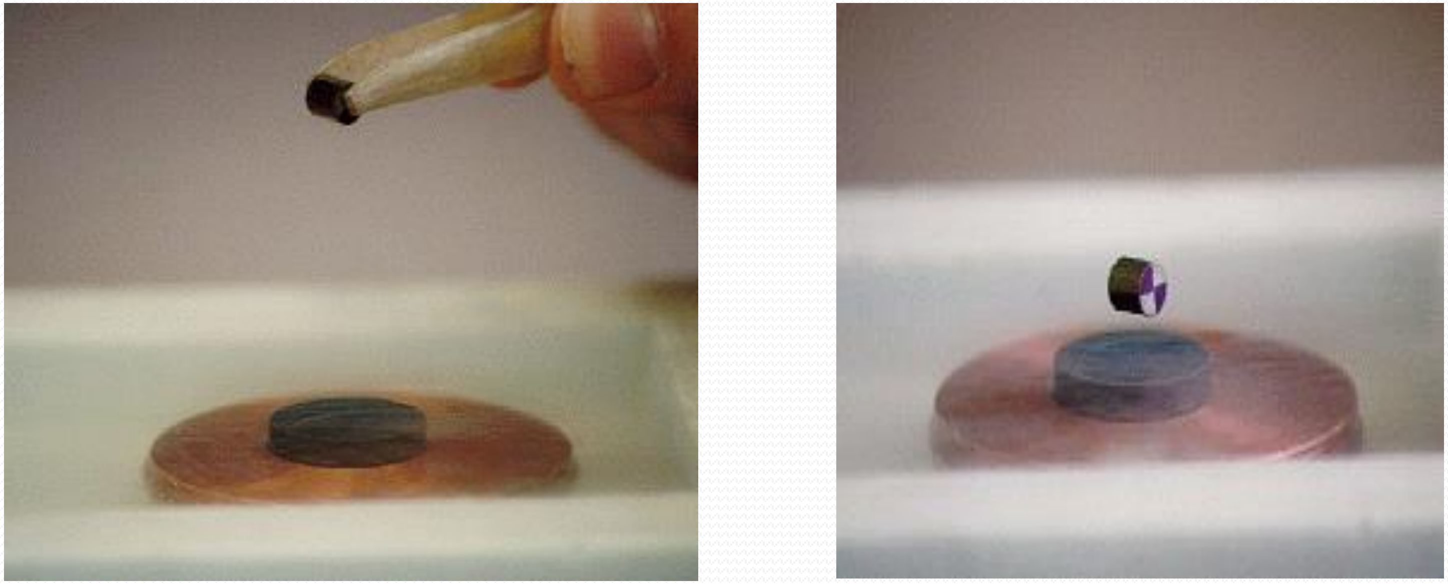
UNIT VI
Engineering Materials

Chapter 18
Superconductivity

Superconductivity is an exciting field of physics! (Picture below is the levitation of a magnet above a cooled superconductor, the **Meissner Effect,** which will be discussed later.)



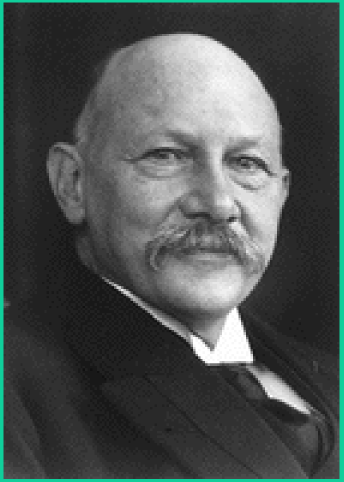
Source: University of Oslo, Superconductivity Lab

Definition

- *Superconductivity* is the flow of electric current without resistance in certain metals, alloys, and ceramics at temperatures near absolute zero, and in some cases at temperatures hundreds of degrees above absolute zero = -273^{o}K.

Discoverer of Superconductivity

- Superconductivity was first discovered in 1911 by the Dutch physicist,Heike Kammerlingh Onnes.



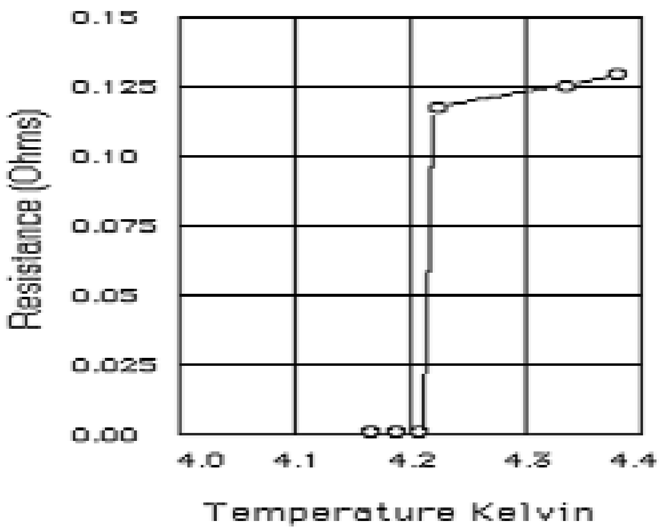
◆Source: Nobel Foundation

The Discovery

- Onnes, felt that a cold wire's resistance would dissipate. This suggested that there would be a steady decrease in electrical resistance, allowing for better conduction of electricity.
- At some very low temperature point, scientists felt that there would be a leveling off as the resistance reached some ill-defined minimum value allowing the current to flow with little or no resistance.
- Onnes passed a current through a very pure mercury wire and measured its resistance as he steadily lowered the temperature. Much to his surprise there was no resistance at 4.2K.

At 4.2K, the Electrical Resistance (opposition of a material to the flow of electrical current through it)Vanished, Meaning Extremely Good Conduction of Electricity-Superconductivity

Fig. 1



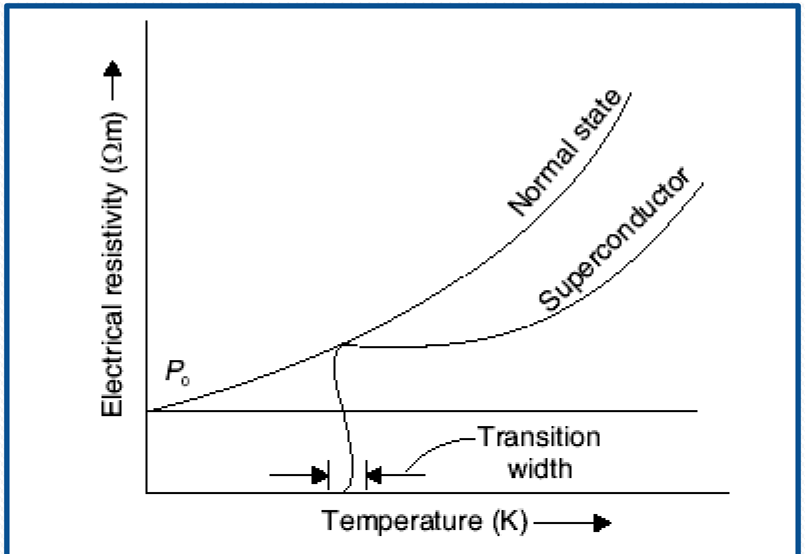
Superconductivity Today

- Today however, superconductivity is being applied to many diverse areas such as: medicine, theoretical and experimental science, the military, transportation, power production, electronics, as well as many other areas.

TEMPERATURE DEPENDENCE IN SUPERCONDUCTING MATERIALS

- Generally, the electrical resistivity of a material decreases as the temperature is reduced.

- When the temperature reaches a few degrees just above the absolute zero, the material suddenly loses all its electrical resistance and a state called *superconducting is reached*.



Dependence of Superconductivity on the impurities

- It is clear from the figure (18.2) that the electrical resistance disappears below 4.2 K.
- It also shows that the width of the transition region in a particular specimen depends on the purity and metallurgical perfections, and can be as sharp as close to 10^{-3} degree or spread over several degrees, while the breadth of the transition region may increase if the sample is metallurgically imperfect.
- Figure 18.3 gives a comparison of the superconducting transition in a pure and an impure sample of tin.

