WHAT IS SUPERCONDUCTIVITY?
WHAT IS IT GOOD FOR?

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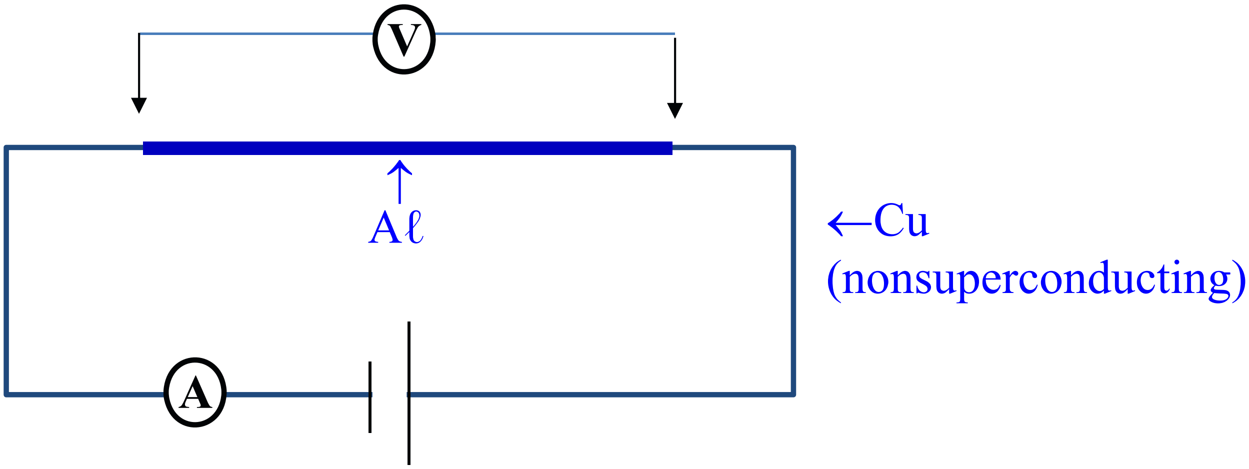
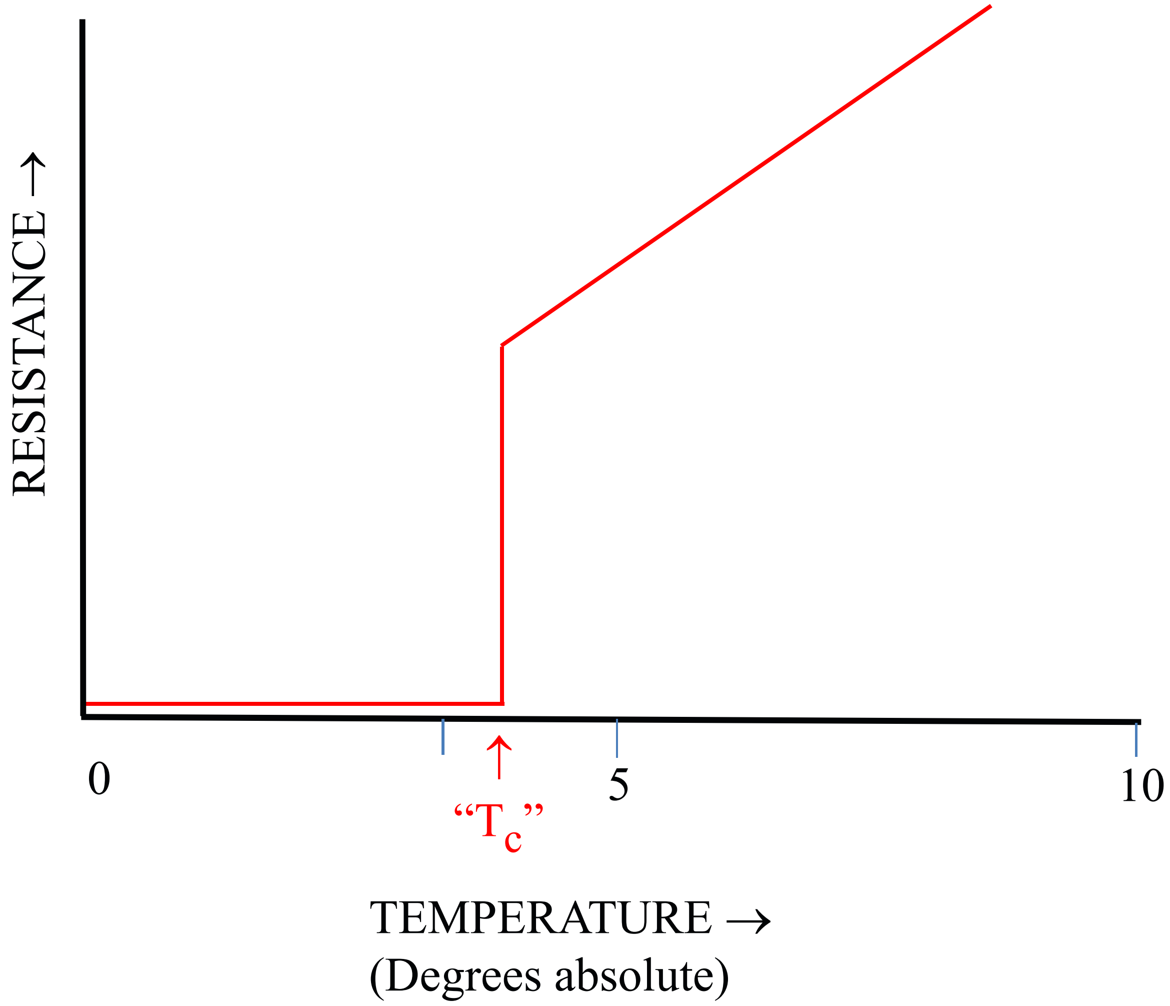
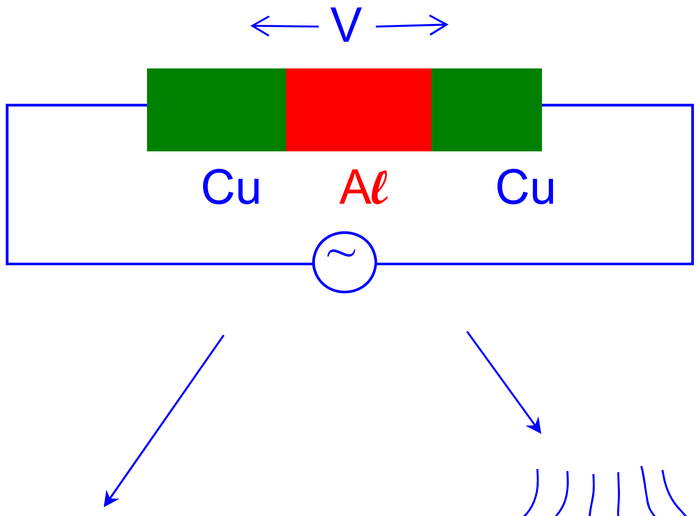
WHAT IS SUPERCONDUCTIVITY?

