UES022
Quantum Materials

Thapar Institute of Engineering & Technology
(Deemed to be University)
Bhadson Road, Patiala, Punjab, Pin-147004
Contact No. : +91-175-2393201
Email : info@thapar.edu

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OF ENGINEERING & TECHNOLOGY
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Quantum Materials

Superconductors: Fundamentals of superconductivity: Zero resistance and expulsion of magnetic fields (Meissner effect). Differentiation between Type I and Type II superconductors. Introduction to Cooper pairs and the BCS theory. Exploration of high-temperature superconductors and their applications in fields like energy transmission.

Topological Materials: Introduction to topological phases of matter and their unique properties. Topologically protected surface states and their relevance to fault-tolerant quantum computing.

2D Materials and Graphene: Structure, properties, and significance of graphene in electronic and thermal applications. Exploration of other 2D materials, such as transition metal dichalcogenides (TMDs) and their emerging applications. Applications of 2D materials in fields like sensors, quantum computing, and renewable energy.

Introduction to Solids:

Challenge for harnessing quantum technologies:

- Quantum states are exceptionally fragile, susceptible to the slightest disturbances.
- Understanding the intricate correlations between particles in quantum systems.

Need novel materials and structures where quantum effects play a pivotal role.

Quantum materials: materials having properties that cannot be easily described by classical, or low-level, quantum physics. Include topological materials, low-dimensional materials, and engineered quantum materials.

The ability to manipulate these materials at the nanoscale opens up possibilities for creating innovative quantum devices.

What are ‘Quantum Materials’?

Why are all materials not quantum materials whereas properties can have quantum mechanical origin?

Although the properties arise from quantum mechanics, classical models and approximations are sufficient to describe them.

Example: Magnetism

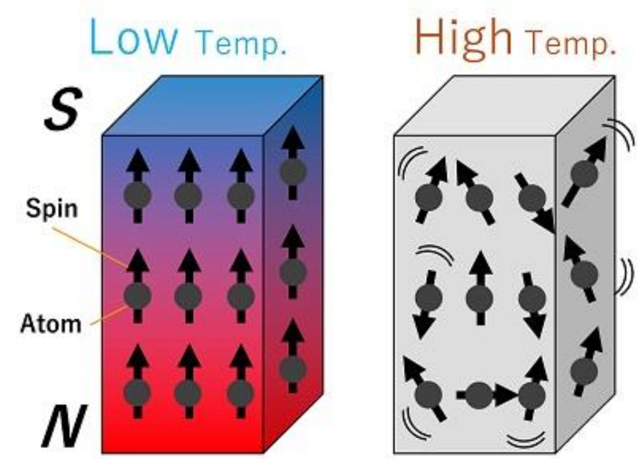
Spin
Spin-spin interaction

Quantum mechanical phenomena

Ordinary magnetic materials cannot be considered as quantum materials

However, magnetic ordering can be well described by thermal randomization of spins

Classical model



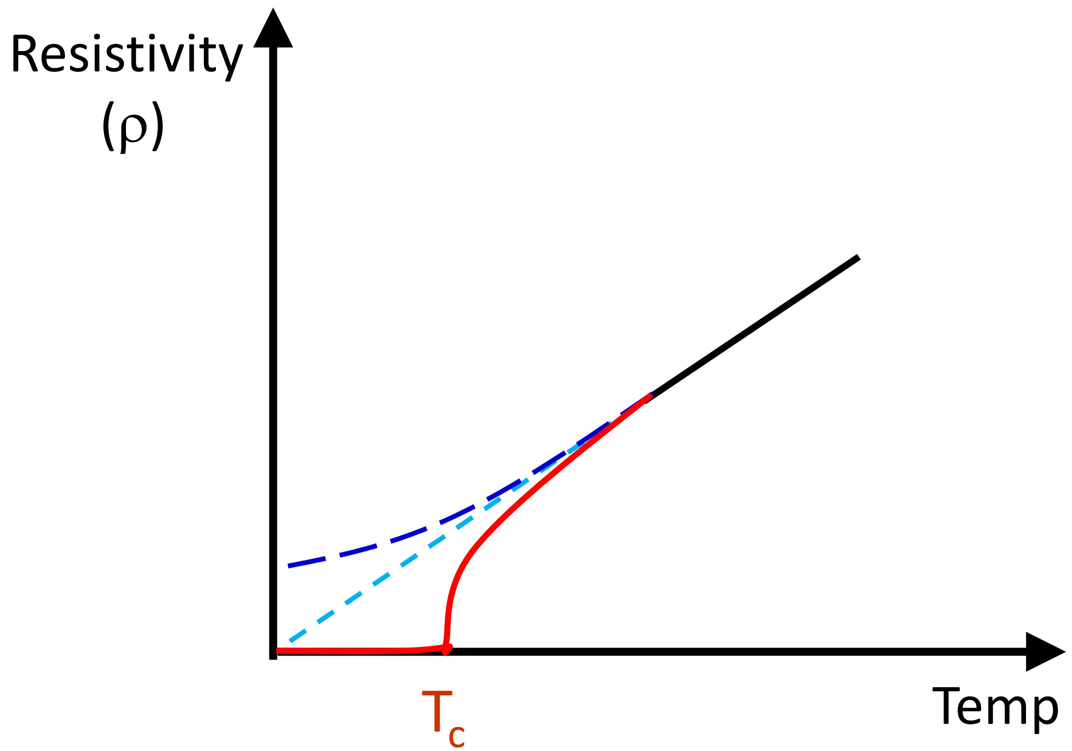
Few quantum phenomena observed in quantum materials are:

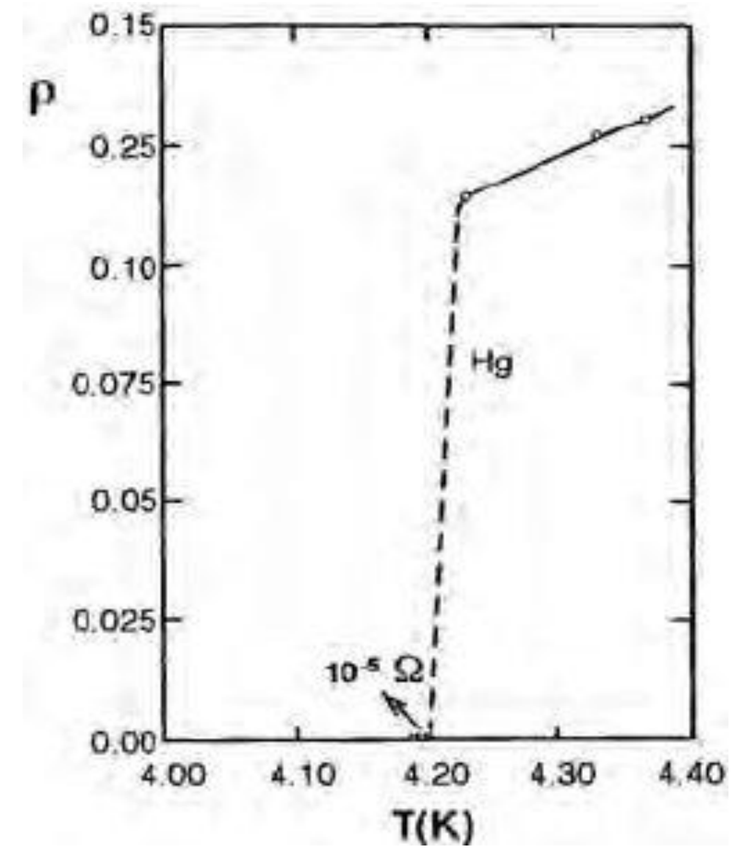
- **Superconductivity**
- **Topological order / topological phases of matter**:
  States of matter characterized by global, non-local properties which cannot be change by perturbation.
  Example of materials with such states: topological insulators, topological semimetals, topological superconductors, quantum Hall systems.)

Nobel prizes for research on superconductivity

- Heike Kamerlingh Onnes (1913), "***for his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium***".
- John Bardeen, Leon N. Cooper, and J. Robert Schrieffer (1972), "***for their jointly developed theory of superconductivity, usually called the BCS-theory***".
- Leo Esaki, Ivar Giaever, and Brian D. Josephson (1973), "***for their experimental discoveries regarding tunneling phenomena in semiconductors and superconductors, respectively" and "for his theoretical predictions of the properties of a supercurrent through a tunnel barrier, in particular those phenomena which are generally known as the Josephson effects***".
- Georg Bednorz and K. Alex Müller (1987), "***for their important break-through in the discovery of superconductivity in ceramic materials***".
- Alexei A. Abrikosov, Vitaly L. Ginzburg, and Anthony J. Leggett (2003), "***for pioneering contributions to the theory of superconductors and superfluids***".

What is superconductivity?





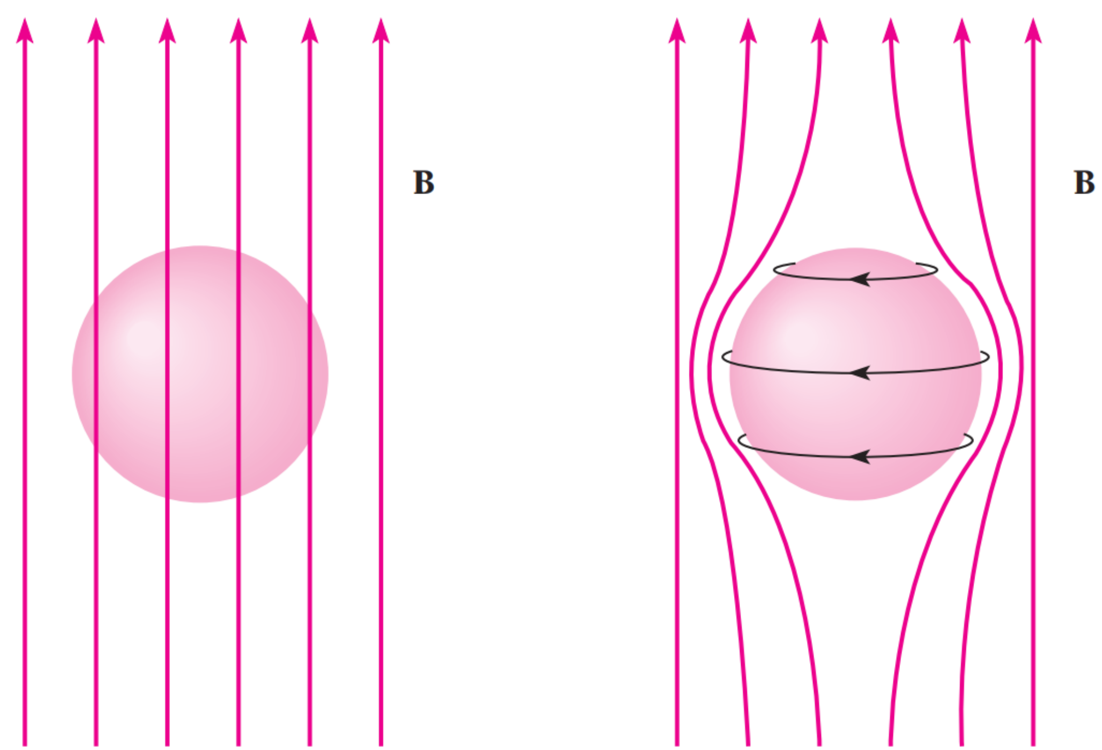
Kamerlingh Onnes (1911)

In certain conditions (below Critical Temperature, T_c), material may exhibit 'zero' resistivity.

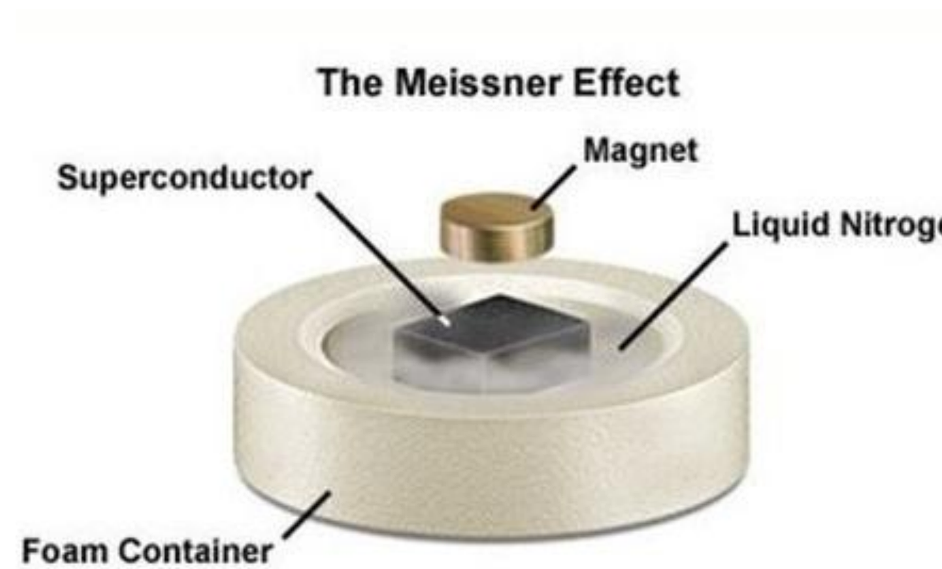
- superconductivity state

Meissner effect

- Meissner and Ochsenfeld discovered that when a magnetic field is applied to a superconductor, the applied field is excluded, so that B = 0 throughout its interior - known as the **Meissner effect**
- The magnetic field is always expelled from a superconductor.
- $B = 0$, Magnetic susceptibility $\chi = -1$
- This is achieved spontaneously by producing currents on the surface of the superconductor. The direction of the currents is such as to create a magnetic field that exactly cancels the applied field in the superconductor.



(*a*) $T > T_c$ (*b*) $T < T_c$



Important quantities in magnetism

- The response of a material to a Magnetic Field H is called Magnetic Induction B.
- The relationship between B and H is a property of the material.
- In some materials and in *free space* B is a linear function of H but in general it need not be.

$$B = \mu_o H \ (for\ free\ space)$$

$$B = \mu H \ (for\ a\ material)$$

Under external magnetic field H, field inside a material is

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

where,
M is the magnetic moment per unit volume, called magnetization.
In linear magnetic materials,

$$M \propto H$$
$$M = \chi H$$

So,

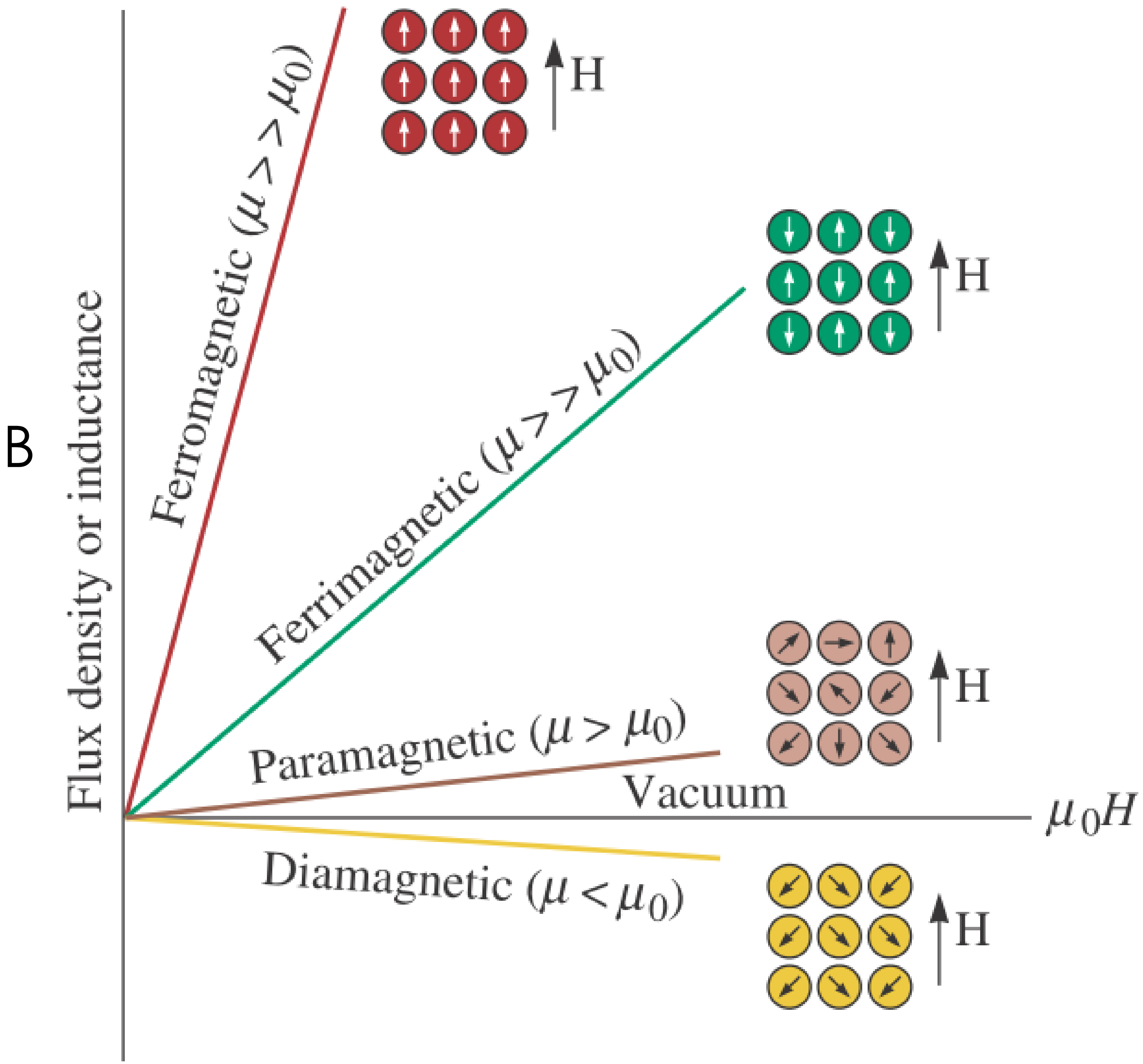
$$B = \mu_0(1 + \chi)H$$
$$B = \mu H$$

$\mu_0 \rightarrow$ magnetic permeability of vacuum
Unit: Wb/A/m = mKg/s^{2}A^2)
$\mu \rightarrow$ permeability of material (Ability of the material to permeate magnetic field)

