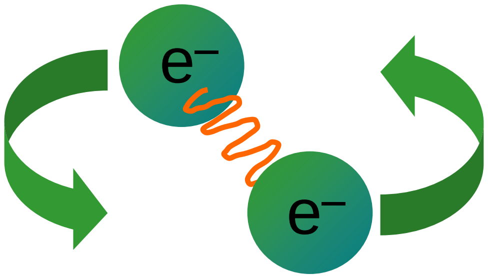
Superconductivity – Lecture 1

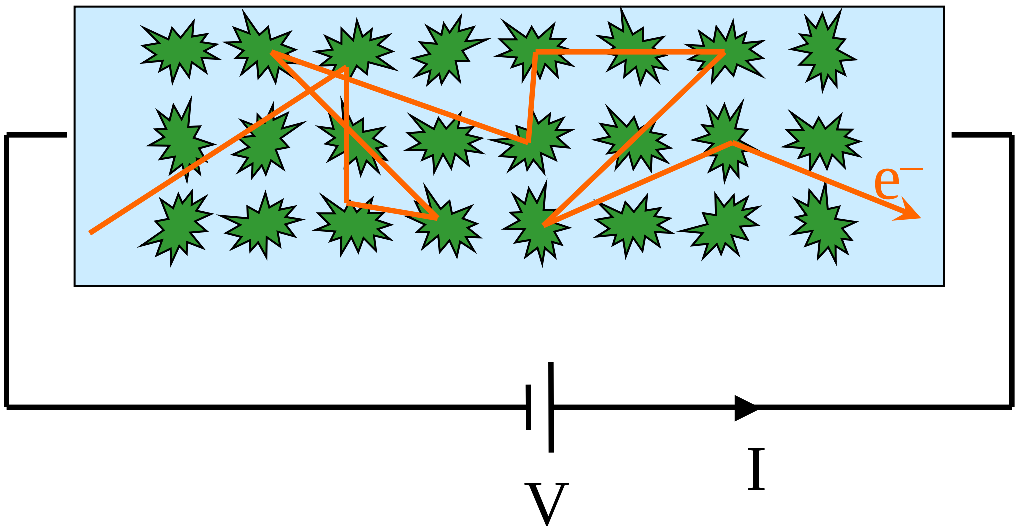
Professor Andrew Boothroyd
University of Oxford

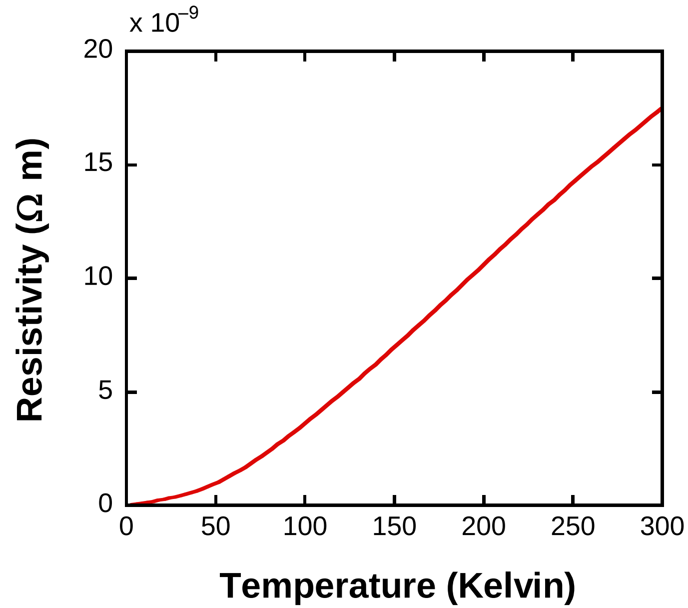
- What is electrical resistance?
- Discovery of superconductivity
- Superconductors in magnetic fields
- Electron pairing and the energy gap
- Superconducting magnets and other applications



UNIQ Summer School, 21-25 July, 2014

What is resistance?





