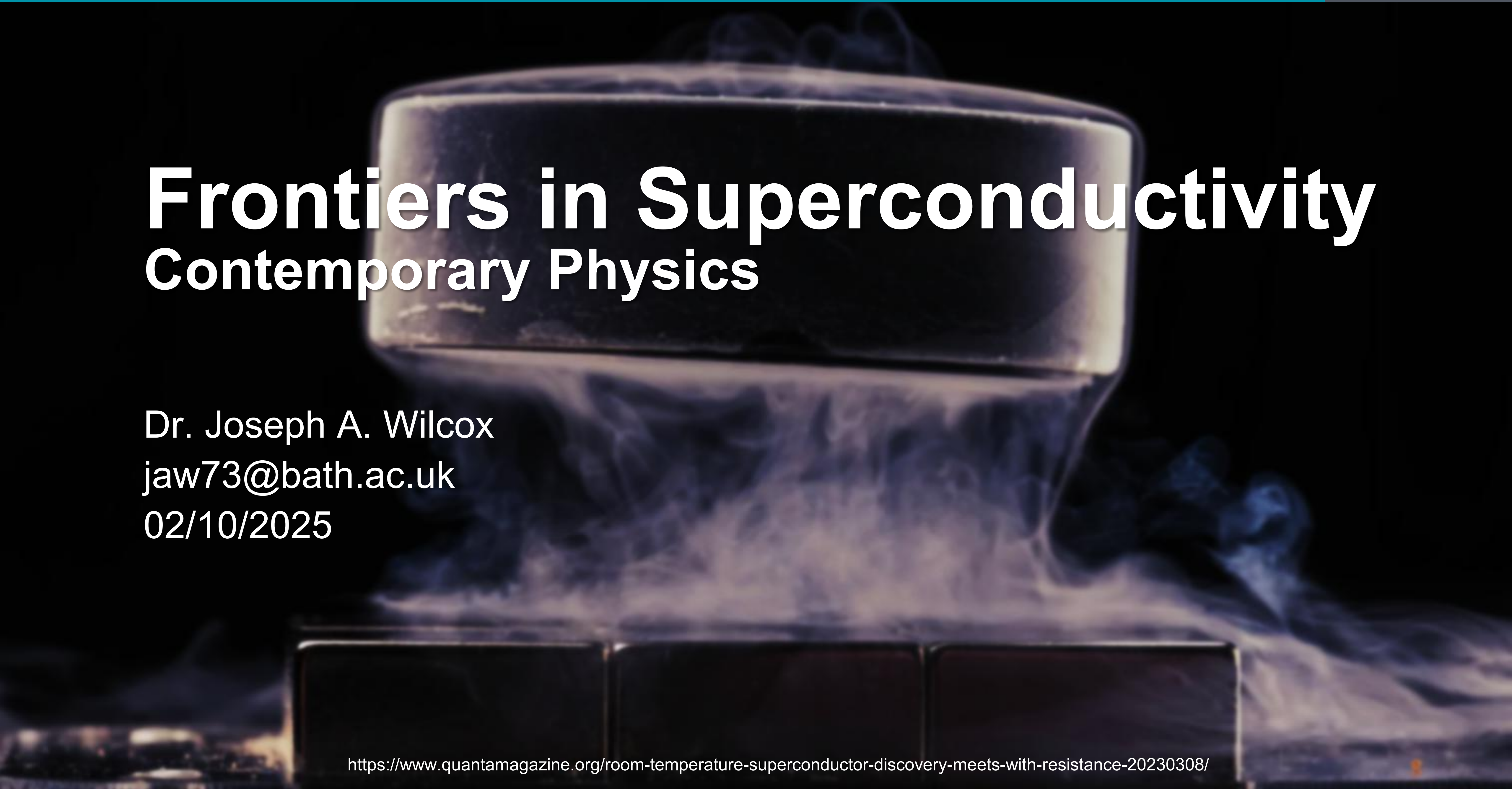

Frontiers in Superconductivity
Contemporary Physics

Dr. Joseph A. Wilcox
jaw73@bath.ac.uk

02/10/2025

https://www.quantamagazine.org/room-temperature-superconductor-discovery-meets-with-resistance-20230308/

Schedule

- Today/Now! Lecture on “Frontiers in Superconductivity”

  - Brief introduction to superconductivity and current state of research

- Tuesday 7th October at 17:15, 8W 2.30 : “Technical Surgery 1”

  - Opportunity to ask further questions, discuss topic ideas etc

- Tuesday 14th October at 17:15, 8W 2.30: “Technical Surgery 2”

  - You should have most of a draft completed, we can discuss some specific parts of your reports, but **I cannot give feedback on your drafts before submission!**

  - Final opportunity to clarify understanding, get suggestions etc

- Tuesday 21st October 12:00pm, Moodle: Submission deadline for report

Structure

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Structure of Lecture

- ❑ Introduction
- ❑ Basics of Superconductivity
- ❑ Overview of (some) current research
- ❑ Assignment & Resources

Superconductivity is a big subject, sadly I won’t be able to cover very much of it today.

Hopefully, I can give you a sense of things which you can follow up on later.

These slides will be available on the Moodle.

Introduction

2010 – 2014
MSci, University of Bristol

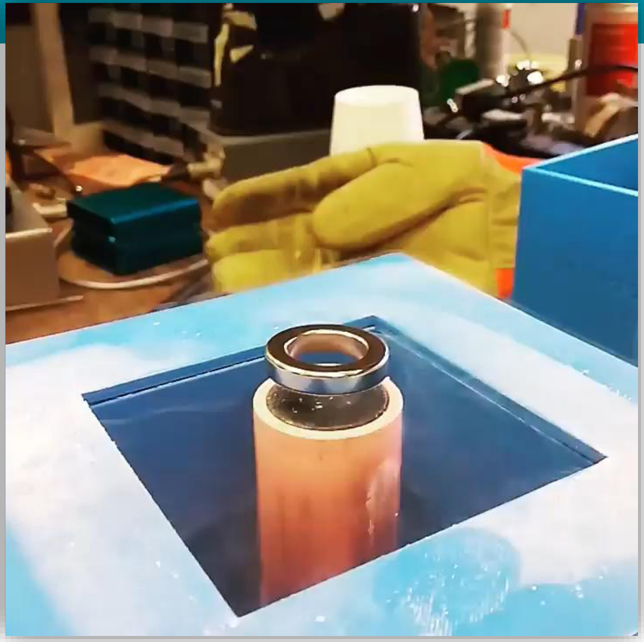
2014 – 2019
PhD, University of Bristol (+ Bath)
Magnetic behaviours of unconventional superconductor

2019 – 2023
Postdoctoral Research, University of Bristol
Competing orders in high-temperature superconductors

2023 – Present
Postdoctoral Research, University of Bath
Vortex pinning in ferromagnetic iron-based superconductors

I am an experimentalist!

I am interested in novel superconducting phenomena & materials, and in developing new measurement techniques.