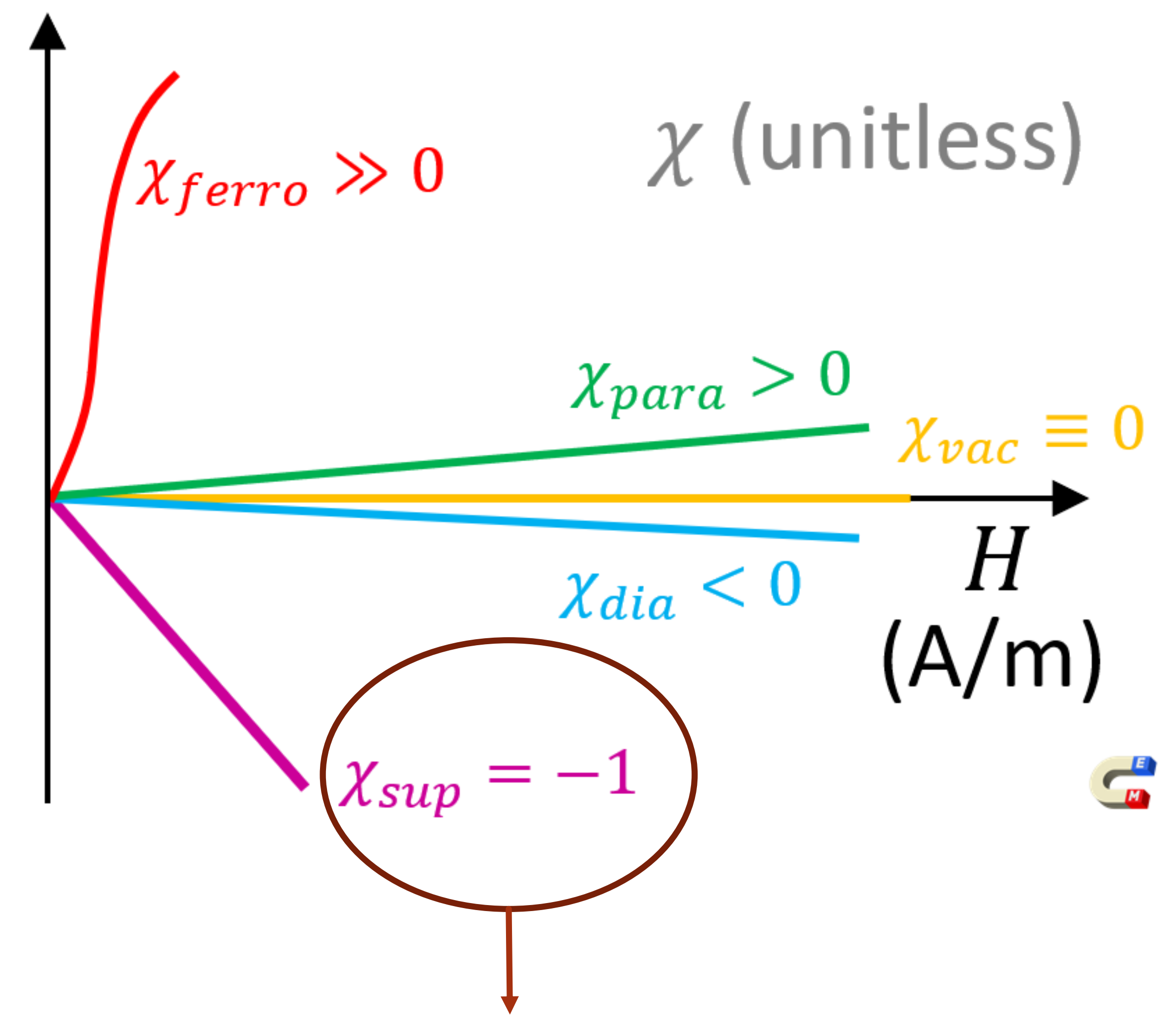
$\chi \rightarrow$ magnetic susceptibility (How much magnetic field it can hold)
Units: dimensionless

$$\mu = \mu_0(1 + \chi) = \mu_0\mu_r$$

μ_0: Relative permeability



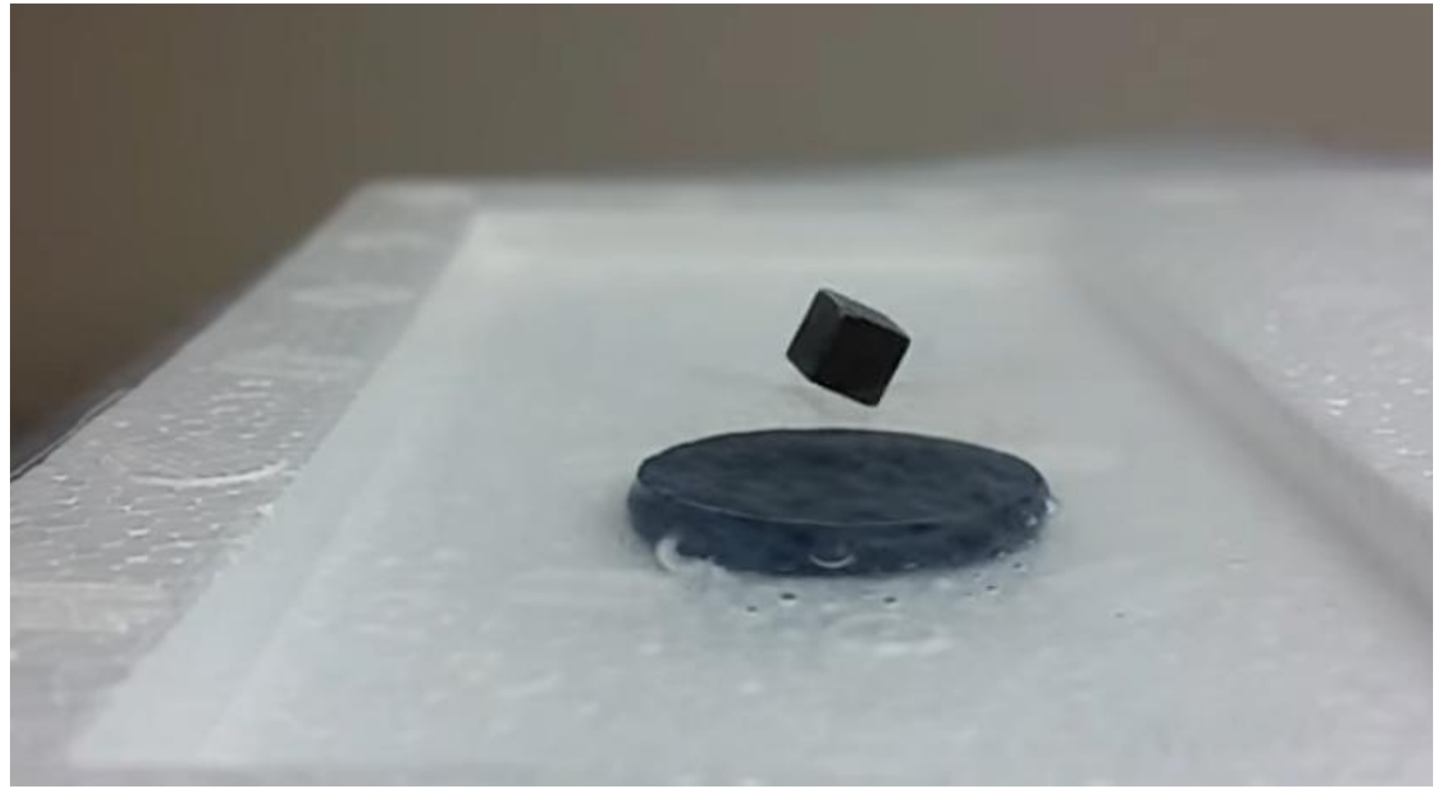
$M = \chi \cdot H$ (A/m)



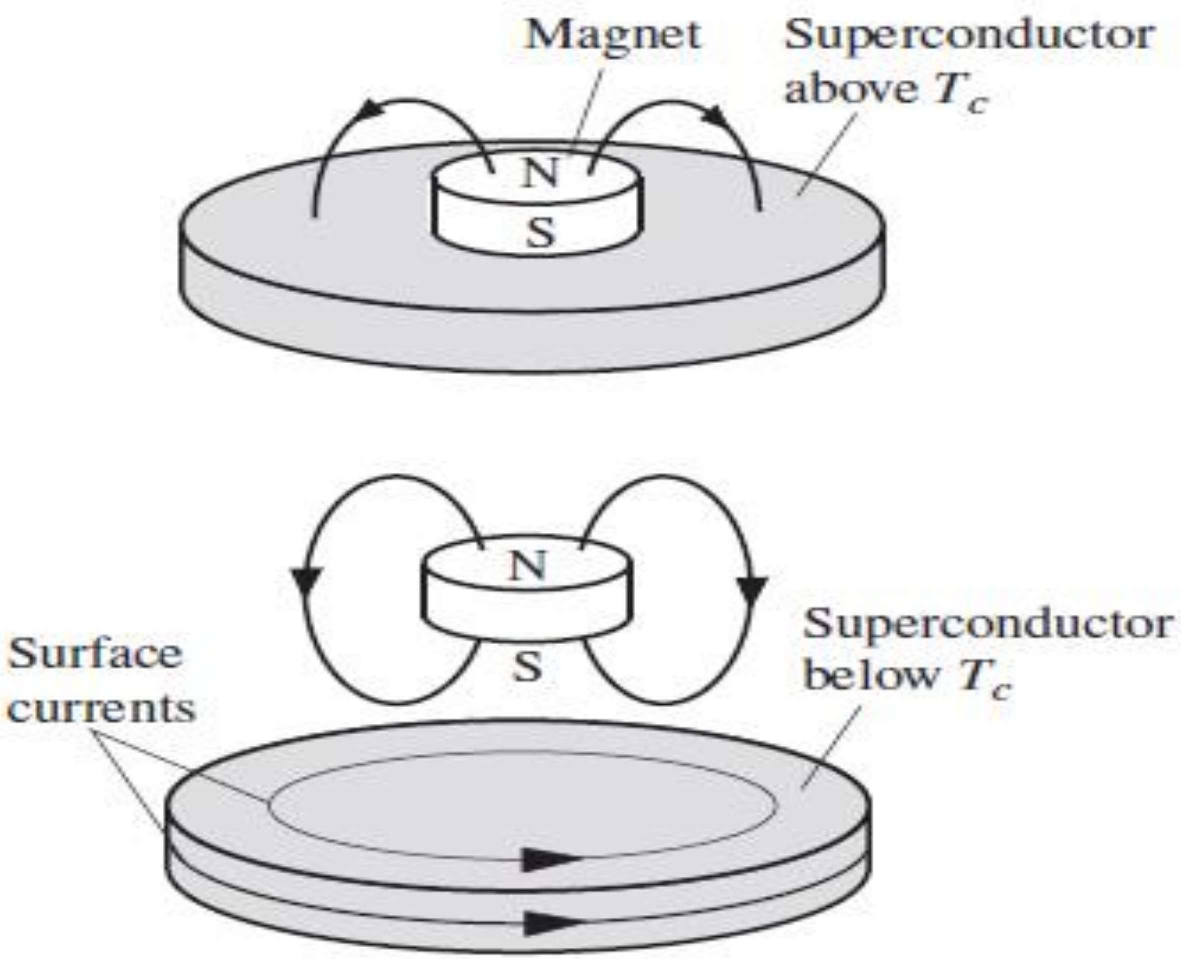
$$B = (1 + \chi)H = 0$$
$$M = -H$$

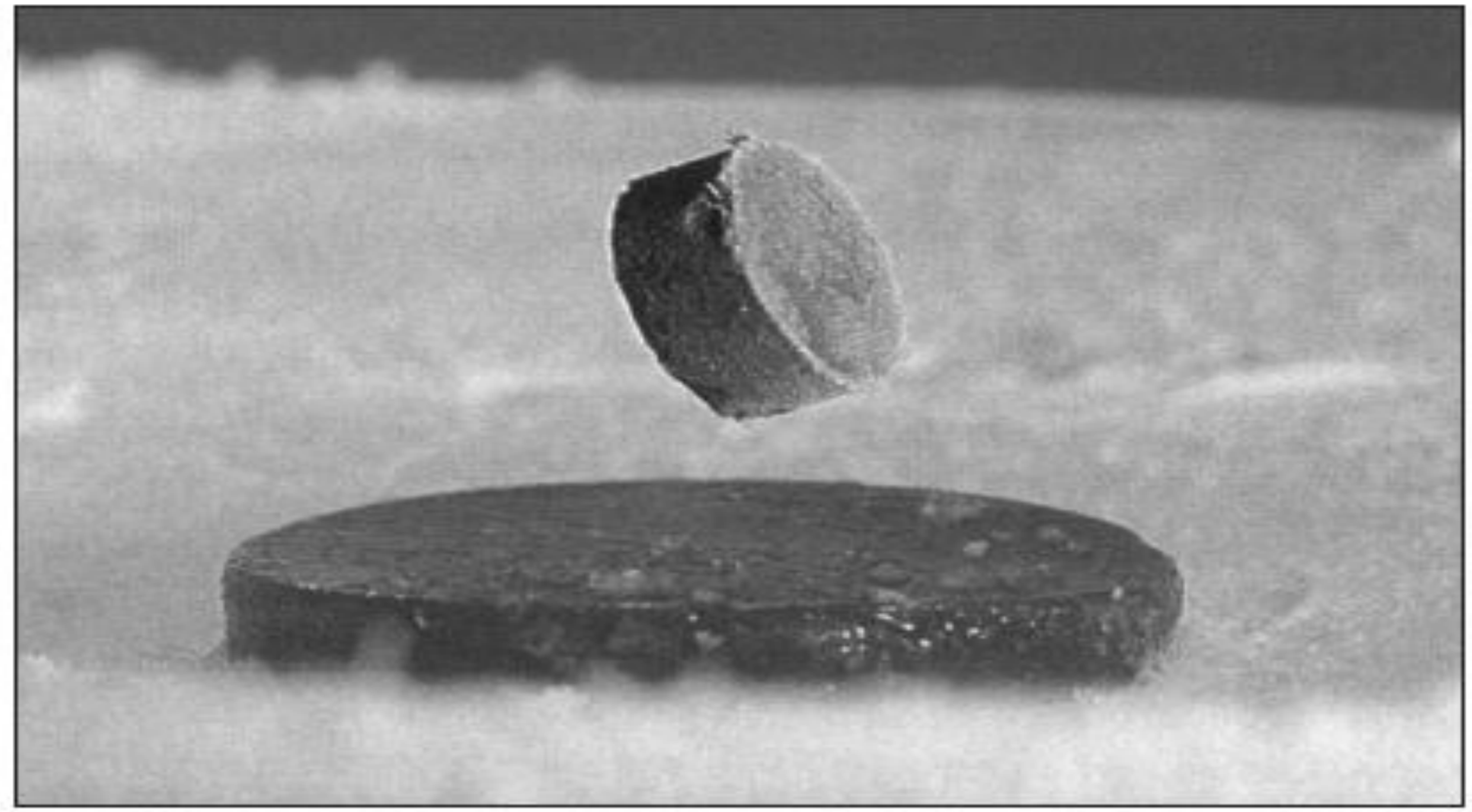
Meissner effect

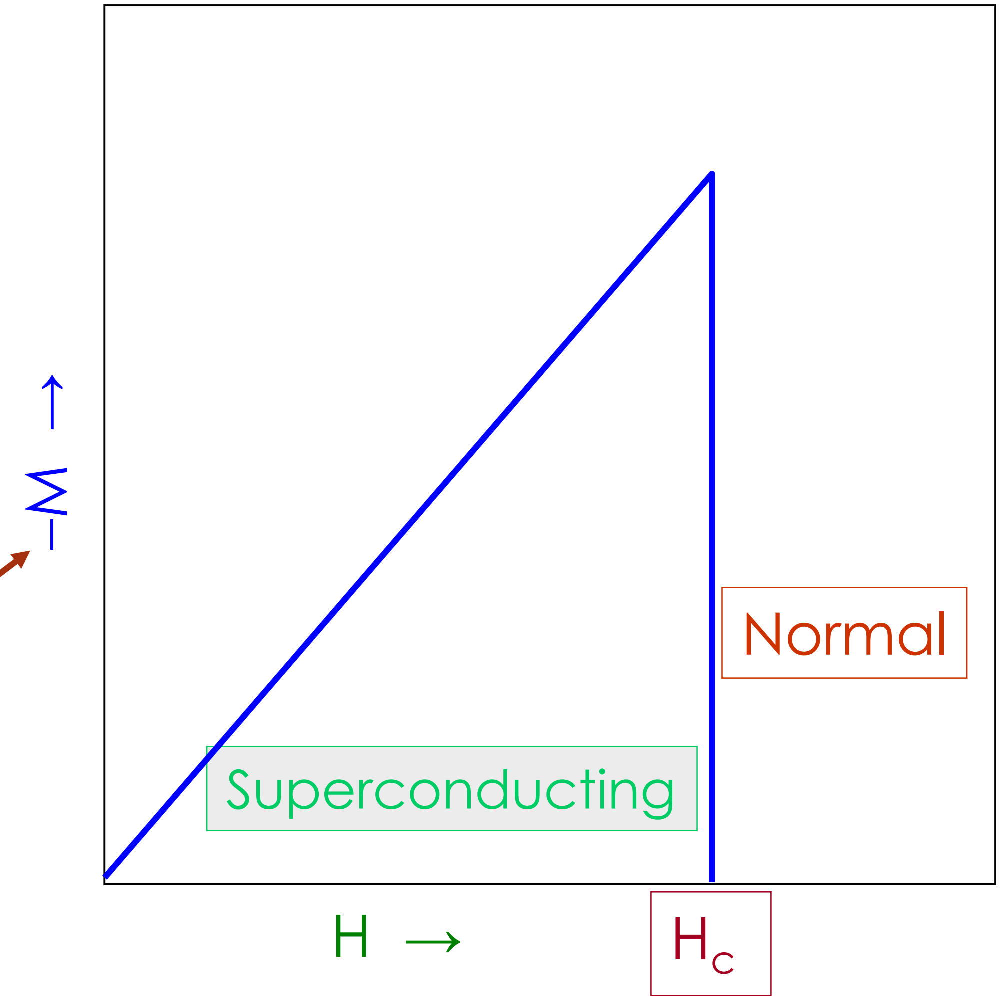
YBCO doesn’t interact with magnet



Below Tc, YBCO becomes superconductor and expels magnetic field lines from its core.


Magnet
Superconductor above T_c
N
S
N
S
Surface currents
Superconductor below T_c

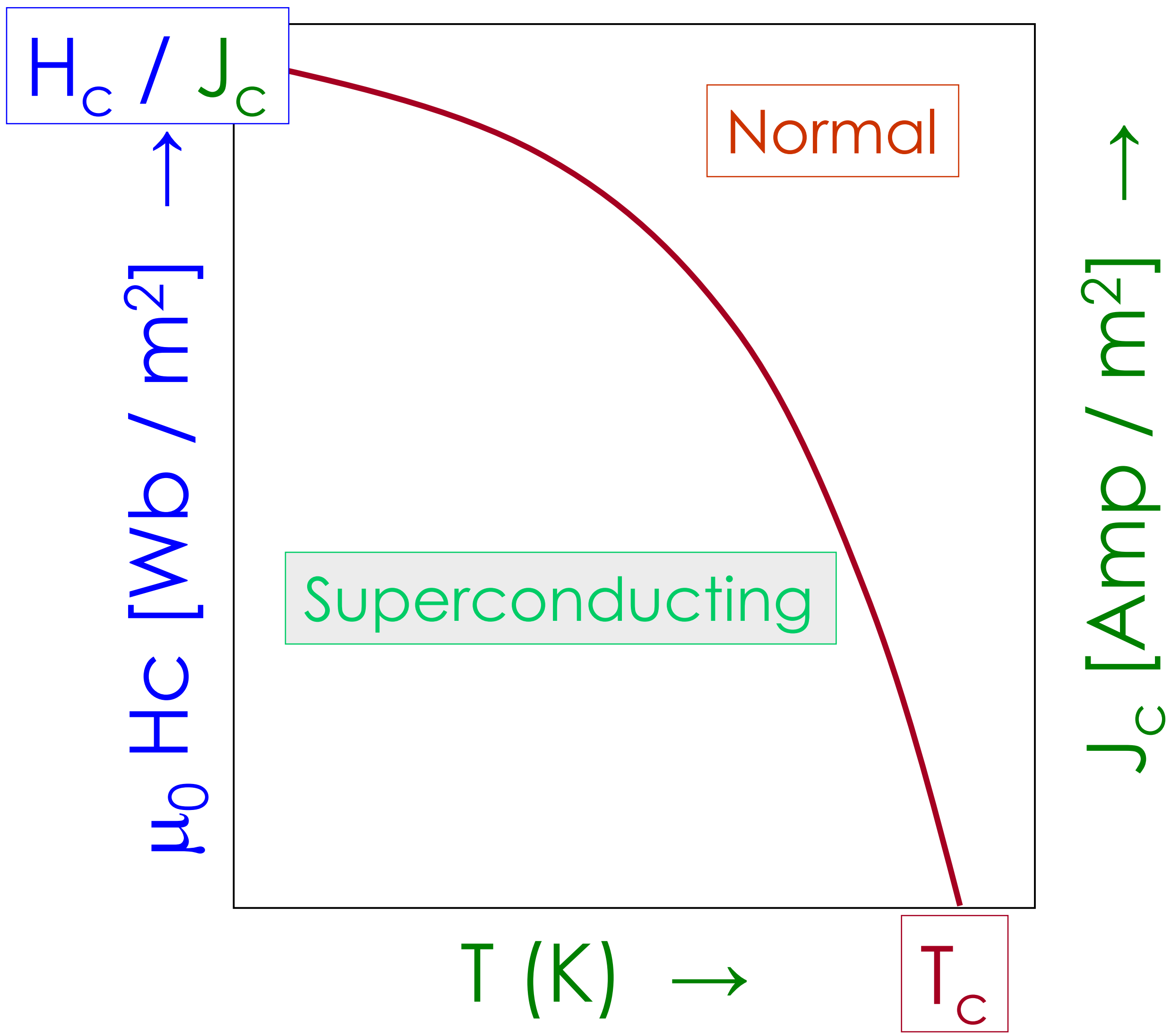




Note that M is negative

$$M = \begin{cases} -H & \rightarrow \quad H < H_c \\ 0 & \rightarrow \quad H > H_c \end{cases}$$