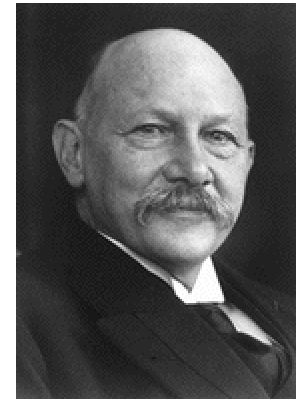
Ohm's Law: $V = IR$

Resistivity: $R = \rho \frac{L}{A}$

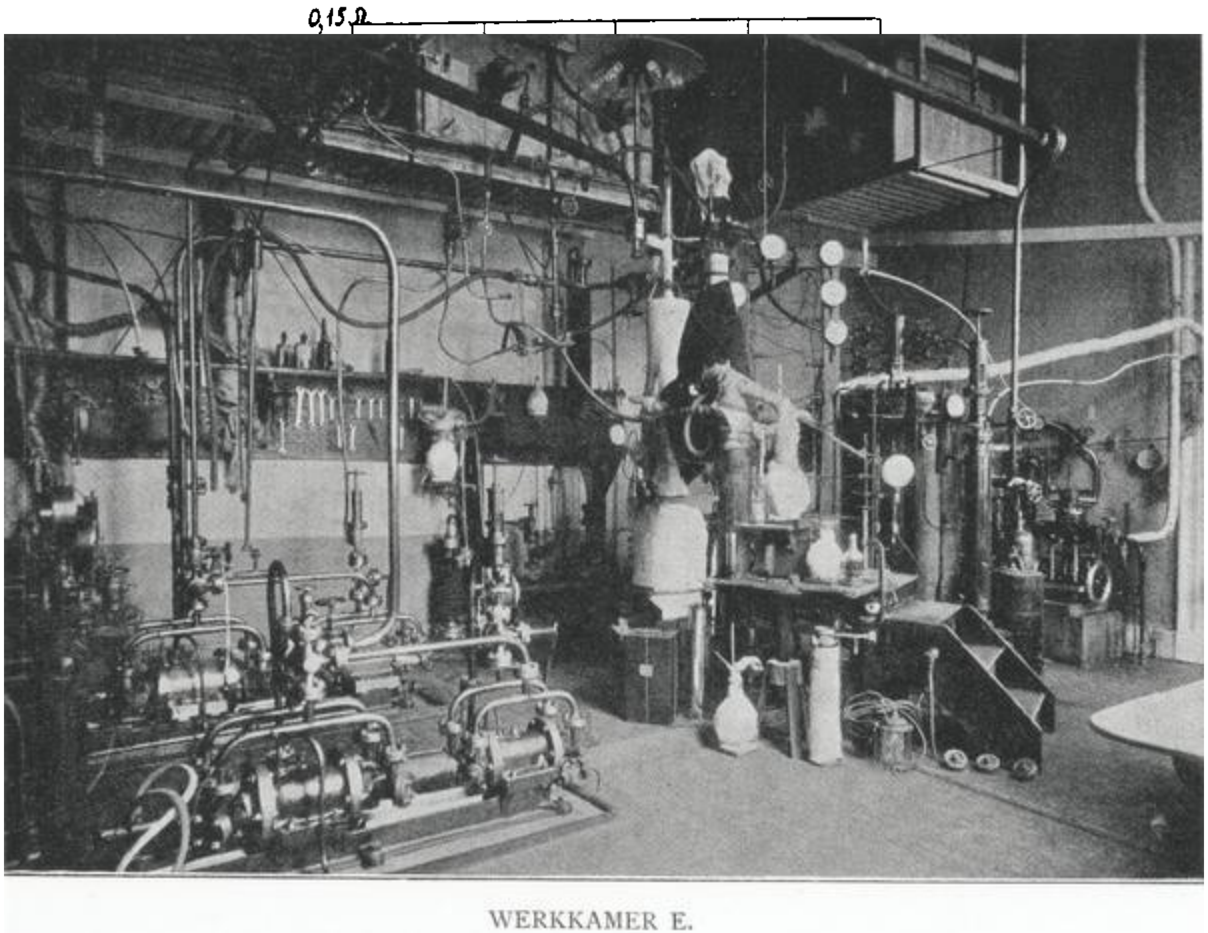
Conductivity: $\sigma = 1/\rho$