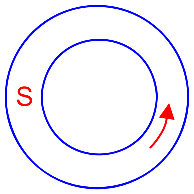
Basic expt: (Onnes 1911)



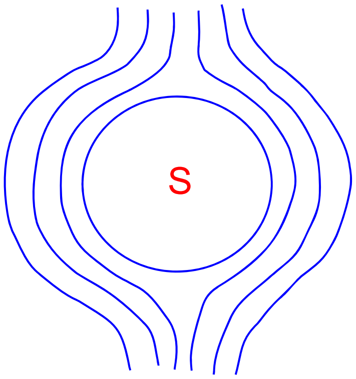
resistance of ▬ = V/A = voltage/current







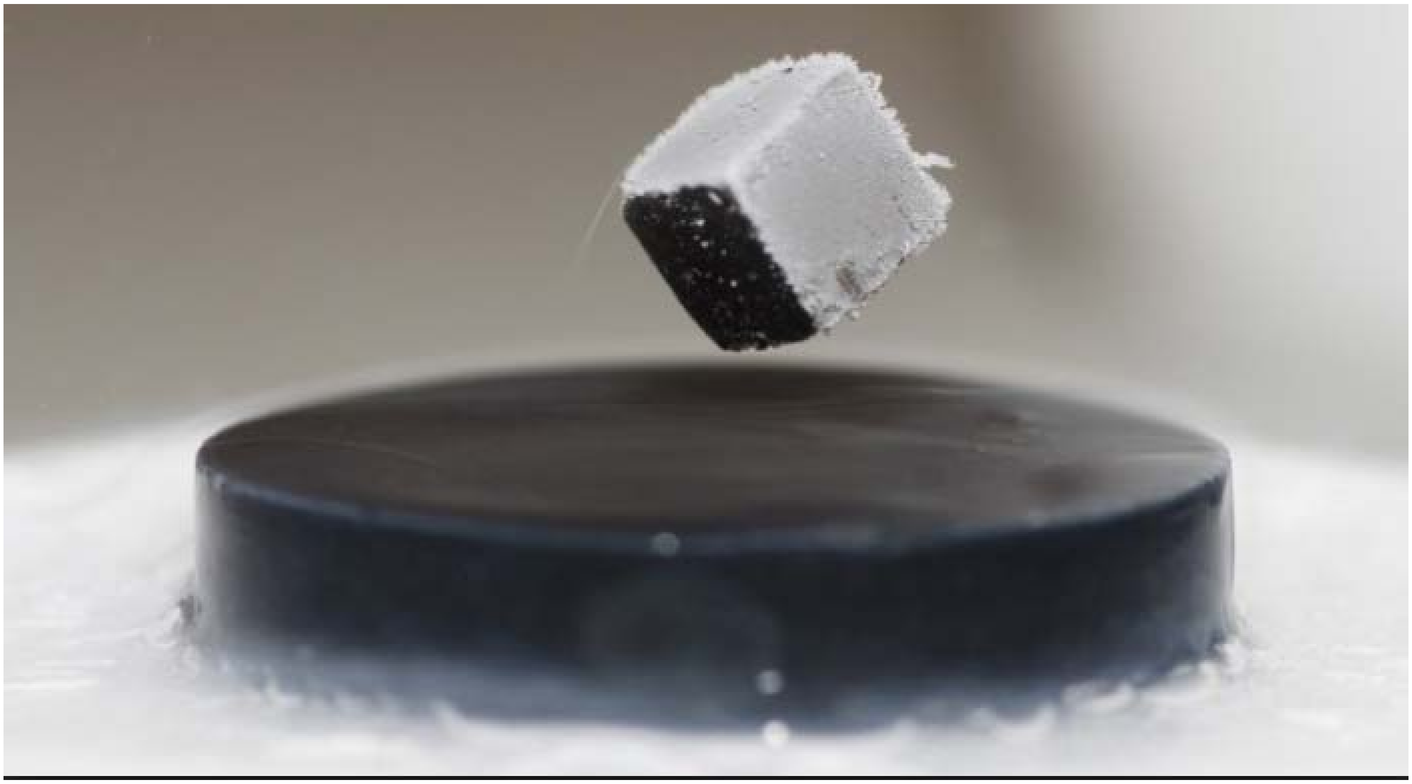
persistent currents,
astronomically
stable
(1911→)