Effect of magnetic field and current

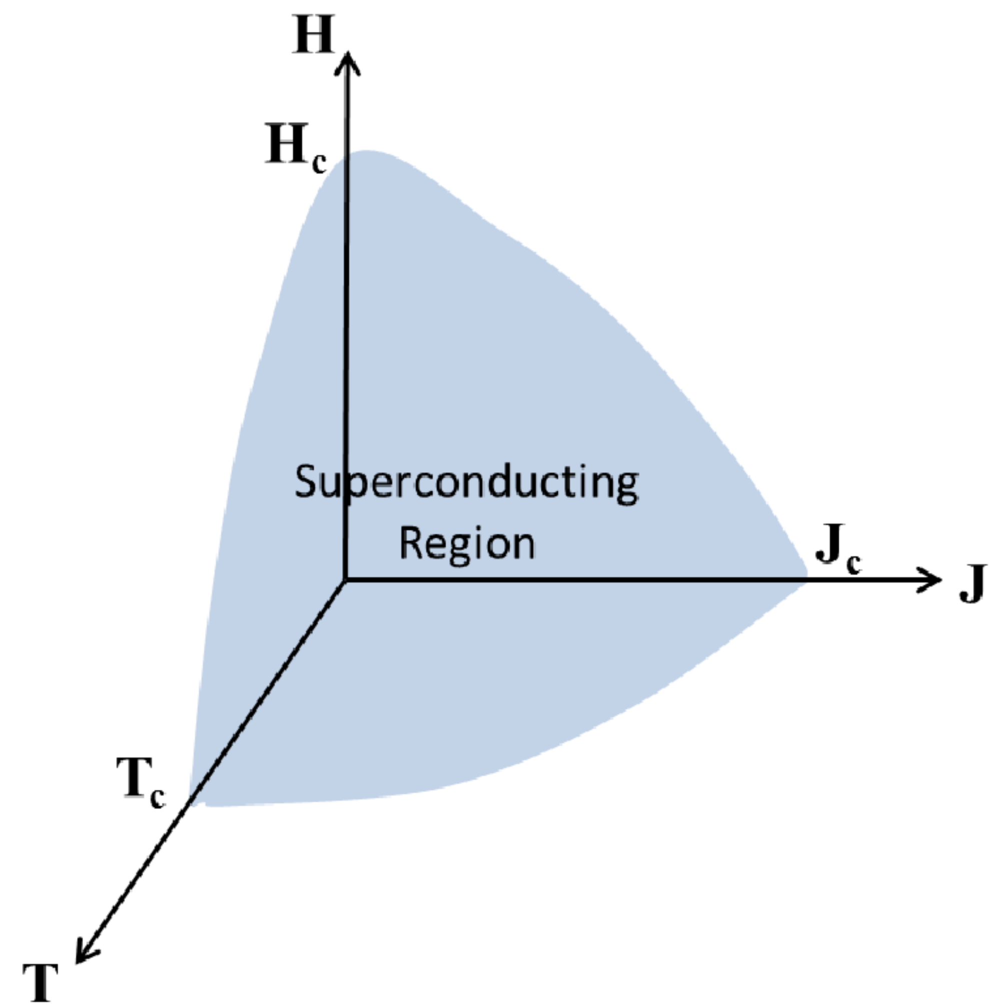


Superconducting state if

$T < T_c$

$J < J_c$

$H < H_c$



Effect of magnetic field and current

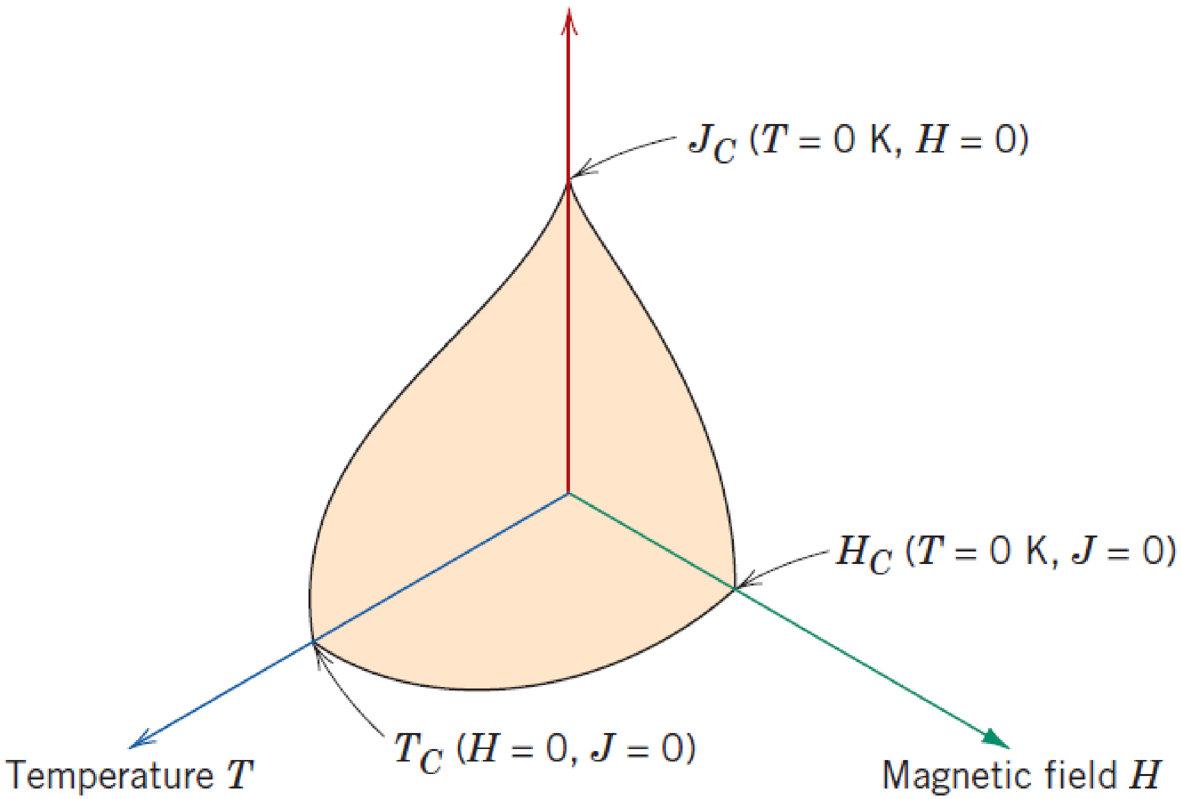
- **Magnetic field causes the critical temperature Tc of superconductors to decrease.**

  Above certain value of the external magnetic field, superconductor becomes non-superconducting . The minimum magnetic fields required to destroy the superconducting state is called the **critical magnetic field (H_C)**

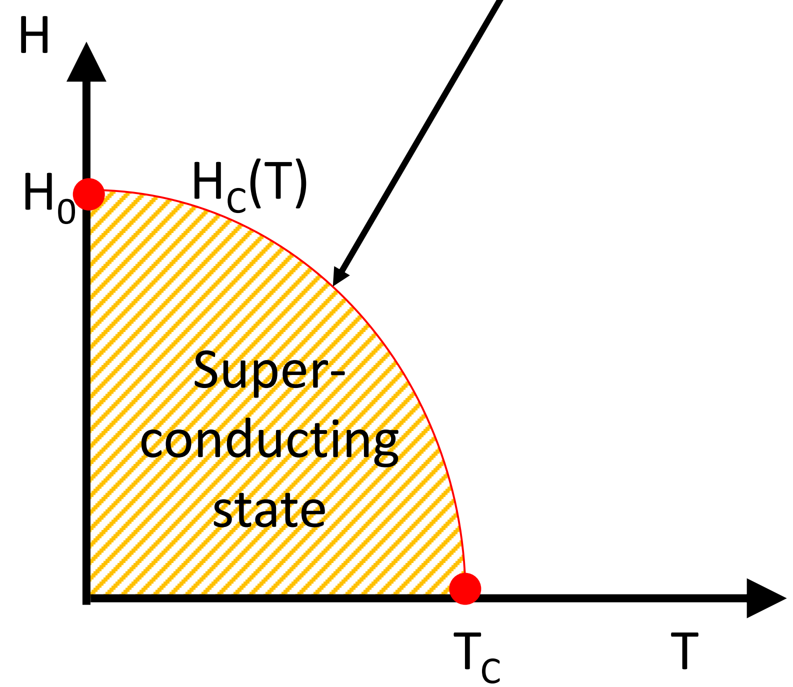
- **Increase of current density also causes the critical temperature Tc of superconductors to decrease.**

  There is an upper limit of current density (J_c) that a superconductor can carry without losing its superconducting state.

Effect of magnetic field and current



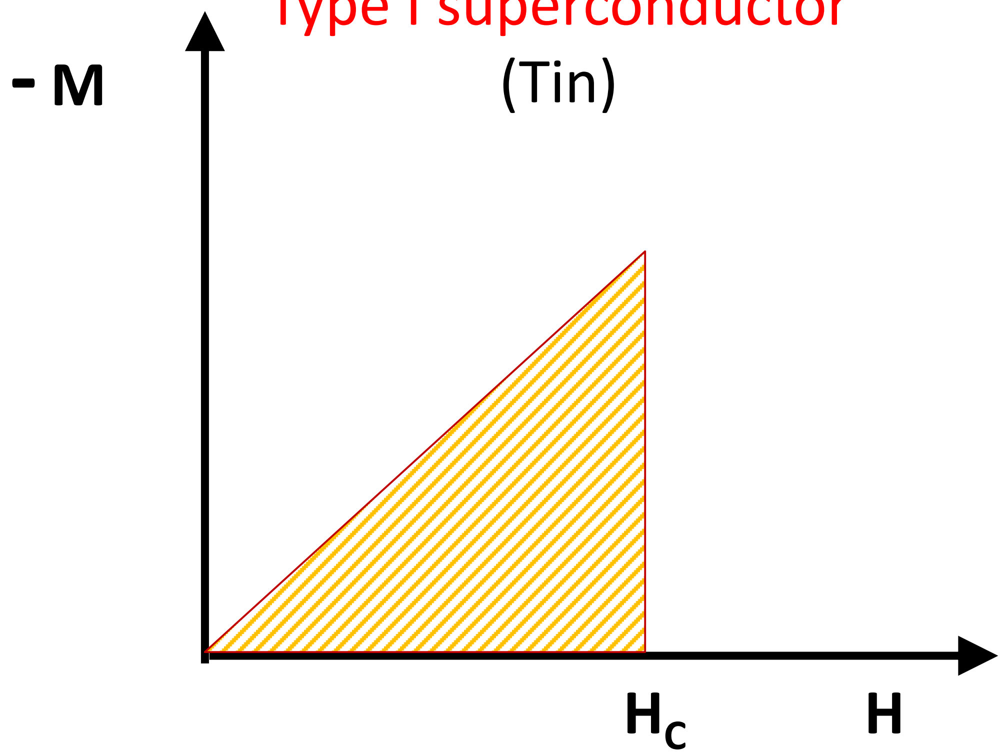
$$H_c(T) = H_0\left[1 - \frac{T^2}{T_c^2}\right]$$



Types of Super conductors

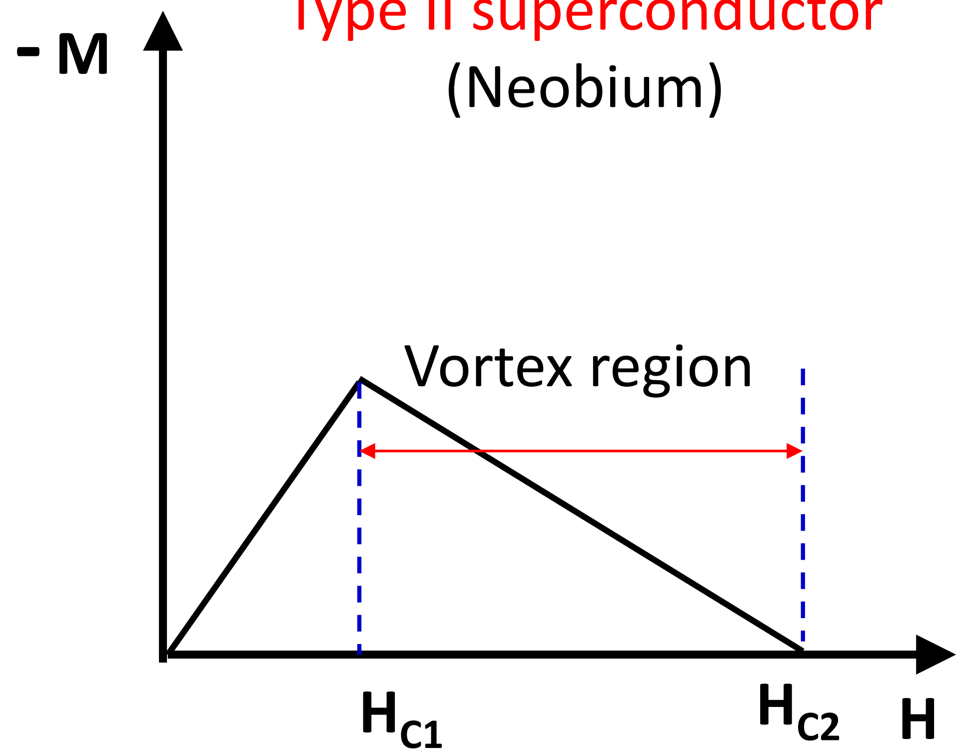
Type I superconductor

(Tin)



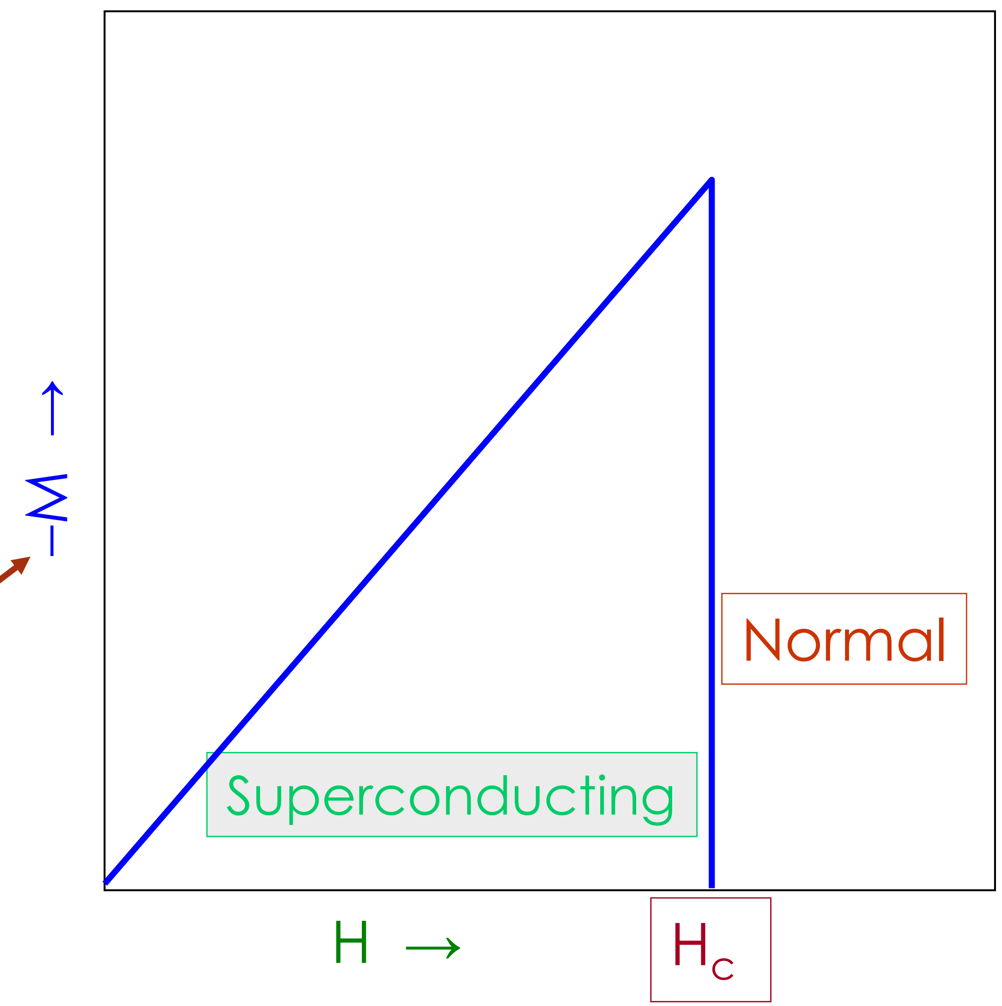
Type II superconductor

(Neobium)



Type-I (Ideal) superconductors

Type I SC placed in a magnetic field totally repels the flux lines till the magnetic field attains the critical value H_c

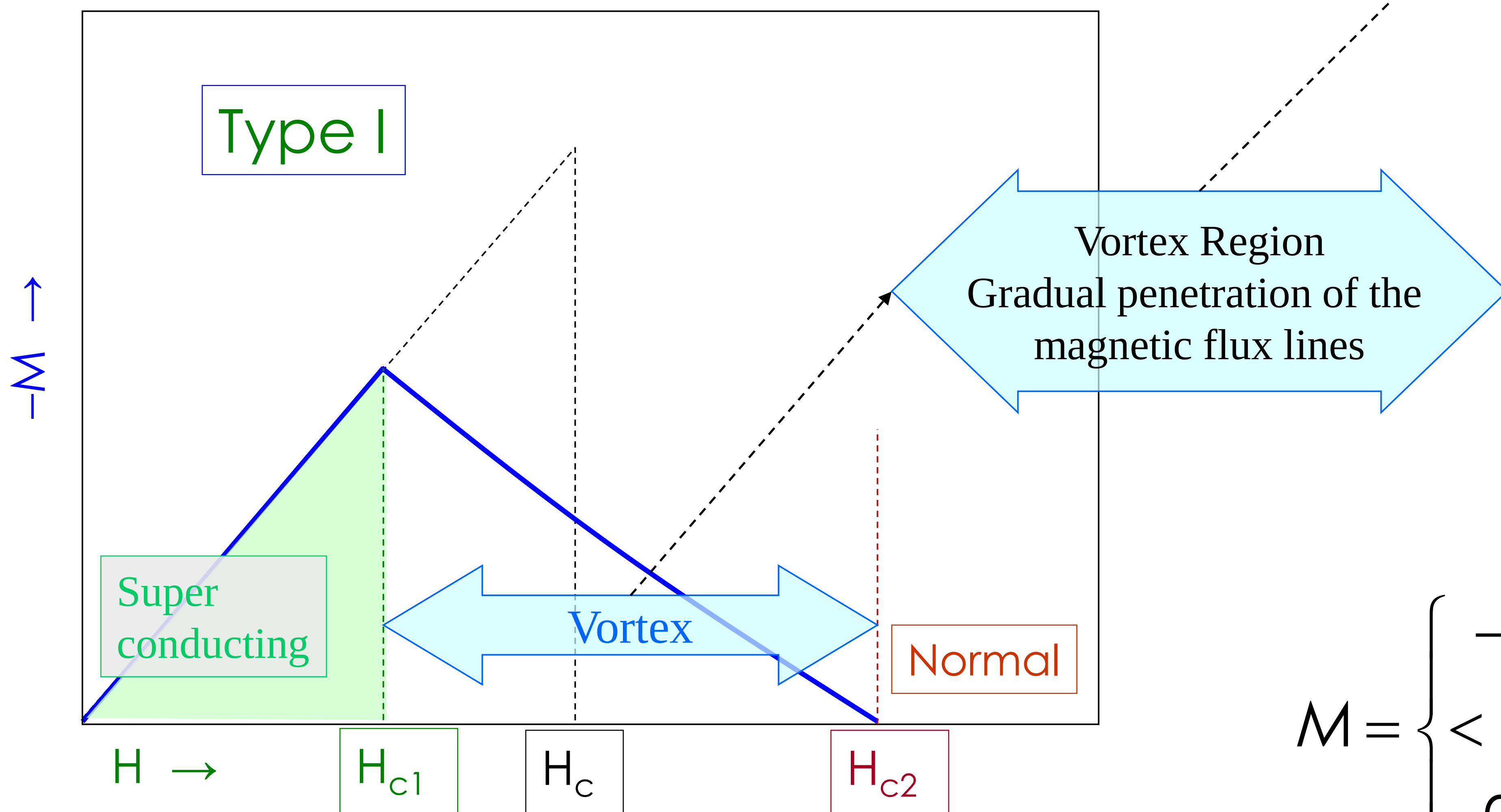


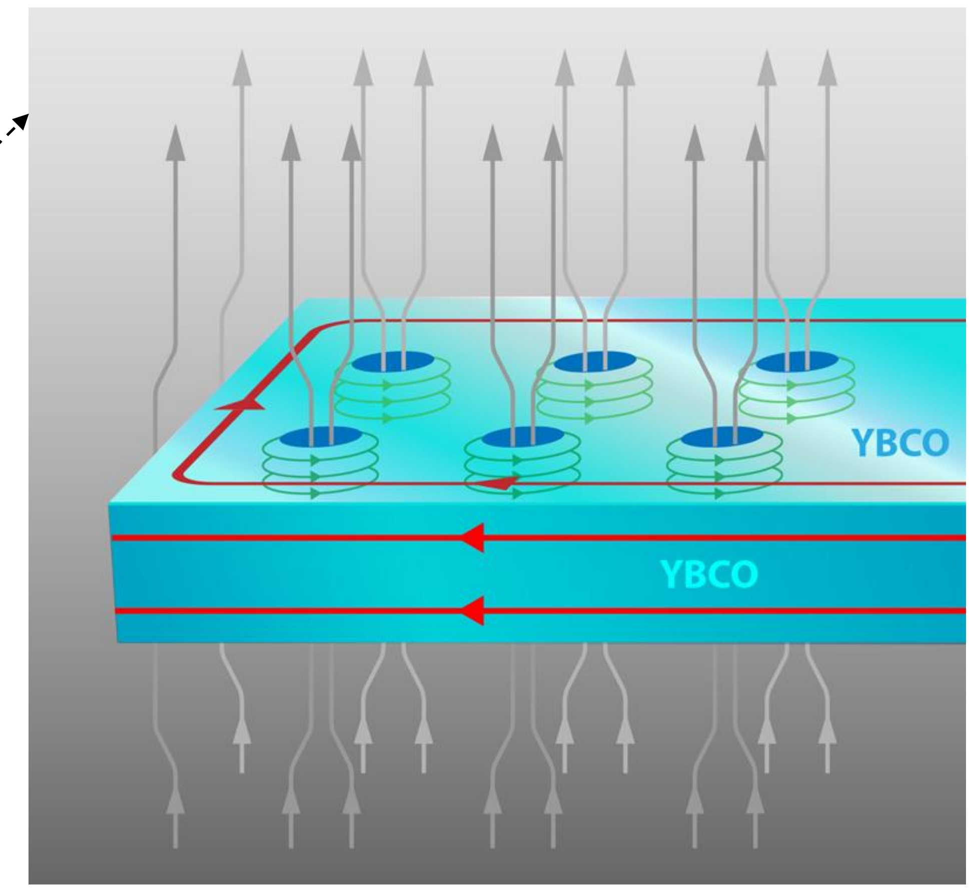
Note that M is negative

$$M = \begin{cases} -H & \rightarrow \quad H < H_c \\ 0 & \rightarrow \quad H > H_c \end{cases}$$

