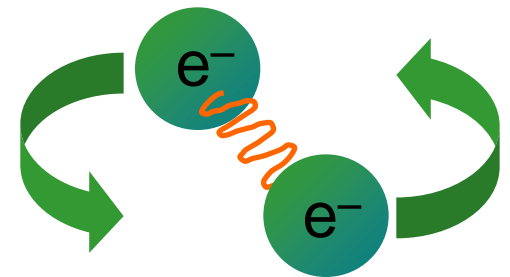


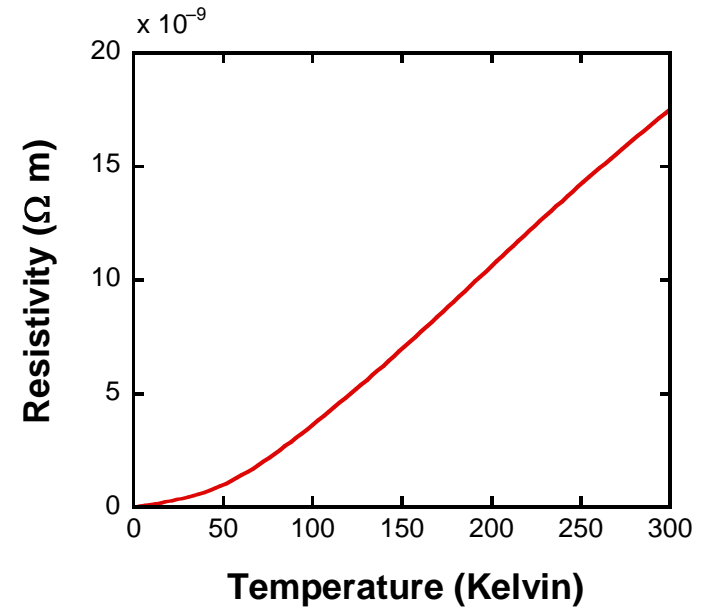
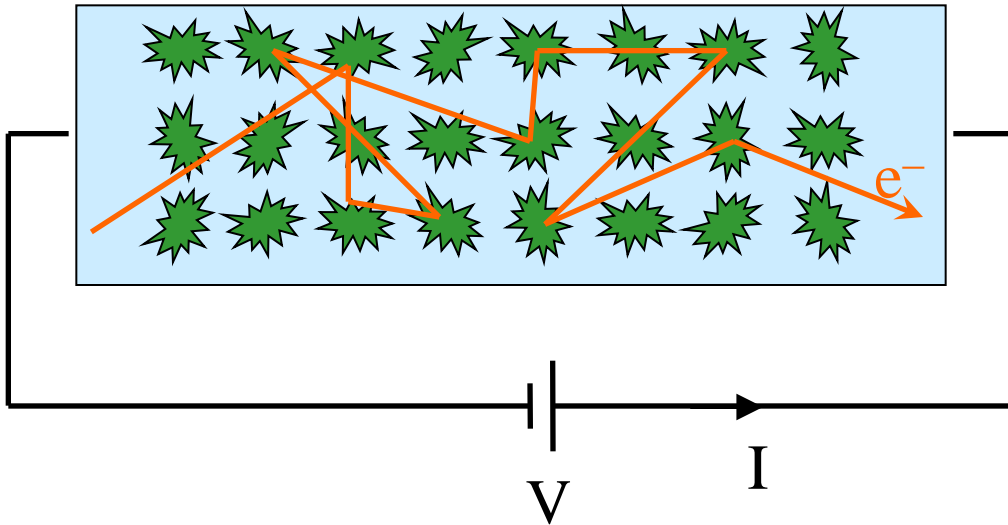
# Superconductivity – Lecture 1

