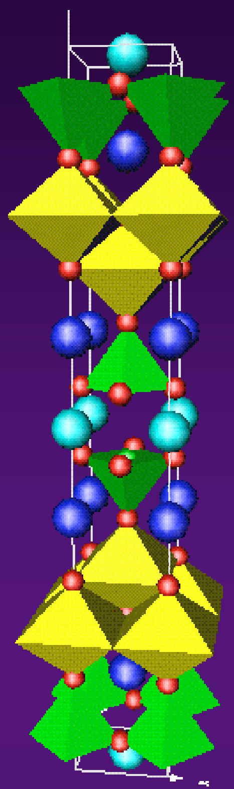
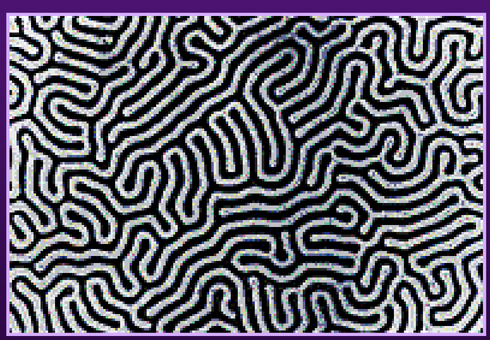


High Temperature Superconductivity: The Secret Life of Electrons in Cuprate Oxides



Erica W. Carlson

PURDUE UNIVERSITY

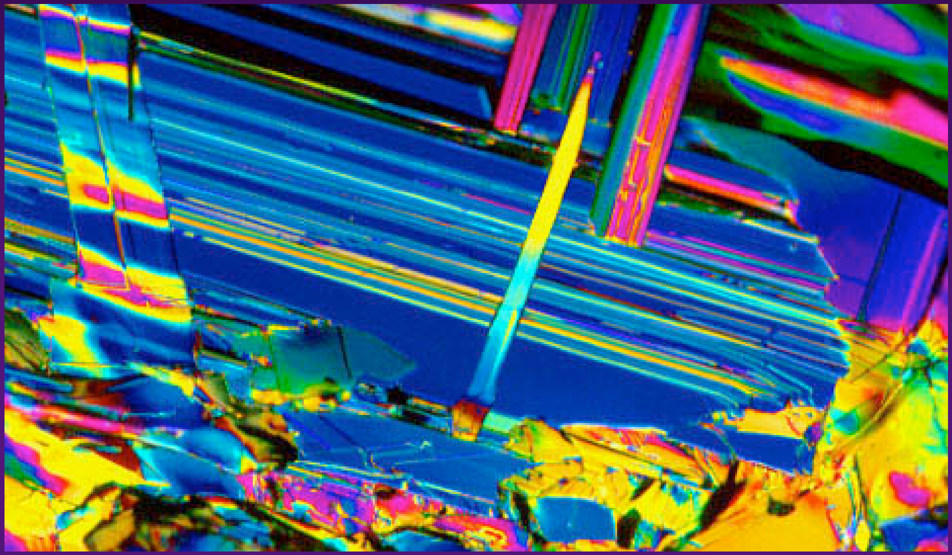
Metals

- Shiny
- Smooth
- Malleable
- Carry current (conduct electricity)

Metals and Current

- V = IR
- Resistance
- Wires radiate power away as heat
- You pay for more electricity than you receive!
- Electrons “scatter” off lattice, and lose energy