Type-II superconductors

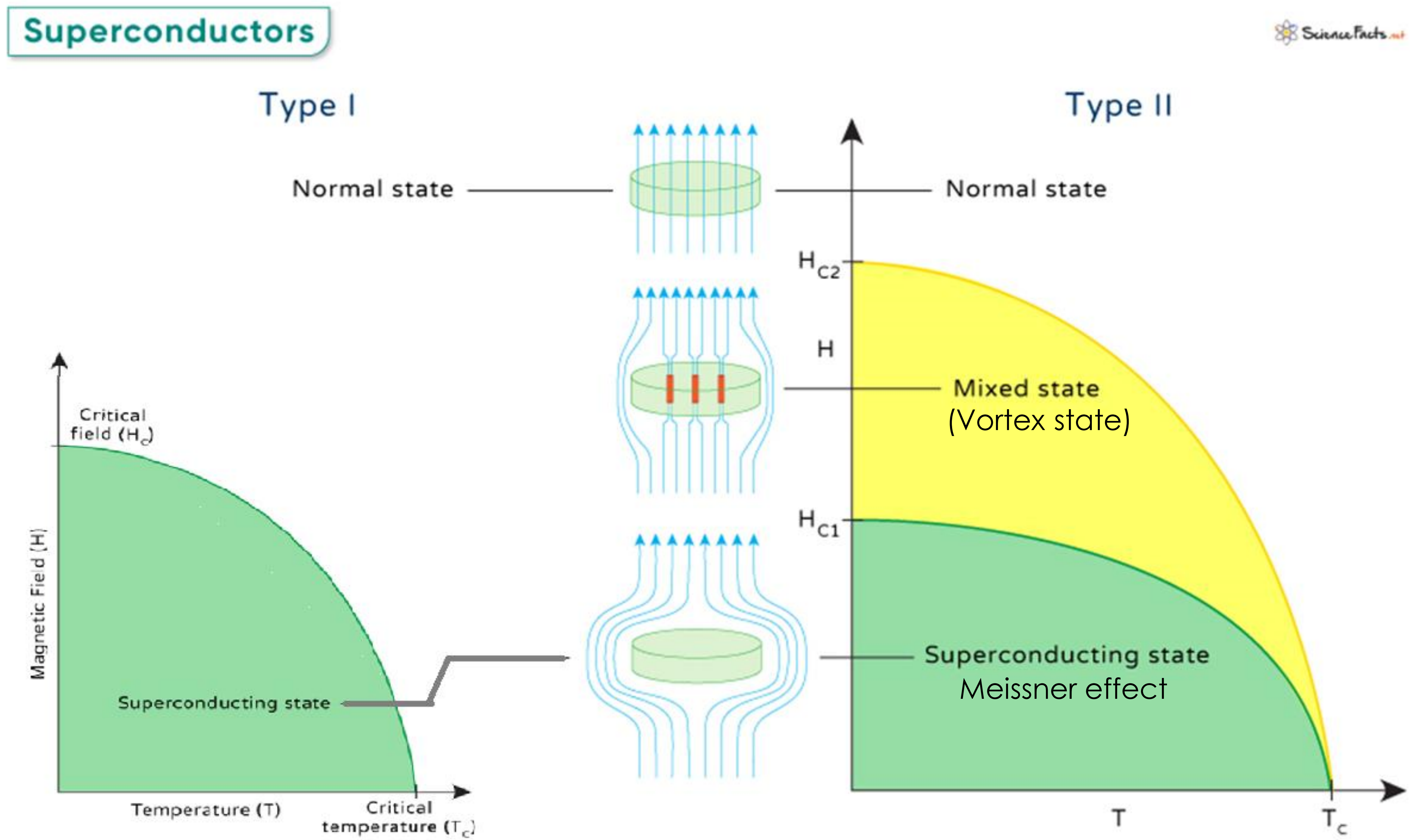
Type II superconductor has three regions





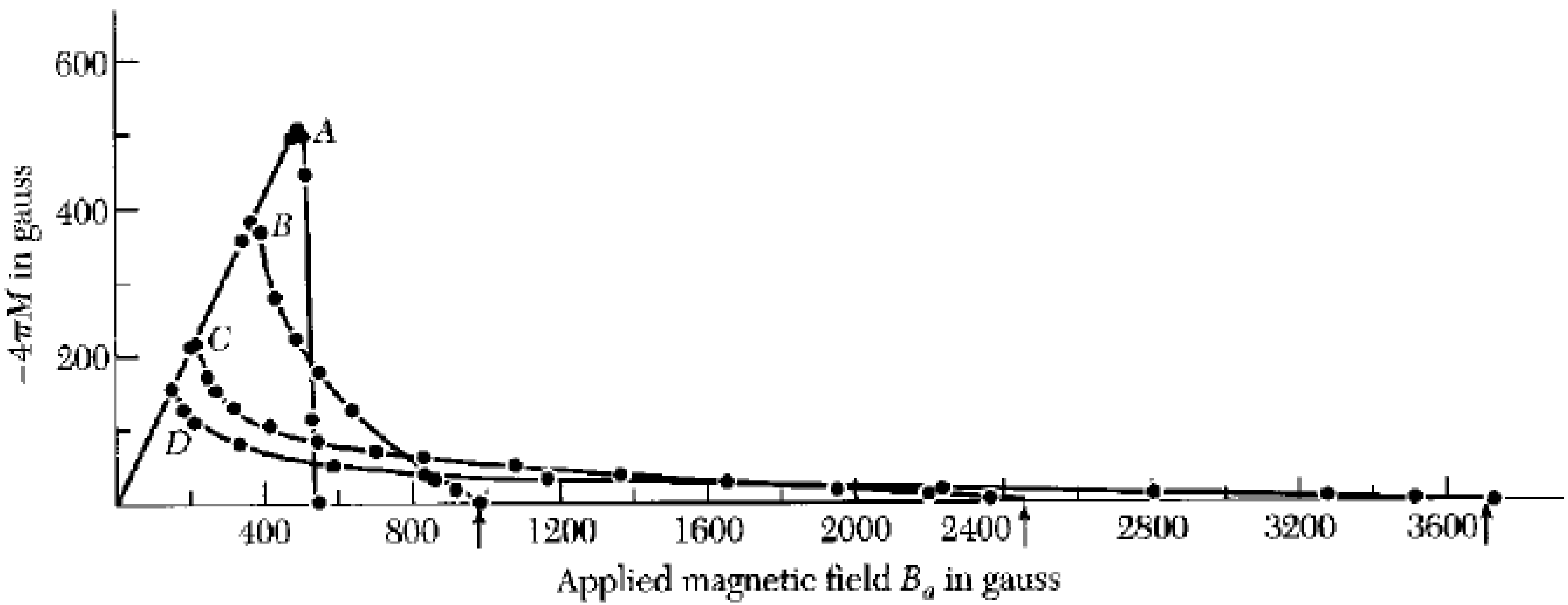
$$M = \begin{cases} -H & \rightarrow \quad H < H_{c1} \\ < -H & \rightarrow \quad H \in (H_{c1}, H_{c2}) \\ 0 & \rightarrow \quad H > H_{c2} \end{cases}$$

Type-I and Type-II superconductors



Type-II as hard superconductors

- The penetration characteristics of the magnetic flux lines *(between H_{c1} and H_{c2})* depends on defects and impurities of the crystal structure ⇨ acts as pinning centers in the material.
- As type II SC can carry high current densities *(J_c)* they are of great practical importance



Comparison

	Type I superconductors	Type II superconductors
1	Soft superconductors- can tolerate impurities without affecting properties.	Hard superconductors- cannot tolerate impurities and affects the properties.
2	Low critical field (0.1 T)	High critical field (30 T)
3	Show complete Meissner effect.	Traps magnetic flux, hence, incomplete Meissner effect.
5	Sudden loss of magnetization.	Gradual loss of magnetization.
6	Current flows through the surface only.	Current flows throughout the material.
6	e.g. Tin, Aluminum, Zinc	e.g. Tantalum, Neobium, NbN

High temperature superconductors

Compound	$\mathbf{T_c}$	**Comments**
Nb_3Ge	23 K	Till 1986
La-Ba-Cu-O	34 K	Bednorz and Mueller (1986)
$YBa_2Cu_3O_{7-x}$	90 K	> Boiling point of Liquid N_2
Tl (Bi)-Ba(Sr)-Ca-Cu-O	125 K	
H_2S	203 K	Gas solidifies on application of high pressure (in GPa)

This transition temperature is 13 K above the boiling point of liquid N_2 (77 K).
That a superconductor can function in liquid nitrogen is itself a remarkable achievement. A liquid nitrogen environment is far easier and cheaper to obtain than a liquid helium medium. Further, it takes about 25 times more energy to cool from 77 K to 4 K than from room temperature to 77 K.

Mechanism of superconductivity

Earlier, it was discovered that the critical temperatures *Tc* of the isotopes of a superconducting element decrease with increasing atomic mass. For instance, in ^{199}Hg *Tc* is 4.161 K in but only 4.126 K in ^{204}Hg. This is known as **isotope effect.**

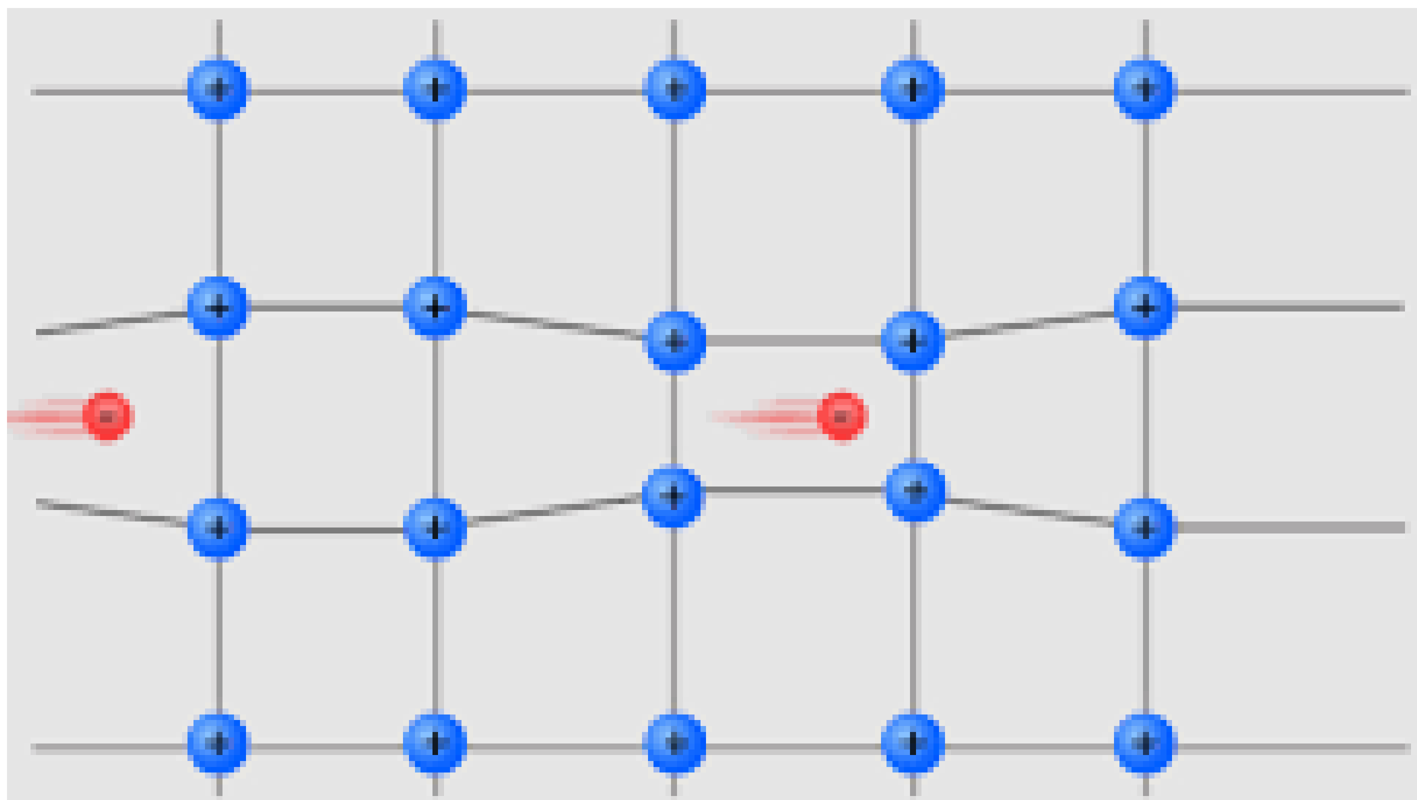
This indicates that the ion lattice plays an important role in superconductivity and there must be some interaction between the electrons and the lattice.

Bardeen-Cooper-Schreiffer (BCS) theory

Bardeen-Cooper-Schreiffer (BCS) theory

Two electrons in a superconductor could form a bound state despite their coulomb repulsion.

HOW??: **The lattice is slightly deformed as an electron moves through it**, with the positive ions in the electron's path being displaced toward it. The deformation produces a region of increased positive charge. Therefore, the deformed region is locally polarized.

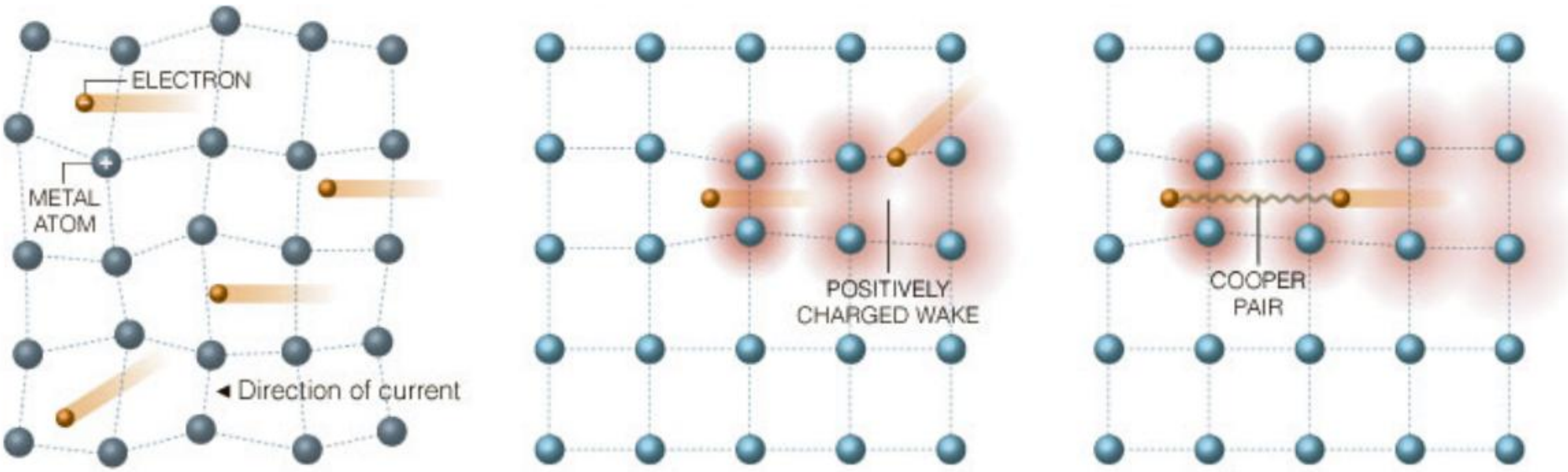


A schematic picture of lattice distortion due to moving electron

Cooper pair

Another electron moving through this polarized region will be attracted by the greater concentration of positive charge there.

If the attraction is stronger than the repulsion between the electrons, the electrons are effectively coupled together into a **Cooper pair** with the deformed lattice as the intermediary.



Normal state

At Tc

Superconducting state

Cooper pair formation can also be viewed as electron-phonon Interaction

1. Phonon is a quanta of lattice vibration energy.
   (Analogous to photon, which is a quanta of EM wave energy)
2. Produced by a distortion due to lattice vibrations.
3. Phonon can interact with another phonon or electrons.
4. Therefore, the ‘electron-lattice interaction’ can also be treated as ‘electron-phonon interaction’.

Bardeen-Cooper-Schreiffer (BCS) theory

Properties of cooper pair according to BCS theory

- There is force of attraction between the electrons in the Cooper pair (at $T < T_c$).
- correlations length ~10^{-6} m.
- The binding energy of a Cooper pair, called the **energy gap E_g**, ~ 10^{-3} eV.
- Cooper pair has a total spin of zero → **the electron pairs in a superconductor are bosons.**

How superconductors shows zero resistivity?

- Phonon scattering due to lattice vibrations felt by one electron in the Cooper pair is nullified by the other electron in the pair.
- The **entire system of electron pairs acting as a unit**.
- Altering the state requires the correlated states of motion of *all* the electron pairs to change, **not just the states of motion of some individual electrons** as in an ordinary conductor. Requires high energy and not easy.

How do you measure ‘zero’ resistance?

Start a current flowing round a superconducting ring and observe whether the current decays.

If there is no decay in current, there is no resistance.

But, if we put an ammeter in the superconducting loop, this would introduce a resistance and the current would rapidly decay.

Instead, measure magnetic field associated with the current.

If magnetic field remains constant $\rightarrow$ current is constant $\rightarrow$ no resistance

Using this method, resistivity of ~10^{-23} Ωm has been measured.

(For Cu at room temperature, resistivity is ~ 10^{-8} Ωm.)

Possible Applications

- Power Transmission: No I^2R loss

- Transportation: Magnetic levitation

- Production of Strong Magnetic Fields (>50 T): Low power consumption and low power loss (less cooling) MHD (magnetohydrodynamic) power generators, Magnetic Imaging, Magnetic sensors

- Highly sensitive detection of small Magnetic Fields

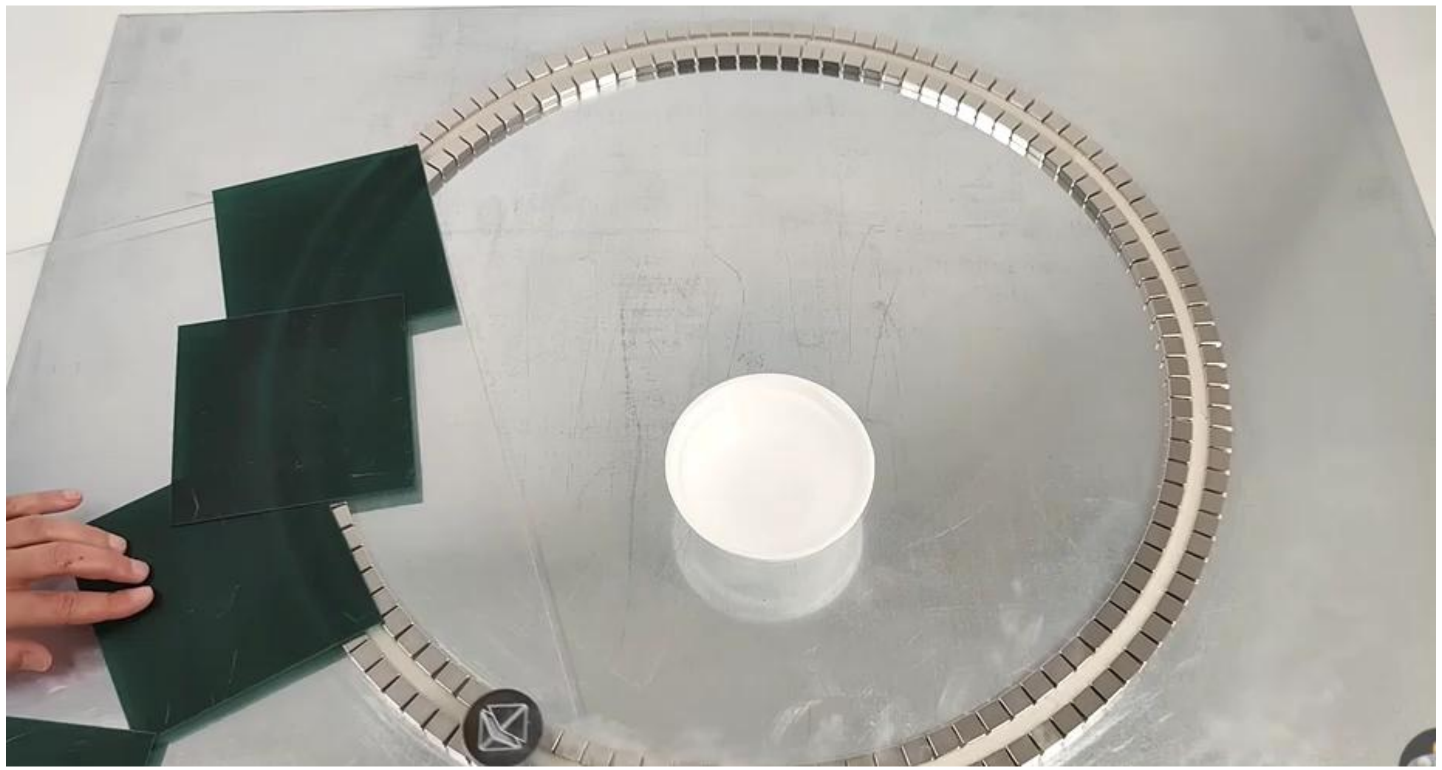
- Logic and storage functions : A Josephson junction (s-i-s): The unique current-voltage characteristics associated with the Josephson junction are suitable for memory elements. Switching times of the order of 10 ps have been measured.