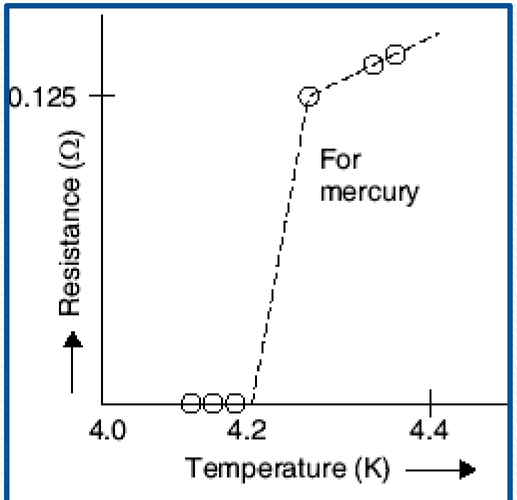


Fig. 18.2 H.K. Onnes' observation

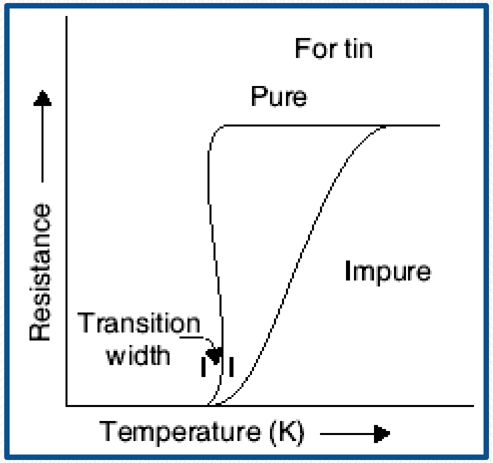
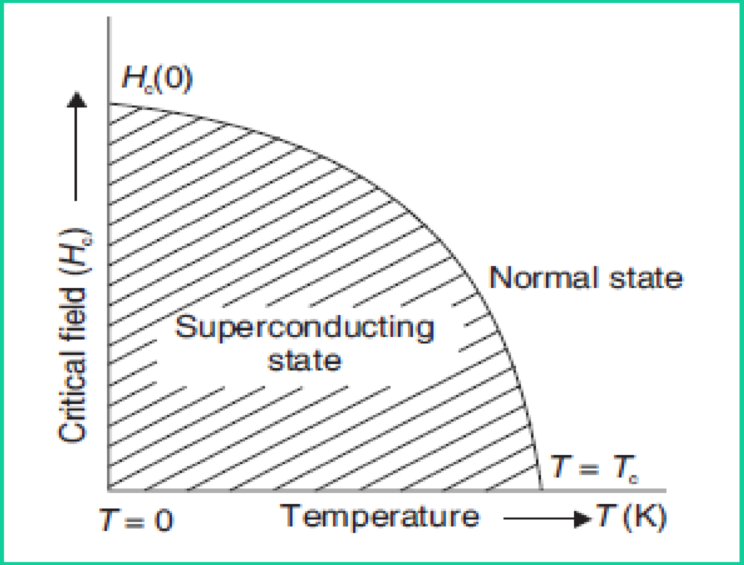


Fig. 18.3 Comparison between pure and impure samples of tin

Temperature Dependence of Critical Field (Effect of External Magnetic Field) on Superconductors

The dependence of the temperature on the magnetic field can be represented by

$$H_c = H_c(0)\left[1-\left(\frac{T}{T_c}\right)^2\right]$$



Dependence on temperature

MEISSNER EFFECT (EFFECT OF MAGNETIC FIELD)

- The phenomenon of exclusion of the magnetic flux from the interior of a superconductor below the transition temperature (*Tc) is the Meissner effect.*

$$B = \mu_0 (H + M)$$

$$0 = \mu_0 (H + M)$$

or $$M = -H$$

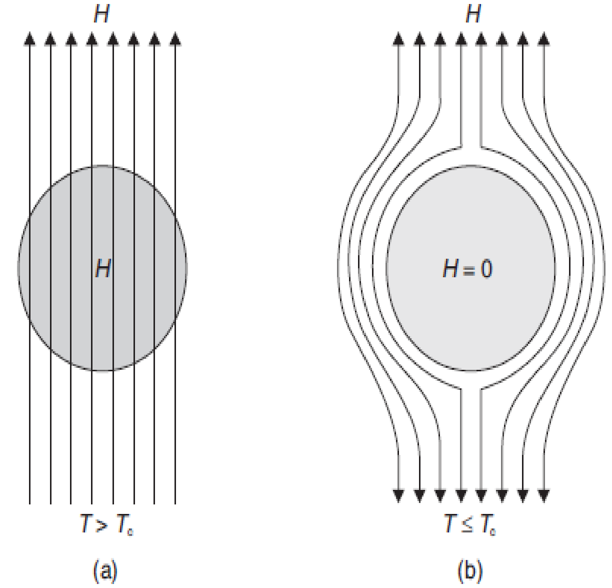
or magnetic susceptibility, $\chi = \frac{M}{H} = -1$

$$\vec{\Delta} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

We can have

$$\frac{\partial B}{\partial t} = 0$$

or $$B = \text{Constant}$$



Meissner effect: Magnetic field lines are excluded from a superconductor when it is below transition temperature

Demonstration of the Meissner Effect

Source: University of Oslo

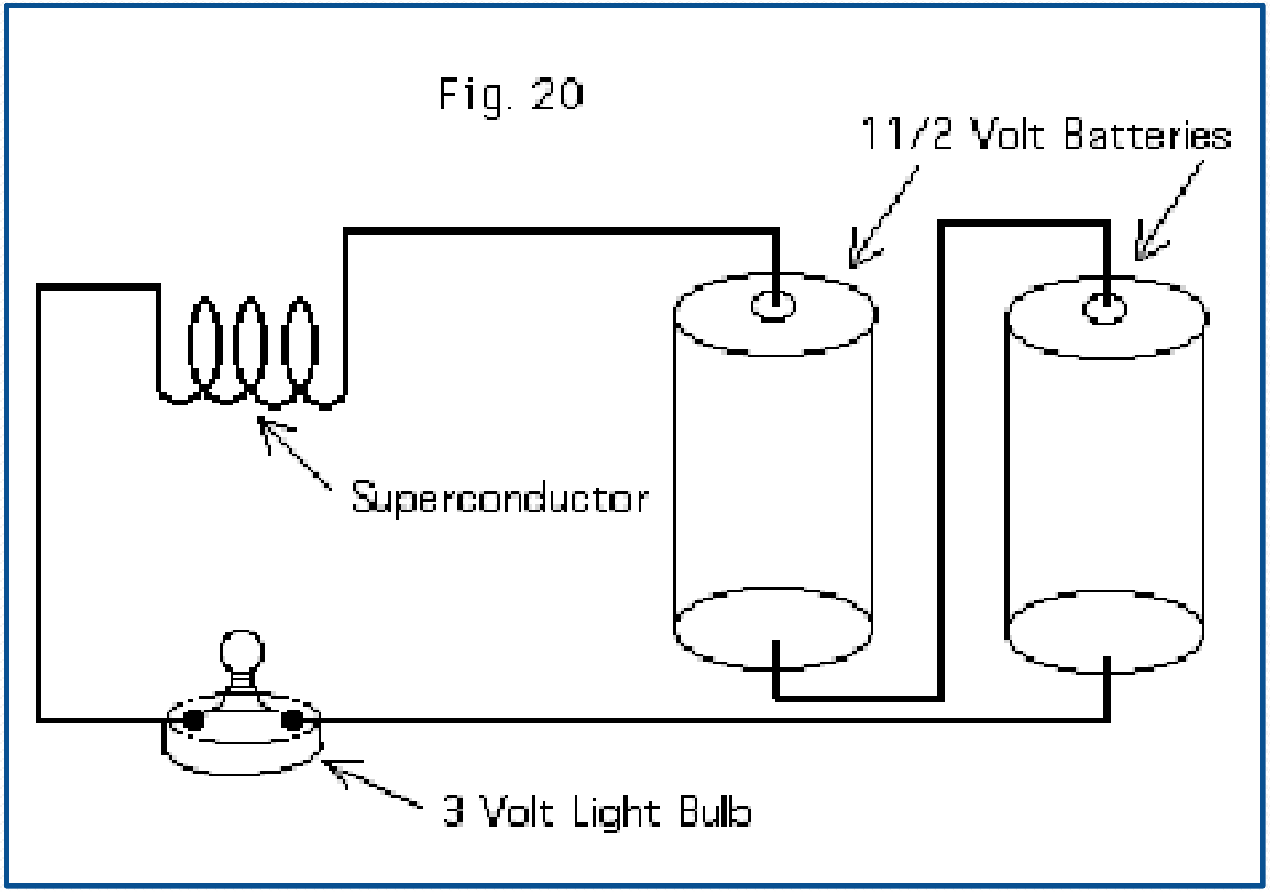
Materials Needed

- YBCO superconductive wire with attached leads
- 2 Size C batteries with holder
- 3 volt flash light bulb with holder
- liquid nitrogen
- styrofoam cup

Procedure

1. Connect superconductor, light bulb and batteries.
2. When the superconductor is at room temperature it is in the normal state and will have high resistance.The bulb will not light.
3. Place the superconductor into the liquid nitrogen. The bulb will light as the resistance decreases.
4. Remove the superconductor from the liquid nitrogen. The bulb will begin dim and eventually go out as the resistance increases.