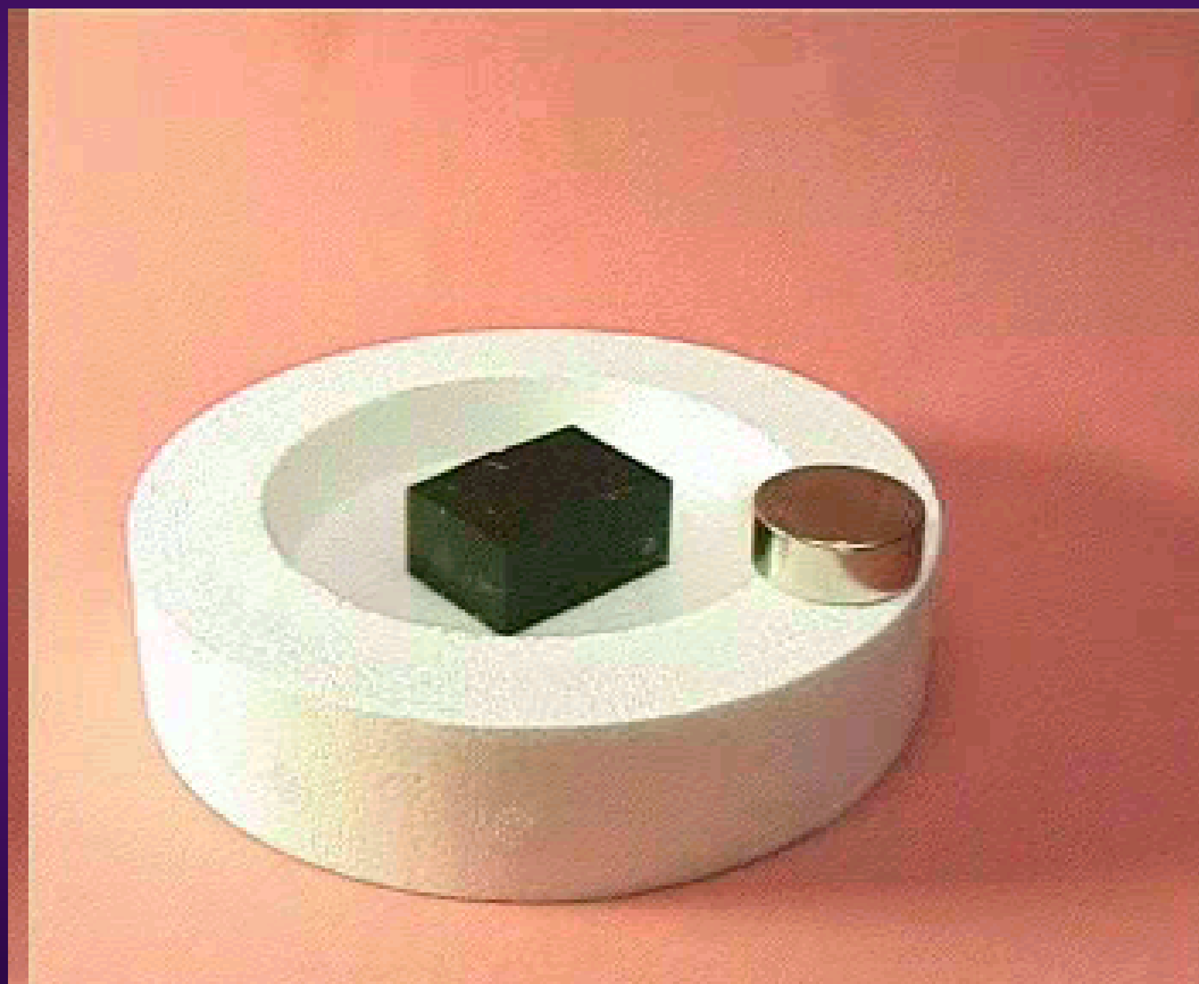
Superconductors



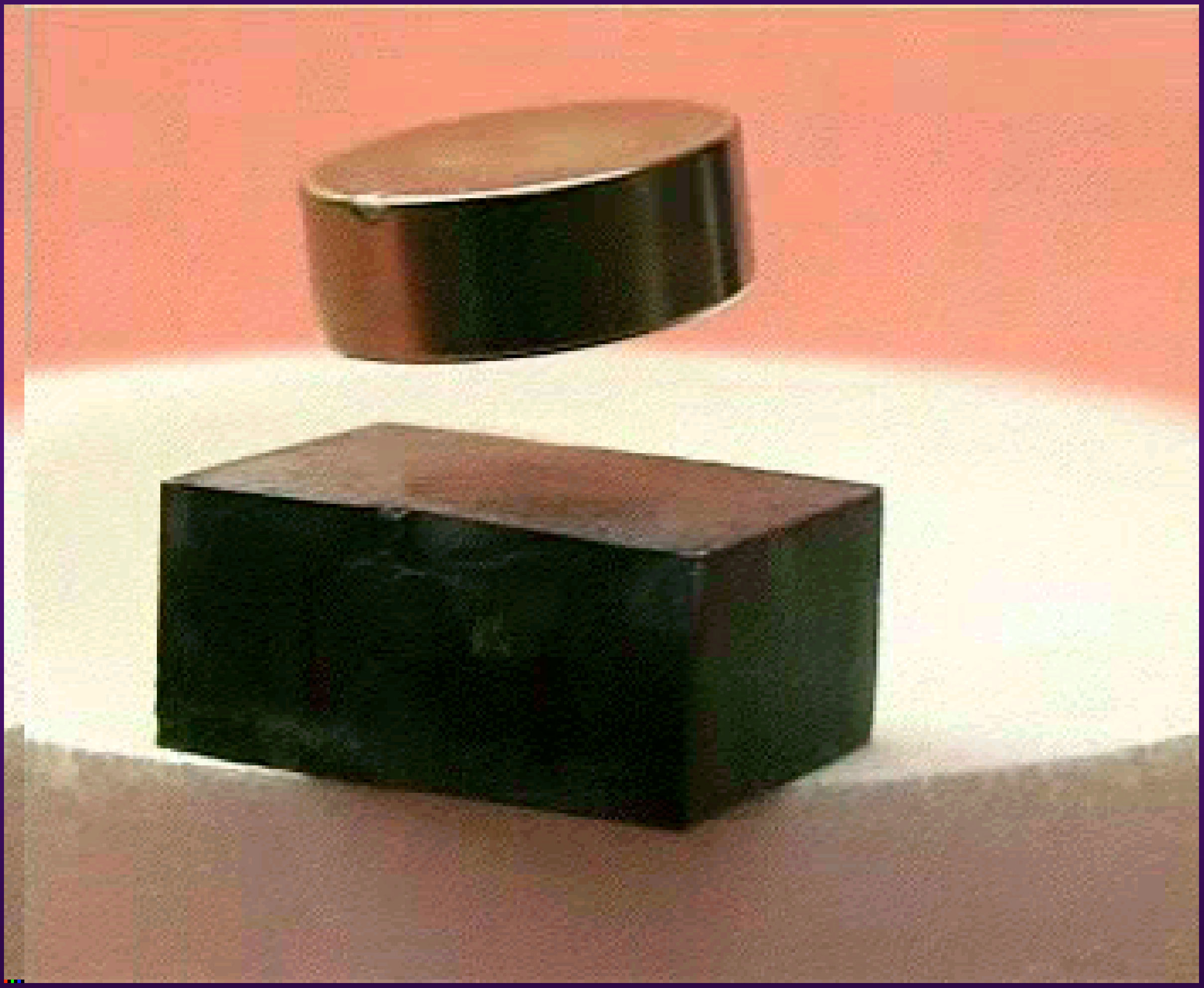
http://micro.magnet.fsu.edu

- Carry current perfectly
- Do not lose energy
- Current in a loop will run *forever*
- Expel magnetic fields (Meissner effect)

Levitation



Levitation



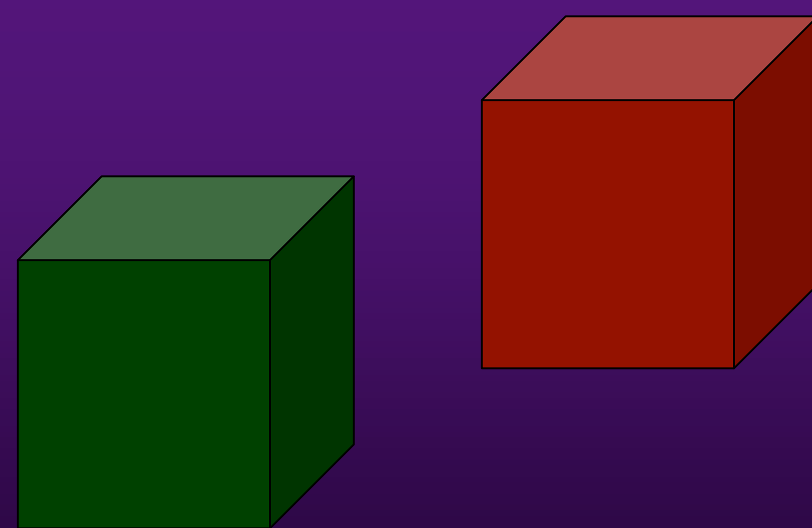

浮いた
土佐ノ海
TOSANOUMI
(Sumo Wrestler)
Height of Tosanoumi 186cm
Weight of Tosanoumi 142kg
Weight of disk 60kg
Total weight 202kg
協力：財団法人　日本相撲協会

How does it happen?

Matter

No two pieces of matter may occupy the same space at the same time

(Only half true)



Two kinds of particles

Fermions
(spin 1/2, 3/2, 5/2, etc.)

- Cannot occupy the same space at the same time
- Pauli exclusion principle

Antisocial

Bosons
(spin 0, 1, 2, etc.)