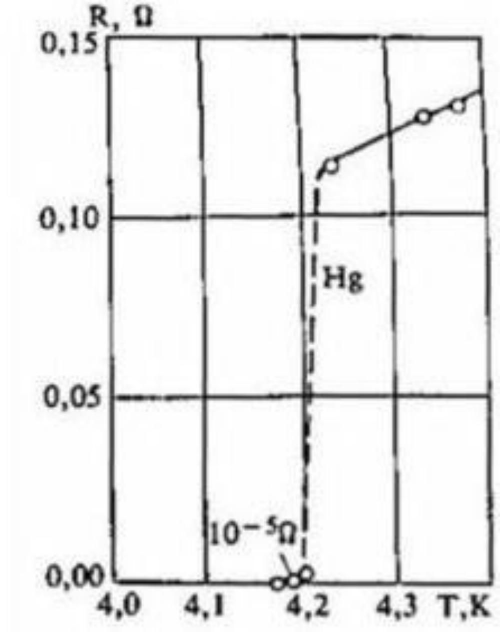


Introduction

Superconductivity

- Discovered by Heike Kamerlingh Onnes in 1911, shortly after successfully liquefying helium
- Observed resistivity of mercury drop rapidly to zero at ~4.2 K – a very surprising result!
- Since discovery, subject has expanded massively. Very active area of research. 5 SC-related Nobel Prizes.
- Many more superconductors known today (and discovered frequently)
- Numerous useful technological applications (e.g. MRI, quantum computers, high-sensitivity magnetometers)
- Despite maturity, many open questions remain regarding mechanism. Holy grail: room-temperature superconductor
- Good news 😊
  Breadth of topic ➡️ something for everyone
- Bad news 😑
  Lots of literature to search through / keep up with

Delft and Kes, Physics Today **63**, 38 (2010)



Vanishing resistance of mercury

Heike Kamerlingh Onnes
- Winner of Nobel Prize 1913

https://www.pexels.com/license/

Modern MRI machine – the magnetic field is produced by a superconducting electromagnet

What is superconductivity?

Two main defining properties

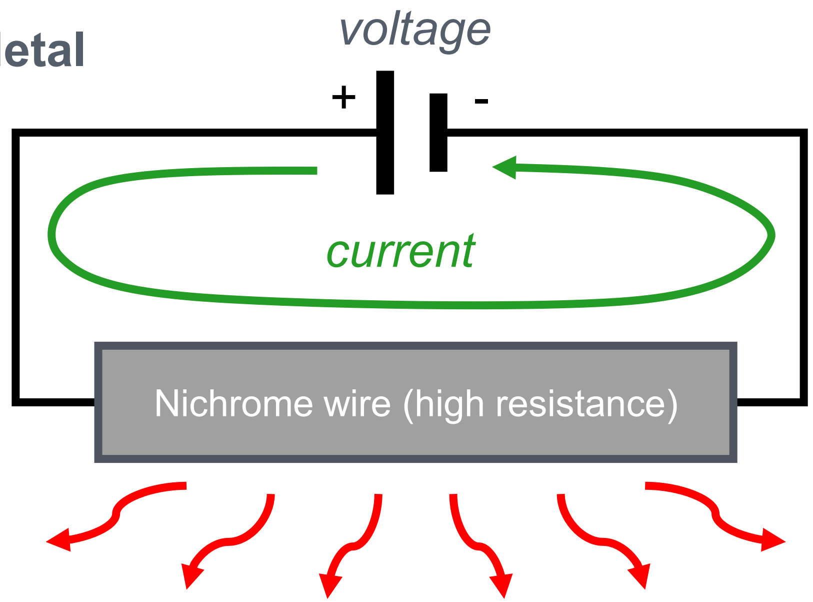
1. **Zero DC resistance**, i.e. perfect conductor, $R = 0$
2. **Expels magnetic fields**, i.e. perfect diamagnet, known as the Meissner effect (also Meissner-Ochsenfeld effect)

- Second property more significant as perfect conductivity can be derived from it
- Distinct thermodynamic phase, characterised by a critical temperature T_c
- Above T_c, material is "normal" & below T_c, material is superconducting
- Destroyed by magnetic field (H_c) and electrical current (J_c)
- Gap Δ in the electronic DOS at the Fermi surface (similar to semiconductors)
- Macroscopic quantum wavefunction – i.e. there is coherence between more than 10^{23} superconducting electrons* in a macroscopic piece of superconductor
- Quantum coherence gives superconductors some very unique properties

*Cooper pairs!

Metal vs. Superconductor

Metal

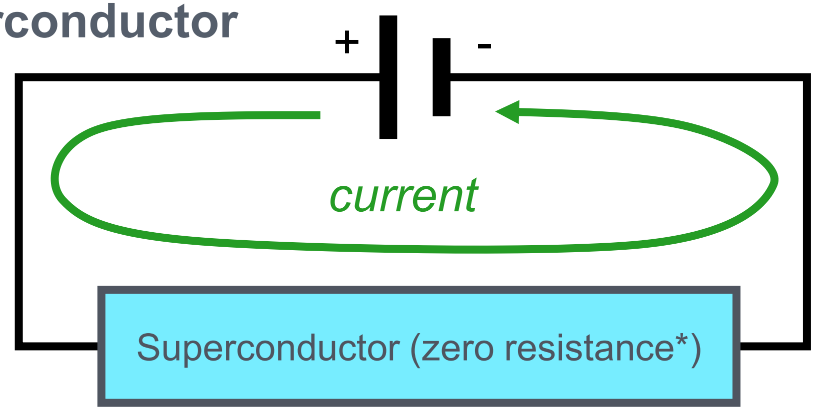


energy dissipated as heat
(Joule heating)

$$P = I^2 R$$

My toaster!

Superconductor



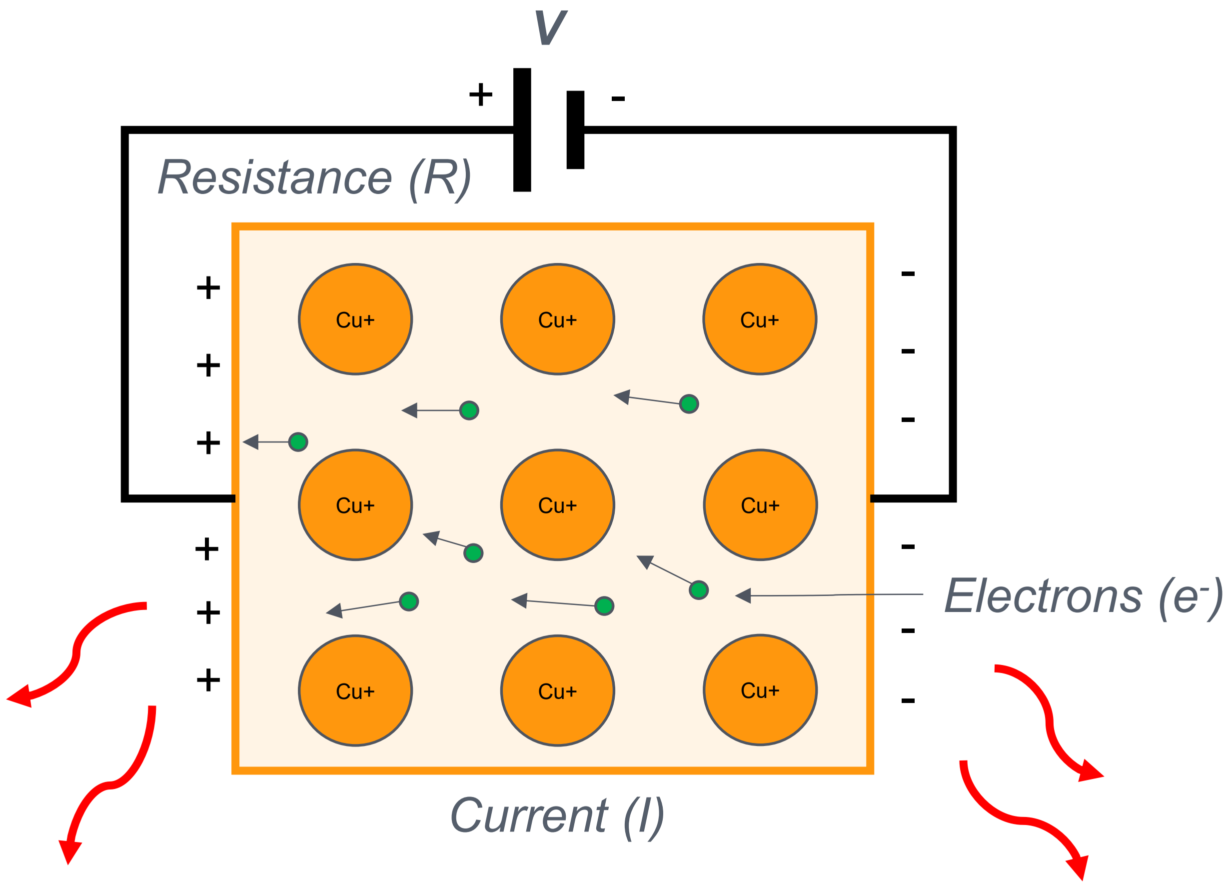
No energy lost!