Applications of superconductors

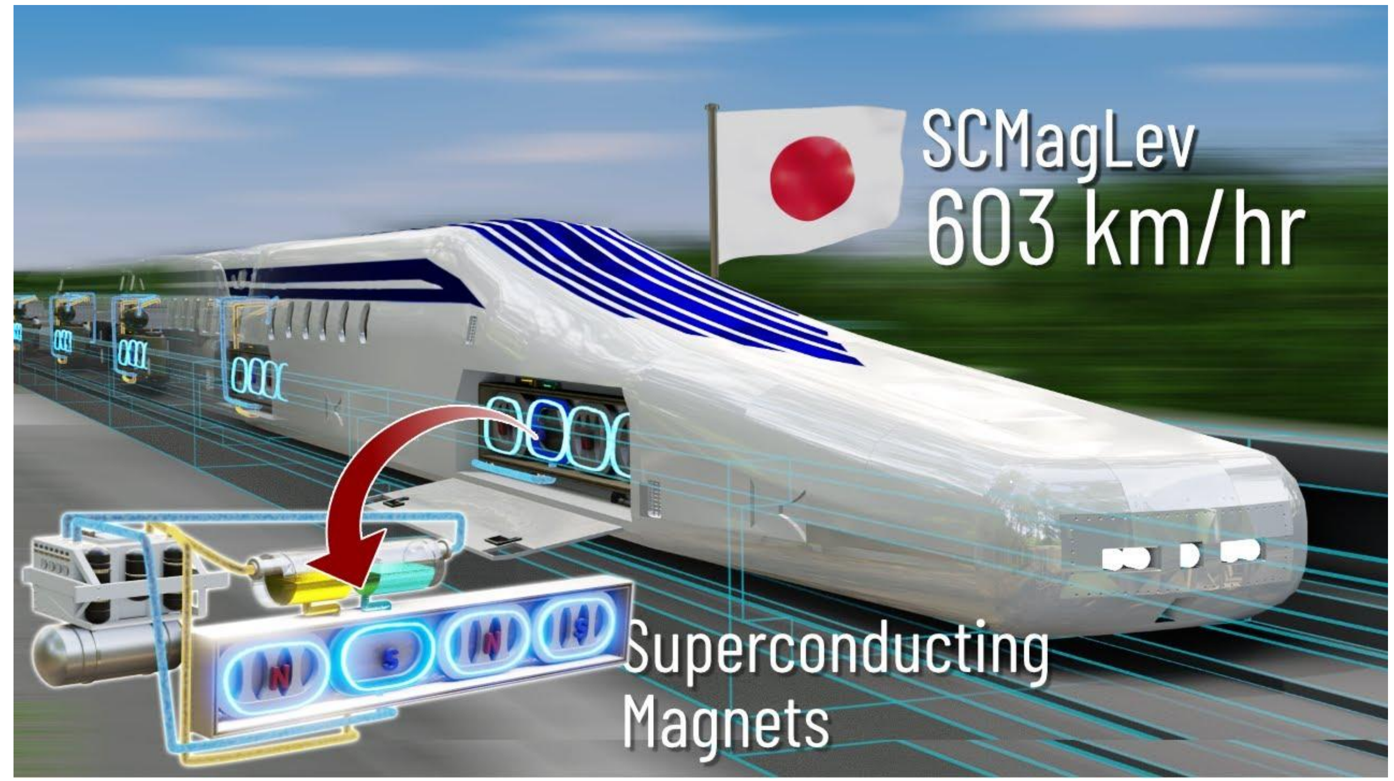
❑Magnetic levitation (arising from Meissner effect)

Superconductors are perfect diamagnetic ($\chi = -1$)

Can levitate on magnet.



A $YBa_2Cu_3O_{7-x}$ superconductor levitating on permanent magnetic arrangement

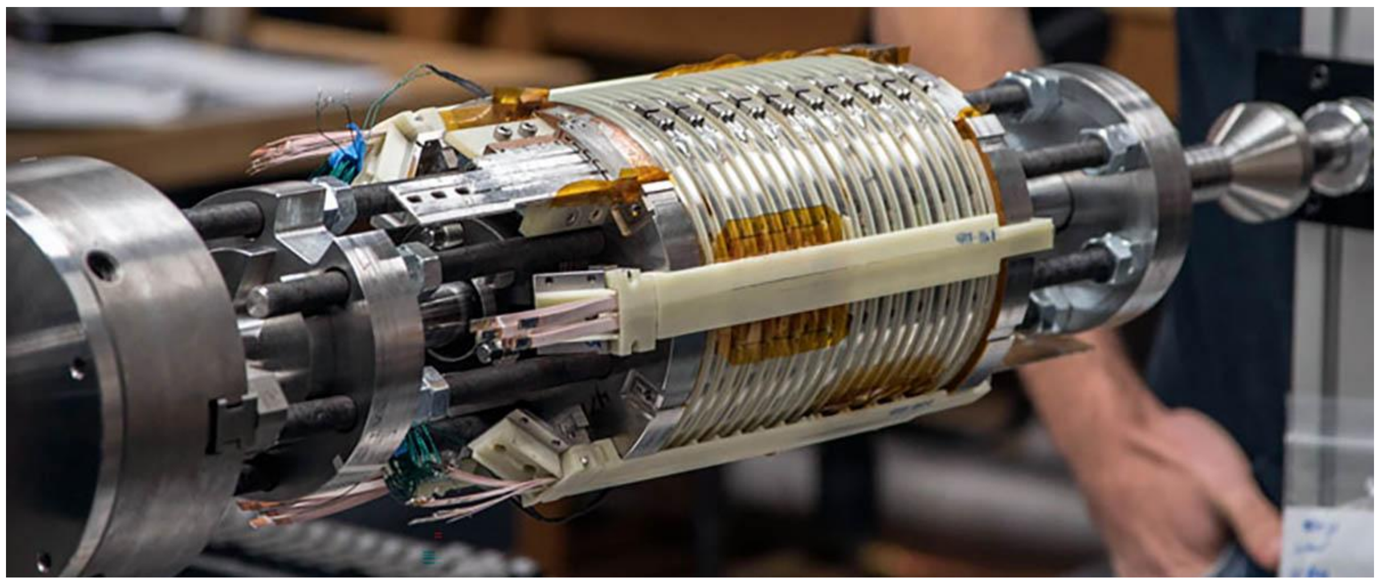


Levitation → no friction!
The fastest train in the world.

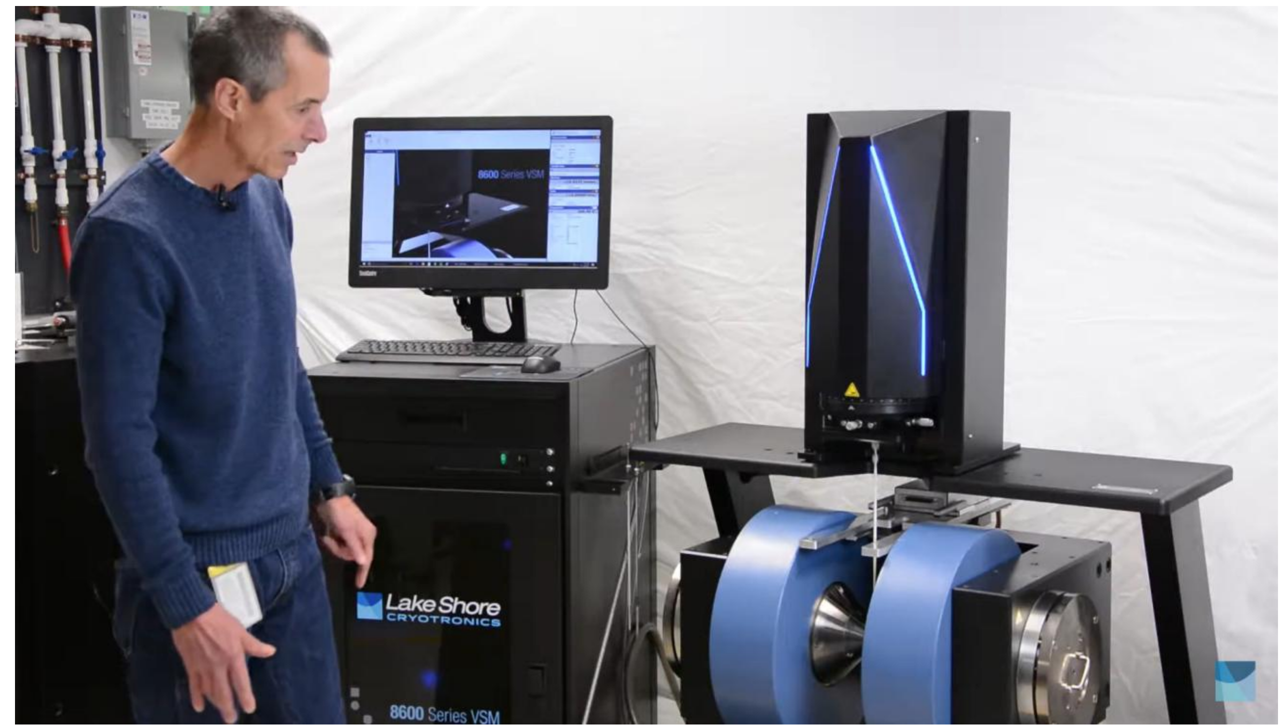
Applications of superconductors

Strong magnetic fields

- No dissipation of current- magnetic field retained once created.
- No heating up due to zero resistance
- Large and steady magnetic field (as high as 50 T) can be created



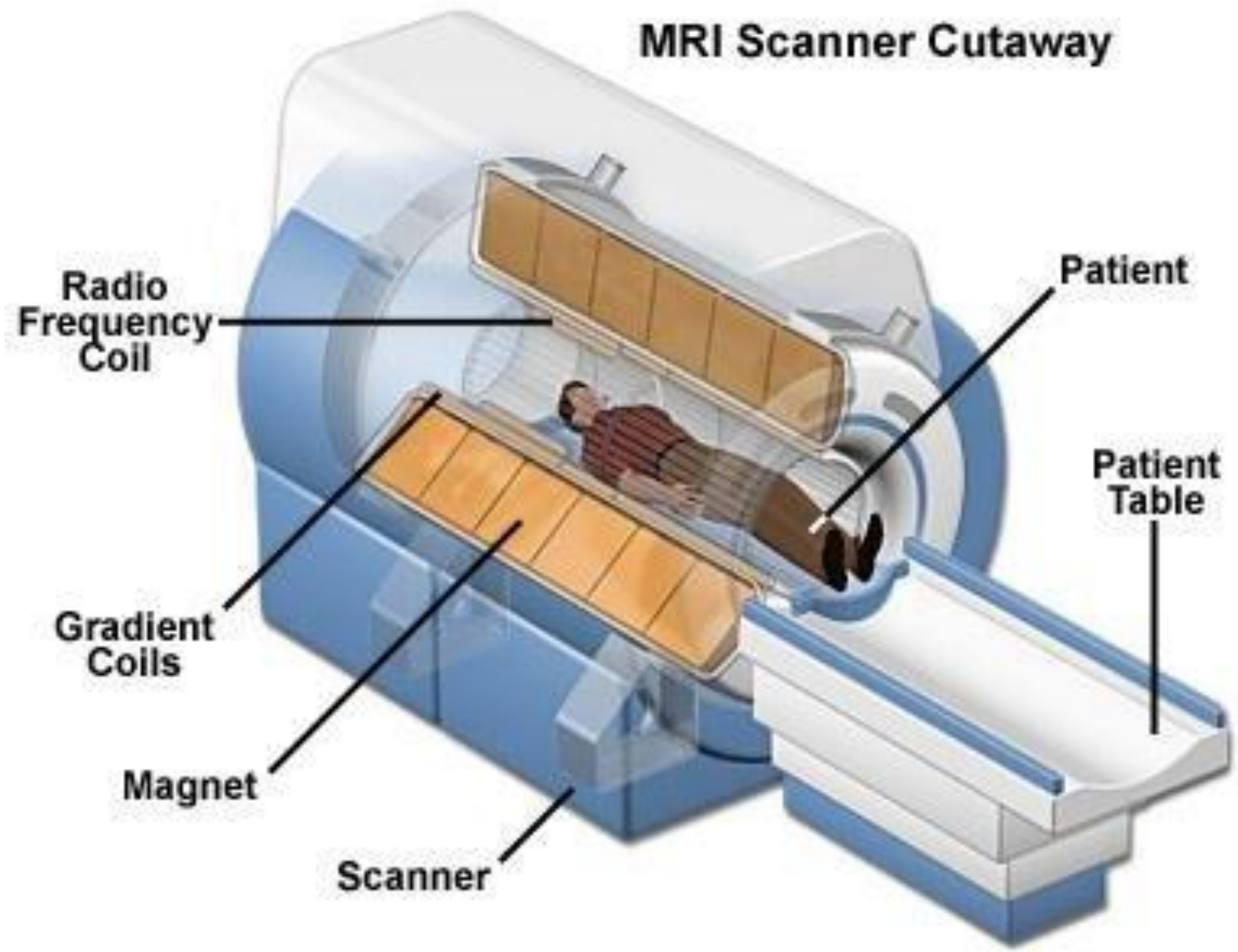
32 Tesla Superconducting Magnet in The National High Magnetic Field Laboratory, Tallahassee, Florida.
(Note the human hand in the background to provide a sense of scale.)



A 3.5 T magnet with normal conductor coil.

Application in medical science

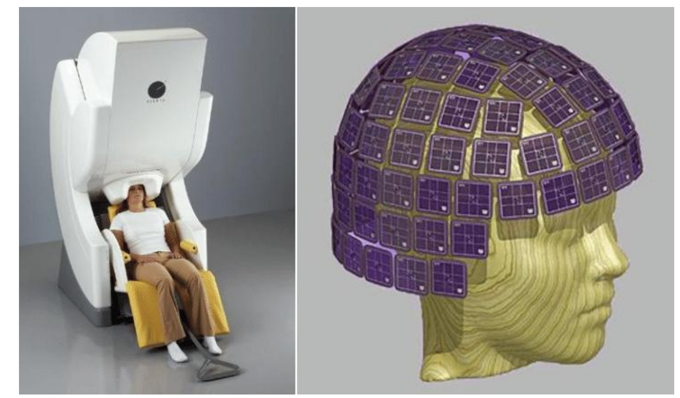
- **High magnetic field, high stability**

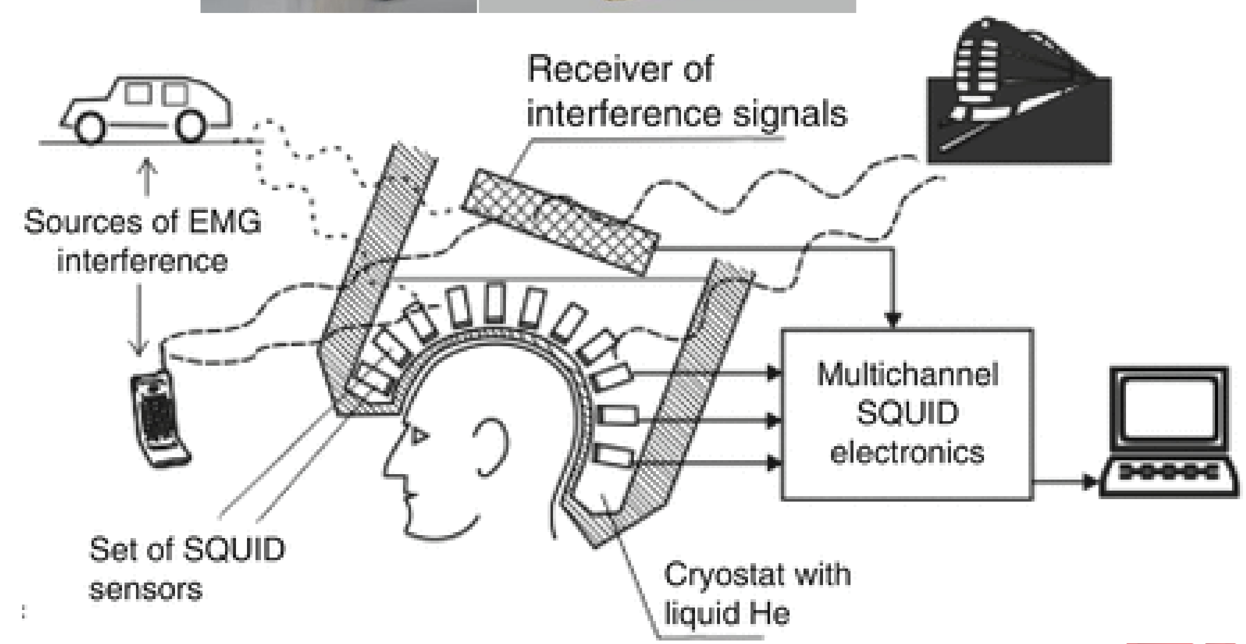


Magnetic resonance imaging

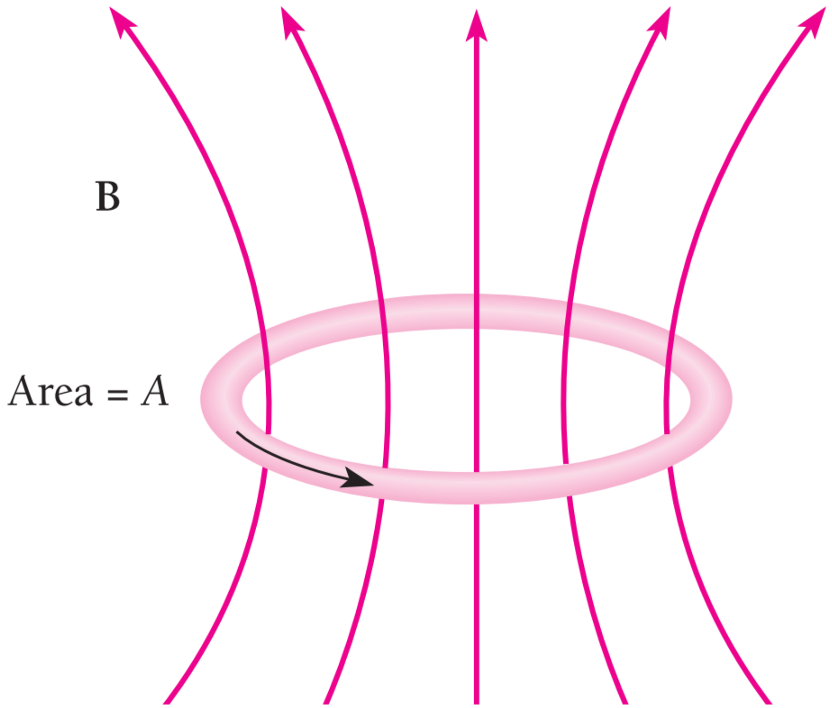
- **Possibility to sense weak magnetic fields produced by biological currents such as those in the brain (SQUID)**

Magnetoencephalography (MEG)-
a non-invasive brain imaging technique that measures the magnetic fields produced by the brain's electrical activity





Flux quantization through a superconducting ring



Consider a ring with area **A** made of superconductor. If kept under magnetic field **B**, the net flux associated to the ring is

$$\phi = \boldsymbol{B}.\boldsymbol{A}$$

According to Faraday's law of induction, any change in the flux will change the current in the ring so as to
oppose the change in flux.
Because the ring has no resistance, the change in flux will be perfectly canceled out. **The flux therefore is permanently trapped.**

The phase of the single wave function representing the cooper pairs in the ring must be continuous around the ring in order to survive. This condition causes ϕ to be quantized. It turns out that,