- Can occupy the same space at the same time

All Follow the Crowd

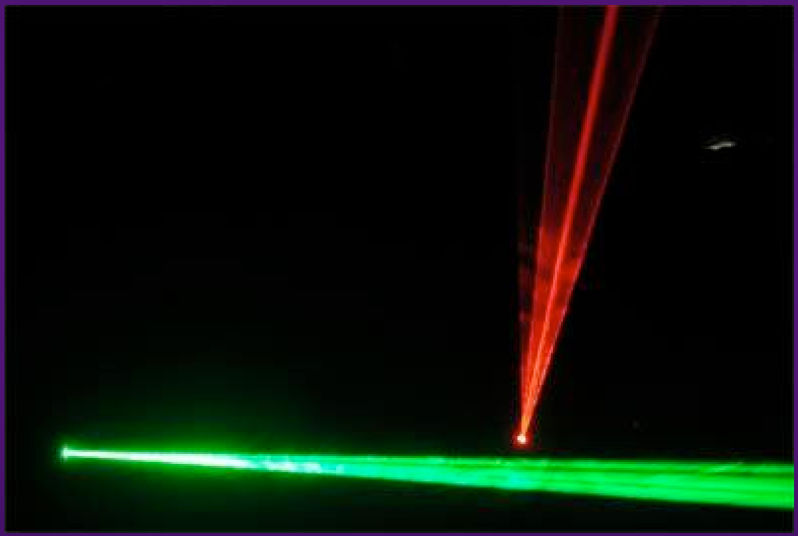
Electrons are Fermions

Pauli exclusion principle

Why most matter cannot occupy the same space at the same time

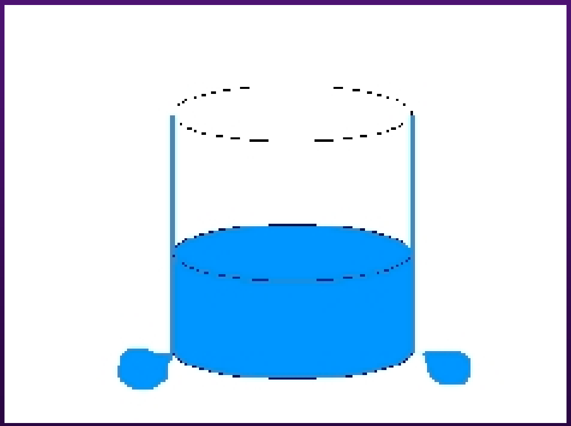
Bosons

Can occupy the same space at the same time



Photons are bosons
→ lasers

Helium is a boson
→ superfluidity



Bose condensation

- At low temperature, bosons flock to the lowest level
- Very stable state!
- Dissipationless flow
- Superfluidity (Helium)
- Superconductivity (metals at low temperature)

Superconductivity

- Pair electrons → form *bosons*
- Bosons condense into the lowest orbital
- Quantum mechanics! Very stable state
- Dissipationless current flow

Conventional Superconductivity

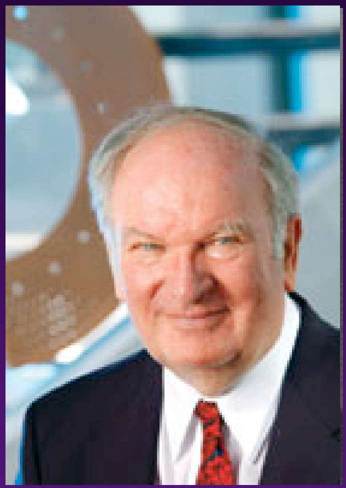
Based on an *instability* of the simple metallic state

Superconductors Have Zero Resistance?

- Metals: electrons "scatter" off lattice and lose energy → resistance
- Superconductor: electrons pair
- Bosonic electron pairs in lowest state already
- There's no lower state for them to scatter into
- Same as why atoms are stable

John Bardeen

Leon Cooper



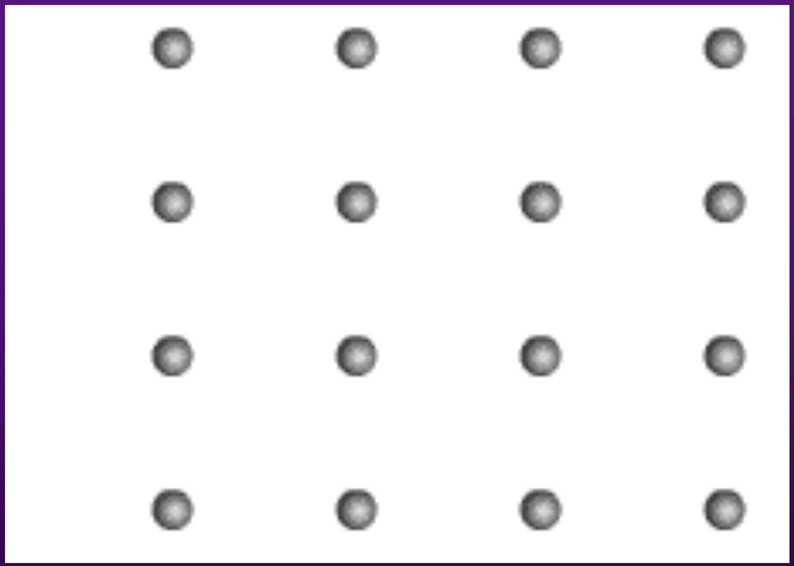
Bob Schrieffer

Conventional Superconductivity

- BCS Theory
- *Instability* of the metallic state

Cooper Pairing

- Electrons in Metal Can Pair via the lattice



www.superconductors.org

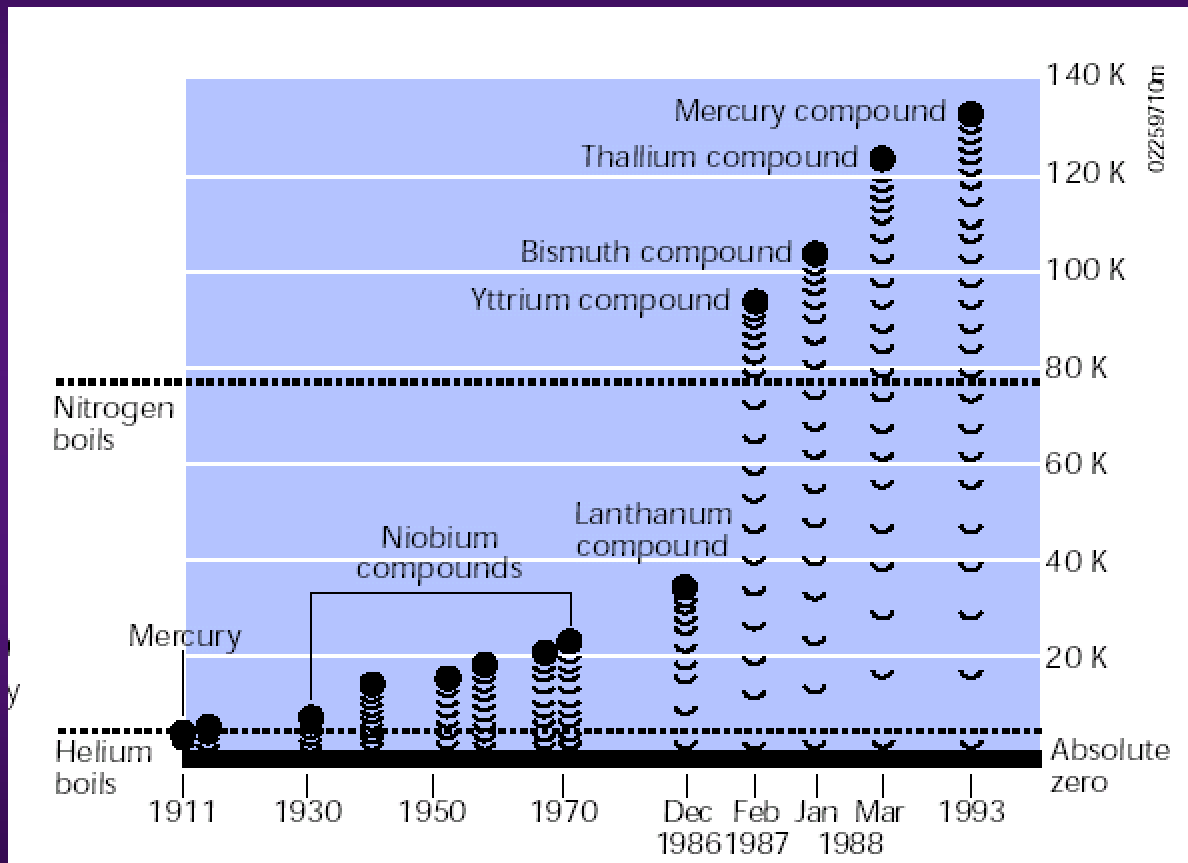
BCS Haiku:

Instability

Of A Tranquil Fermi Sea—

Broken Symmetry

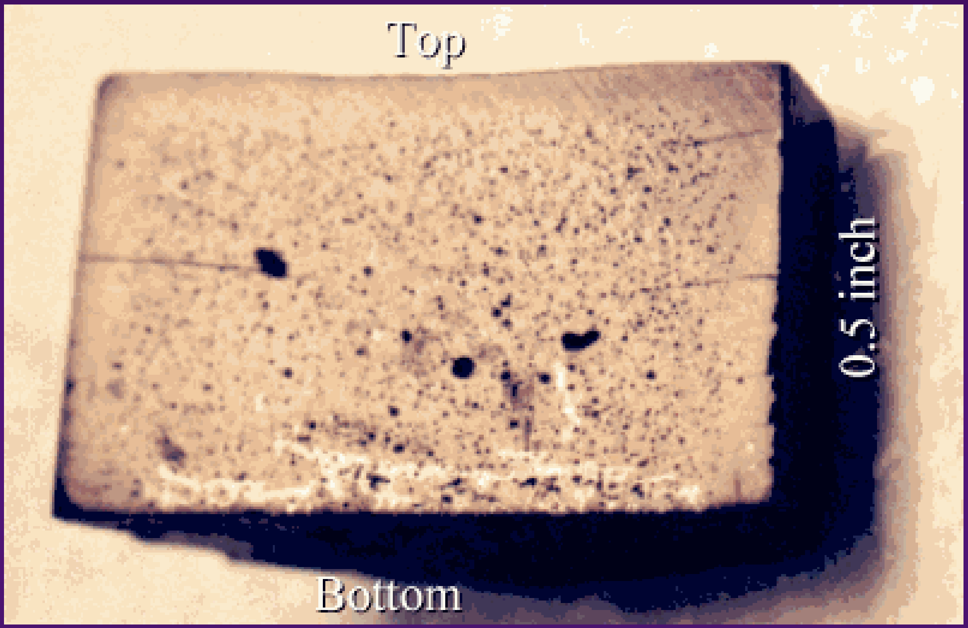
And then there was 1986



http://www.eere.energy.gov/superconductivity/pdfs/frontiers.pdf

A Ceramic Superconductor?

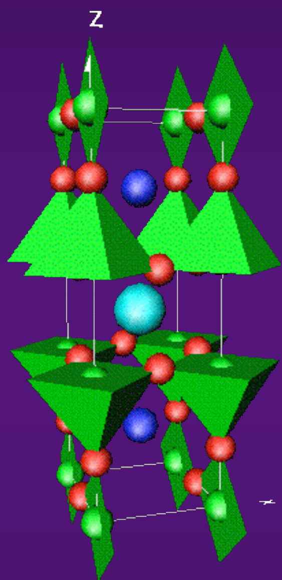
- Brittle
- Ceramic
- Not Shiny
- Not metallic



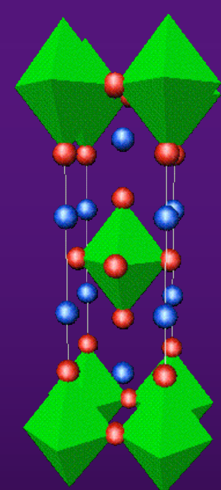
http://www.superconductivecomp.com/

- Why do they conduct at all?