Diagram



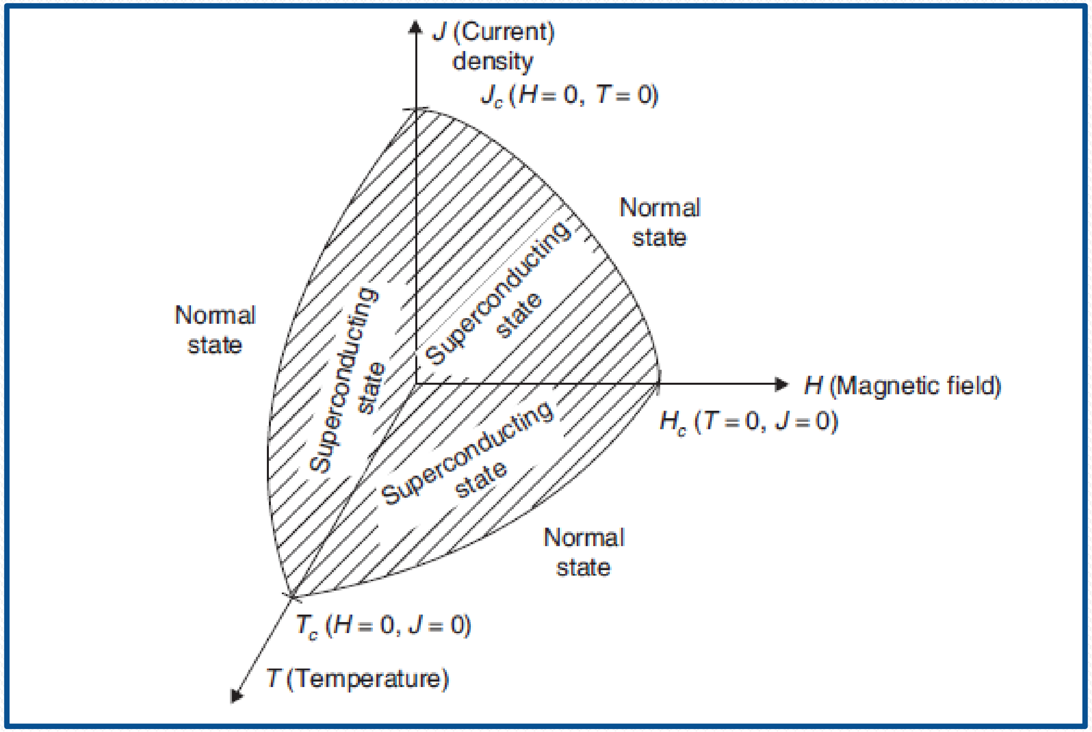
CRITICAL CURRENTS

- The minimum value of the current that can be passed in a sample of superconductor without destroying the superconductivity is known as *critical current (Ic)*

$$H_s = \frac{I_c}{2\pi r}$$

$$H_c = H_s + 2H$$

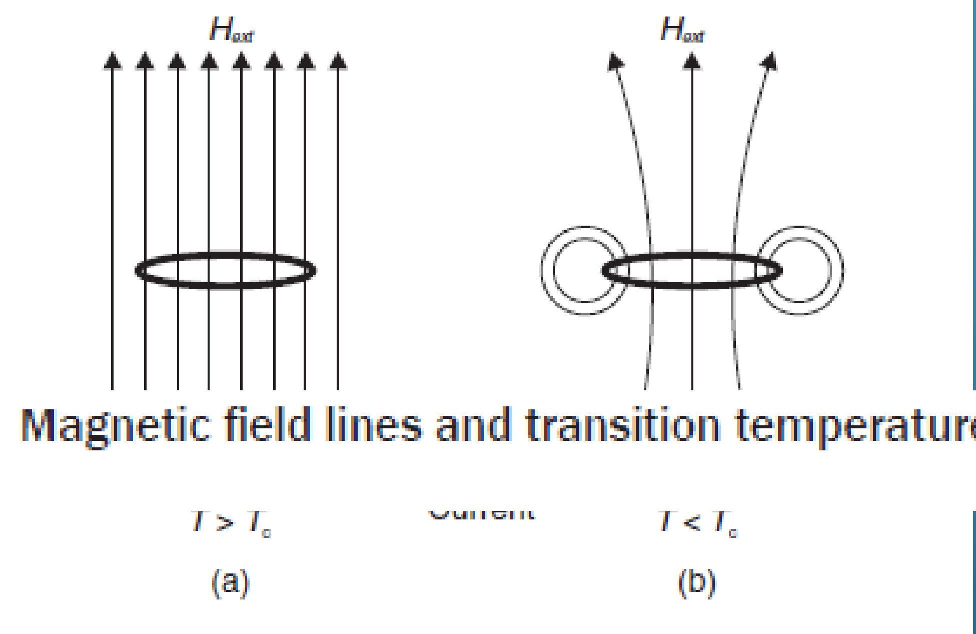
$$I_c = 2\pi r H_c$$



Conditions within the boundary produce superconductivity

PERSISTENT CURRENT:

When an electric current is set up in a superconductor, it can persist for a long time even without any emf. Due to the presence of the persistent current, a superconductor also produces a magnetic field.



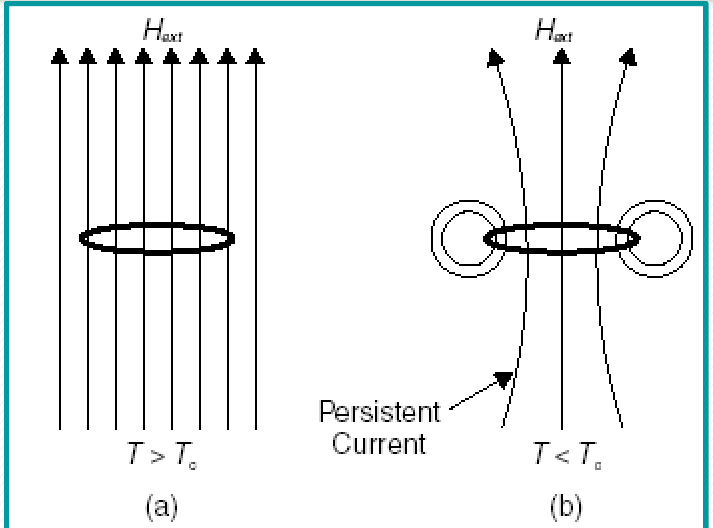
Magnetic field lines and transition temperature

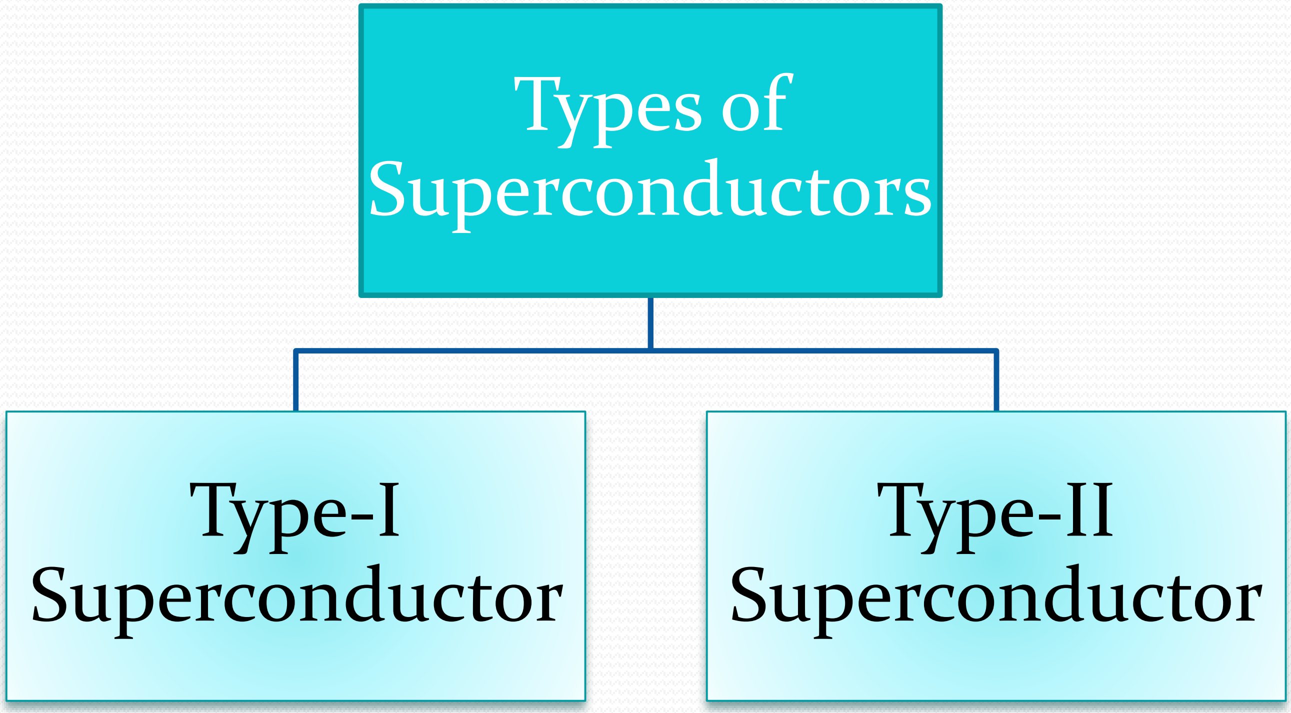
PERSISTENT CURRENT:

- When an electric current is set up in a superconductor, it can persist for a long time even without any emf. Due to the presence of the persistent current, a superconductor also produces a magnetic field.