Normal metals:
$R > 0, P > 0$

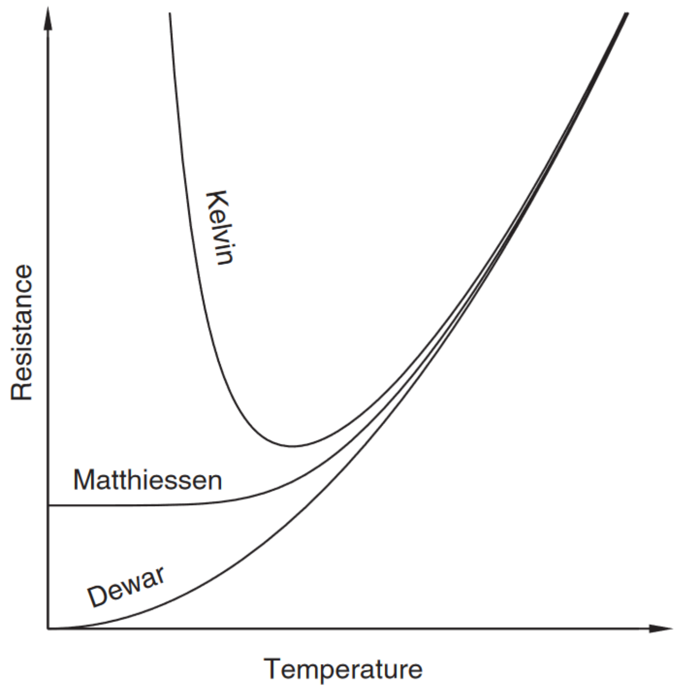
Superconductors:
$R = 0, P = 0$

*DC resistance,
More complicated in AC

Metallic conduction at lower temperatures



Blundell, Superconductivity: A Very Short Introduction, Oxford University Press (2009)



Joule heating due to scattering of electrons by vibration of crystal lattice (a.k.a. phonons).

At low temperatures, what happens to the resistance?

Less thermal energy => fewer vibrations => less scattering

Theories at beginning of 20th century:

Kelvin: electrons freeze in place

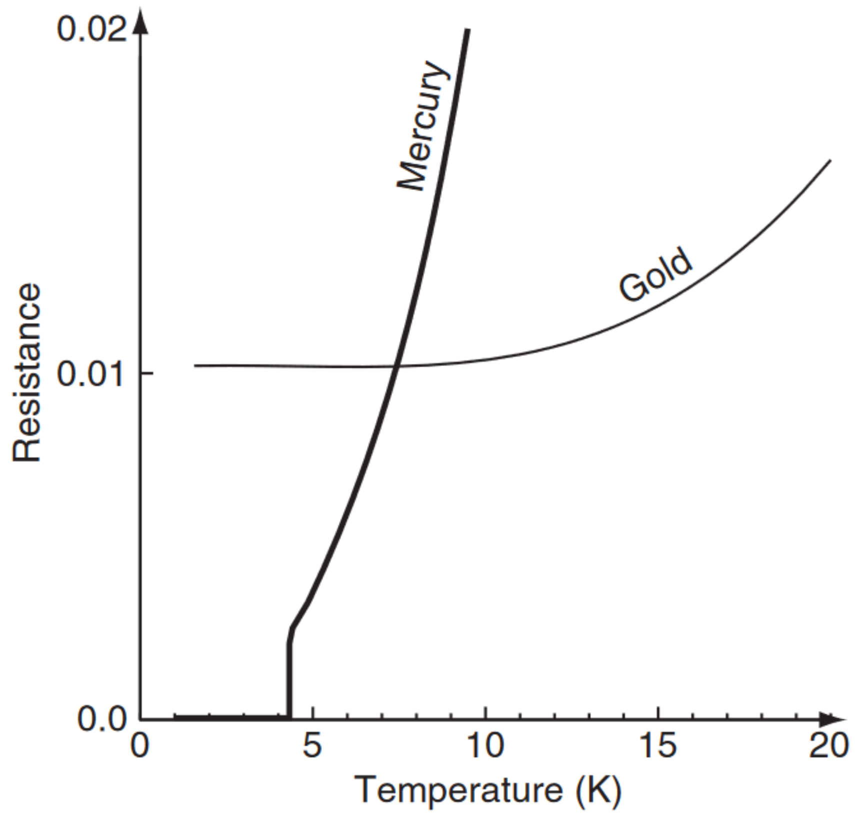
Matthiessen:
resistance limited by impurities