Resistivity of copper

The Discovery of Superconductivity

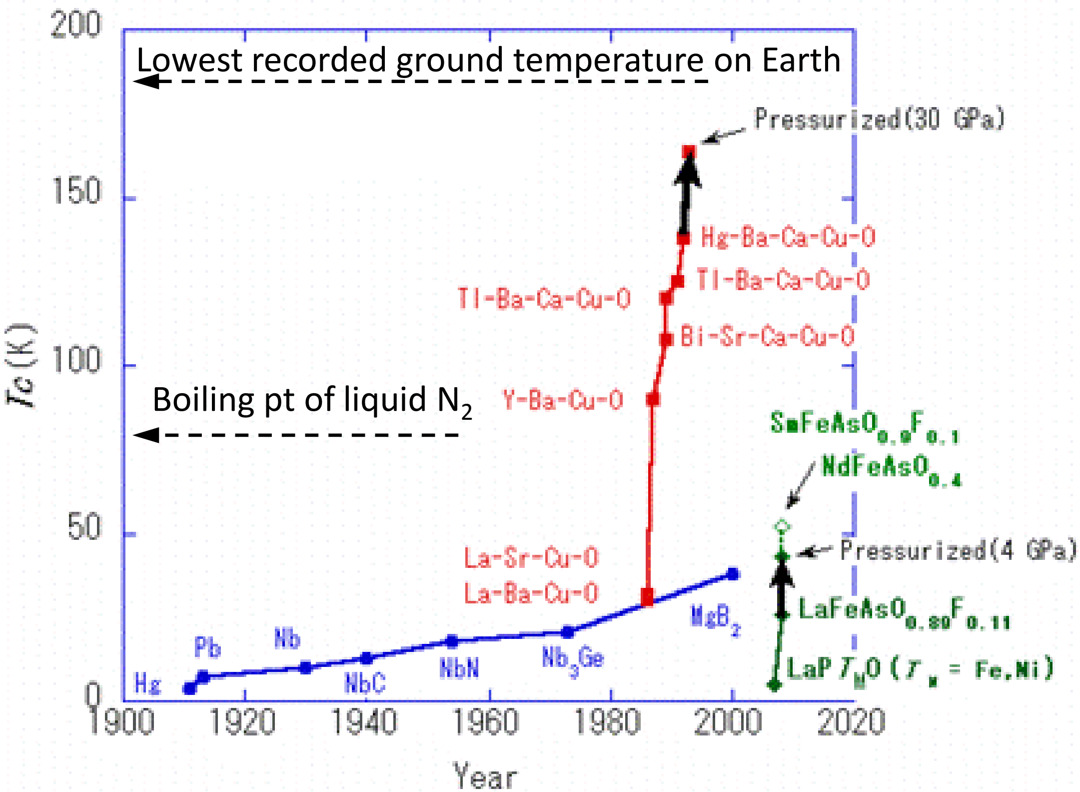


H. Kamerlingh Onnes
(1853–1926)
Nobel Prize 1913



of mercury (1911)