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



# What is resistance?



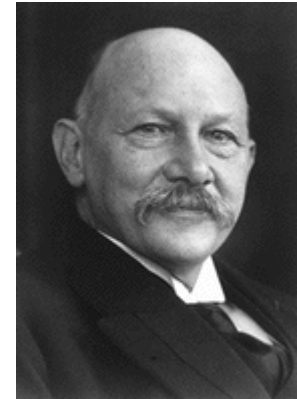
Ohm's Law:  $V = IR$

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

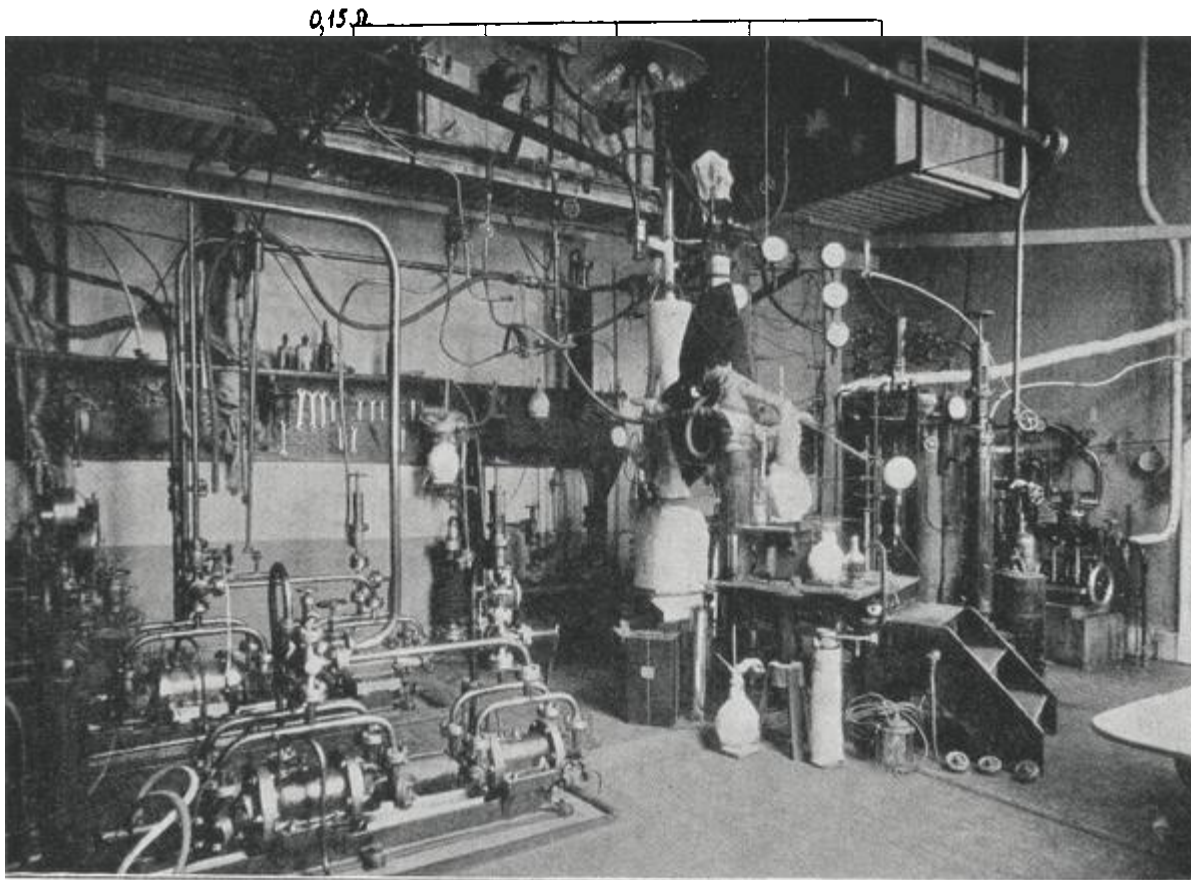