perfect diamagnetism
(Meissner effect)
(1933→)

No a priori guarantee these two phenomena always go together!

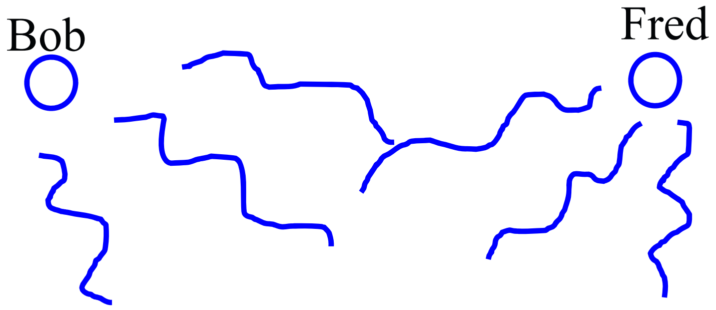
(but in fact seem to, in all "superconductors" known to date).



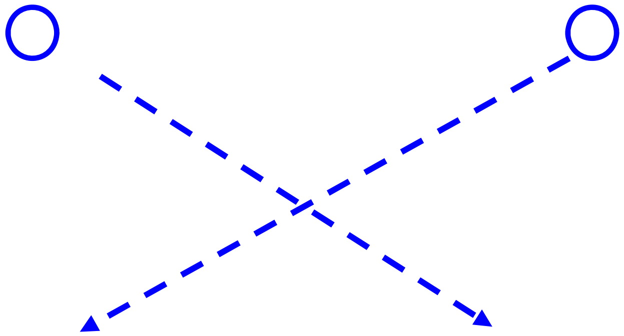
Origin of superconductivity:

Indistinguishablity of elementary particles

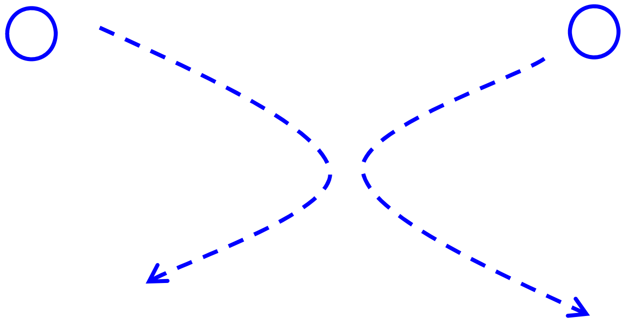
Because in quantum mechanics particles behave like waves, impossible to "tag" them.




Which is Bob and which is Fred?



or



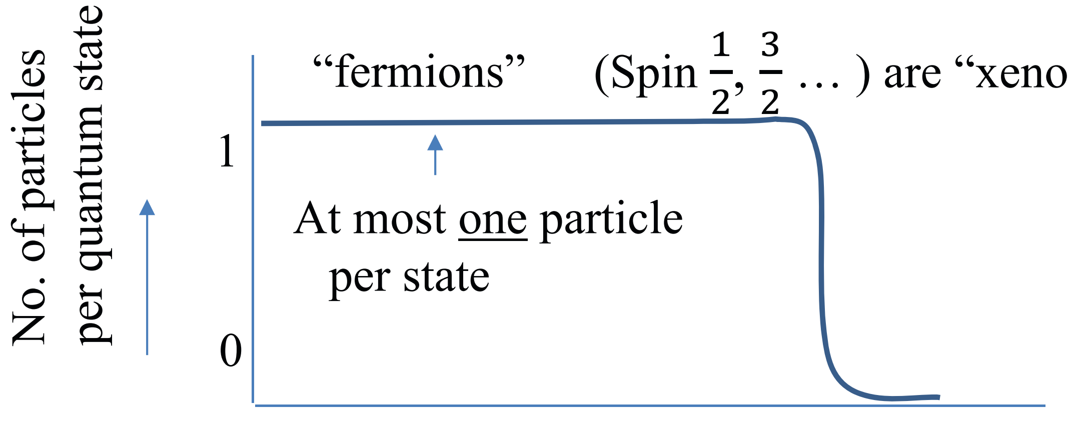
?

Evidently, for this property to be important, must be able to change places (true for electrons in a metal).

