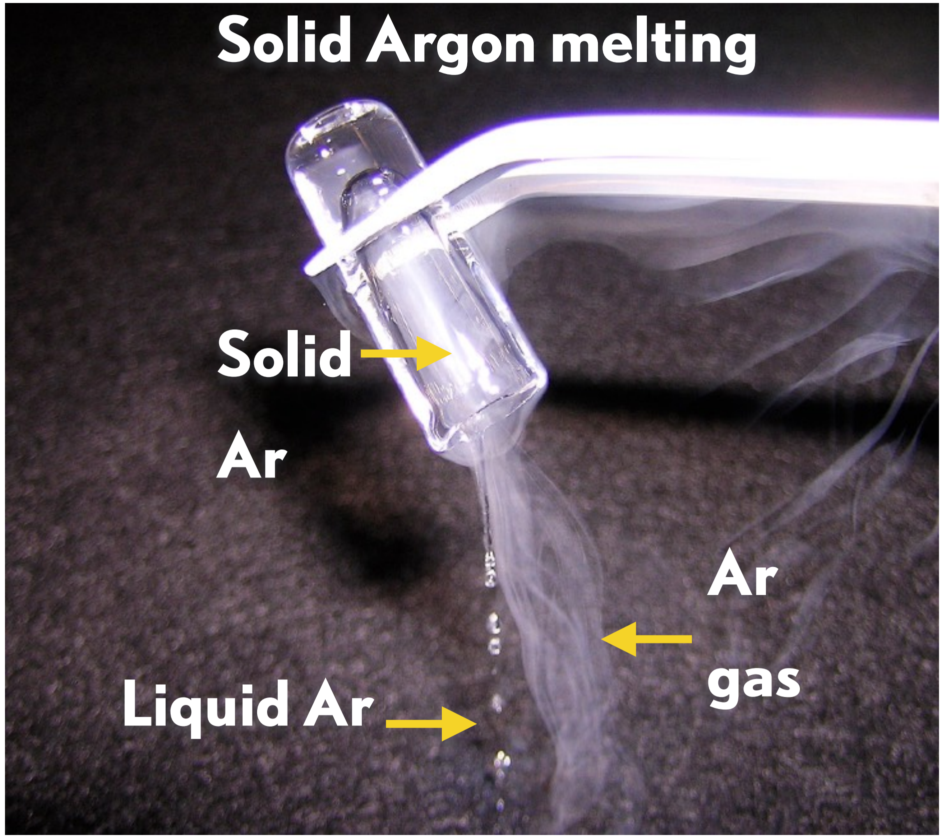
BROKEN SYMMETRY = EMERGENCE OF A NEW PHASE



Decreasing Temperature or Energy

<M> ≠ 0 <M>=0



A tri-critical point of Ar

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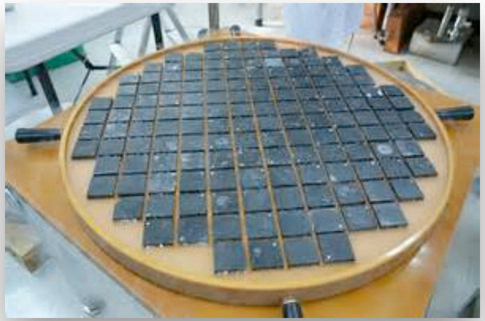
(BROKEN) SYMMETRY AND ORDER PARAMETER

Temperature or Energy

liquid

metal

magnetic insulator



disordered phase

higher symmetry

critical temperature Tc

solid

insulator

superconductor

ordered phase

lower symmetry

Broken symmetry means the appearance of an ordered phase with a **non-zero order parameter**

WHERE ARE THE NEW PHASES OF MATTER?

Lev Landau

Nobel prize

1962

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