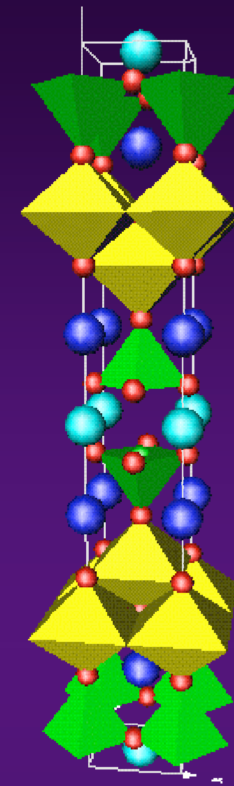
High Temperature Superconductors



$YBCO_7$

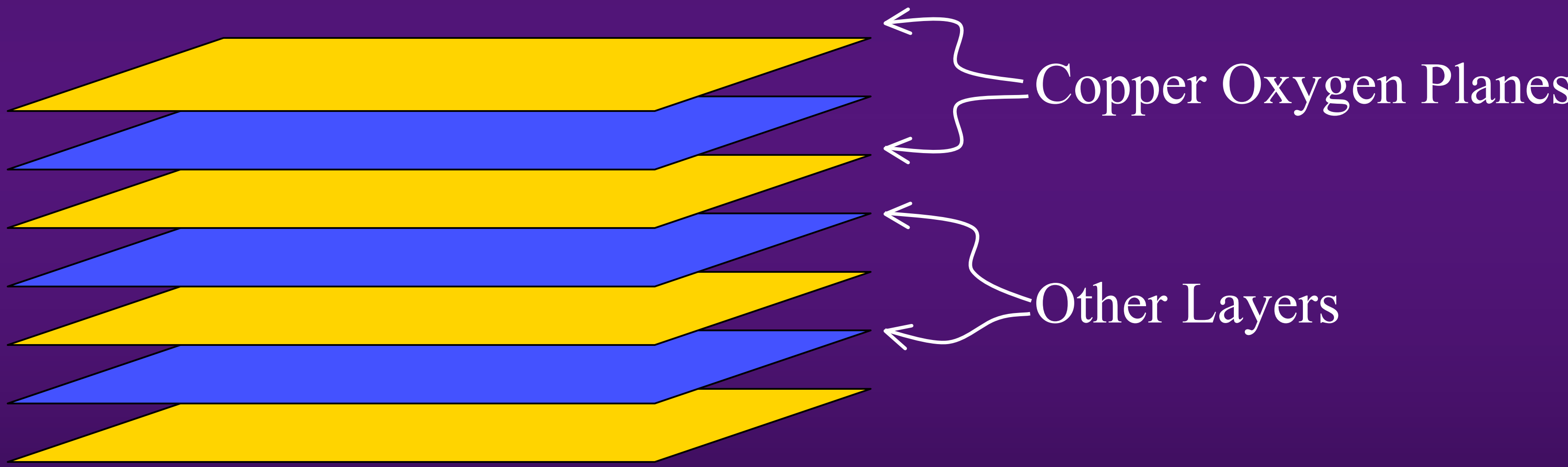


LSCO



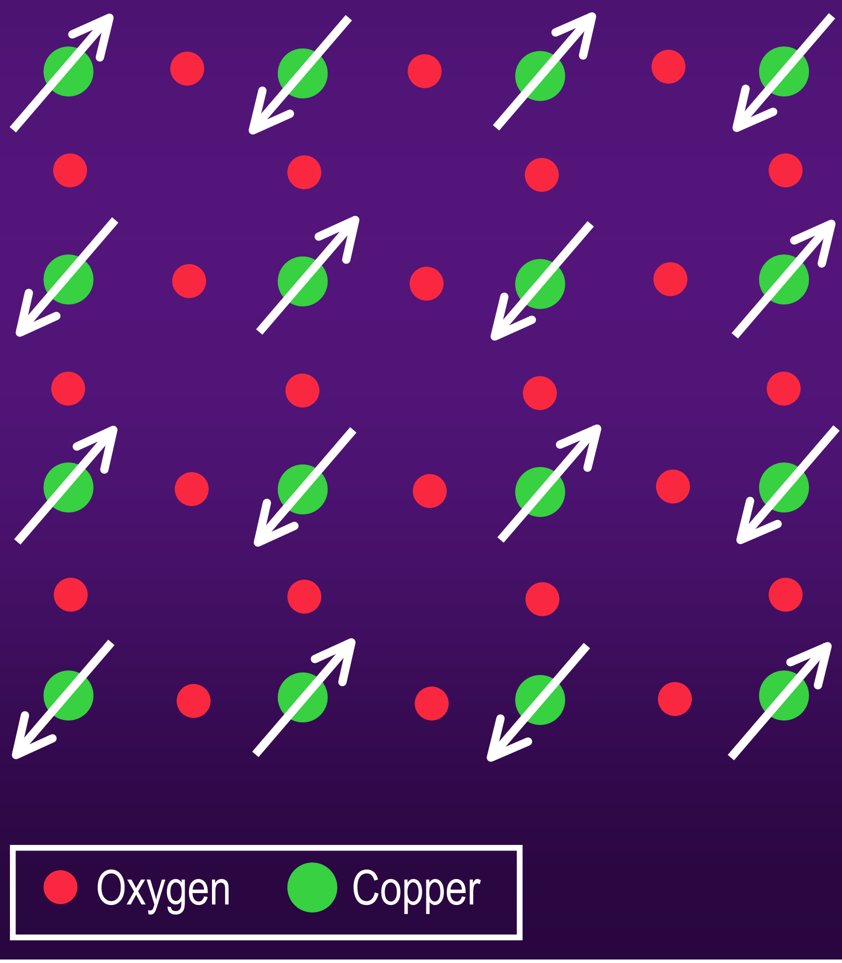
HgCuO

High Temperature Superconductors



Layered structure → quasi-2D system

High Temperature Superconductors



Copper-Oxygen Planes Important

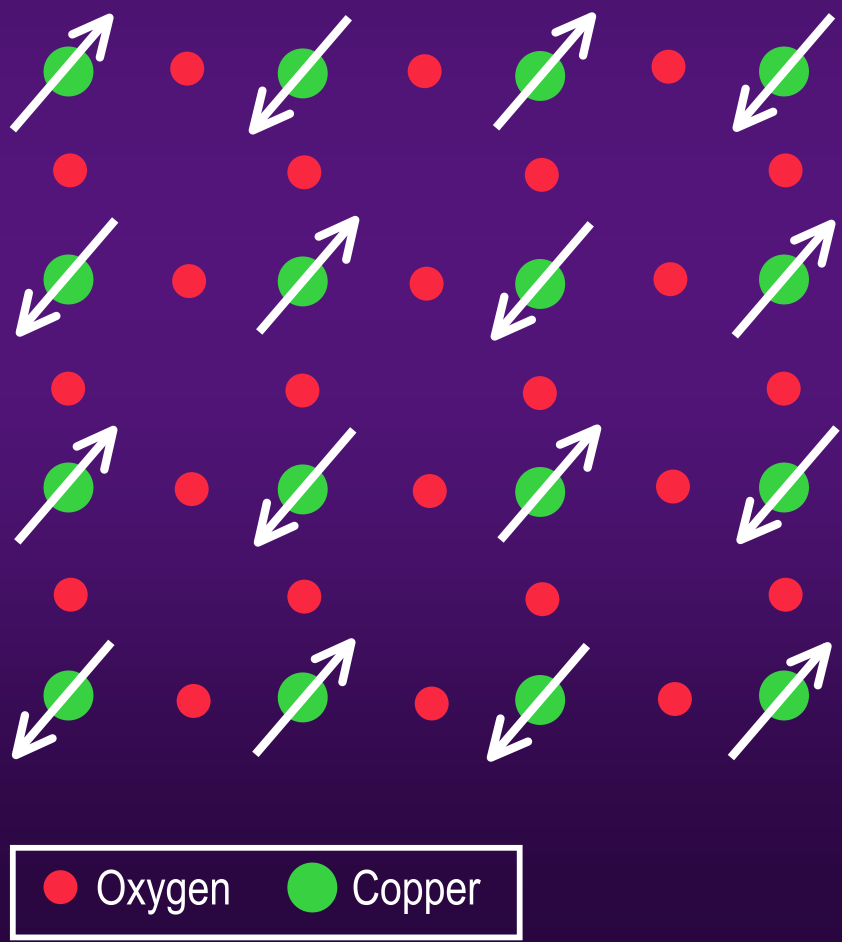
"Undoped" is half-filled

Antiferromagnet

Naive band theory fails

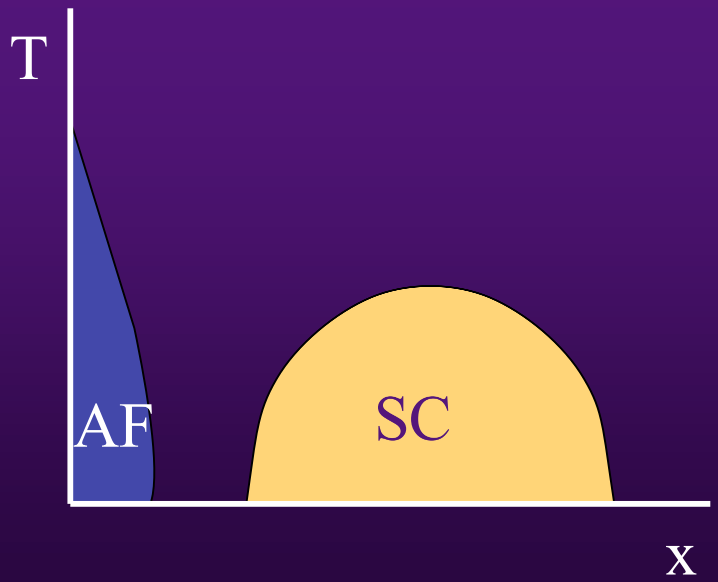
Strongly correlated

High Temperature Superconductors



Dope with holes

Superconducts at certain dopings



Mysteries of High Temperature Superconductivity

- Ceramic! (Brittle)
- Not a simple metal
- Magnetism nearby (antiferromagnetism)
- Make your own   (robust)
  http://www.ornl.gov/reports/m/ornlm3063r1/pt7.html
- BCS inadequate!