Result of indistinguishability:

“QUANTUM STATISTICS”

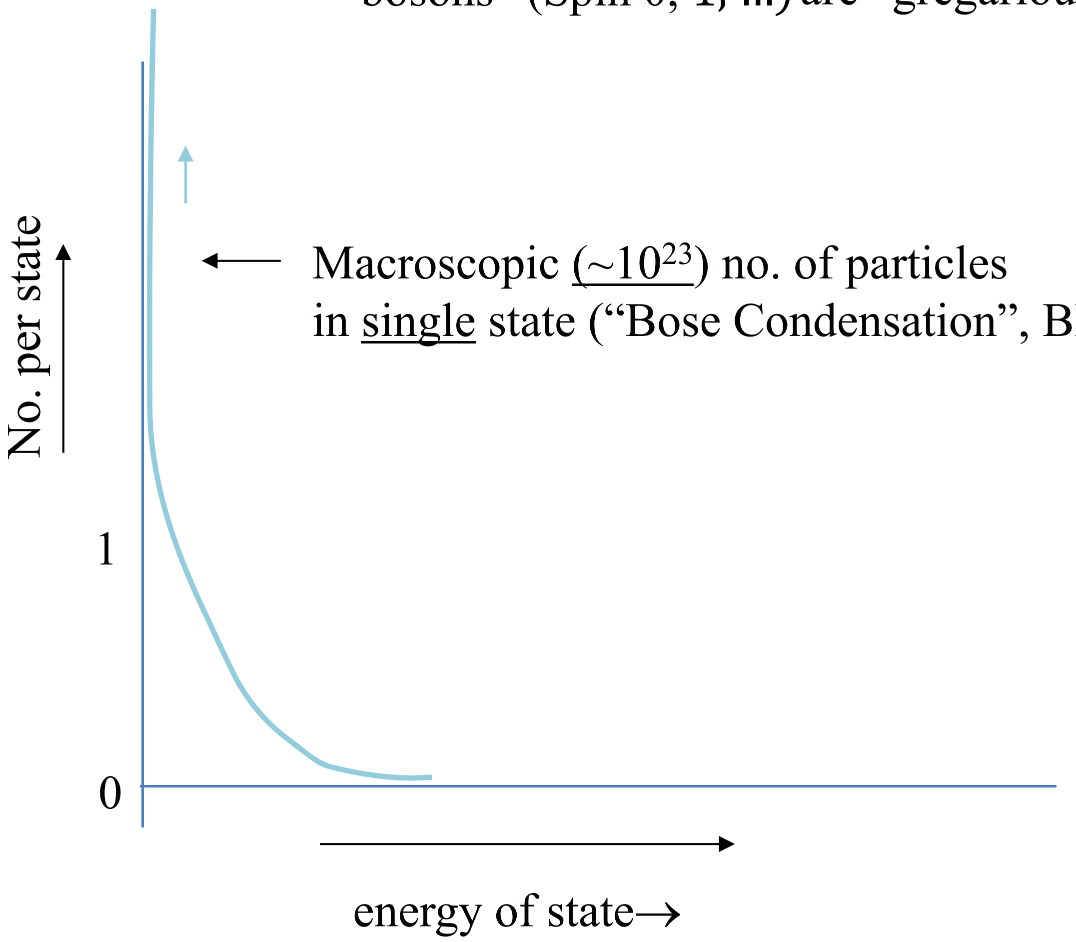
“fermions” (Spin $\frac{1}{2}$, $\frac{3}{2}$ …) are “xenophobic”



At most one particle per state

↑ “Fermi energy”

“bosons” (Spin 0, 1, ...) are “gregarious”



Macroscopic (~10^{23}) no. of particles in single state (“Bose Condensation”, BEC)