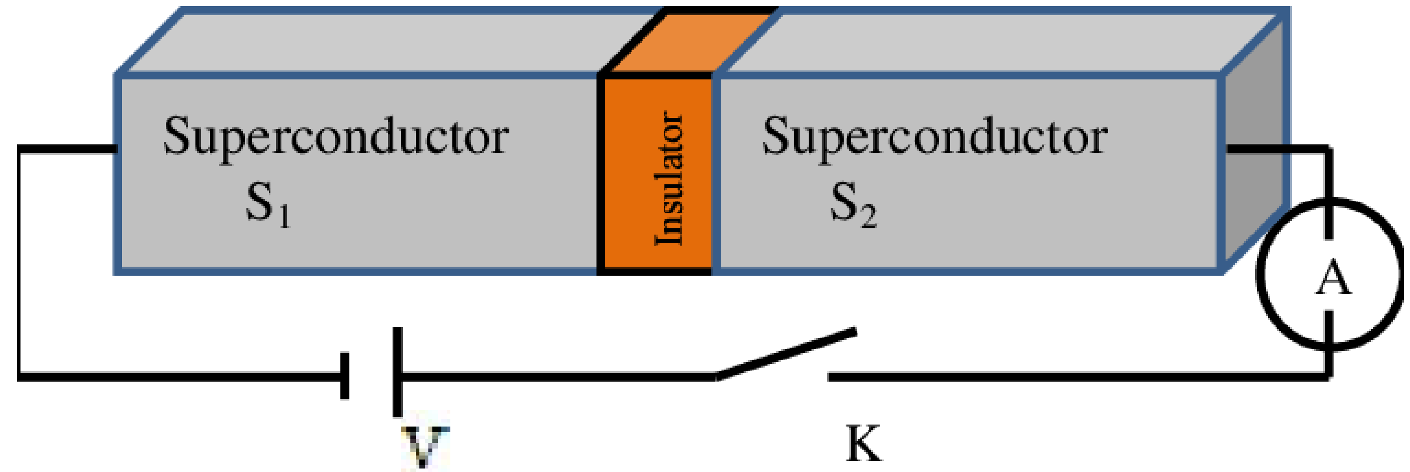
$$\phi = n\left(\frac{h}{2e}\right) = n\phi_0 \quad \text{Where, n} = 1, 2, 3 \ldots$$

The quantum of magnetic flux is

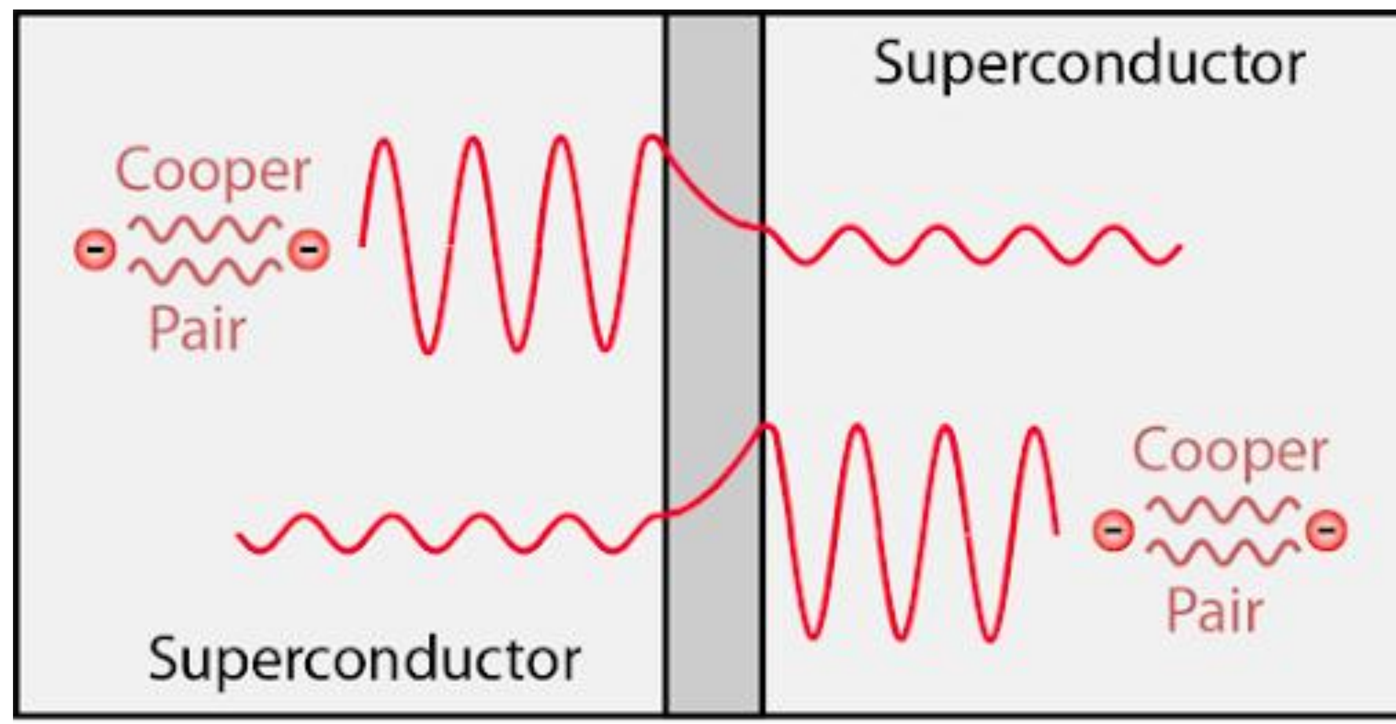
$$\phi_0 = \frac{h}{2e} = 2.068 \times 10^{-15}\ T\, m^2$$

Josephson junction

A Josephson junction is an **superconductor-insulator-superconductor** layer structure placed between two electrodes.
Brian Josephson, predicted that Cooper pairs could tunnel through the insulating layer if thin enough (practically ~2 nm).



A schematic representation of Cooper pairs tunneling through the insulating barrier. Note the exponential decay of the wave function amplitude across the barrier width.



Josephson junction

DC Josephson effect: A dc current flows across the junction in the absence of any electric or magnetic field.
(***Happens because of tunneling***)

When V=0, (consider already existing current in a loop), the current through the junction

$$I_J = I_{max} \sin \phi$$

where, ***ϕ is the phase difference of the wave function*** of the Cooper pairs on either side of the junction and I_{max} is the maximum or the critical current at T=0 K.

AC Josephson effect: When a DC voltage V is applied across a Josephson junction. Josephson showed that, in this case ϕ increases with time such that,

$$\frac{d\phi}{dt} = \frac{2e}{h} V$$

Therefore,

$$I_J = I_{max} \sin\left(\phi_0 + \frac{2e}{h} V t\right)$$

Which shows that I_J varies sinusoidally with time with frequency $\nu = \frac{d\phi}{dt} = \frac{2e}{h} V$

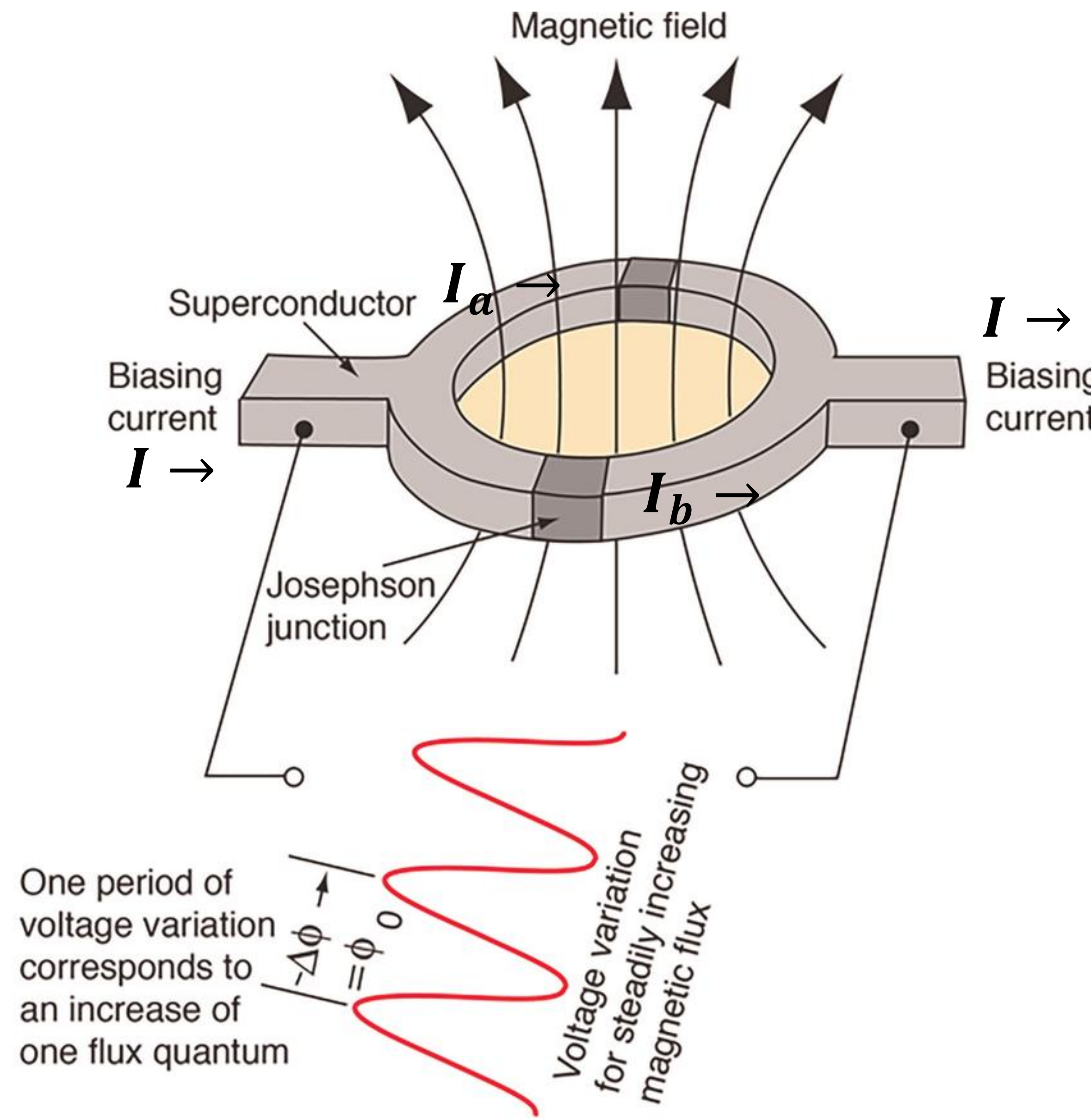
With a fixed voltage V_{DC} across the junction, the phase varies linearly with time and the current will be a sinusoidal AC.

This means a Josephson junction can act as a perfect voltage-to-frequency converter.

Application of Josephson junction

Superconducting Quantum Interference Device (SQUID): extremely sensitive magnetometers

A SQUID consists of a loop of superconductor with one or more Josephson junctions, called weak links.



<u>Operation and working principle:</u>

- Current made to flow around the loop through both Josephson junctions.

$$I_a = I_b = \frac{I}{2} \;\; when\ there\ is\ no\ flux\ change$$

- If flux (magnetic field) through the loop changes with time, it induces a current around the loop. Then,

$$I_a \neq I_b$$

- Resulting potential difference across the loop varies periodically as the magnetic flux through the ring changes.
- The periodicity equals to ϕ_0 (flux quanta) and is interpreted as an interference effect involving the wave functions of the Cooper pairs.

By measuring the periodic voltage, a magnetic field as low as ~10^{-21} T can be sensed.

Applications of superconductors

A ***Josephson junction*** has the unique capability of:

- transferring Quantum Mechanics rules to macroscopic systems
- a versatile component of all superconducting electronics with its key feature of carrying a dissipation less phase-driven current.

Progress in materials science and nanotechnology consolidates expectations for a series of challenging applications:
- the realization of multi-qubit quantum processors
- SQUIDs,
- RSFQ digital electronics (Rapid single flux quantum)
- unconventional hybrid and high critical temperature superconductor Josephson junctions keep disclosing novel problems at the frontier of our knowledge.

Quantum Materials

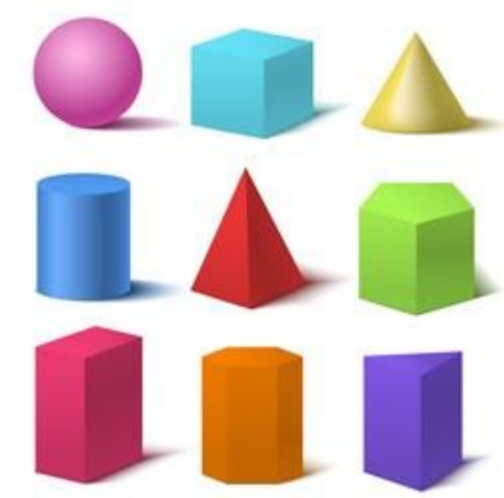
Superconductors: Fundamentals of superconductivity: Zero resistance and expulsion of magnetic fields (Meissner effect). Differentiation between Type I and Type II superconductors. Introduction to Cooper pairs and the BCS theory. Exploration of high-temperature superconductors and their applications in fields like energy transmission.

Topological Materials: Introduction to topological phases of matter and their unique properties. Topologically protected surface states and their relevance to fault-tolerant quantum computing.

2D Materials and Graphene: Structure, properties, and significance of graphene in electronic and thermal applications. Exploration of other 2D materials, such as transition metal dichalcogenides (TMDs) and their emerging applications. Applications of 2D materials in fields like sensors, quantum computing, and renewable energy.

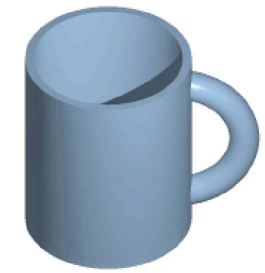
Topology

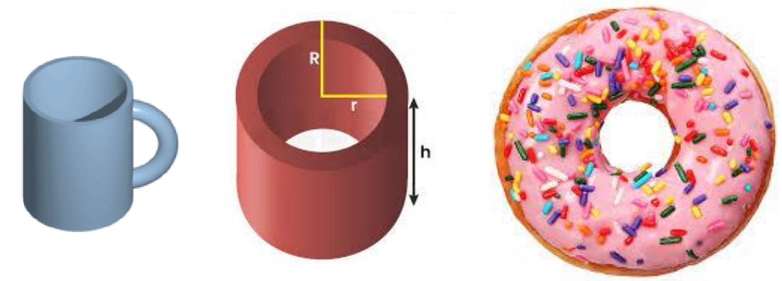
Though different in shape, *<u>‘something’</u>* is equivalent and one shape can be transformed into other by ‘smooth deformation’



Topologically same

Transformation is not possible by smooth deformation
- They are topologically different





Topologically same

Topology is a branch of mathematics concerned with geometrical properties that are insensitive to smooth deformation.

How to characterize topology of an object?

By determining a **“topological invariant”**

“Topological invariant” = quantity that does not change under continuous deformation

Objects with same topological invariant have same topology though different in shapes.

It will be different for objects with different topology.

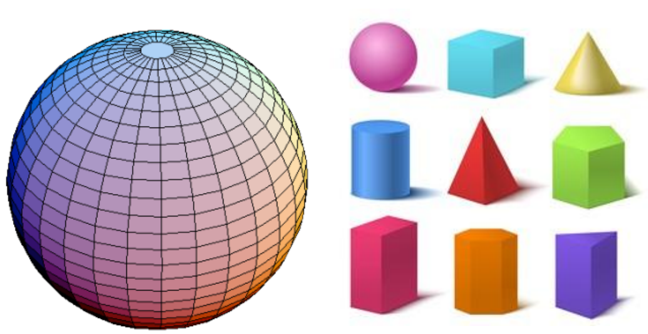
Let’s define a topological invariant: Gauss Bonnet theorem

$$\frac{1}{2\pi}\int_S K\, dA = \chi = 2(1-g)$$

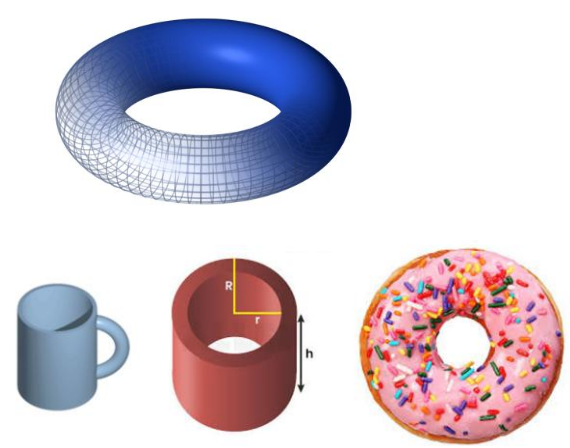
Where, $K = Gausian\ curvature = (r_1 r_2)^{-1}$

g = “genus”

g = 0



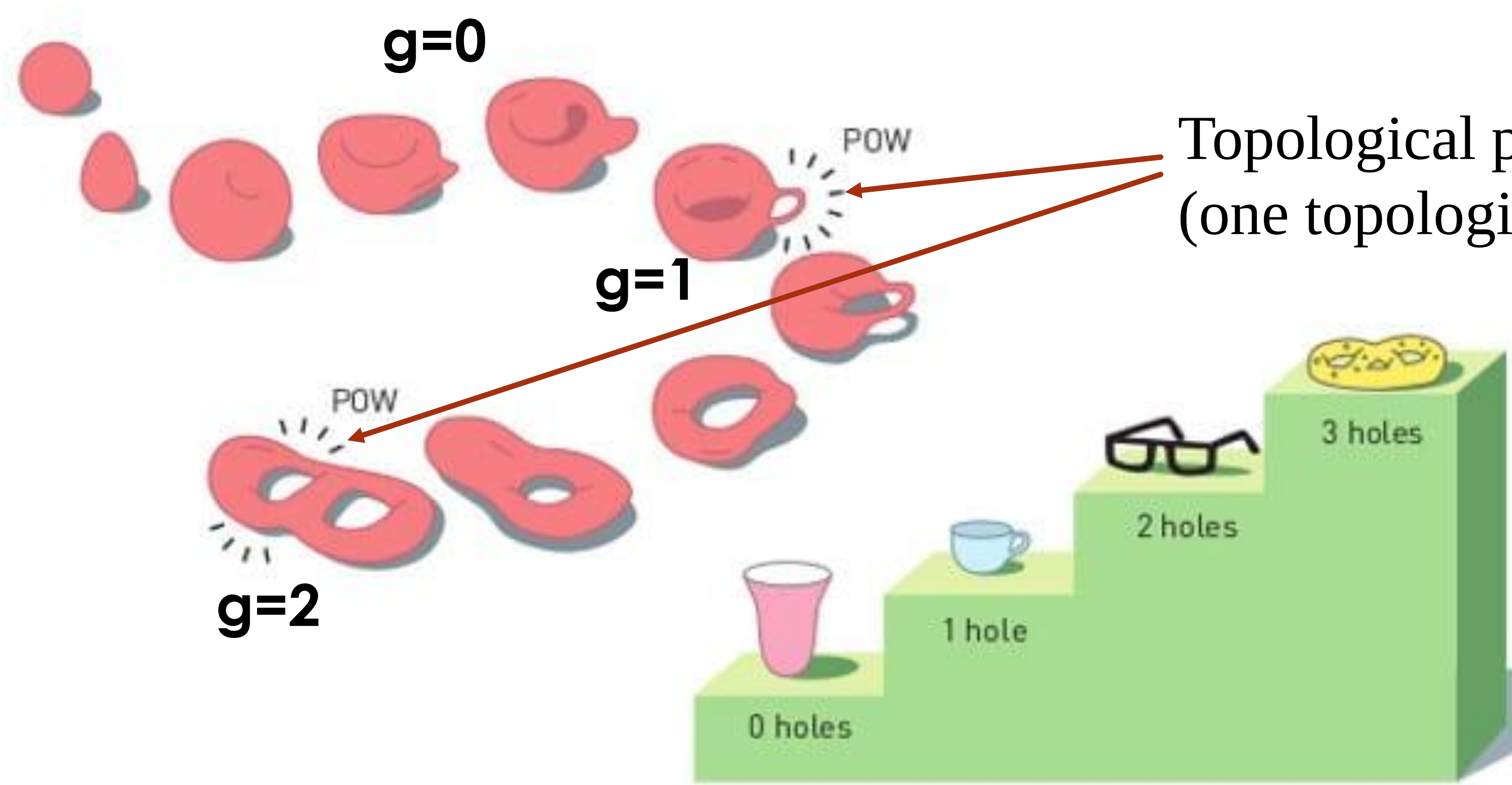
g=1,



g = n for “n-holed torus”.

$\chi\ or\ g \rightarrow topological\ invariant\ here$

Topological phases



Topological phase transition
(one topological phase to other)

Nobel Prize in Physics 2016 with one half to David J. Thouless and the other half to F. Duncan M. Haldane and J. Michael Kosterlitz for theoretical discoveries of topological phase transitions and topological phases of matter.

Topology in condensed matter physics

The **single electron wave function** in a crystal (Bloch wave function) of energetically isolated bands in crystalline solids **can carry topologically quantized numbers** — known as topological invariants — that correspond to experimentally measurable quantized response effects

⇨

These properties remains intact even if the object undergoes deformation or impurity or doping (as long as the lattice symmetry, and hence the topology remains unchanged)

How to determine the topological invariant (band topology) ?