Two Ingredients for Superconductivity

Pairing	Condensation
Single Particle Gap	Superfluid Density

BCS is a mean field theory in which pairing precipitates order

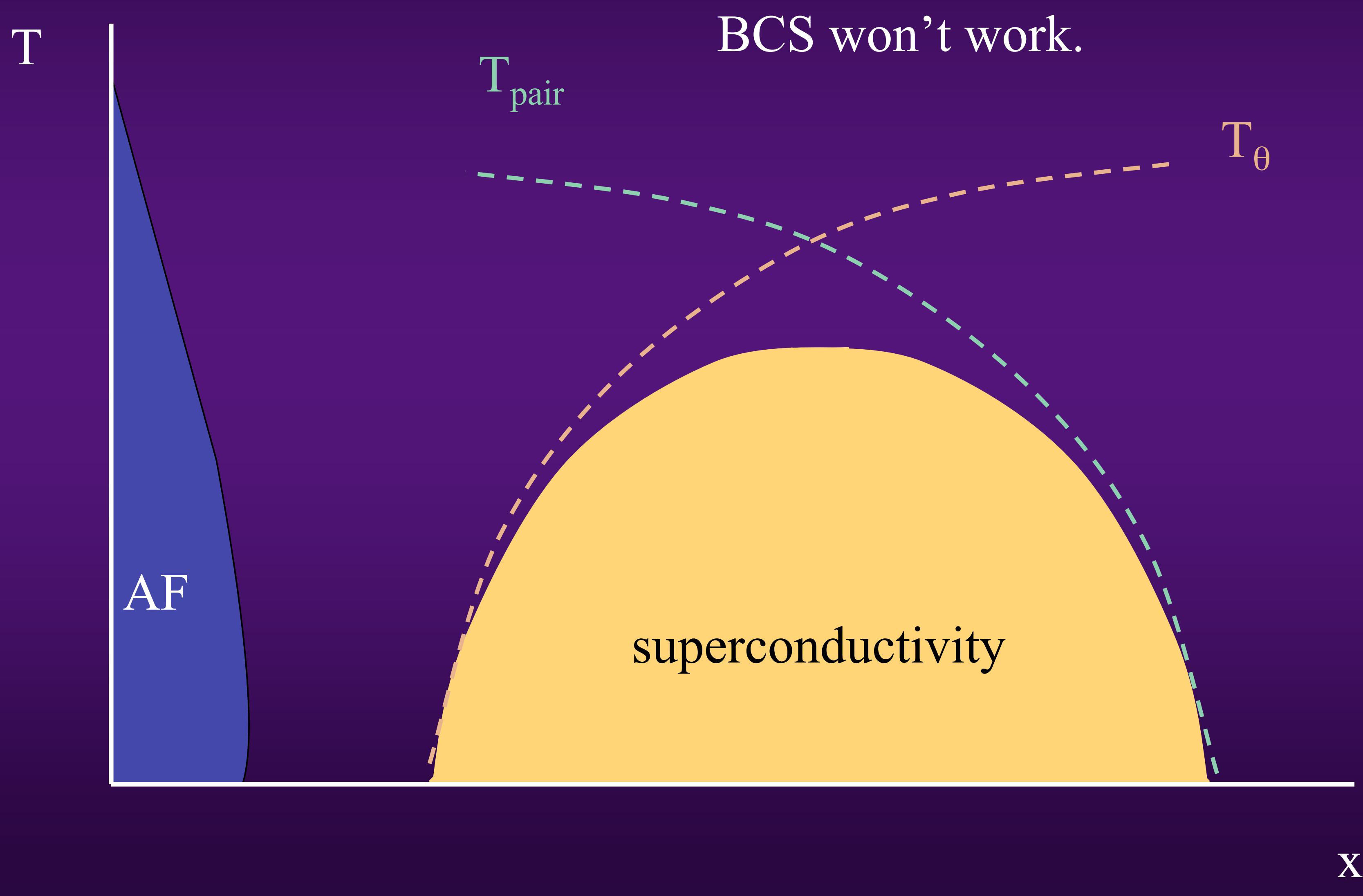
Material	T_{pair}[K]	T_c[K]	T_θ[K]
Pb	7.9	7.2	6X10^{5}
Nb_3Sn	18.7	17.8	2X10^{4}
UBe13	0.8	0.9	10^{2}
BaKBiO	17.4	26	5X10^{2}
K_3C_{60}	26	20	10^{2}
MgB_2	15	39	1.4X10^{3}

Phase Fluctuations Important in Cuprates

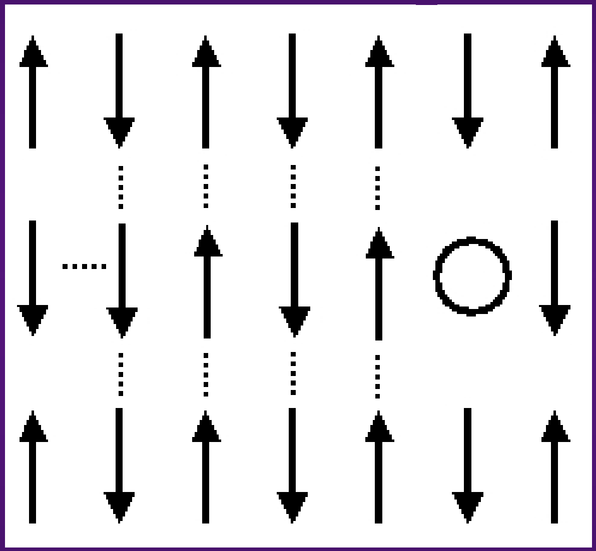
Material	T_{pair}[K]	T_c[K]	T_θ[K]
LSCO (ud)	75	30	47
LSCO (op)	58	38	54
LSCO (od)		20	100
Hg-1201 (op)	192	96	180
Hg-1212 (op)	290	108	130
Hg-1223 (op)	435	133	130
Tl-2201 (op)	122	91	
Tl-2201 (od)		80	160
Tl-2201 (od)	26	25	
Bi-2212 (ud)	275	83	
Bi-2212 (op)	220	95	60
Bi-2212 (od)	104	62	
Y-123 (ud)		38	42
Y-123 (op)	116	90	140
Y-123 (od)	55	140	

Emery, Kivelson, Nature, **374**, 434 (1995)
EC, Kivelson, Emery, Manousakis, PRL **83**, 612 (1999)