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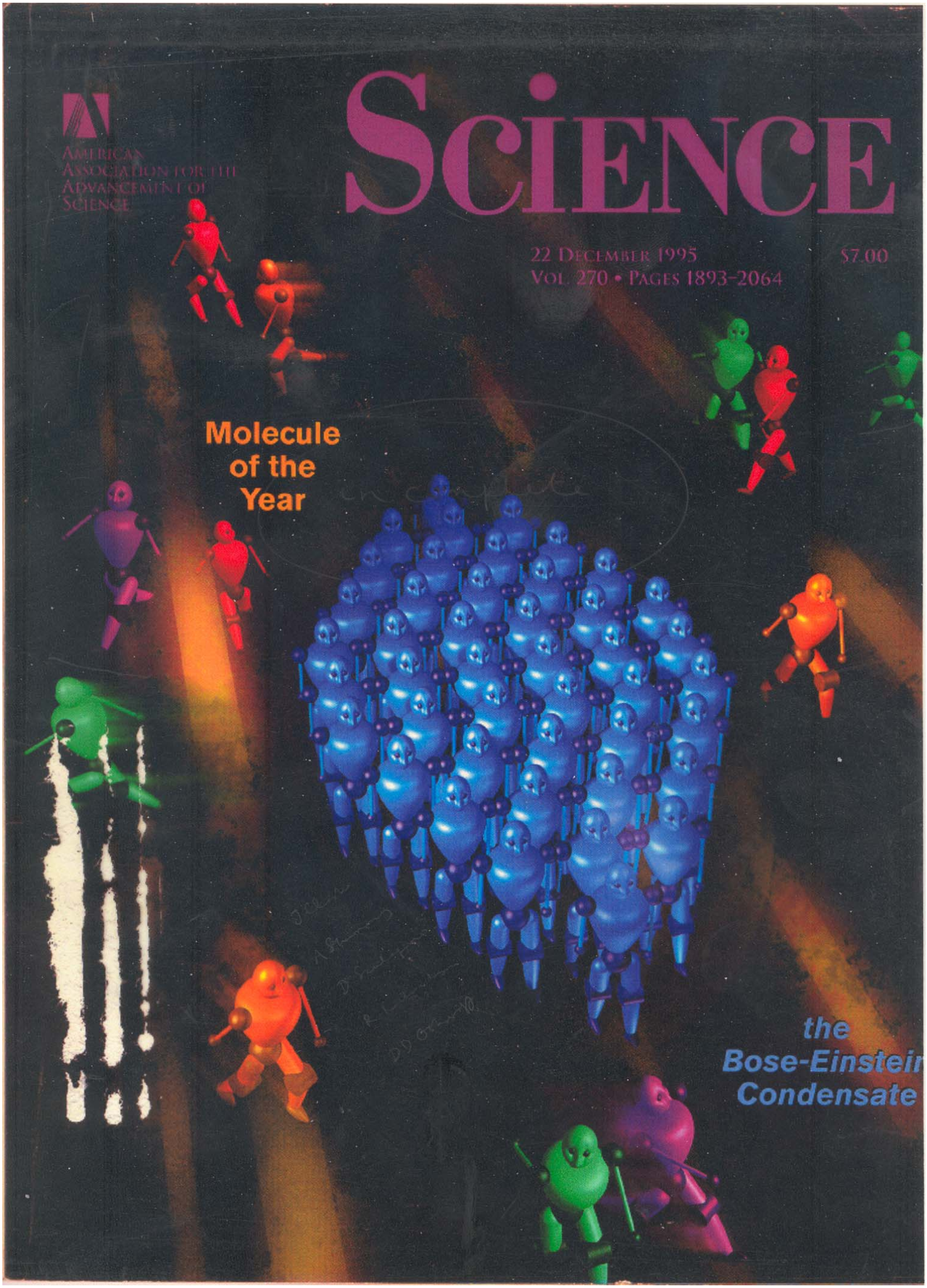


in complete

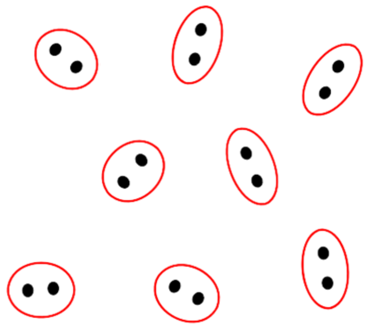
Electrons in metals: spin ½ $\Rightarrow$ fermions

But a compound object consisting of an even no. of fermions has spin 0, 1, 2 … $\Rightarrow$ boson.

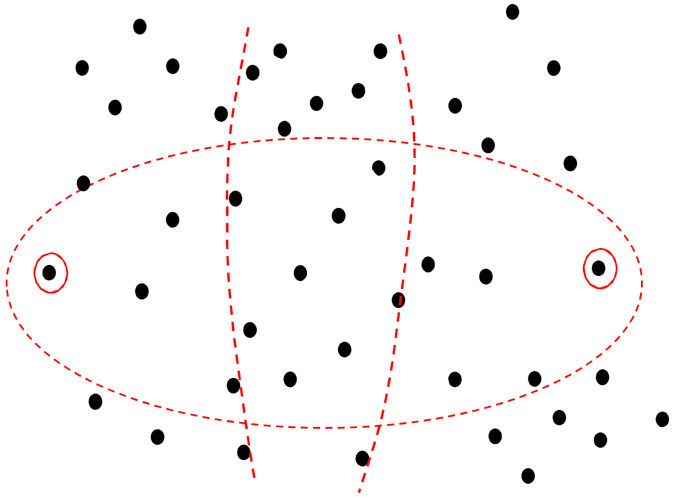
(Ex: $2p + 2n + 2e = {}^4$He atom)

$\Rightarrow$ can undergo Bose condensation

Pairing of electrons in a superconducting metal:



"di-electronic molecules"

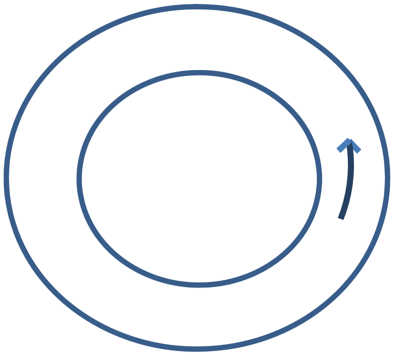


Cooper Pairs

In simplest ("BCS") theory, Cooper pairs, once formed, must automatically undergo Bose condensation!