Conductivity:  $\sigma = 1/\rho$

Resistivity of copper

# The Discovery of Superconductivity



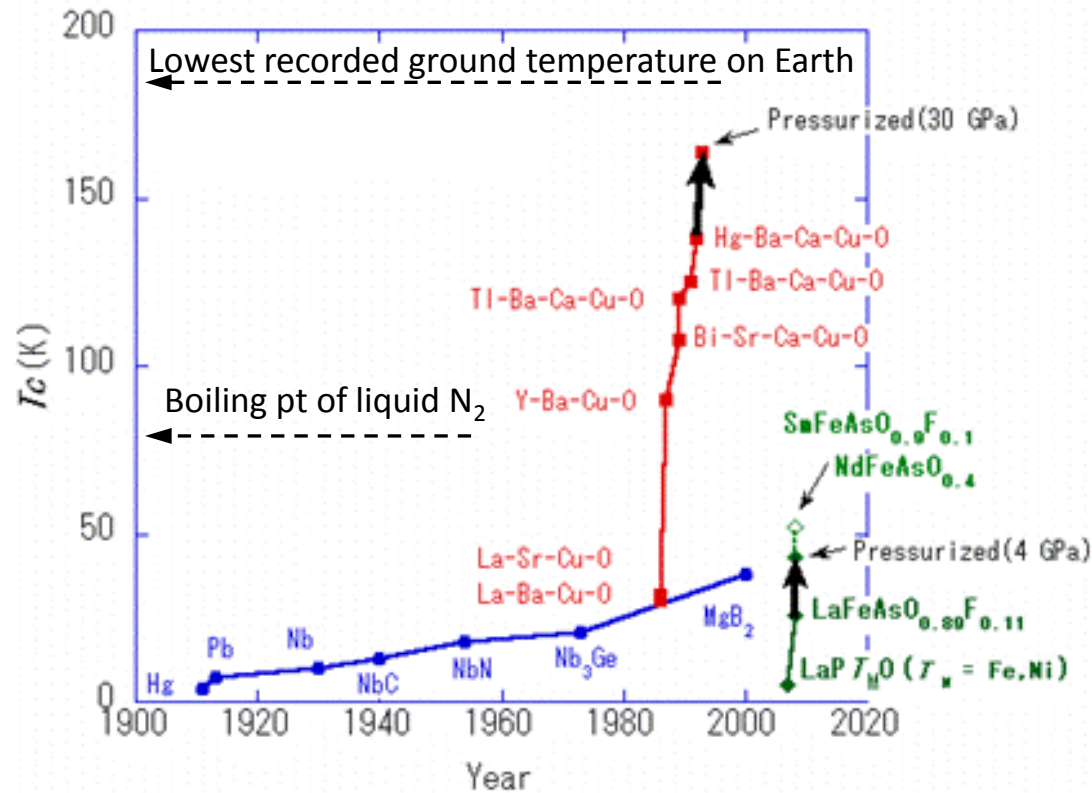
H. Kamerlingh Onnes  
(1853–1926)  
Nobel Prize 1913



of mercury (1911)

WERKKAMER E.