How to determine the topological invariant (band topology) ?

Bloch's theorem: One-electron wavefunctions in a crystal (i.e., periodic potential) can be written

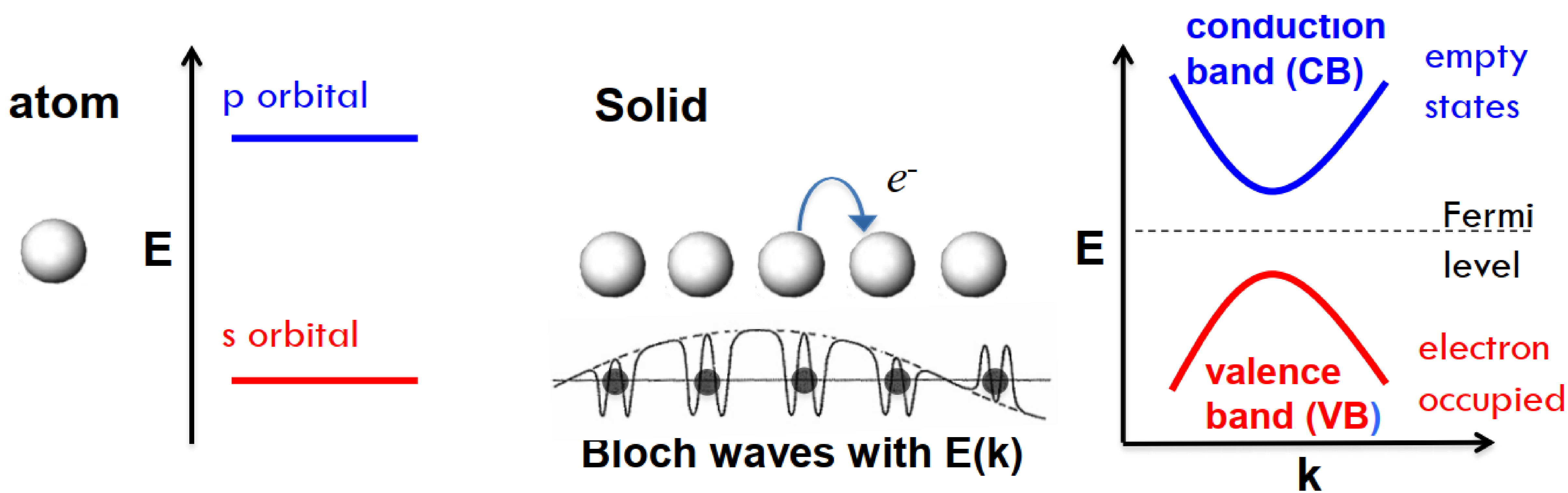
$$\psi_k(\boldsymbol{r}) = e^{i\boldsymbol{k}.\boldsymbol{r}} u_k(\boldsymbol{r})$$

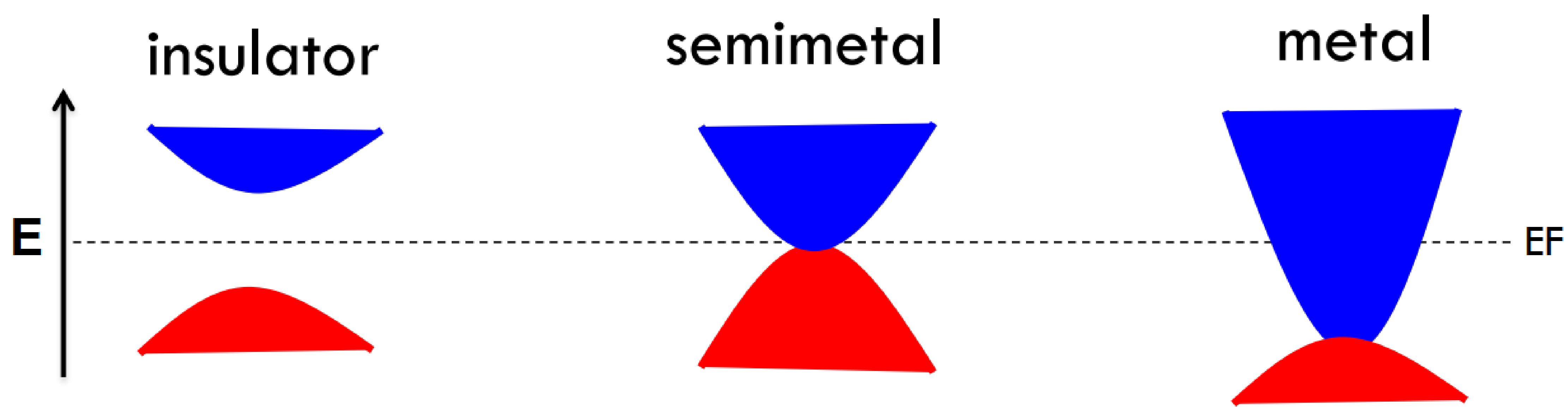
where k is "crystal momentum" and u a periodic function with same periodicity as the lattice.

Crystal momentum k can be restricted to the Brillouin zone, a region of k-space with periodic boundaries.
As k changes, we map out an "energy band".
Set of all bands = "band structure".
So, the **Brillouin zone will play the role of the "surface"** as in the previous example.

A quantum mechanical property, the **Berry phase**, will give us the **"curvature".**

Ordinary materials (trivial band topology)





Berry phase in solid

The Berry phase describes the geometric phase acquired by an electron wave function as it is transported around a closed path in parameter space, such as the reciprocal space (Brillouin zone) of a crystal.

This phase is independent of the specific representation of the wave function and is a consequence of the wave's ability to "remember" its path.

It's crucial for understanding topological properties of materials and various phenomena like the quantum Hall effect and topological insulators.

Berry phase in solid

$$\psi_k(\boldsymbol{r}) = e^{i\boldsymbol{k}.\boldsymbol{r}} u_k(\boldsymbol{r})$$

Berry connection A is defined as

$$\boldsymbol{A} =< u_k|-i\boldsymbol{\nabla}_{\boldsymbol{k}}|u_k >$$

Berry curvature is defined as

$$F = \boldsymbol{\nabla} \times \boldsymbol{A}$$

Then, the Berry phase is

$$\gamma_c = \oint_C \boldsymbol{A}.\boldsymbol{dk} = \iint_S F\, d^2k$$

Berry phase in solid

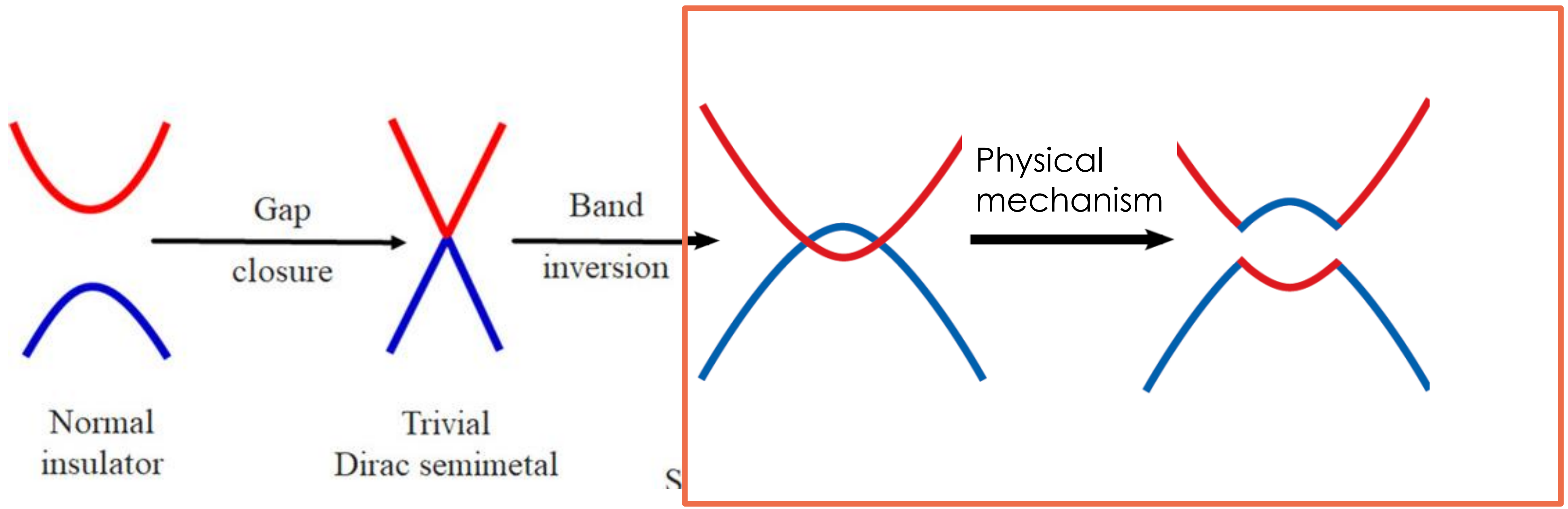
Berry phase, calculated over a 2D *closed manifold in k space* (Brillouin zone)

$$\oiint F\, d^2k = 2\pi n$$

n is an integer, called the "**Chern number"** or "Chern index" of the surface, and can be regarded as a "topological index" or **"topological invariant"** attached to the manifold of states $\psi_k(\boldsymbol{r})$ defined over the surface.

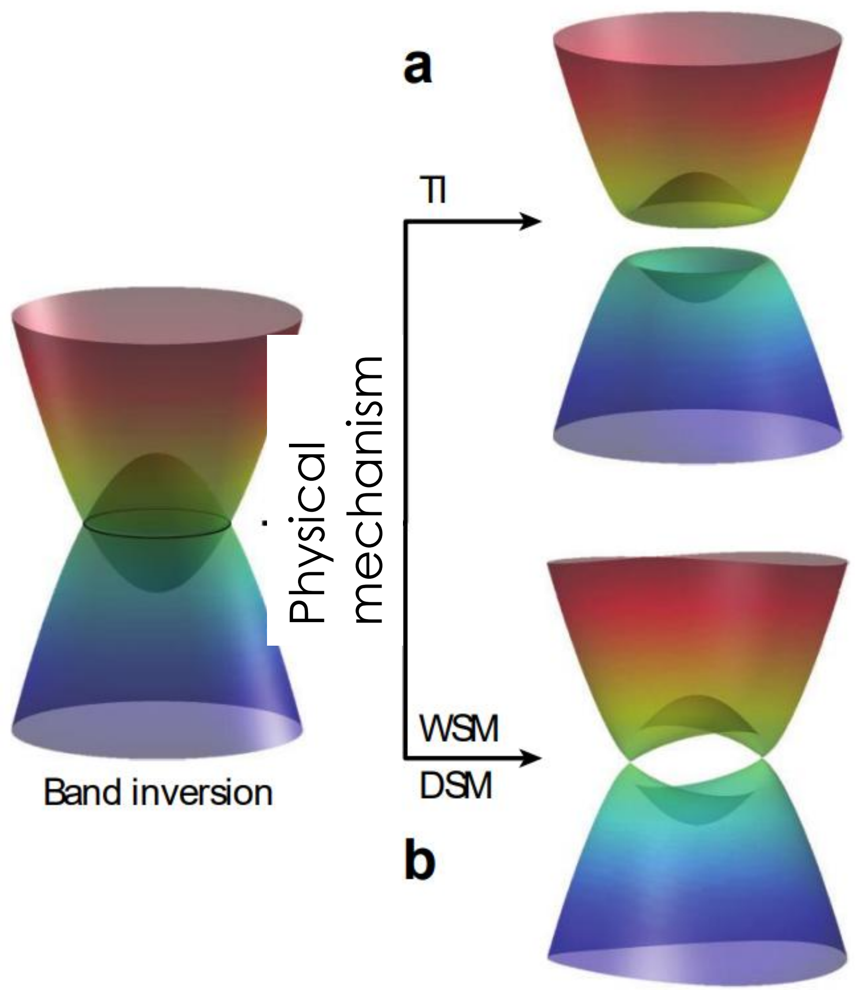
Nontrivial band topology

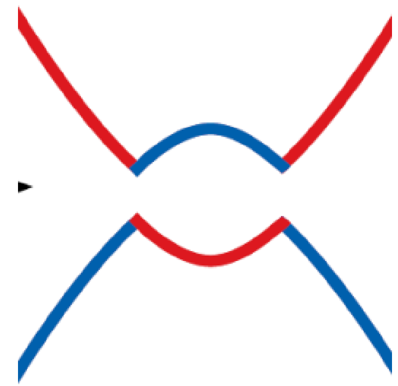
Nontrivial topology corresponds to nonzero Berry phase



Topologically nontrivial state
Nonzero Berry curvature and topological invariant

Nontrivial band topology





Topological insulator
An insulator, but topologically different than normal insulator.

Topological semimetal
Very small band overlap, so semimetal, but topologicallydifferent than normal semimetal.

Edge state of topological materials

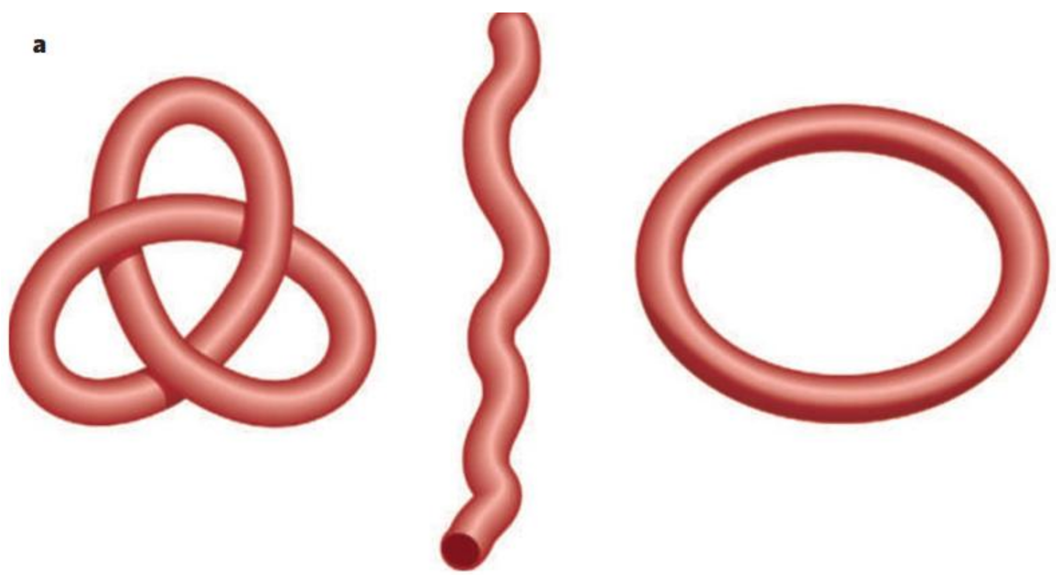
A topological phase **always has metallic edges/surfaces** when put next to vacuum or an ordinary phase.

Imagine a “smooth” edge where the system gradually evolves from ***Topological Insulator*** to ordinary insulator. The topological invariant must change across the surface. But the definition of our “topological invariant” means that, if the system remains insulating even at surface (so that every band is either full or empty), the invariant cannot change.

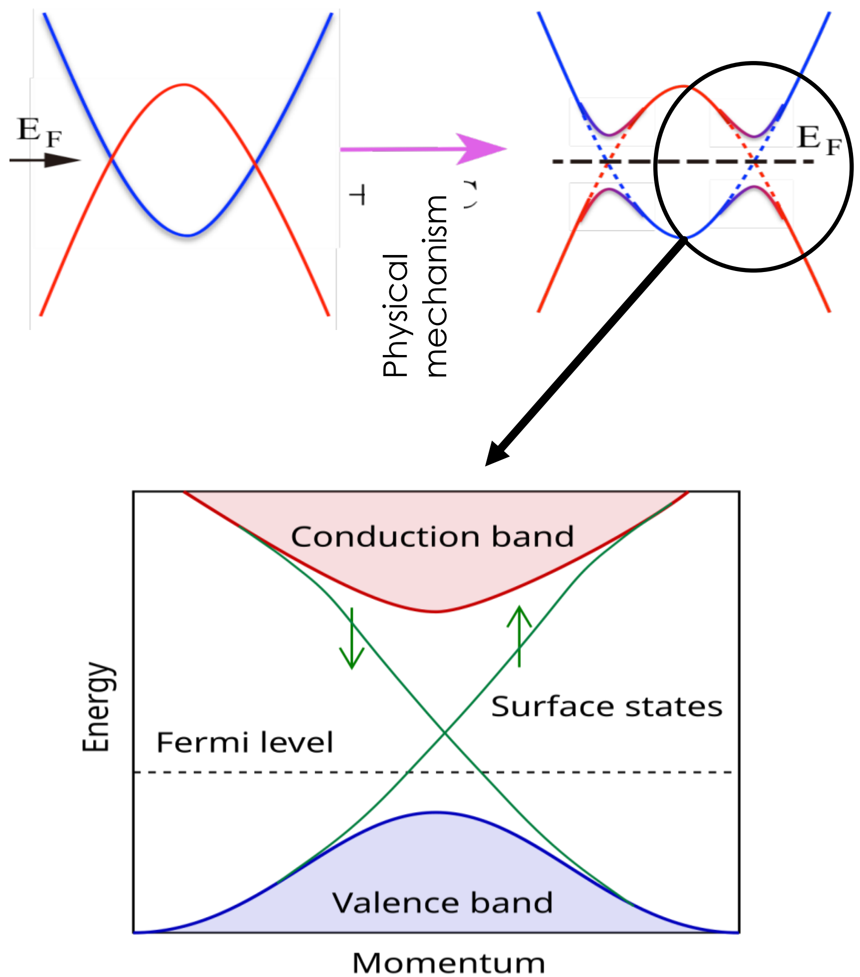
∴ **The system must not remain insulating at the surface. There must be metallic (gapless) surface/edge states**

An illustration of topological change and the resultant surface state is shown.

The trefoil knot (left) and the simple loop (right) represent different insulating materials: the knot is a topological insulator, and the loop is an ordinary insulator. Because there is no continuous deformation by which one can be converted into the other, **there must be a surface where the string is cut**, shown as a string with open ends (centre), to pass between the two knots.



Edge state in topological insulator



Metallic edge state in topological insulator.

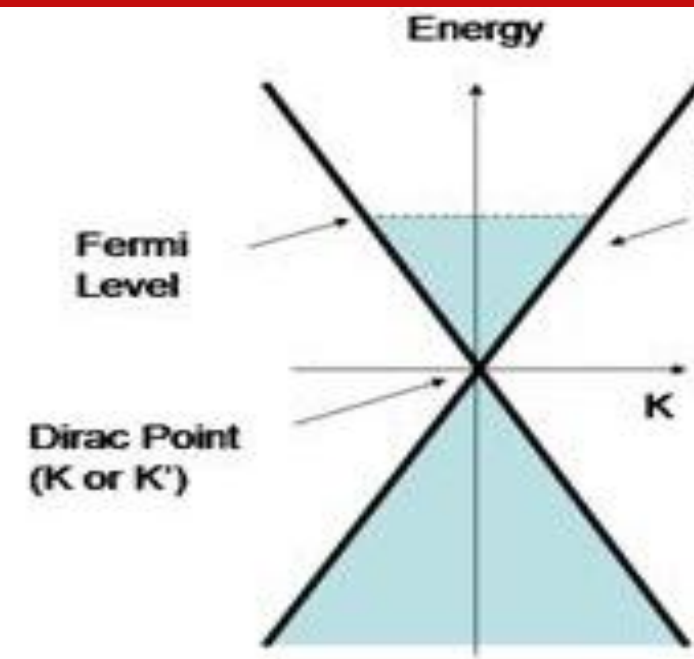
Bulk is insulating but the surface is conducting !!!