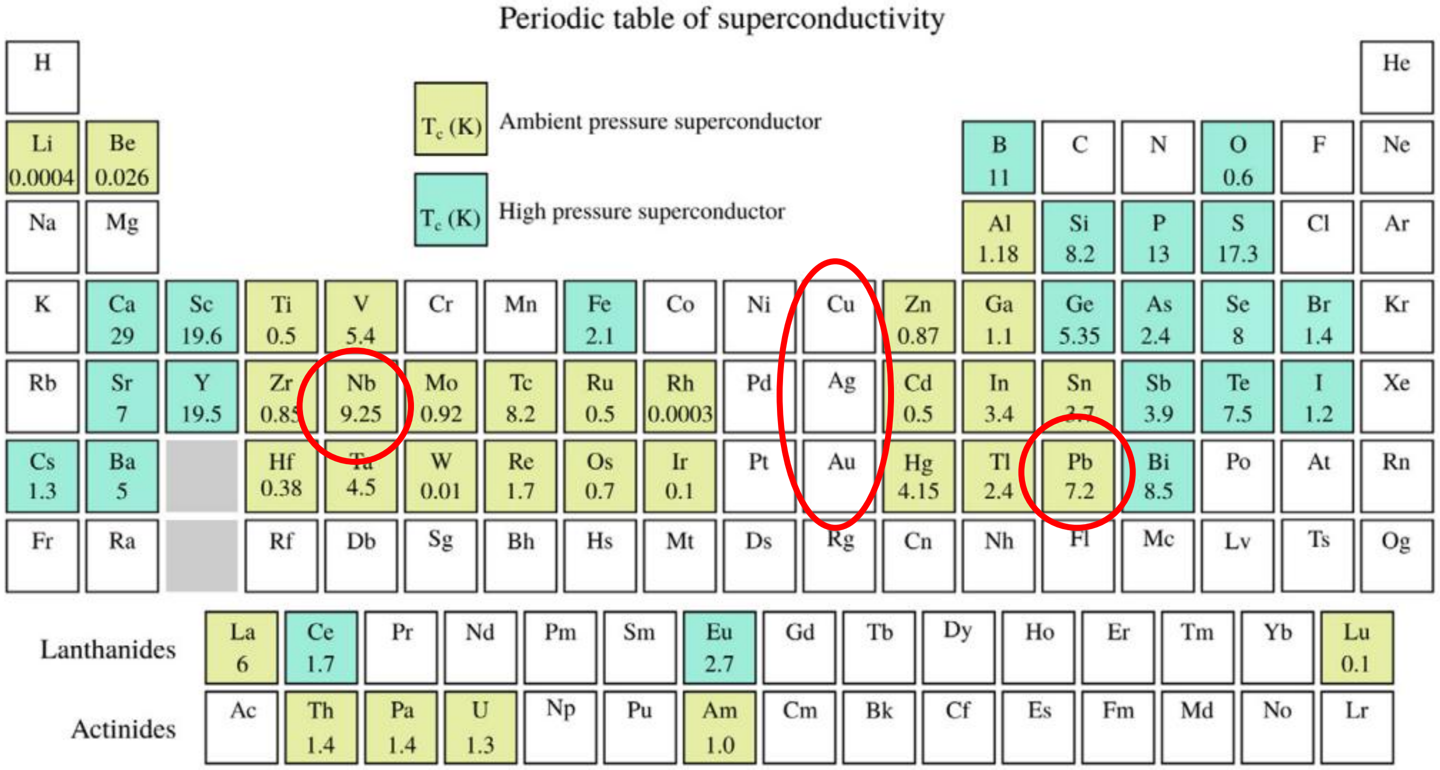
Dewar: vanishing resistance as T -> 0

Metallic conduction & superconductivity

Blundell, Superconductivity: A Very Short Introduction, Oxford University Press (2009)

Flores-Livas et al., Physics Reports **856**, 1 (2020)





Experiments by Onnes found resistance of gold to plateau, consistent with predictions from Mathiessen – this is quite typical of most metals.

Mercury, with a higher high-temperature resistance, instead becomes superconducting with $T_c \sim 4.2$ K

Good electrical conductors tend not to be superconducting …

But bad conductors do! Very surprising.

The Meissner Effect

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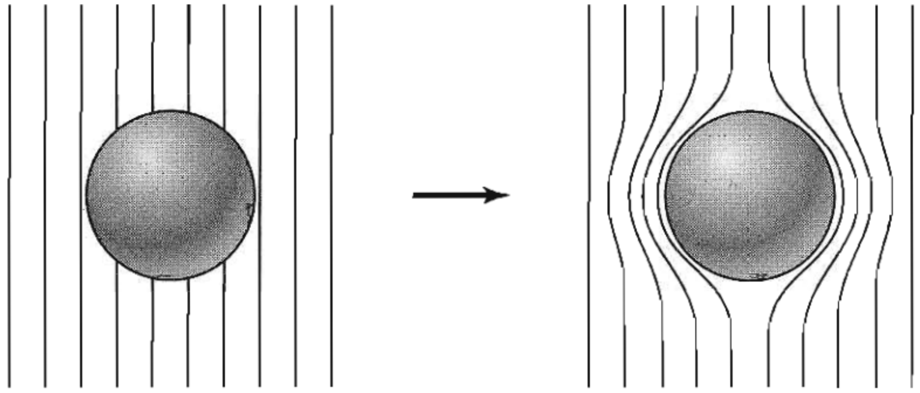
Kittel, Introduction to Solid State Physics, 8th ed, Wiley (2005)

Applied field H



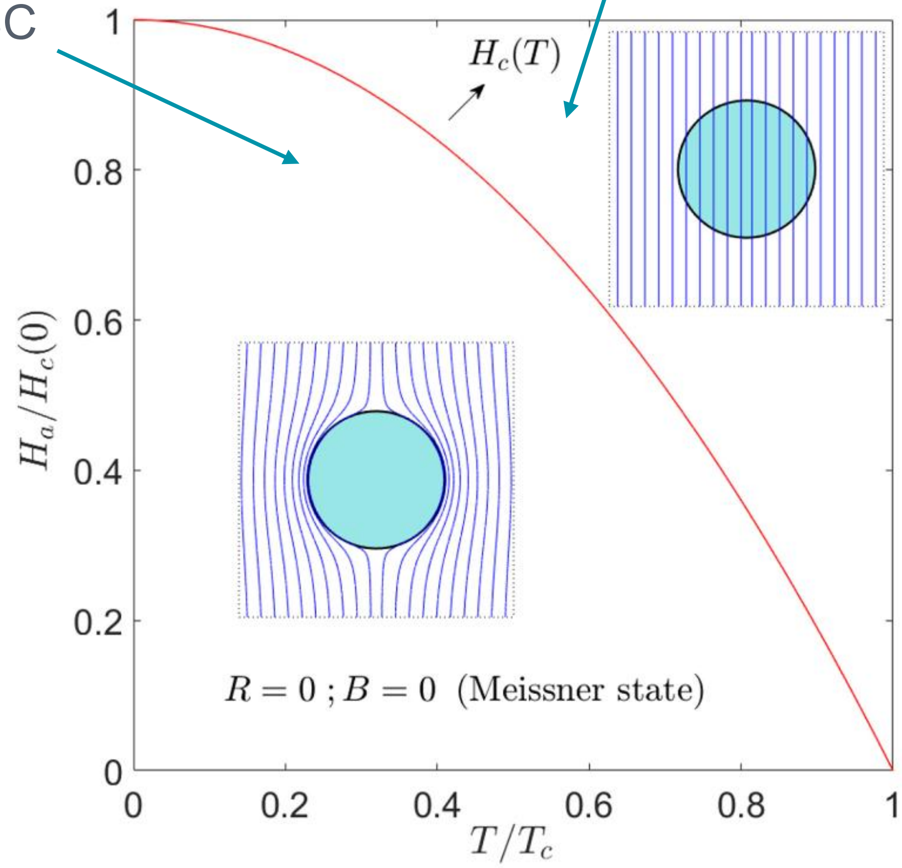
$T > T_c$, $B \neq 0$ $\qquad$ $T < T_c$, $B = 0$

$$B = 0$$
$$M = -H$$
$$\chi = -1$$

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

Normal

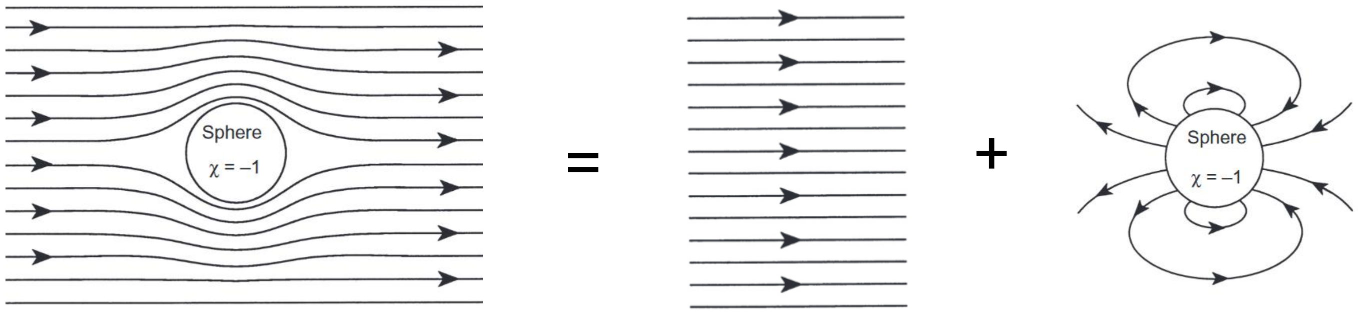
SC



Badía-Majós, Macroscopic Superconducting Phenomena, IOP Publishing (2021)