- An induced current can flow in a ring of superconducting material by cooling it in the presence of a magnetic field below the transition temperature and then by switching off the field [Fig. 18.7(a)].

- When the field is switched off, the flux outside the ring disappears, but it remains trapped inside the ring [Fig. 18.7(b)].





Types of Superconductors

Type-I Superconductor

Type-II Superconductor

Type -I Superconductors or Soft Superconductors

- The superconductors which never allow a magnetic flux density inside in it, i.e., those which are perfectly diamagnetic, are classified as *Type I or soft superconductors*

- These superconductors exhibit complete Meissner effect.

- In these superconductors, the transition from the superconducting state to the normal state occurs sharply in the presence of magnetic field at *Hc*

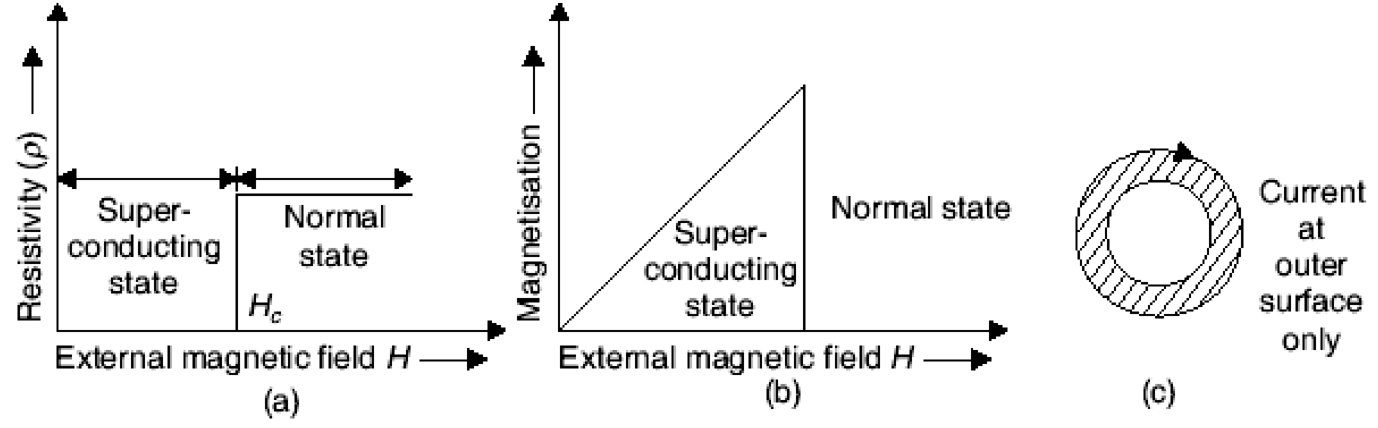
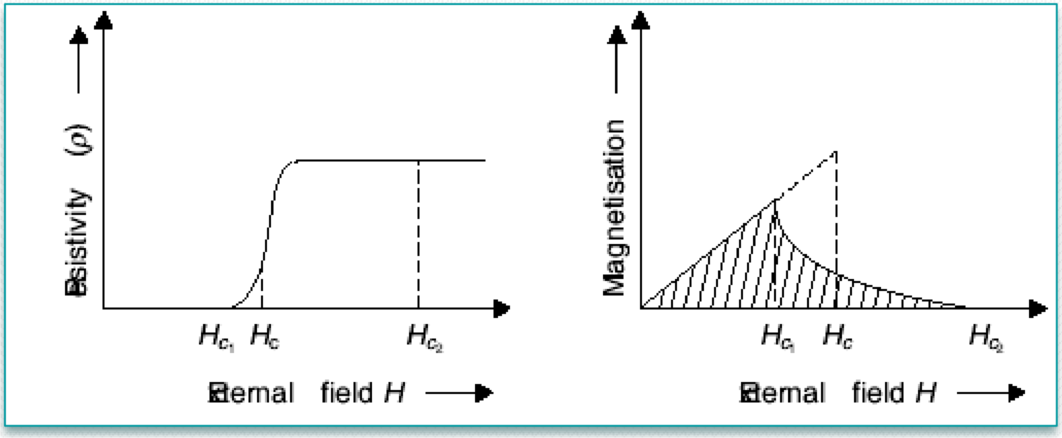


Fig. 18.8 Behaviour of magnetic field for Type I superconductor

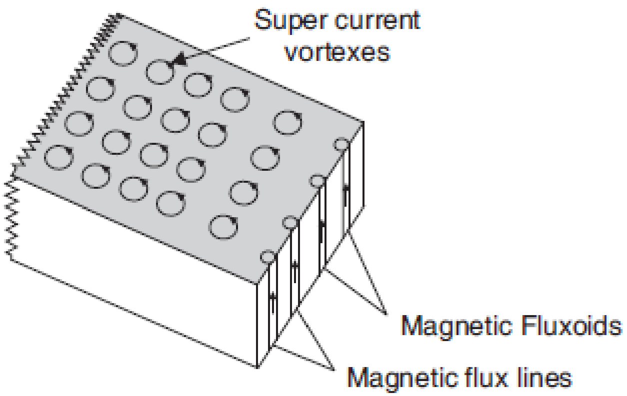
Type II Superconductors or Hard Superconductors

- The superconductors which exhibit incomplete Meissner effect or admit partial magnetic flux density and have zero resistivity are called *Type II or hard superconductors*
- Above the upper critical field Hc_2 , the magnetisation vanishes completely and the external magnetic field penetrates so as to destroy the superconductivity.
- This indicates that above the critical field Hc_2 , a superconductor becomes a normal conductor. Thus, a superconductor in the region Hc_1 to Hc_2 can conduct electric current within the specimen.



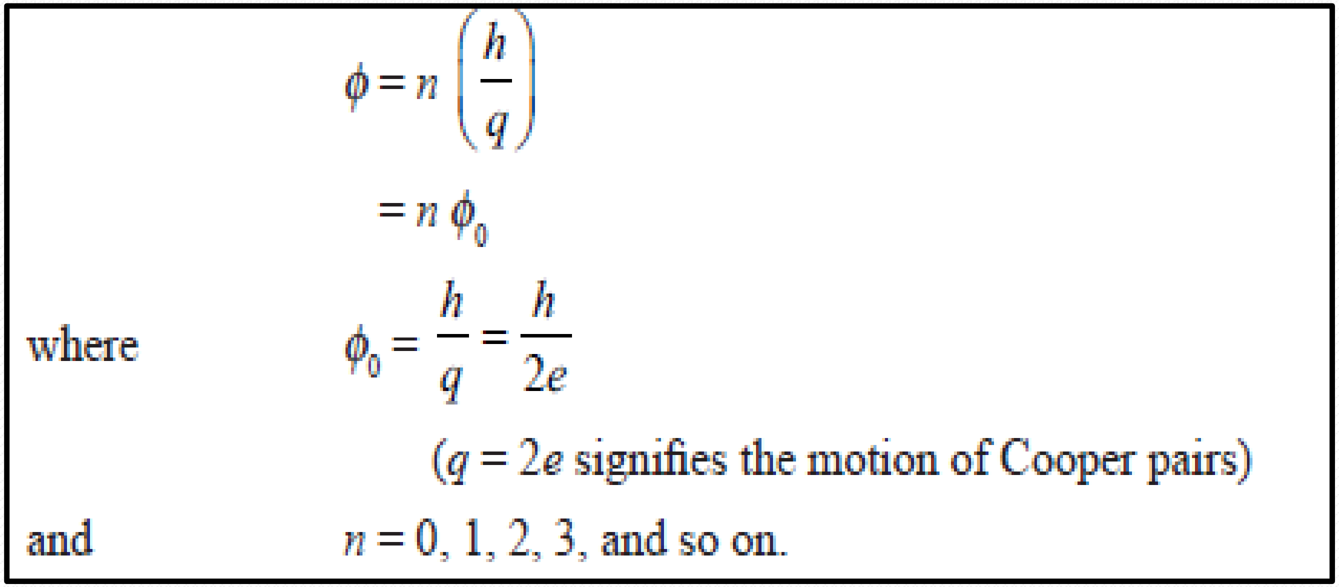
FLUXIOD

- In the region Hc_1 to Hc_2, *the current carriers inside the superconductors are called filaments, and the field penetrates the superconductors in the form of individual quantised flux bundles called fluxoids.*
- *With the increasing magnetic field strength, more and more fluxoids enter the superconductor and form a periodic array. When the magnetic field is between Hc_1 and Hc_2, Type II superconductors carry high current.*