$\Rightarrow$ must all do exactly the same thing at the same time (also in nonequilibrium situation)

Persistent Currents:



Apply transient voltage pulse around ring:

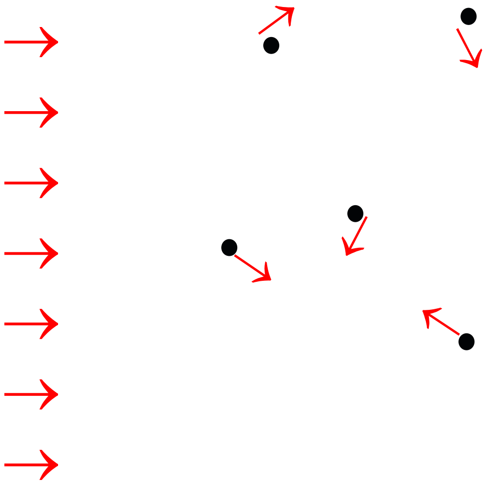
if ring is in normal state: current is excited, but rapidly dies away: the higher the resistivity, the faster the decay

if ring is in superconducting state: current persists forever!

(i.e. resistivity → 0)

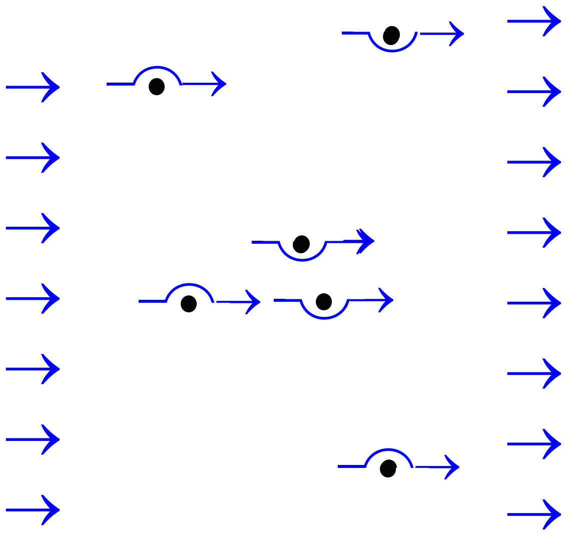
Why?

Answer: Bose condensation!



Single electrons in normal metal

Analogy: schoolchildren



Cooper pairs in superconductors

Analogy: platoon of soldiers

So far, so good…

But wait: persistent currents (zero resistivity) are not the only signature of superconductivity!

What about the Meissner effect (⇒ superconducting levitation)?

This is not just a consequence of zero resistivity!

(Zero resistivity: 1911, Meissner effect: 1933)

It is a consequence of Bose condensation, but the explanation is subtle (effectively, superconductor behaves like a giant closed-shell atom).

WHAT IS SUPERCONDUCTIVITY GOOD FOR?

Experimental fact:

For temperature below some “critical” temperature T_c (which depends on the material) and current below some “critical current density” J_c (ditto), many materials including Al are superconductors, i.e., have zero (dc) resistance. If we could use superconductors for long-distance power transmission, we would have

ZERO TRANSMISSION LOSS!

Some other advantages of using superconductors for transmission/ storage of electrical energy:

Automatic quenching of “runaway” current

High current density ⇒ smaller transmission lines (e.g. underground)

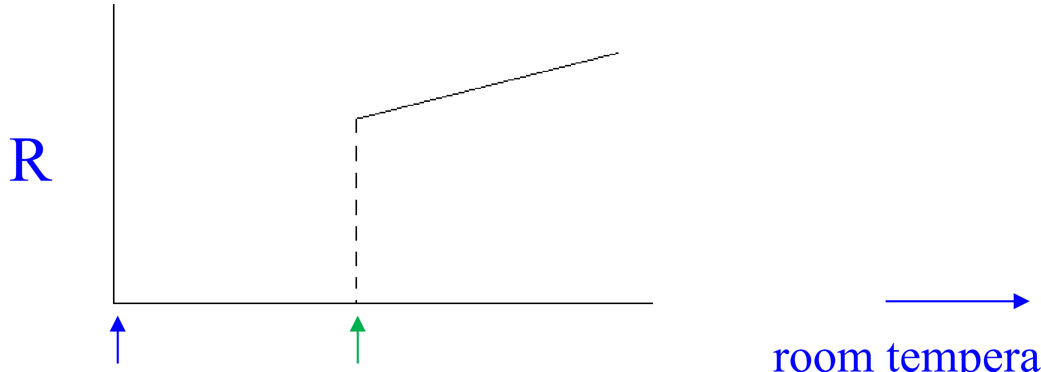
Lossless magnetic energy storage

Magnetic levitation ….

ALAS, ONE SLIGHT PROBLEM:

IN MOST MATERIALS, T_c IS VERY LOW!

e.g. Al: superconductivity



room temperature

Absolute zero

(0 K, –273.15 C)

T_c

(1.3K, –271.8 C)

OUR UNDERSTANDING OF (TRADITIONAL) SUPERCONDUCTIVITY

The occurrence of superconductivity in a material such as Al can be understood in terms of a theory due to Bardeen, Cooper, and Schrieffer (1957), ("BCS") roughly as follows:

(recap)

According to the principles of quantum mechanics, "particles" can be classified into two types:

"fermions"-- very xenophobic

"bosons"– very gregarious

Under appropriate conditions, bosons display the phenomenon of "Bose Einstein condensation (BEC)": all must behave in exactly the same way. ("platoon of well-drilled soldiers")