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

B : magnetic flux density
H : magnetic field strength
M : magnetisation

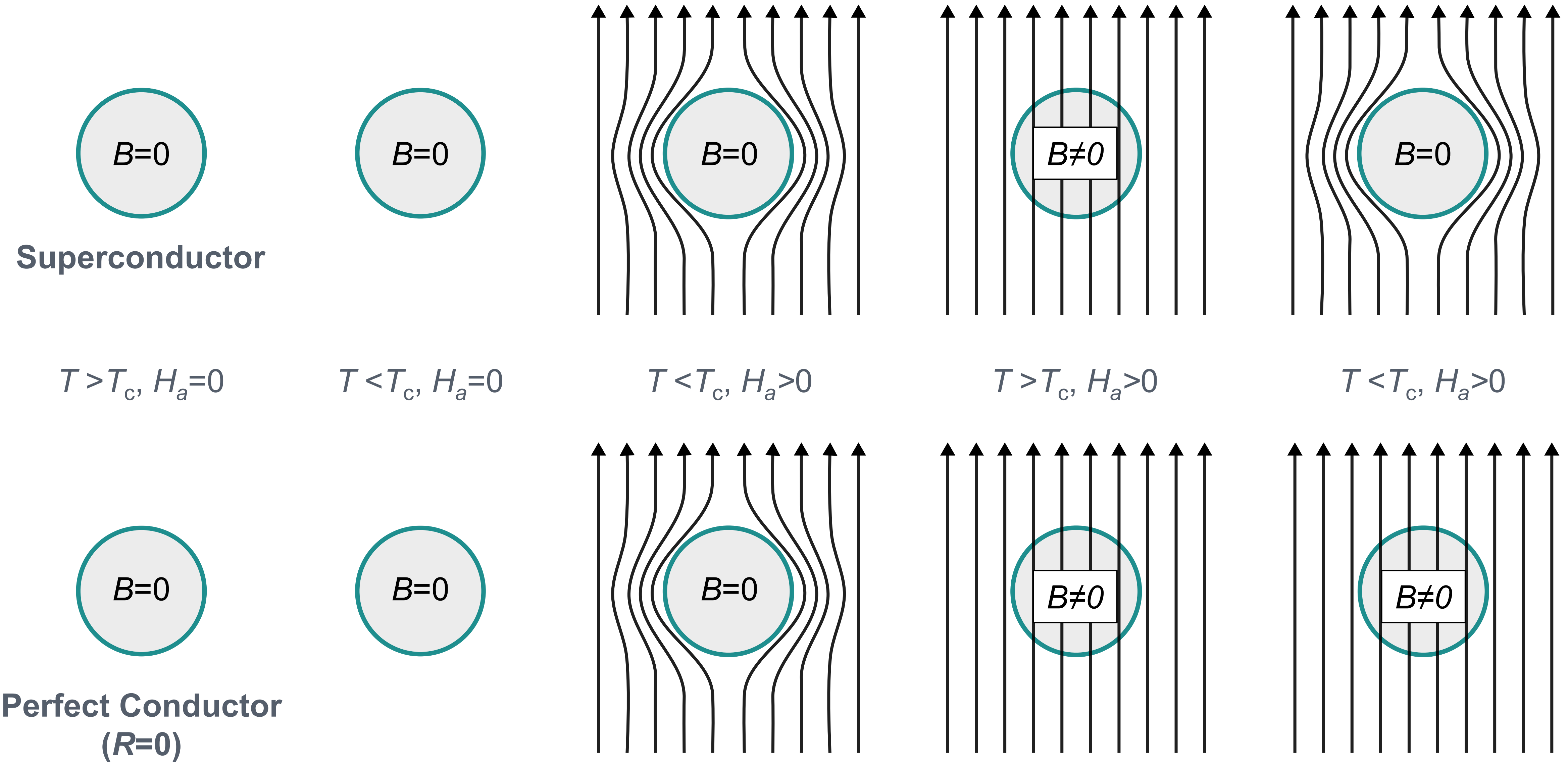


B $\qquad$ *H* $\qquad$ *M*

Superconductor vs Perfect Conductor

Behaviour is reversible

B = 0 deep inside the SC, so long as $H_a < H_c$



Behaviour is NOT reversible

Remember Lenz's law: $V \propto d\phi/dt$ ➡️ *Eddy currents appear*

Electrodynamics of Superconductors

$$\mathbf{J} = \frac{ne^2\tau}{m}\mathbf{E} = \sigma\mathbf{E} \qquad V = IR$$

- Conduction in metals understood in terms of e.g. Drude model, free electron model, gives rise to familia Ohm's law
- Current density **J** is proportional to conductivity and electric field **E**
- Scattering (τ) inhibits motion of electrons
- But in a superconductor, current can flow with no potential (persistent currents)

Fritz and Heinz London

- In 1930s, London brothers proposed phenomenological theory to describe (current) observations, two so-called London equations:

$$\frac{\partial \mathbf{j}_s}{\partial t} = \frac{n_s e^2}{m}\mathbf{E} \qquad \nabla \times \mathbf{j}_s = -\frac{n_s e^2}{m}\mathbf{B}$$

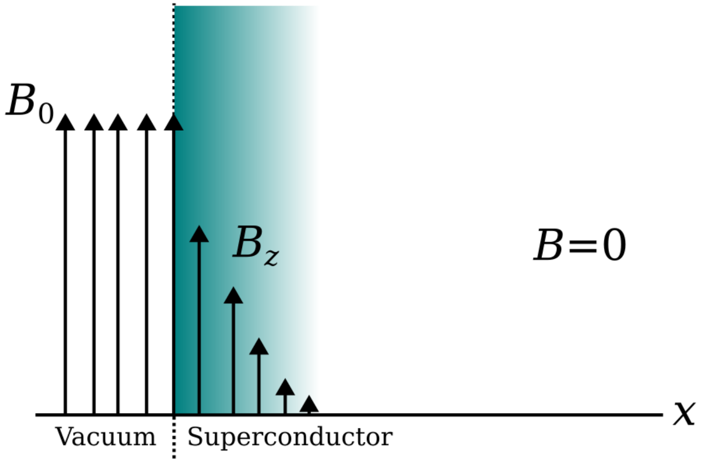
- Current density due to ***changing*** **E** field as well as magnetic field **B** ! (*n_s : number of superconducting charge carriers)*
- With Maxwell's equations:

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} \qquad \nabla^2 \mathbf{B} = \frac{1}{\lambda_s^2}\mathbf{B} \qquad \lambda_s = \sqrt{\frac{m}{\mu_0 n_s e^2}}$$