FLUX QUANTISATION

- A superconducting ring when placed in an external magnetic field encloses a magnetic flux that is quantised and is an integral multiple of a fundamental quantum of flux,



$$\phi = n\left(\frac{h}{q}\right)$$

$$= n\,\phi_0$$

where $\phi_0 = \frac{h}{q} = \frac{h}{2e}$

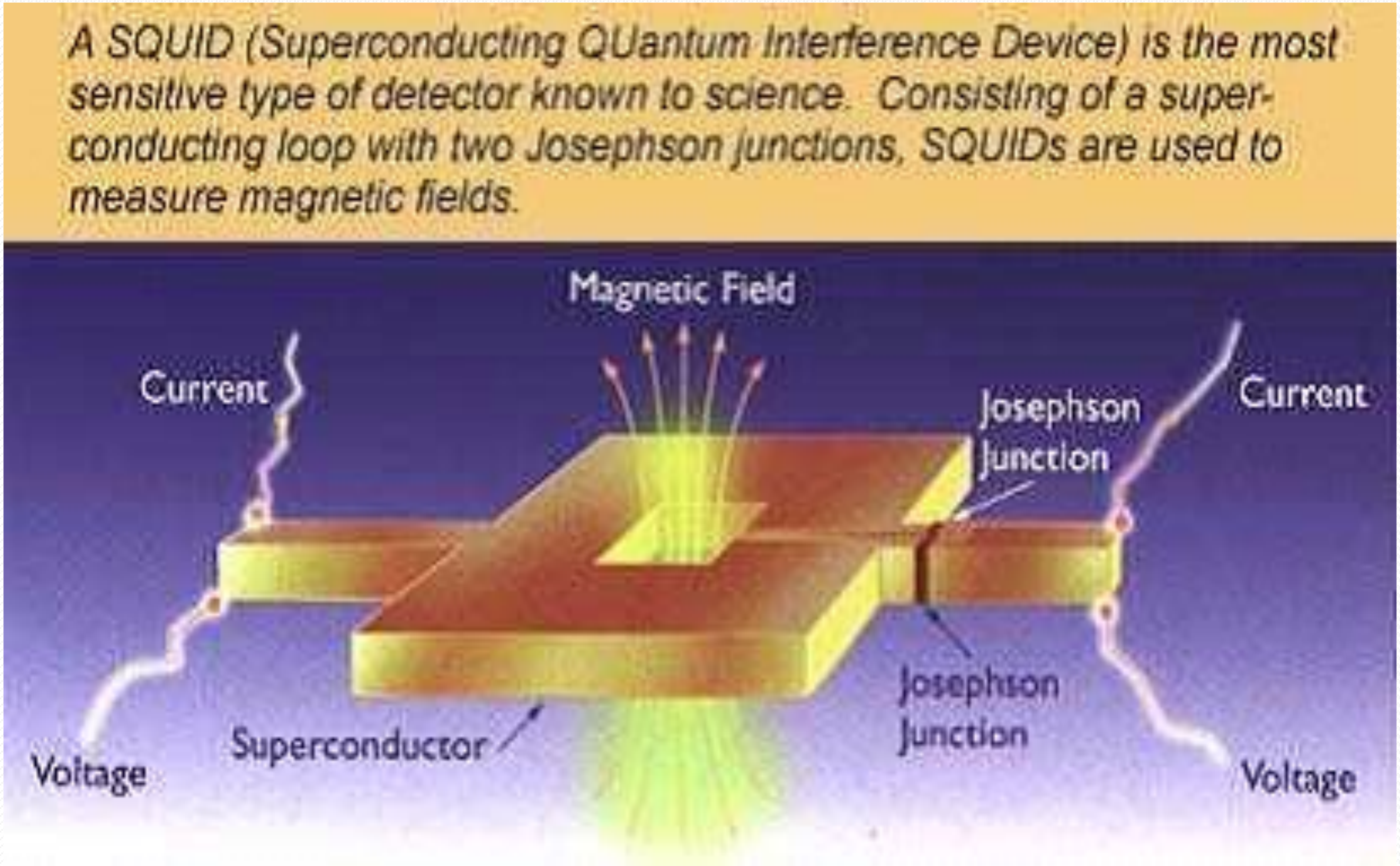
($q = 2e$ signifies the motion of Cooper pairs)

and $n = 0, 1, 2, 3,$ and so on.

Current Applications of Superconductors

- magnetic shielding devices
- medical imaging systems, e.g. MRI’s
- superconducting quantum interference devices (SQUIDS) used to detect extremely small changes in magnetic fields, electric currents, and voltages.
- infrared sensors
- analog signal processing devices
- microwave devices

SQUIDS

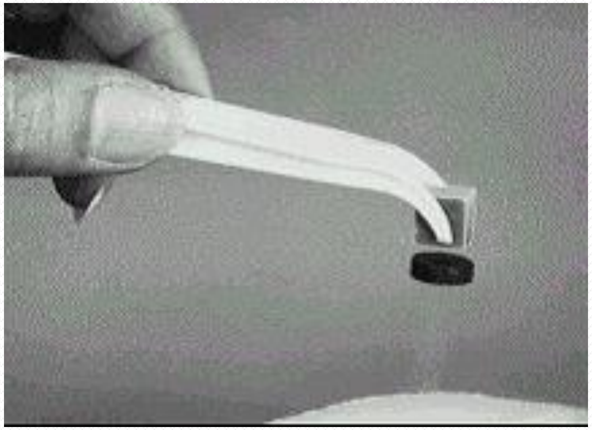


A SQUID (Superconducting QUantum Interference Device) is the most sensitive type of detector known to science. Consisting of a superconducting loop with two Josephson junctions, SQUIDs are used to measure magnetic fields.

Flux-Pinning:

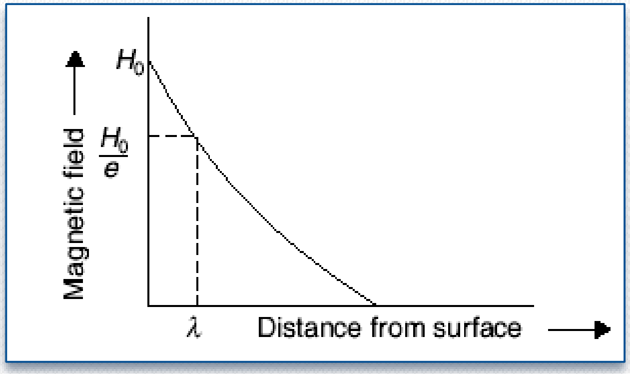
- **The phenomenon where a magnet's lines of force (called flux) become trapped or "pinned" inside a superconducting material. This pinning binds the superconductor to the magnet at a fixed distance.**

Picture of **Flux-Pinning:**



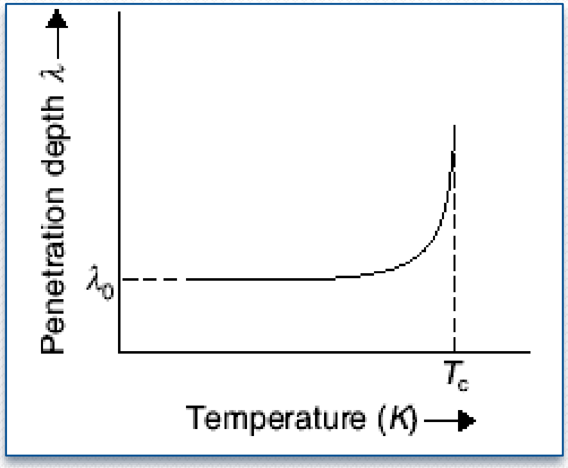
LONDON PENETRATION DEPTH

- The magnetic field at the surface of a superconductor does not vanish suddenly, but decays exponentially to zero according to the following equation:



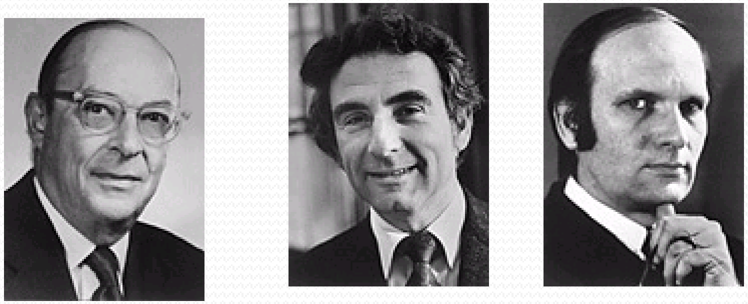
$$H = H_0 \, e^{-x/\lambda}$$

- The penetration depth changes with temperature. At low temperatures, it is almost constant, but at higher temperatures, the penetration depth increases rapidly and tends to infinity as the temperature approaches the transition temperature T_c.



The Science of Superconductivity

- The understanding of superconductivity was advanced in 1957 by three American physicists-John Bardeen, Leon Cooper, and John Schrieffer, through their Theories of Superconductivity, know as the **BCS Theory**.
- Pictures of Bardeen, Cooper, and Schrieffer, respectively.
- The BCS theory explains superconductivity at temperatures close to absolute zero.
- Cooper realized that atomic lattice vibrations were directly responsible for unifying the entire current.
- They forced the electrons to pair up into teams that could pass all of the obstacles which caused resistance in the conductor.



The Science….

- The BCS theory successfully shows that electrons can be attracted to one another through interactions with the crystalline lattice. This occurs despite the fact that electrons have the same charge.

- When the atoms of the lattice oscillate as positive and negative regions, the electron pair is alternatively pulled together and pushed apart without a collision.