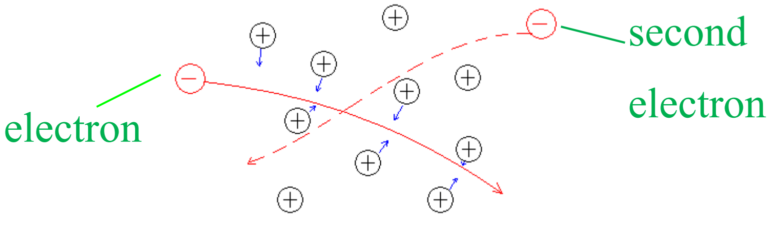
Electrons in materials are fermions, so cannot undergo BEC directly. However,

2 fermions = 1 boson

So, if electrons can form pairs ("di-electronic molecules") then the pairs can undergo BEC.

To form "molecules", electrons must experience an effective attraction. But Coulomb interaction is repulsive!

In BCS theory, this repulsion may be outweighed by effective attraction due to polarization of the ionic lattice:



Superconductivity was discovered in 1911, and for the next 75 years was found to occur only under ~25 K (–248° C). To get to such low temperature one must cool material with liquid helium. So while it's practical to use superconductors for e.g., geophysical magnetometry, application to large scale power transmission out of the question (not enough helium in the world!)

WHY IS T_c SO LOW?

BCS theory gives an explanation:

$$T_c \sim T_D \times F \longleftarrow \text{Dimensionless factor}$$

characteristic ("Debye") temperature of ionic lattice, typically~room temperature (~300 K)

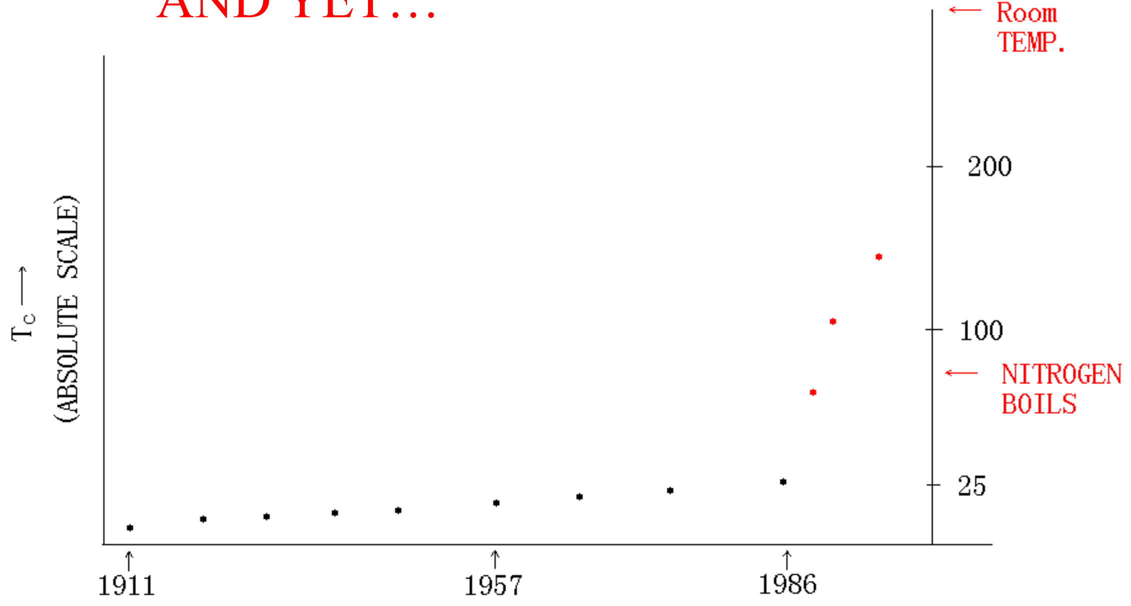
In BCS theory, there are strong arguments that the factor F can never exceed ~0.1

$\Rightarrow T_c$ always $\lesssim 30$ K (–243° C)

(except, since 2014, for some metallic sulfides under huge pressures)

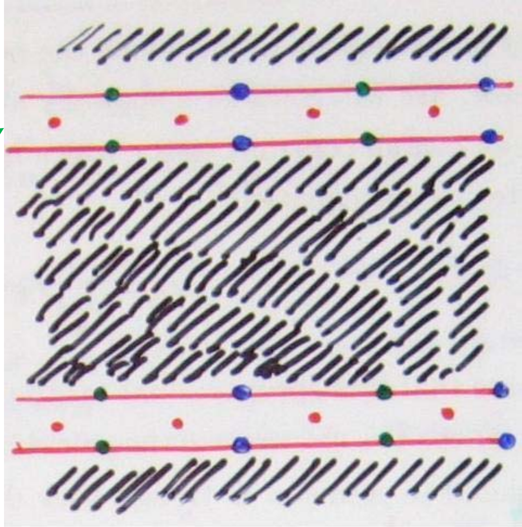
…….