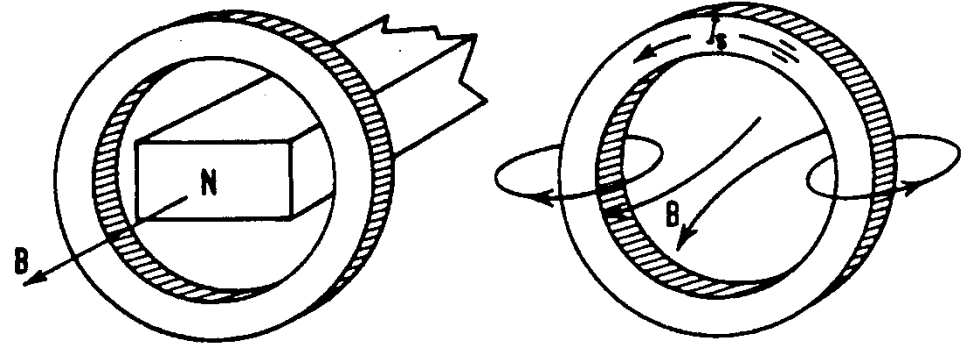
# The Discovery of Superconductors



K.A. Müller, J.G. Bednorz

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

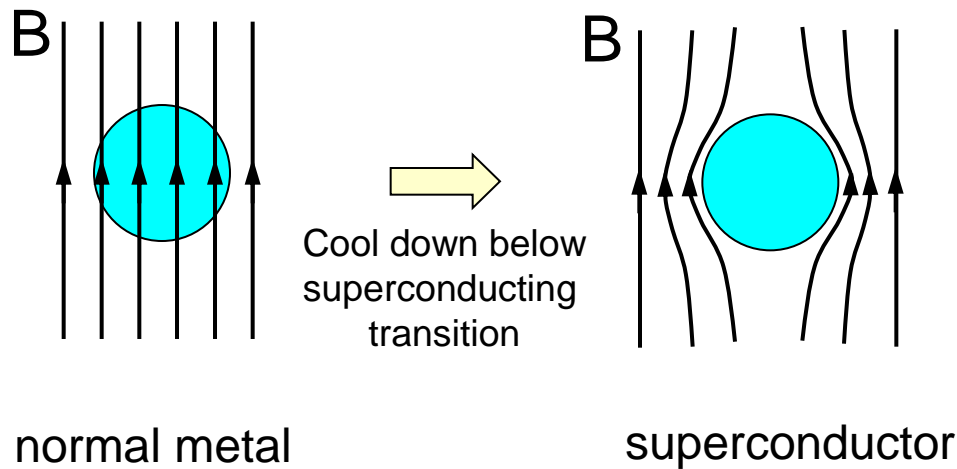
# Everlasting current!



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

- Current persists for  $>10^5$  years
- Resistivity  $<10^{-23} \Omega \text{ m}$

# Magnetic flux exclusion – Meissner effect



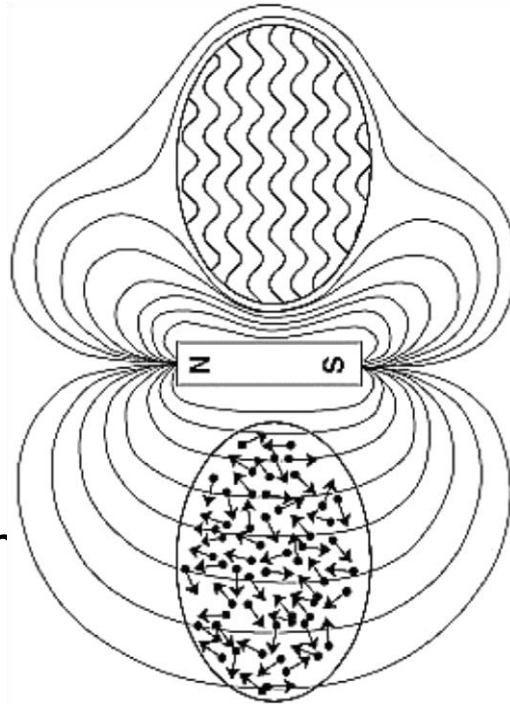
Walther Meissner  
(1882–1974)



Robert Ochsenfeld  
(1901–1993)

W. Meissner and R. Ochsenfeld, 1933

# Magnetic levitation



## Maglev train

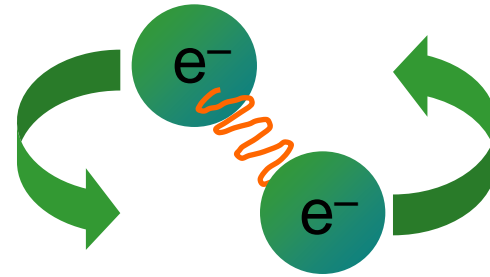
1. Conventional superconducting magnet on board train; can reach speeds up to 550 km/h
2. Meissner effect Maglev, Chengdu, China (2000)



Yamanashi Maglev, Japan

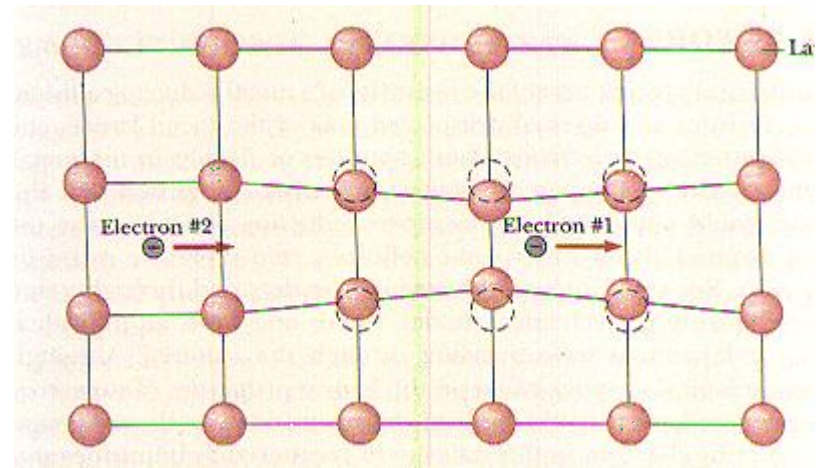
# Electron pairing and energy gap

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

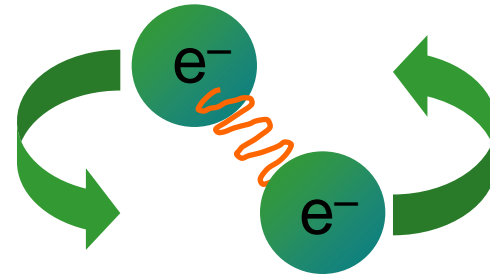
## BCS theory (1957)