- The electron pairing is favorable because it has the effect of putting the material into a lower energy state.

- When electrons are linked together in pairs, they move through the superconductor in an orderly fashion.

The Science….

- One can imagine a metal as a lattice of positive ions, which can move as if attached by stiff springs. Single electrons moving through the lattice constitute an electric current.

- Normally, the electrons repel each other and are scattered by the lattice, creating resistance.

- A second electron passing by is attracted toward this positive region and in a superconductor it follows the first electron and they travel bond together through the lattice.

In Simpler Terms…

- When atoms join to form a solid, they create what is called a lattice. A lattice is like a jungle gym that links all of the atoms together. Electricity can move through a lattice by using the outer parts of the atoms - the electrons. But imagine the jungle gym is shaking. This would make it very difficult for a person to climb through it. Especially if he's in a hurry. So, it is with electrons. They are constantly colliding with vibrating atoms because of the heat within the lattice.

- To solve this problem, let's imagine you are trying to get through a crowd of dancing people. The only way you can do this quickly would be to convince the person ahead of you to lift you up and then, as the next person sees what's happening, the crowd lets you body-surf across the top of them. This is similar to what happens when 2 electrons team up

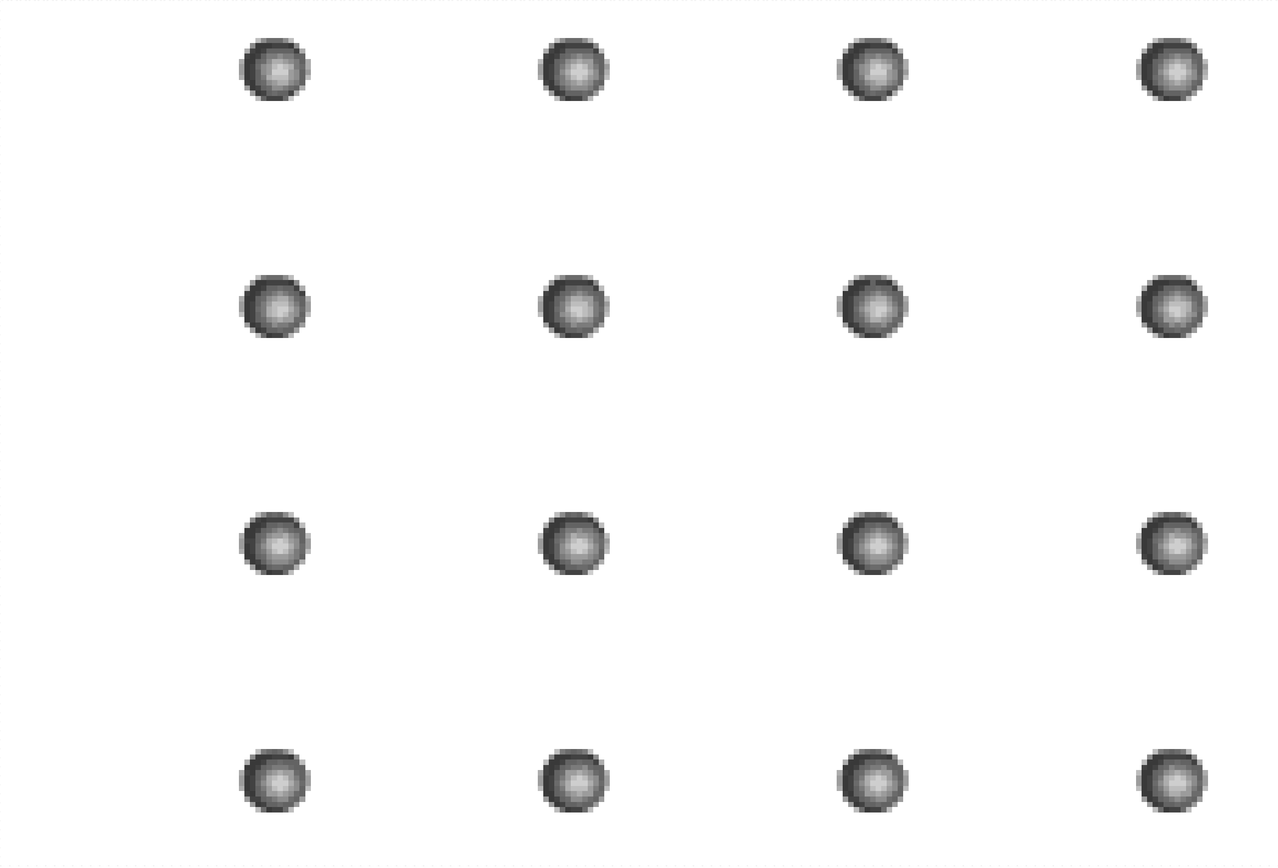
In Simpler Terms Continued…

- The first electron convinces the next atom that you deserve special treatment. Once the process starts, everyone joins in and you begin moving forward effortlessly. The person-to-person exchange represents the 2 electrons. And, your body represents the electrical charge.
- There is, however, one small catch. Since the crowd is so active, you must first slow down the dancing so they can grab you as you arrive overhead. This is done by cooling the atoms to very low temperatures. The fast dance now becomes a slow dance. So our chances are much better to get a free ride across the room. This is superconductivity.

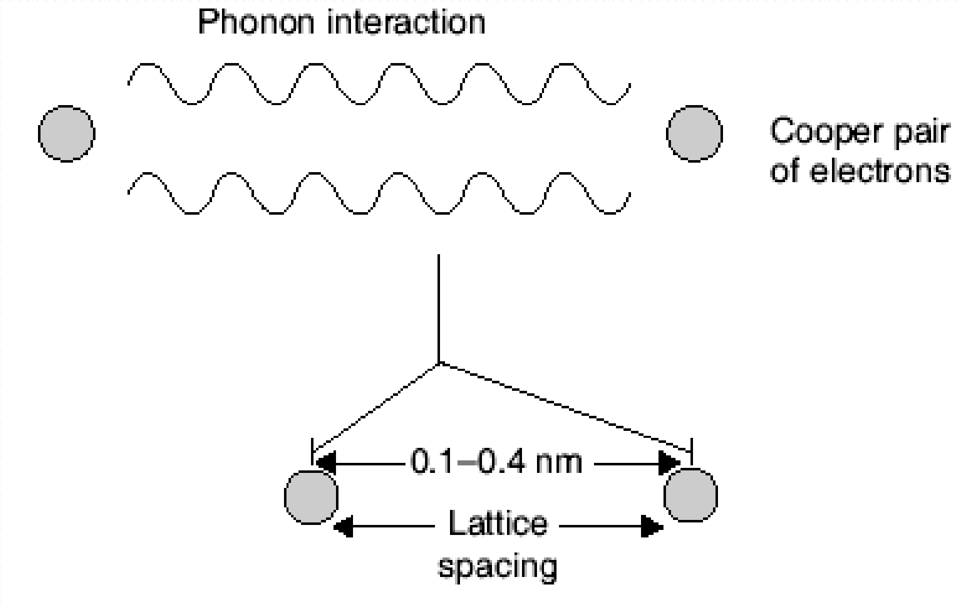
Cooper Pair:

- **Two electrons that appear to "team up" in accordance with theory - BCS or other - despite the fact that they both have a negative charge and normally repel each other. Below the superconducting transition temperature, paired electrons form a condensate - a macroscopically occupied single quantum state - which flows without resistance.**

Animation of Cooper pairs:



- A pair of free electrons coupled through a phonon is called a *Cooper pair.*
- *Each Cooper* pair consists of two electrons having opposite moments and opposite spins.



The Science….

- An electrical current in a wire creates a magnetic field around the wire.

- The strength of the magnetic field increases as the current in the wire increases.

- Because superconductors are able to carry large currents without loss of energy, they are well suited for making strong electromagnets.

The Science….

- Soon after Kamerlingh Onnes discovered superconductivity, scientists began dreaming up practical applications for this strange new phenomenon.

- Powerful new superconducting magnets could be made much smaller than a resistive magnet, because the windings could carry large currents with no energy loss.

The Science….

- Generators wound with superconductors could generate the same amount of electricity with smaller equipment and less energy. Once the electricity was generated, it could be distributed through superconducting wires.

- Energy could be stored in superconducting coils for long periods of time without significant loss.

The Science….

- The superconducting state is defined by three very important factors: critical temperature (T_c), critical field (H_c), and critical current density (J_c). Each of these parameters is very dependant on the other two properties present
  - **critical temperature (T)** The highest temperature at which superconductivity occurs in a material. Below this transition temperature T the resistivity of the material is equal to zero.
  - **critical magnetic field (H_c)** Above this value of an externally applied magnetic field a superconductor becomes nonsuperconducting
  - **critical current density (J_c)** The maximum value of electrical current per unit of cross-sectional area that a superconductor can carry without resistance.