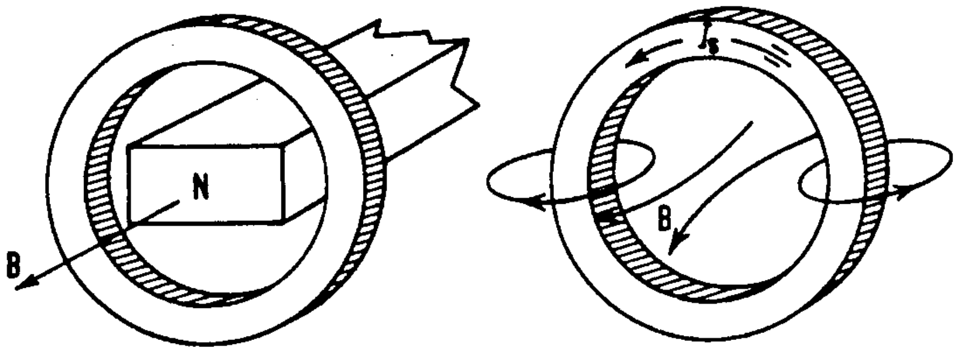
The Discovery of Superconductors



K.A. Müller, J.G. Bednorz

Discoverers of copper-oxide superconductors (1986)
Nobel Prize 1987

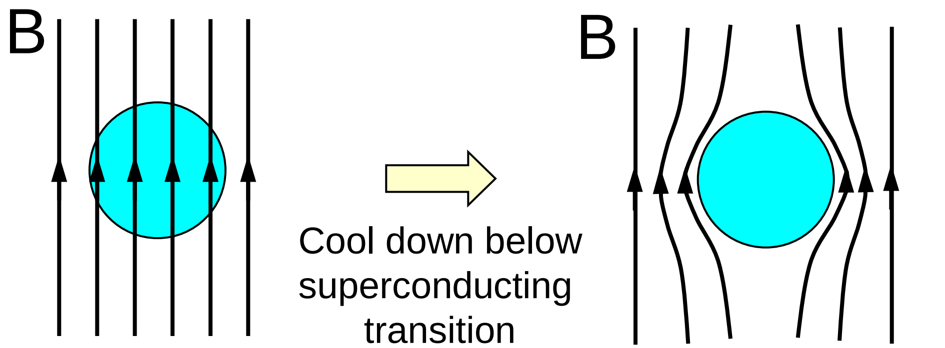
Everlasting current!



Pass magnet through
superconducting ring to induce current
Measure decay of current with time
(File & Mills, 1963)

- Current persists for >10^5 years
- Resistivity <10^{-23} Ω m

Magnetic flux exclusion – Meissner effect



normal metal

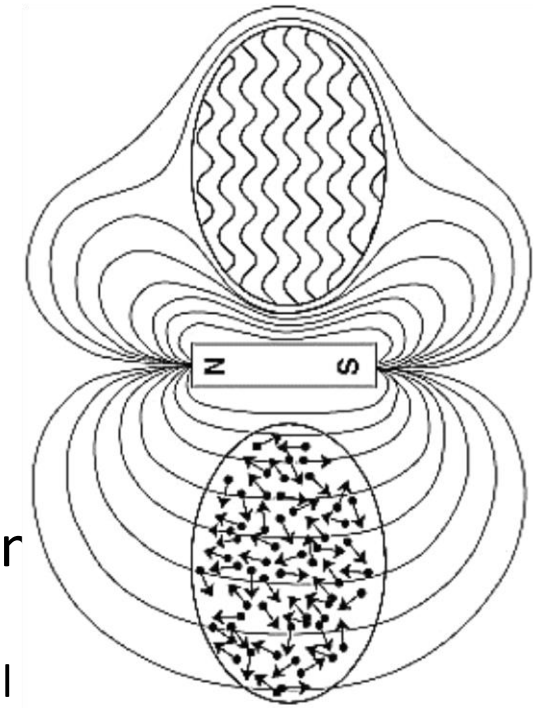
superconductor

Walther Meissner
(1882–1974)

Robert Ochsenfeld
(1901–1993)

W. Meissner and R. Ochsenfeld, 1933

Magnetic levitation



Maglev trar

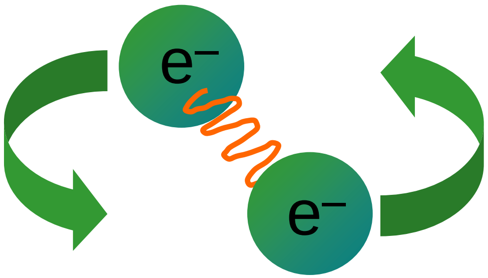
1. Conventional
   superconducting magnet on board train;
   can reach speeds up to 550 km/h