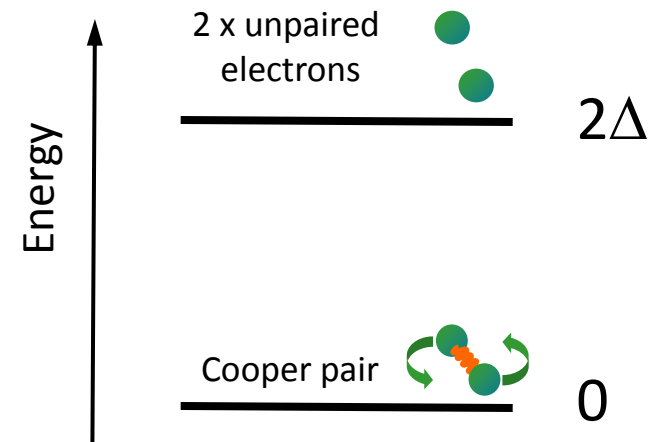
John Bardeen (1908–1991) Leon Cooper (1930–) Robert Schrieffer (1931–)

Nobel prize 1972

Binding energy of a Cooper pair is  $2\Delta$



Cooper pair



# Critical temperature

Classical gas at temperature  $T$ :  $\langle KE \rangle = 3/2 k_B T$  per particle

( $k_B = 1.38 \times 10^{-23} \text{ J K}^{-1}$  ← 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  $2\Delta$

→ Critical current density:  $j_c \approx nek_B T_c / m_e v$

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

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

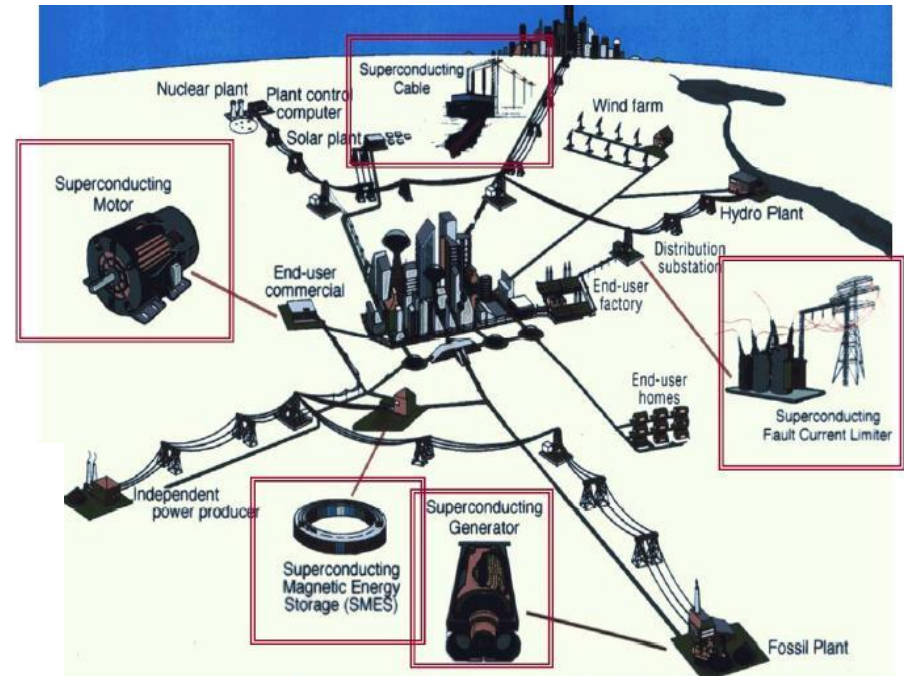
## Applications:

- 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