T_c and the two energy scales



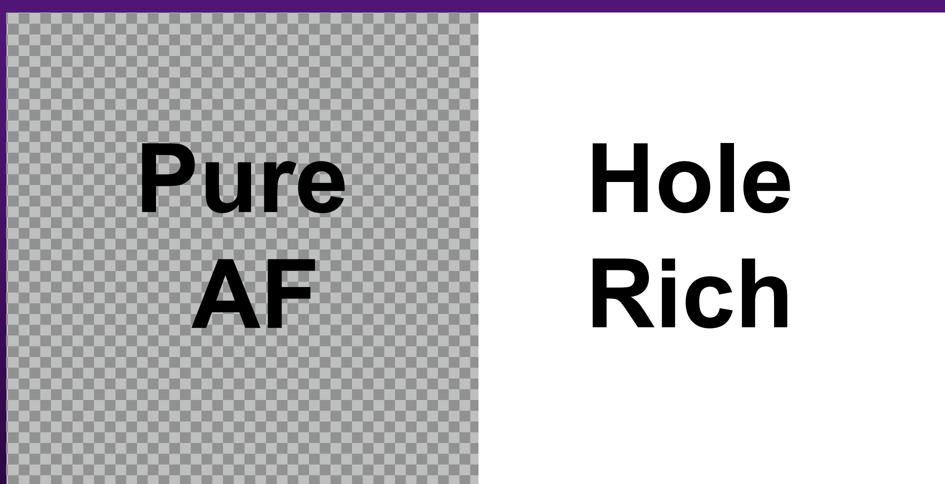
Doped Antiferromagnets



Hole Motion is Frustrated

Doped Antiferromagnets

- Compromise # 1: Phase Separation
- Relieves some KE frustration

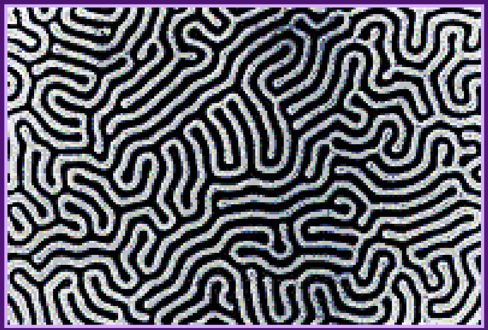


Like Salt Crystallizing
From Salt Water,
The Precipitate (AF) is Pure

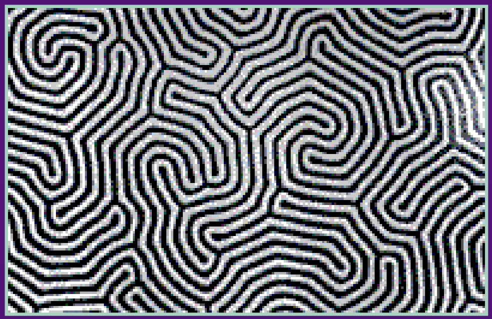
Coulomb Frustrated Phase Separation

- Long range homogeneity
- Short range phase separation
- Compromise # 2: *mesoscale structure*
- Patches interleave
- quasi-1D structure – stripes ?

Competition often produces stripes

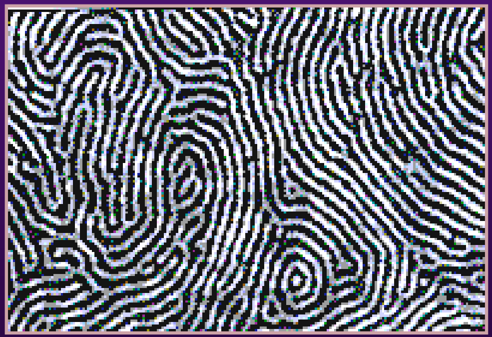


Ferrofluid
confined between
two glass plates
Period ~ 1cm



Ferromagnetic
garnet film
Faraday effect
Period ~ 10^{-5} m

Ferromagnetic
garnet film
Period ~ 10^{-5} m



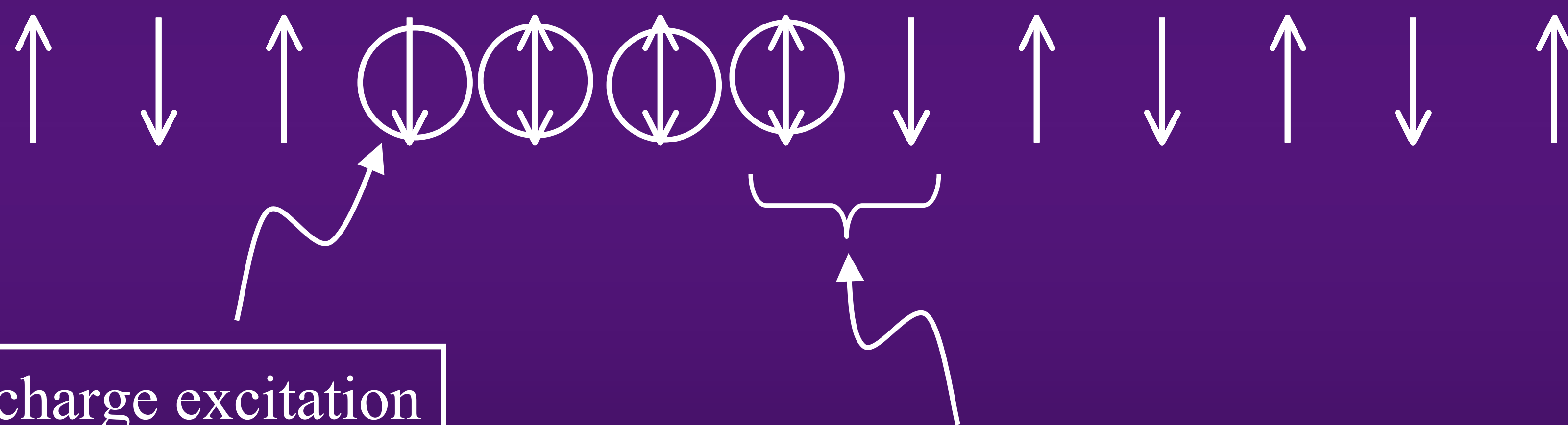
Block copolymers
Period ~ $4X10^{-8}$ m

What's so special about 1D?

→ *solitons*

Disturbances in 3D:	dissipate as ~	$1/R^2$	Like the intensity of light
Disturbances in 2D:	dissipate as ~	$1/R$	Like a stone thrown in a pond
Disturbances in 1D:	"dissipate" as ~	1	Like a wave in a canal

1D: Spin-Charge Separation



charge excitation

spin excitation

Spin Charge Separation
Electron No Longer Exists!

Fermi Liquid

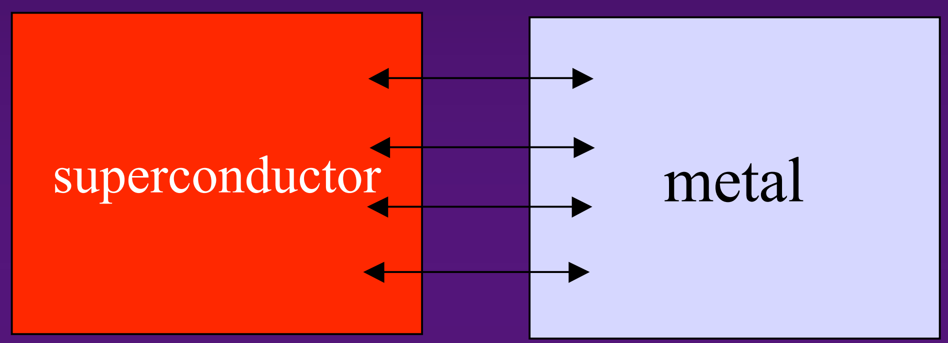
- k-space structure
- Kinetic energy
  is minimized
- Pairing is potential energy driven

Strong Correlation

- Real space structure
- Kinetic energy (KE)
  is highly frustrated
- System works to relieve KE
  frustration
- Look for KE driven pairing

Kinetic Energy Driven Pairing?