2. Meissner effect Maglev,
   Chengdu, China (2000)

Yamanashi Maglev, Japan

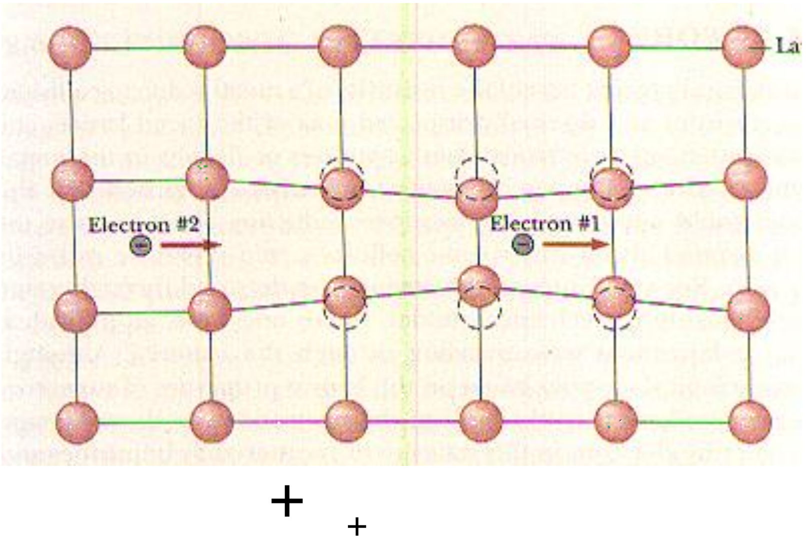
Electron pairing and energy gap

Superconducting electrons
are bound in pairs



What is pairing mechanism?

Electrons cause instantaneous
distortion of the atoms and leave
a trail of positive charge

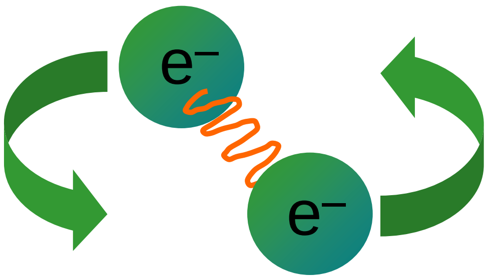


Electron pairing and energy gap

BCS theory (1957)

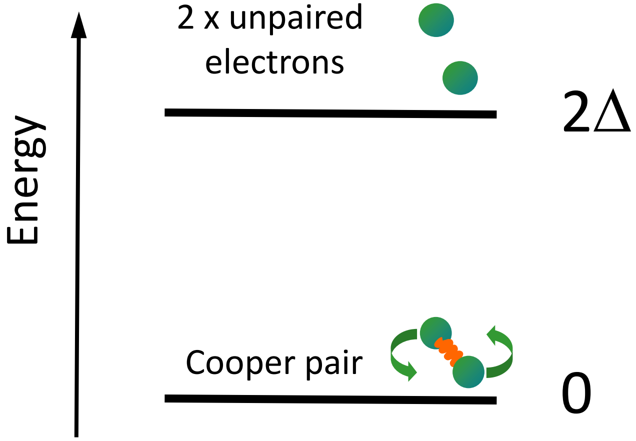
John Bardeen (1908–1991) Leon Cooper (1930–) Robert Schrieffer (1931–)

Nobel prize 1972



Cooper pair

Binding energy of a Cooper pair is 2Δ



Critical temperature

Classical gas at temperature T: <KE> = $3/2\, k_B T$ per particle

($k_B = 1.38 \times 10^{-23}$ J K^{-1} <— Boltzmann's constant)

Cooper pairs unstable when $3/2\, k_B T > 2\Delta$

Transition from superconducting to normal state occurs at a critical temperature, T_c