AND YET…



THE HIGH-TEMPERATURE (CUPRATE) SUPERCONDUCTORS

Generic Pattern:



CuO_2

(copper oxide)

planes

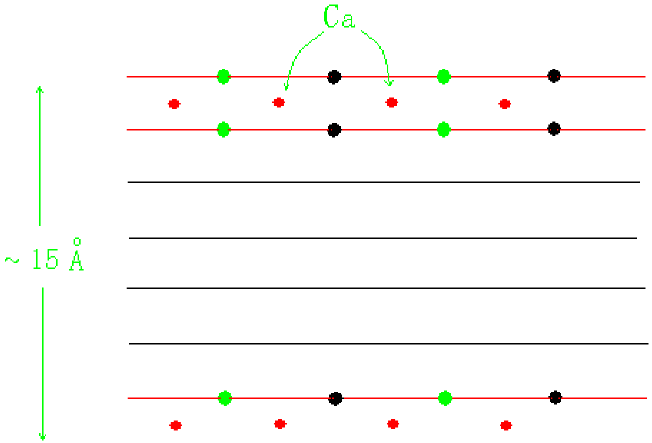
"charge reservoir" layers

example:

BSCCO-2212

($Bi_2Sr_2CaCu_2O_8$)

(T_c=95K)



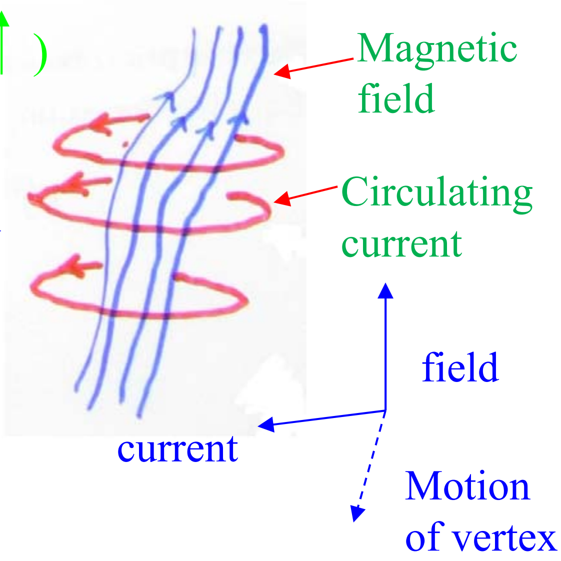
CuO_2
CuO_2
SrO
BiO
BiO
SrO
CuO_2
CuO_2

Critical current is very high along CuO_2 planes (→),

much smaller perpendicular to planes (↑)

In practice, critical current usually determined by motion of vortices, which always occur in a large magnetic field: vortex moves perpendicular to field and to current, and thereby produces voltage

⇒ nonzero resistance.



APPLICATION OF HIGH-TEMPERATURE SUPERCONDUCTIVITY TO GRID:

TWO MAJOR AVENUES OF RESEARCH

1. Using existing (cuprate) high-temperature superconductors

(BSCCO, YBCO($YBa_2Cu_3O_{6+x}$), …)

Already practical for special purposes (e.g. transformers, current fault limiters, offshore wind power…). Also, pilot cables (up to ~1 km) already in operation.

But, for large-scale power transmission, need (inter alia)

- large reduction in manufacturing cost

  (currently >> Cu)

- reduction in cost of refrigeration (50–77K)

- most importantly: increase in $J_c(H,T)$

critical current

magnetic field

temperature

Since the factor limiting electrical current is motion of vortices, most promising route to higher J_c is to find better ways to pin vortices.

(ex.: irradiate with fast ions so as to produce "columnar " defects)

What microscopic conditions are best for pinning of vortices? A major challenge to current microscopic theory of superconductivity in cuprates!

Second major avenue of research:

2. By understanding superconductivity in cuprates, or otherwise, find better high-temperature superconductors (ideally: $T_c >$ room temperature, "large" $J_c(H,T)$).

Problem: we don't understand superconductivity in the cuprates! (in particular, why T_c is so high).

Recall: to form "di-electronic molecules" appear to need effective attraction between electrons. In BCS theory this can be provided by polarization of ionic lattice. (but then predicts $T_c \lesssim 30K$).

Anyway, much evidence that in cuprates effect of ionic lattice is at best secondary.

So, much get superconductivity out of Coulomb repulsion between electrons!

This is a MAJOR challenge for theoretical condensed matter physics ($\sim 10^4$ papers since 1986)

If we can solve it, then we may know where to look for room temperature superconductivity in the "haystack" of possible compounds. (no. of possible 5-element compounds $\sim 10^{10} \Rightarrow 10^6$ person-years of research!)

My guess: look for

Strongest possible repulsion
Strongly layered (2D) structure
weak inter-layer tunneling contact
anomalous optical properties ("MIR peak")

SUMMARY

1. In principle, superconductors could greatly improve the electrical grid, saving a large fraction of the energy currently dissipated in transmission.
2. However, the “classic” (pre-1986) superconductors have much too low values of T_c and J_c to be practical.
3. The high-temperature (cuprate) superconductors are much more promising, but still need improvement, in particular to increase J_c.
4. There seems no reason in principle why we should not get (robust) superconductivity at room temperature (also permitting room-temperature levitations, etc…)
5. However, to know where to look for it we urgently need to understand superconductivity in the cuprates. Most fundamental theoretical question ⇒ most practical application!

WILL WE HAVE ROOM-TEMPERATURE SUPERCONDUCTIVITY BY 2050? MY BET: YES!