Example of topological insulator: Bi_2Te_3, Bi_2Se_3 and Sb_2Te_3 alloys

Dirac points

For ordinary solids, well inside the Brillouin zone

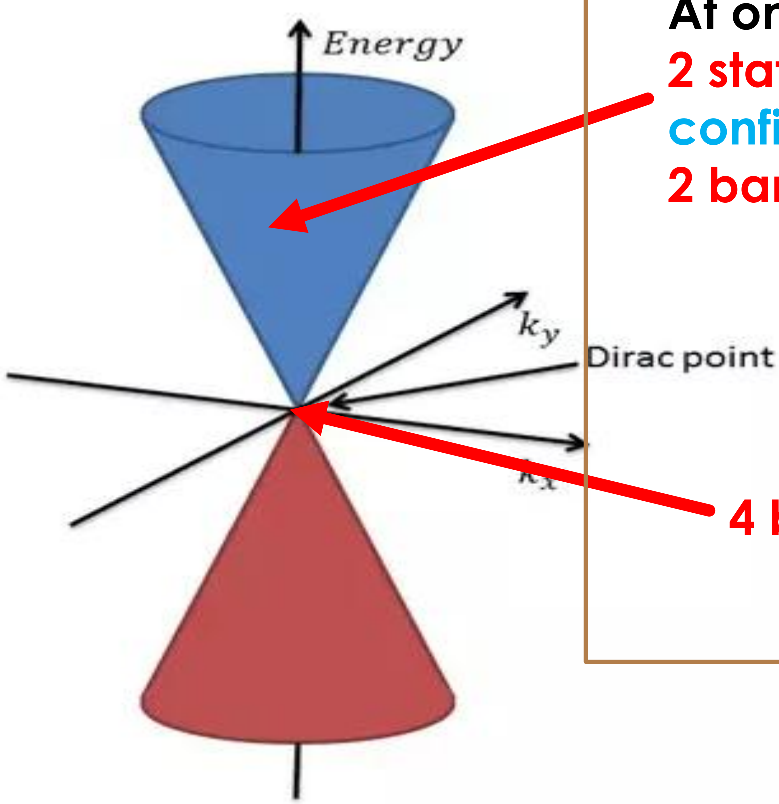
$$E \propto k^2$$



There may be **special points** in k space around which

$$E \propto k$$

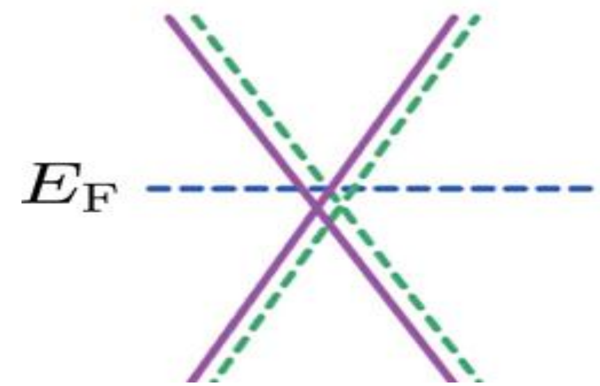
Such point is called **Dirac point**



At one particulate energy value
2 states (with two opposite spin configurations)
2 bands

4 bands at the Dirac point

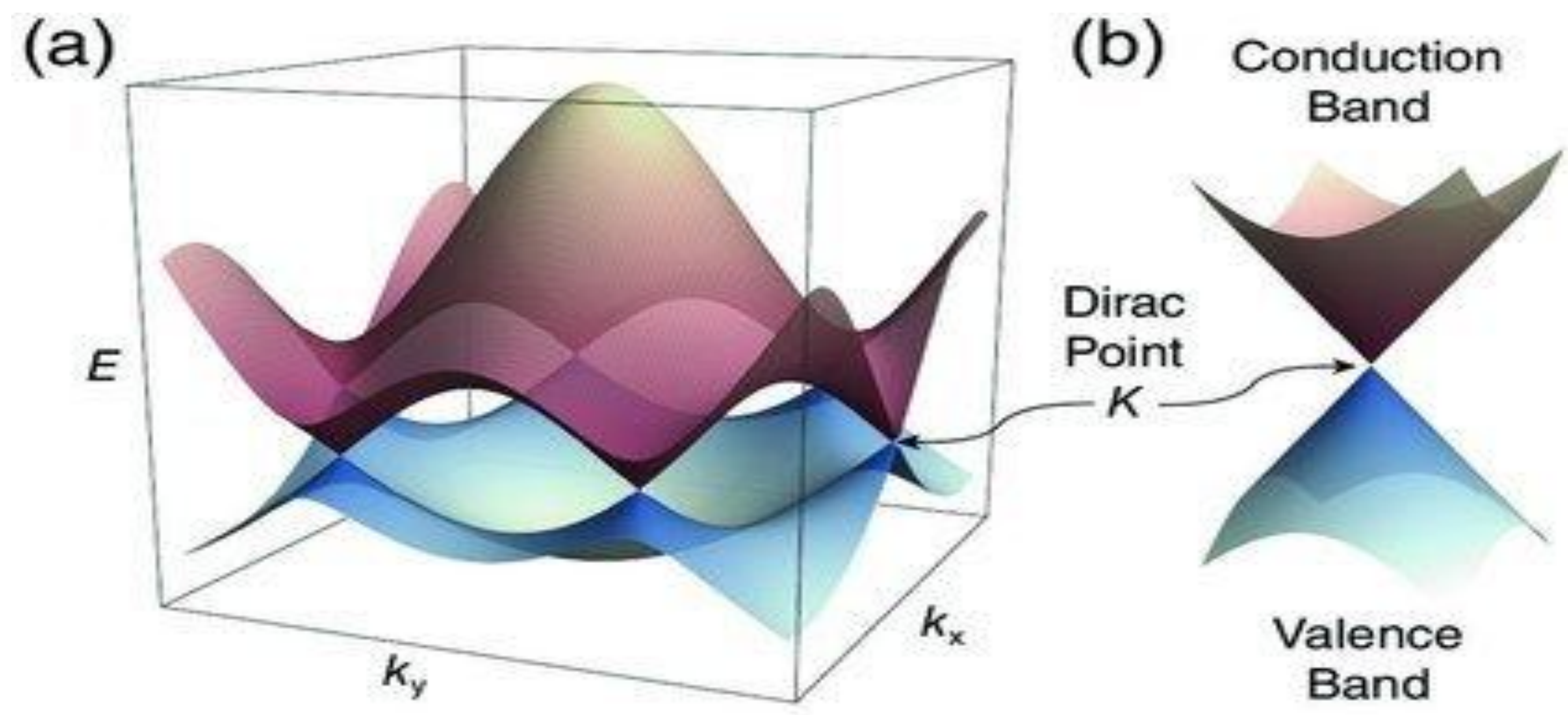
3D analog, cone shaped E-k diagram



Schematic representation: **green** and **purple** color represent bands with opposite spin configuration. (They are overlapped on each other)

Dirac points in real materials

Six Dirac points in graphene band structure



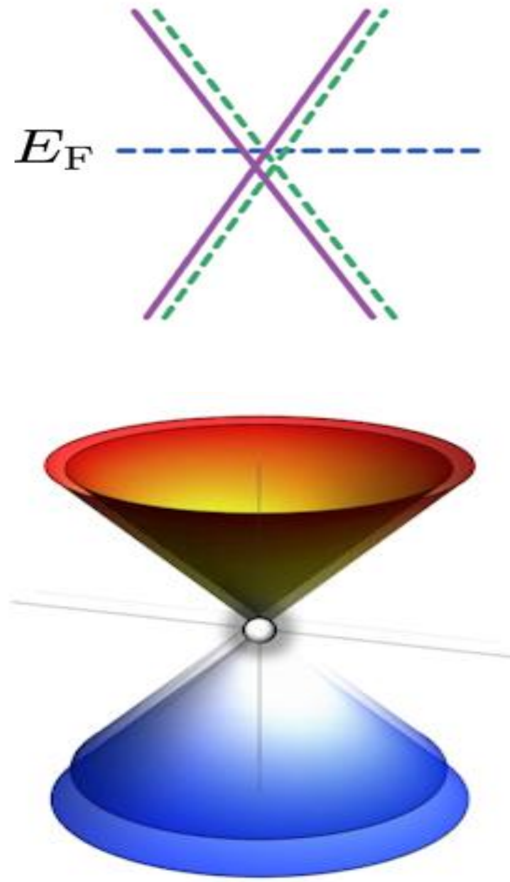
Band structure of graphene

Example of materials having Dirac points: Graphene, Cd_3As_2, BaAuSb, and SrAgBi etc.

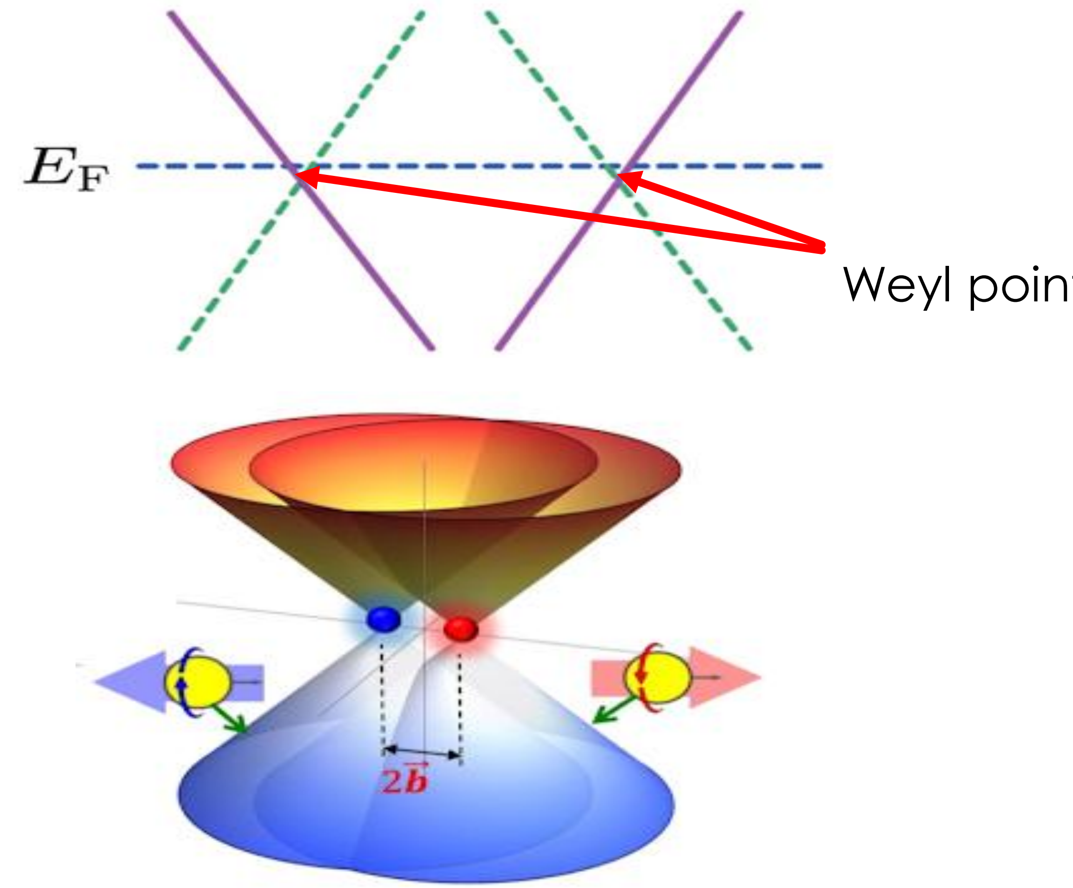
Weyl points

If the two bands are separated in k space

Dirac point separates into a pair of band touching points → each point is a **Weyl point**



Dirac point



Dirac points separated into a pair of Weyl points

Example of materials with Weyl points: TaAs, NbAs, NbP, TaP, $Co_3Sn_2S_2$

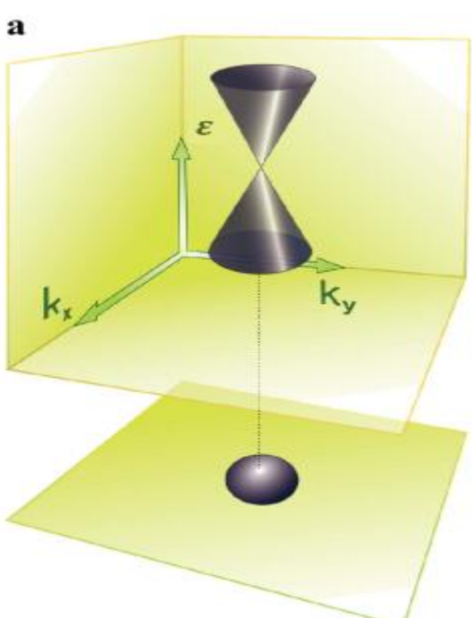
Dirac and Weyl semimetals

Dirac and Weyl semimetals: Materials hosting Dirac or Weyl points in band structure

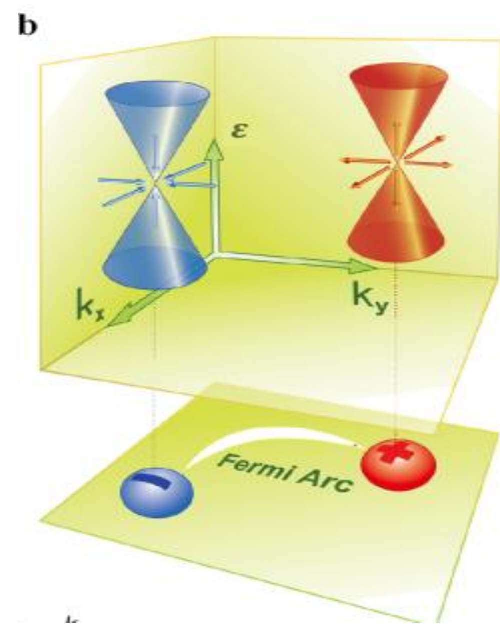
How are they different from ordinary semimetals?

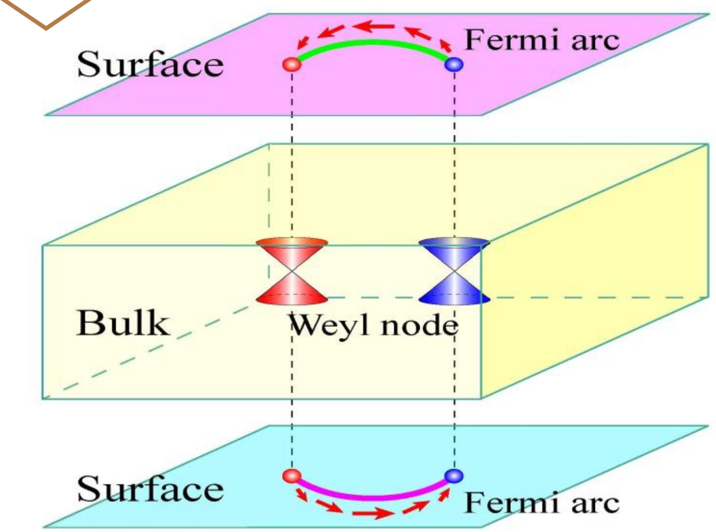
- Dirac or Weyl points are **topologically different** than band structure of ordinary semimetals**.**
- Topologically protected surface states appear → **Arc-like segments of the Fermi surface**

(connecting the projections of Weyl points onto the surface)



In Dirac semimetal





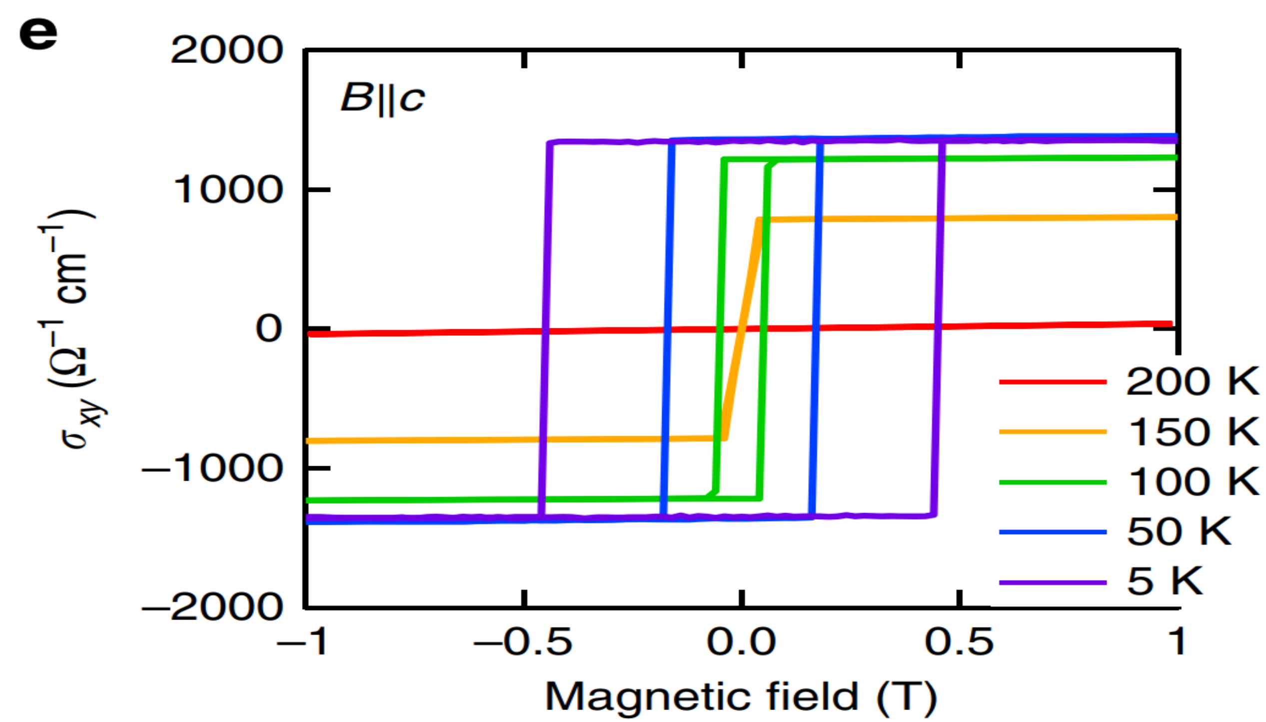
In Weyl semimetal

Novel properties of Dirac and Weyl semimetals

Each of the **Dirac or Weyl points associate fictitious magnetic field in k space** → Anomalous behavior in physical properties observed

<u>For example</u>, Hall effect observed in Weyl semimetals in absence or very small external field (due to the fictitious magnetic field)→ **Anomalous Hall effect**

$$\sigma_{xy} = \frac{current\ through\ sample}{Hall\ voltage} = \frac{I_x}{V_y}$$

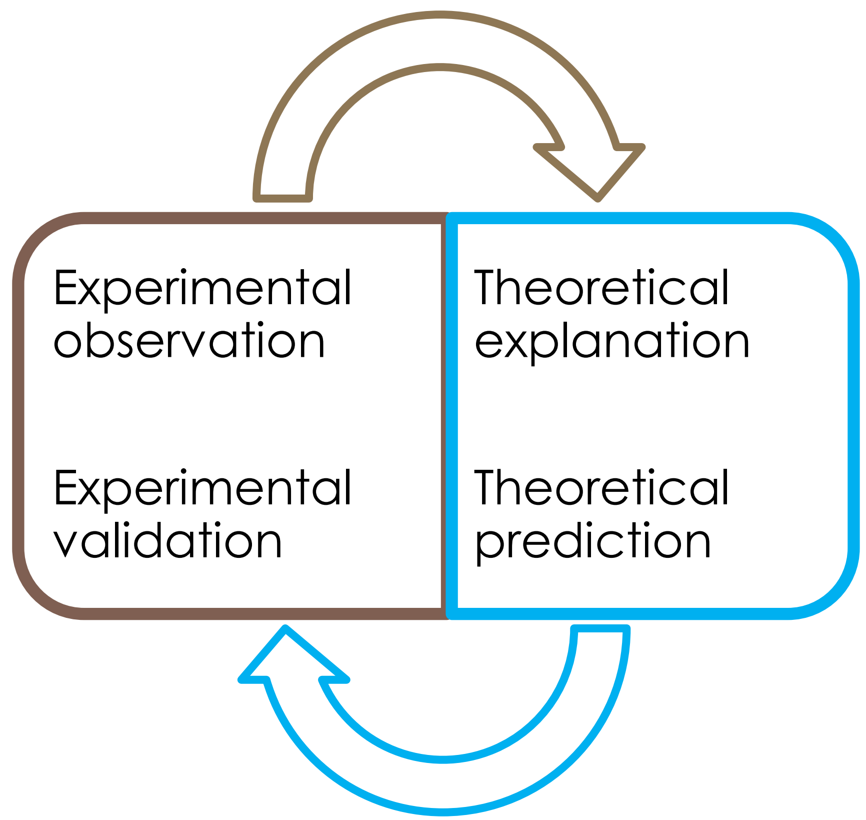


Anomalous Hall effect in $Co_3Sn_2S_2$, a Weyl semimetal

Challenges in quantum materials

- Not many quantum and/or topological materials are explored so far
- Usually, low temperature phenomena
- Yet to understand the underlying physics clearly

How to overcome:



- Topological materials are a class of substances with unique electronic properties where their surfaces exhibit different behaviors compared to their interiors.

- These materials are often characterized by being insulating in their bulk while conducting electricity on their surface, or having semi-metallic behavior with specific boundary states.

- The term "topological" in this context refers to the material's geometric and quantum properties that are invariant under certain distortions, meaning they remain consistent even if the material's shape is altered.

Potential Applications:

Ultrabright Electronic Devices:

The unique properties of topological materials, such as robust surface states and dissipationless charge transport, make them promising for developing energy-efficient and high-performance electronic devices.

Quantum Computing:

Majorana fermions, which can be found in topological superconductors, are a key resource for developing robust quantum computers.

Spintronics and Magnetoelectronics:

The interaction of topological materials with magnetic materials can lead to new phenomena in spintronics and magnetoelectronics, with potential applications in energy-efficient devices.

Thermoelectrics:

Topological materials, particularly topological semimetals, can be used for efficient thermoelectric energy conversion, converting heat into electricity and vice versa.