- λ_s is known as the London penetration depth, 10s to 100s nanometers
- In 1-dimension, solution is:

$$B_z = B_0 e^{-x/\lambda_s}$$

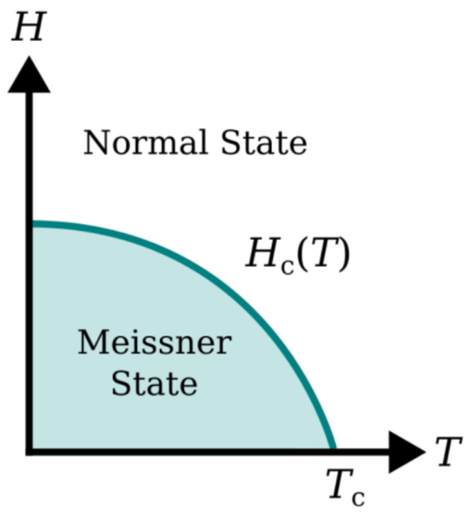
Magnetic field decays exponentially at surface while *B* is zero in the bulk

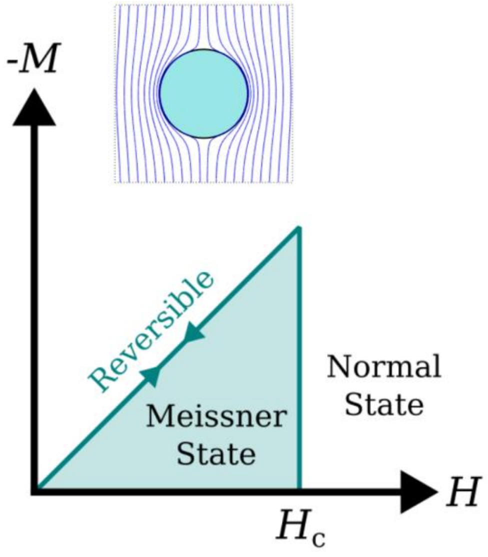


Type I vs Type II

F. S. Wells *et al.*, Scientific Reports **5**, 8677 (2015).

Type I



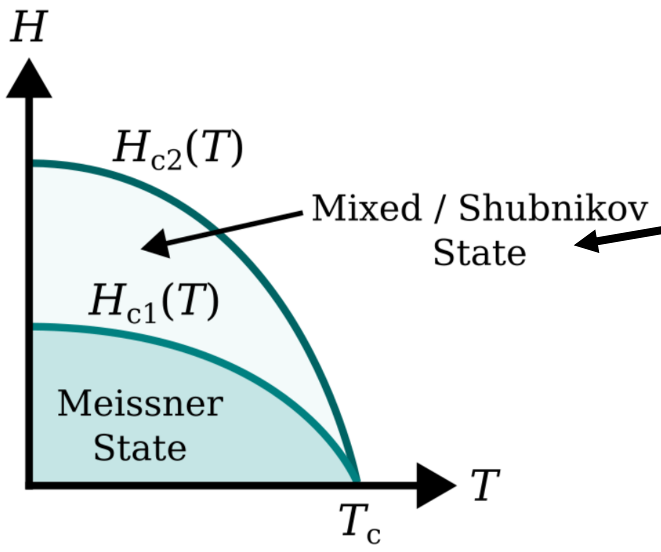


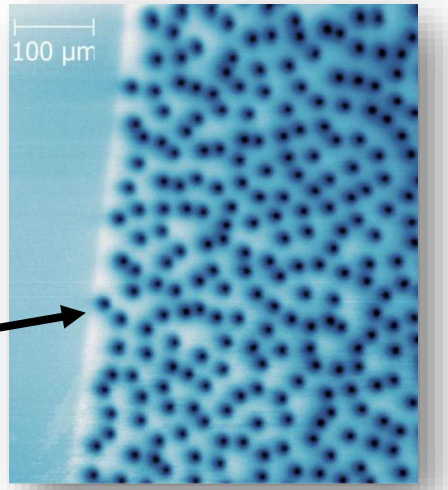
Most elemental superconductors are type I

Vast majority of superconductors are type II, particularly alloys and compounds

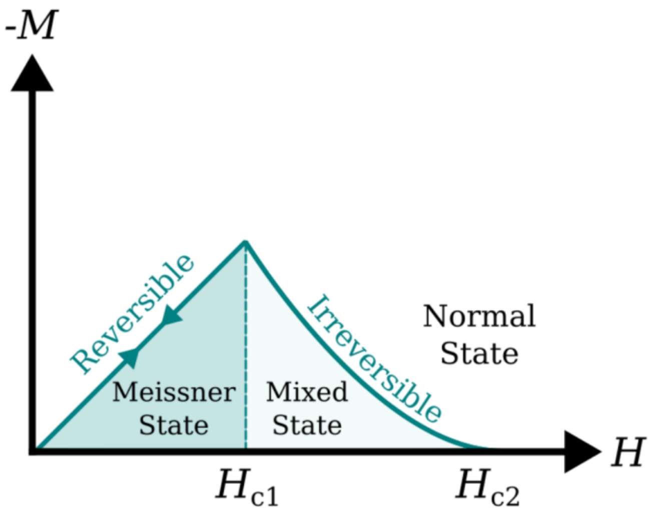
Material properties determine magnetic type