CHARACTERISTICS OF SUPERCONDUCTORS

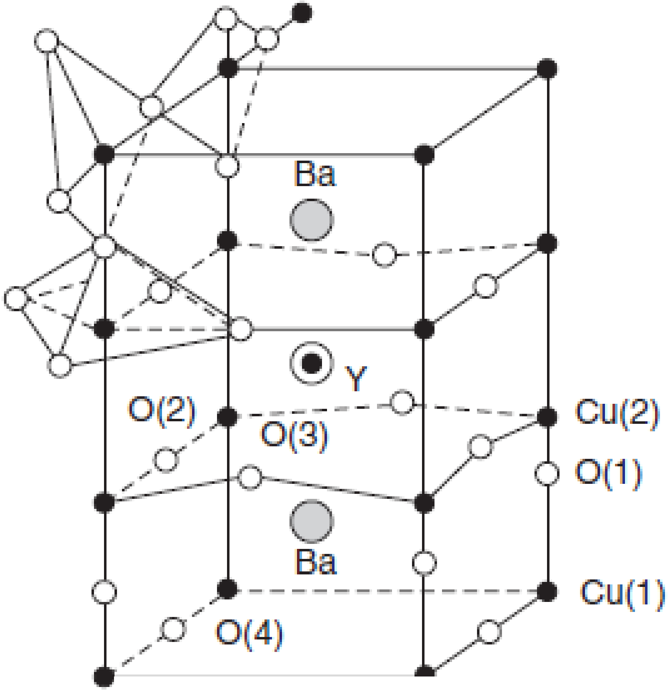
- The current in the superconductors is sustained for a very long period.
- When the current is increased above its critical value (*Ic*), *the superconductor behaves like a normal conductor.*
- The magnetic field does not penetrate the superconductor (Meissner effect). However, above the critical magnetic field, the superconductor becomes a normal conductor.
- Good conductors at room temperature are not superconductors and superconducting materials are not good conductors at room temperature.
- Ferromagnetic materials and anti-ferromagnetic materials are not superconductors.
- Bismuth, antimony, and tellurium become superconductors at high pressure.
- It has been found that most of the materials having high resistivity are superconductors

APPLICATIONS OF SUPERCONDUCTORS

- *In the field of radio electronics*
- *Power generation*
- *In the field of transport*
- *In armed forces*
- *In research and development*
- *In medicine*

HIGH-TEMPERATURE SUPERCONDUCTORS

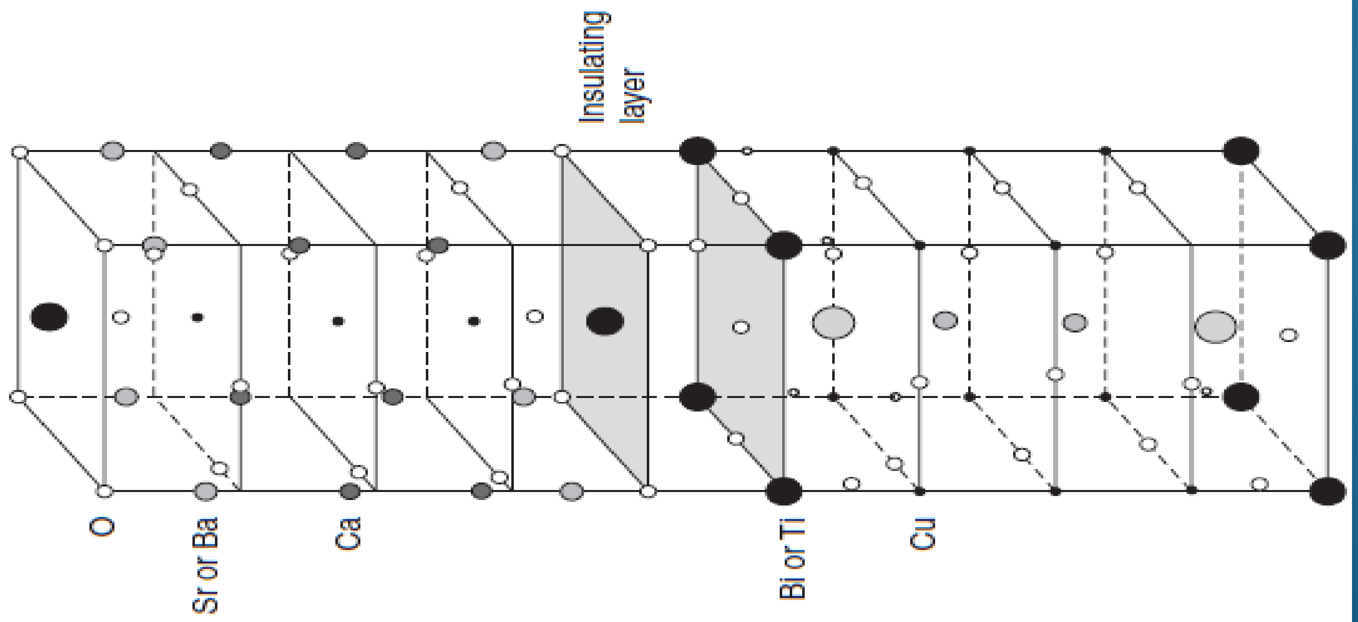
The first high-temperature superconductor was created by J.G. Bednorz and K.A. Miller with the discovery of LaBaCuO at transition temperature 35 K.



Showing YBCO ($Y_1Ba_2Cu_3O_7$)

JOSEPHSON EFFECT

When two superconductors are placed adjacent to each other with an insulating layer between them, a current flows due to the tunneling of the superelectrons through the junction. This phenomenon is called *Josephson effect.*



BSCCO and TBCCO

ISOTOPE EFFECT

It has been experimentally observed that the transition temperature *(Tc) of a superconductor element varies with its isotopic mass as*

$$T_c \propto \frac{1}{\sqrt{M}}$$

$$T_c M^{1/2} = \text{constant}$$

Emerging Applications

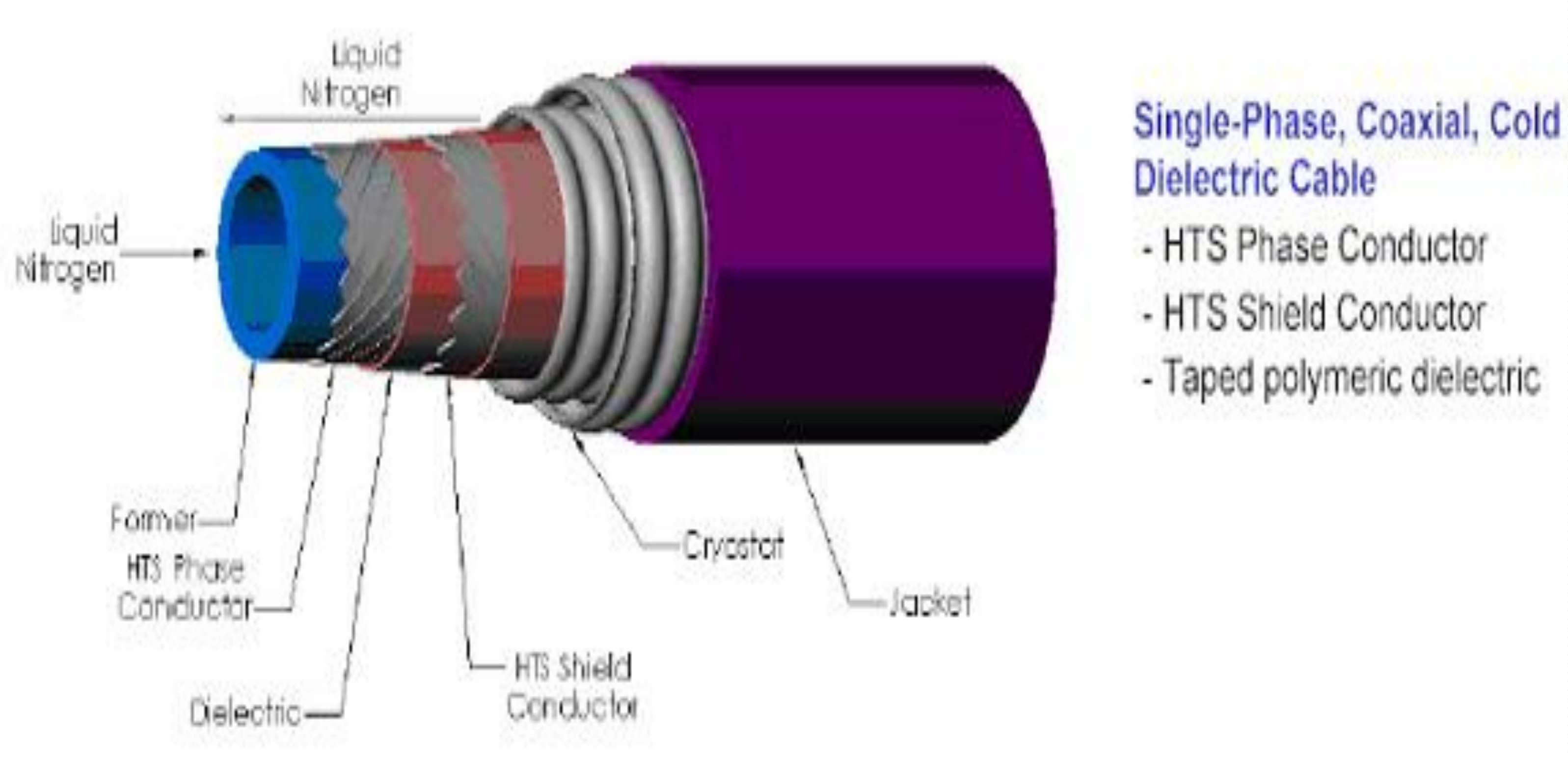
- power transmission
- superconducting magnets in generators
- energy storage devices
- particle accelerators
- levitated vehicle transportation
- rotating machinery
- magnetic separators

How the Science Helps Us

What Types of Superconducting Power Systems Equipment Can Help Us?