BCS theory: $3.52\, k_B T_c = 2\Delta$

Critical current and critical field

Cooper pairs destroyed when energy transferred during collision exceeds 2Δ

$\longrightarrow$ Critical current density: $j_c \approx nek_BT_c/m_ev$

Typically, $j_c \sim 10^{11}$ A m^{-2}

Magnetic fields above some critical value B_c will induce
a current density in excess of j_c and destroy superconductivity

For a cylindrical wire of radius a carrying a uniform current, $B_c = \mu_0 j_c a/2$

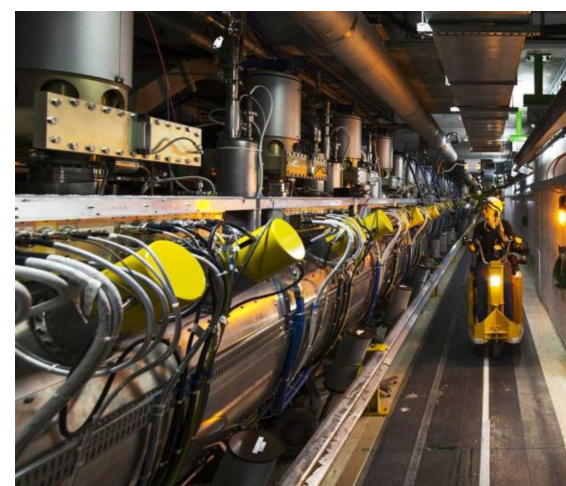
Superconducting magnets

Advantages over resistive magnets:

- Achieve much higher fields, up to 35 Tesla
- Require much less power to run

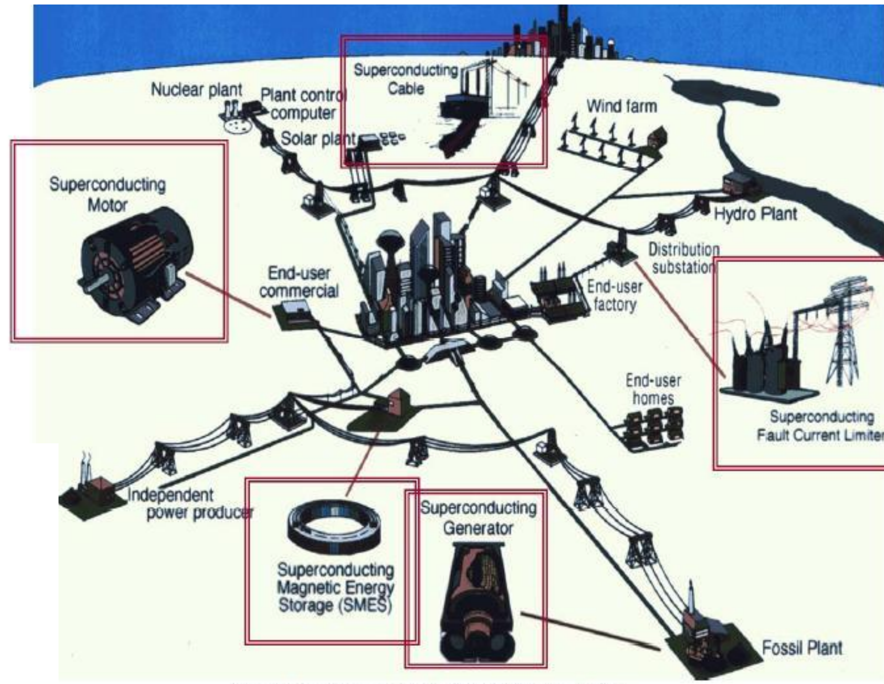
Applications:

- Fundamental research, e.g. bending magnets at CERN
- MRI scanners



Applications of superconductors

- Transportation (MagLev)
- Superconducting magnets (MRI)
- Power transmission
- Energy storage
- Frictionless bearings and flywheels
- Magnetic screening
- Sensitive magnetic field detectors (SQUIDS)
- Quantum computers (maybe one day …)



Symposium on SC Devices for Wind Energy, Barcelona 2/25/11