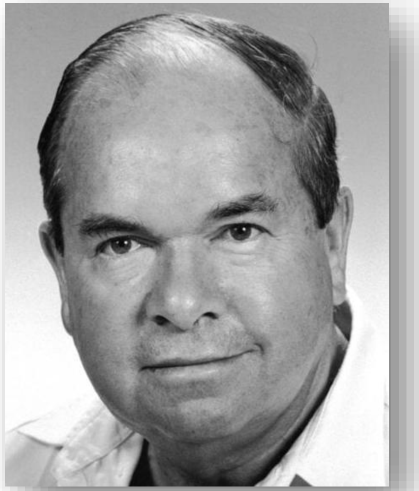
Type II





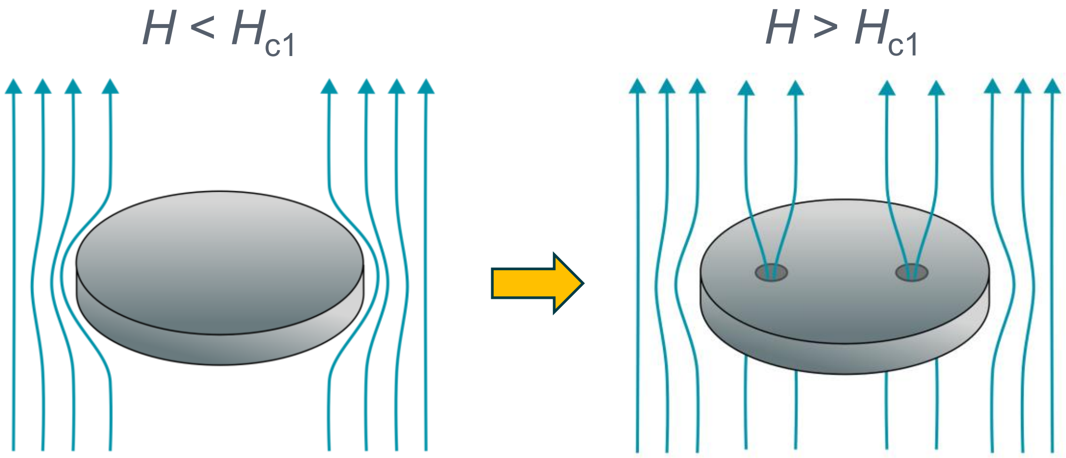
Magnetic vortices





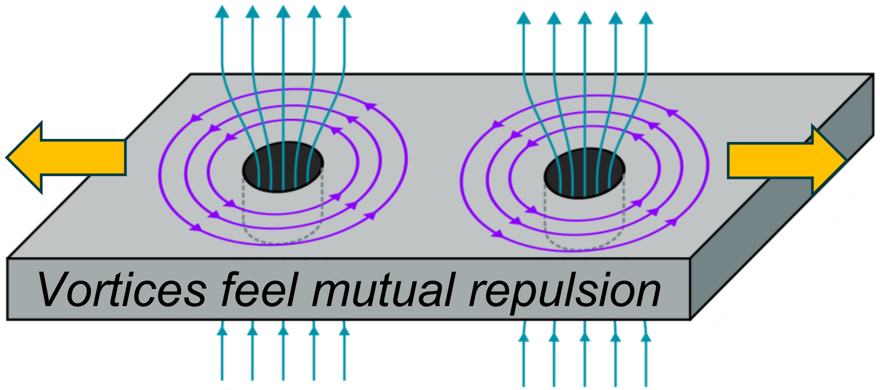
Alexei Abrikosov
Nobel Prize 2003 for prediction of existence of vortices

Vortices and J_c (Type II superconductors)



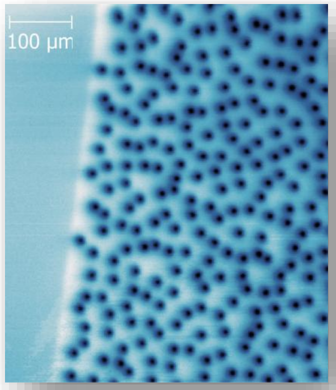
Resisting magnetic field costs energy. Above Hc1, cost is too great so instead easier to allow field to enter in small amounts.

Superconducting currents circulate around flux lines – this is the vortex



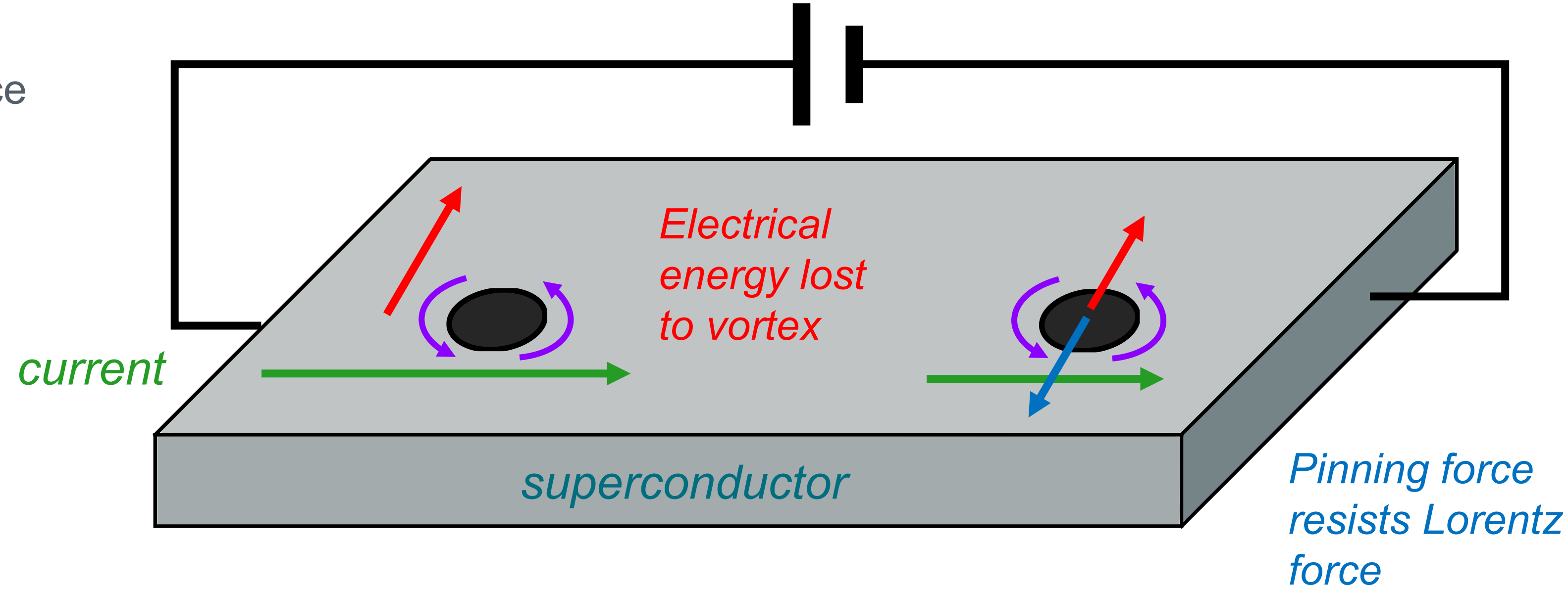
No superconductivity in vortex core – material is normal

Vortices are very small, ~100 nm



Vortices experience Lorentz force from current

Moving vortices dissipate energy ➡️ bad for applications!

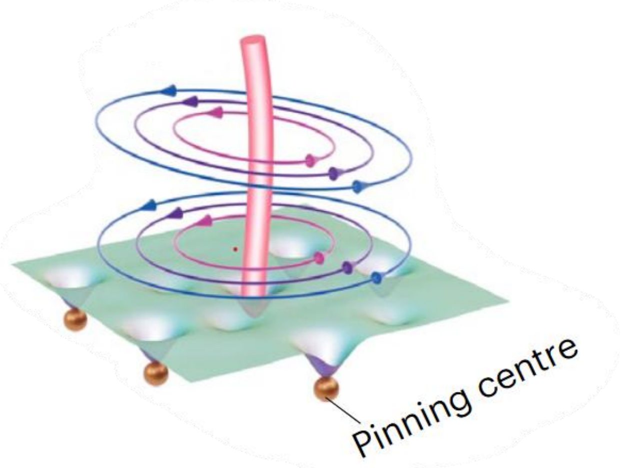


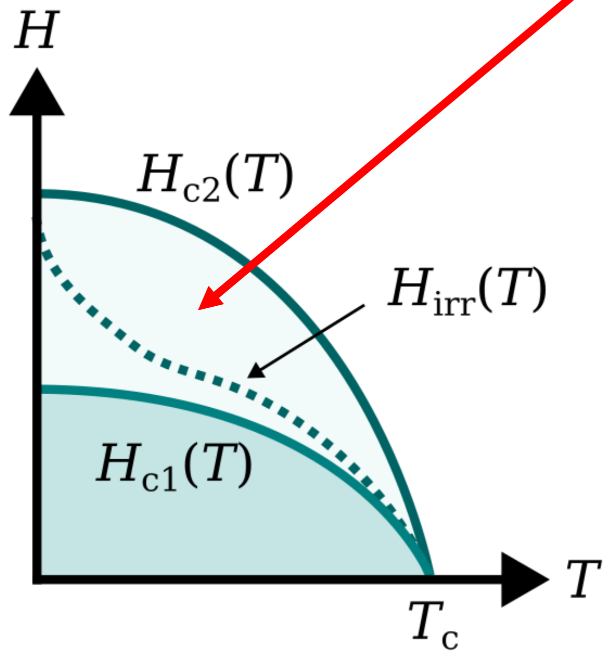
Vortices can be pinned in place ✔

Critical current* ➡️ *when Lorentz force is equal to the pinning force

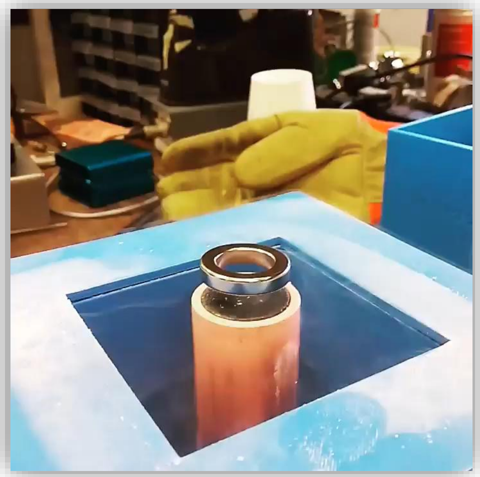
Critical Current Density $J_c\,(T, H)$ & Vortex Pinning