- Underground transmission cables
- Fault current limiters
- Transformers
- Motors
- SMES, Generators, etc.

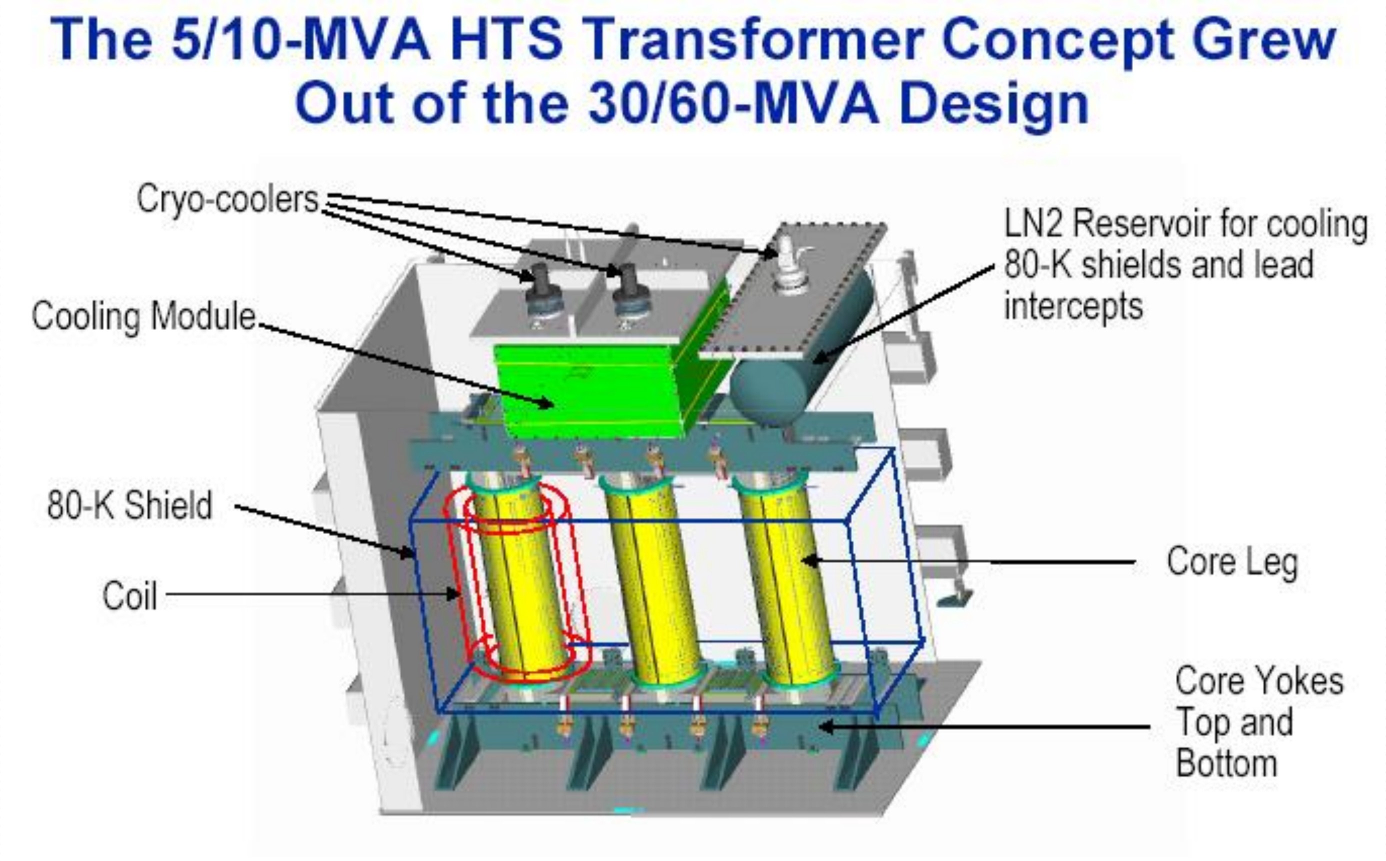
Cable – transmits 3 to 5 times more energy than copper wire



Single-Phase, Coaxial, Cold Dielectric Cable

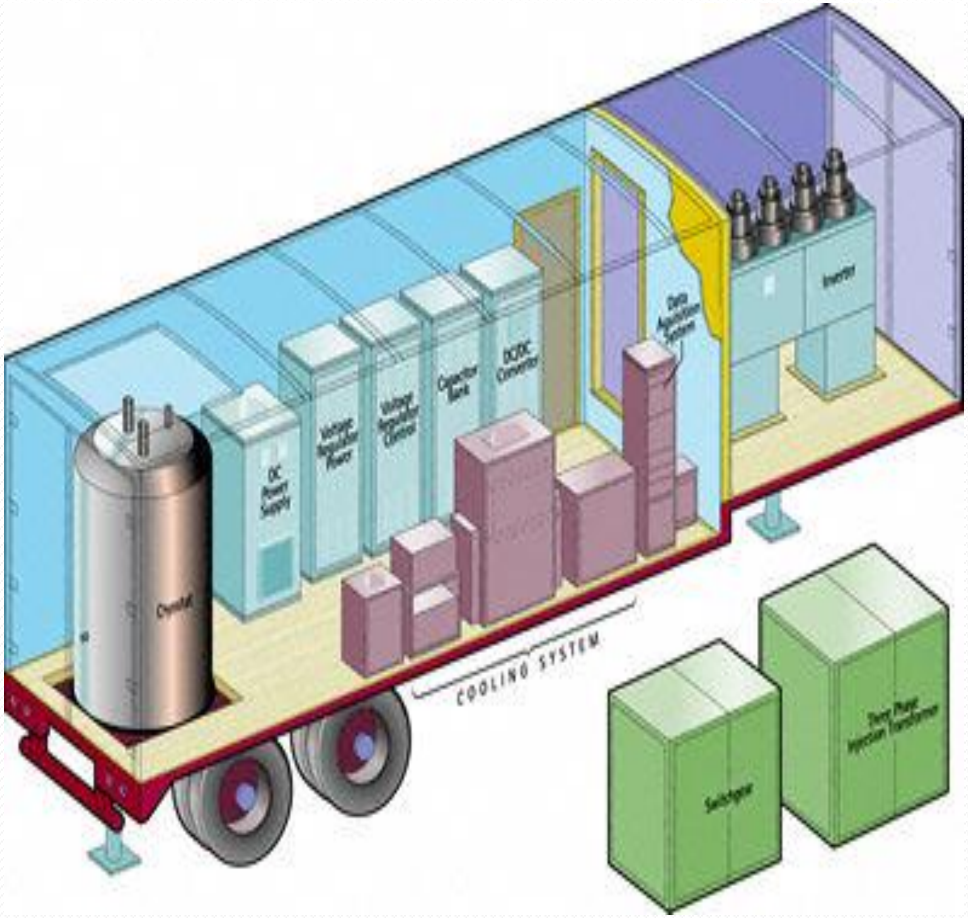
- HTS Phase Conductor
- HTS Shield Conductor
- Taped polymeric dielectric

Transformer- 2 times overload capacity without insulation damage and environmentally friendly due to lack of oil used in operation.



The 5/10-MVA HTS Transformer Concept Grew Out of the 30/60-MVA Design

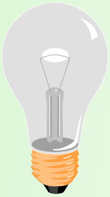
SMES (Superconducting Magnetic Energy Storage)



Economic Impact of Superconducting Equipment

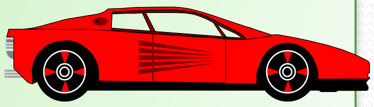
- Utilities
  - Higher density transmission uses & higher economic productivity
  - Reduced environmental impact
- Industrial

  More cost effective industrial processes:
  - Manufacturing & energy production
  - Electrical storage, transmission and expansion



- Transportation

  More cost effective electrical transportation:
  - High Speed Rail & MAGLEV technologies
  - Electric car / bus
  - Ship



Another Nobel Prize for Superconductivity Researchers

- The awards committee honored the trio--Vitaly Ginzburg, Alexei Abrikosov and Anthony Leggett (shown below)--for "decisive contributions concerning two phenomena in quantum physics: superconductivity and superfluidity." Source: *Scientific American*