→ Proximity Effect

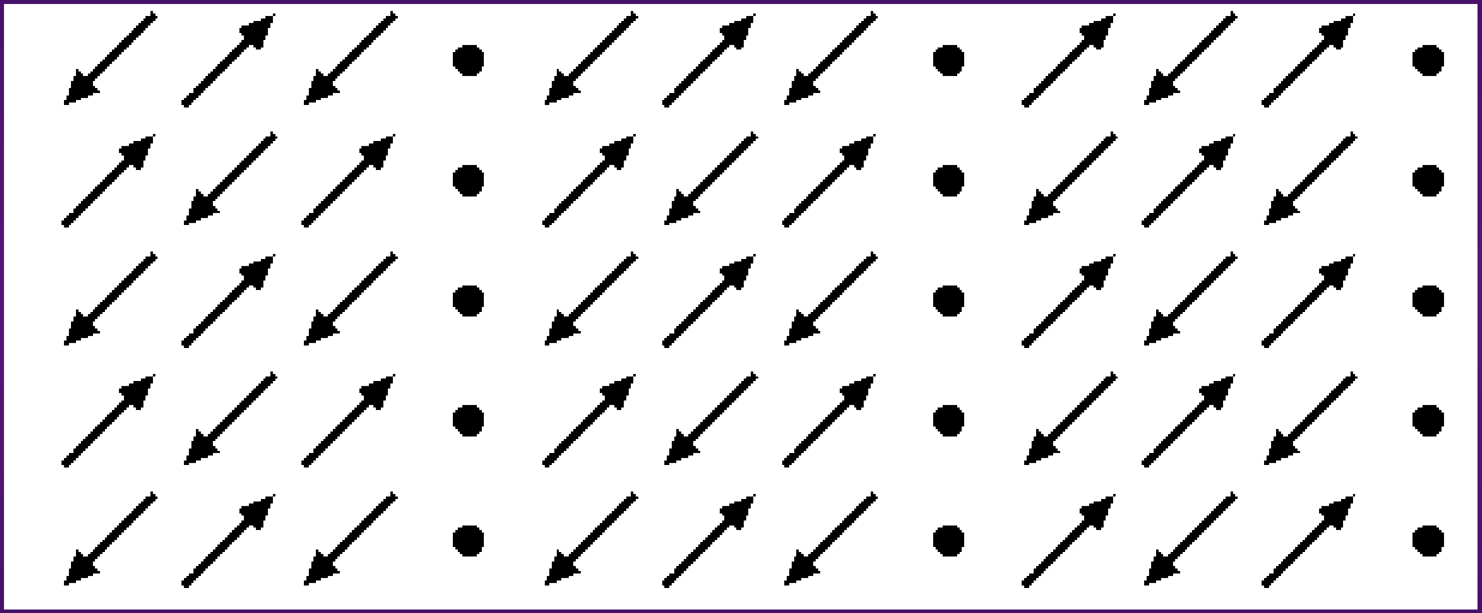


Individually, free energies minimized

Metal pairs (at a cost!) to minimize kinetic energy across the barrier

Stripey Proximity Effect

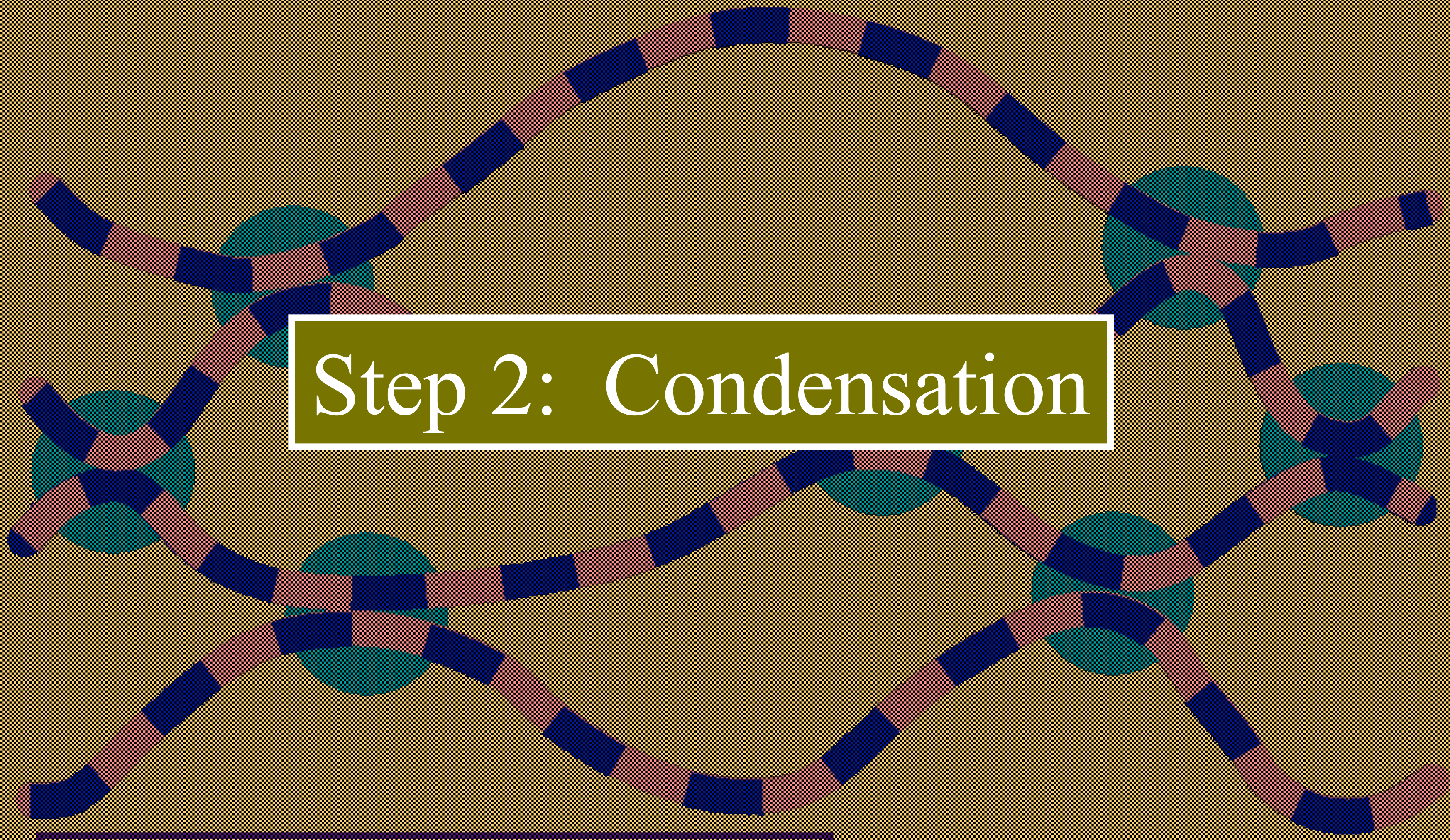
Kinetic energy driven pairing in a quasi-1D superconductor



Metallic charge stripe acquires gap (forms pairs) through communication with gapped environment

Step 1: Pairing

Stripe Fluctuations



Stripe fluctuations
Encourage Condensation

Summary

- Superconductivity
  - Fermions pair to form Bosons
  - Bosons condense → superfluid
  - Very stable phase of matter
  - Zero resistance

- Conventional (BCS) superconductivity:
  - Instability of the simple metallic state

- High Temperature Superconductors
  - Don't follow BCS theory
  - Ceramic – not metallic
  - Stripes: new mechanism
    - Pairing by proximity
    - Coherence by fluctuations
    - → Relieve kinetic energy frustration of strongly correlated system