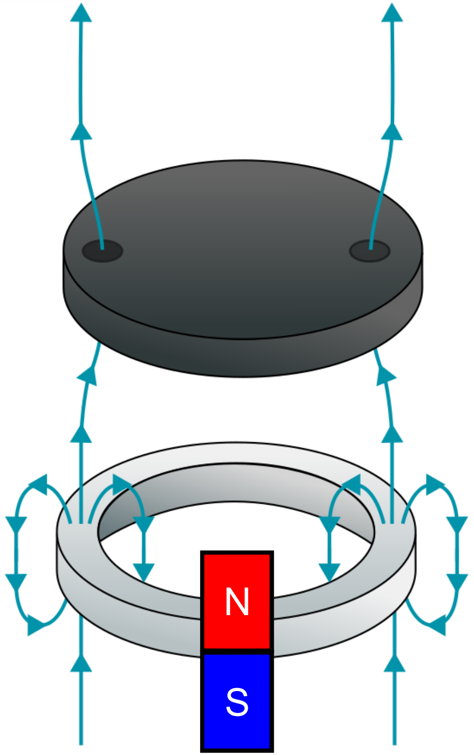
M. Miura *et al.*, Nat. Mater. **23**, 1370 (2024).





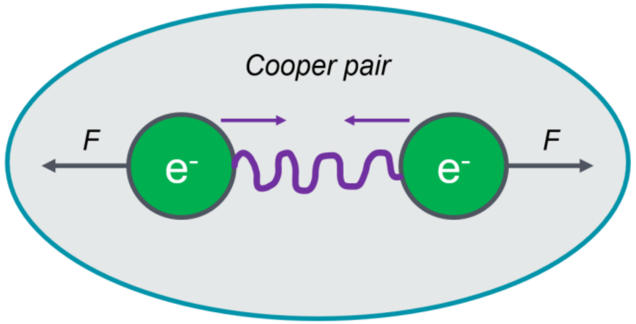
- Enhancing pinning properties is key to high-current applications of superconductivity:
  Better pinning ➡️ higher J_c
- The critical current density J_c is generally a function of both temperature and field.
- Above J_c , material is still superconducting, but moving vortices are big problem (irreversibility line $H_{irr}(T)$)
- Electrical conduction is no longer zero dissipation.
- Heat generated by vortices can lead to thermal runaway and a violent quench – sudden loss of superconductivity
- Vortex pinning (or “flux pinning”) is how superconductors (and magnets) can “levitate”



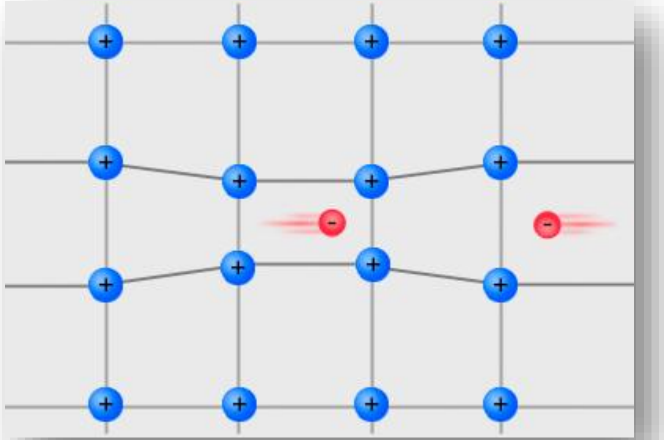


Cooper pairs & BCS Theory

Electrons normally mutually repulsive



In a superconductor, they pair up due to additional attractive interaction – **Cooper pairs**



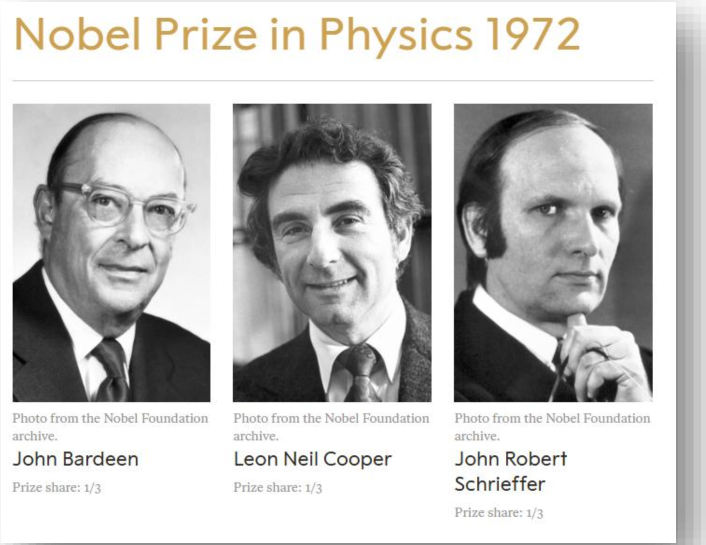
Pairing due to electron coupling with lattice vibrations (i.e. by phonon exchange).

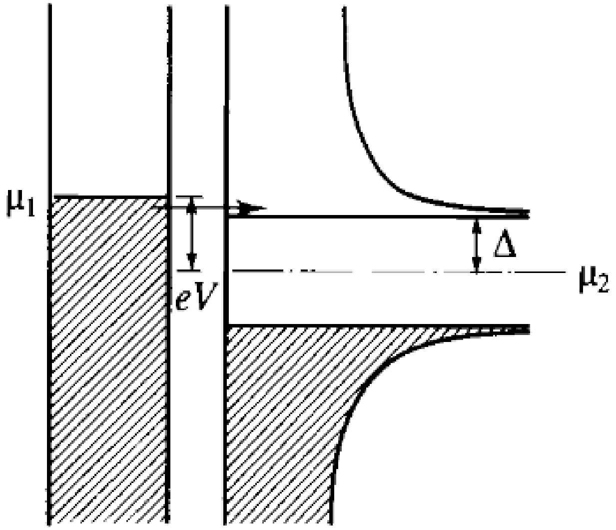
Explained in the B-C-S theory of superconductivity.

PHYSICAL REVIEW VOLUME 108, NUMBER 5 DECEMBER 1, 1957

Theory of Superconductivity*

J. BARDEEN, L. N. COOPER,† AND J. R. SCHRIEFFER‡
Department of Physics, University of Illinois, Urbana, Illinois
(Received July 8, 1957)





Electrons form pairs within Δ of the Fermi surface – leaving a gap in the DOS

Δ is often called the condensation energy, or the binding energy

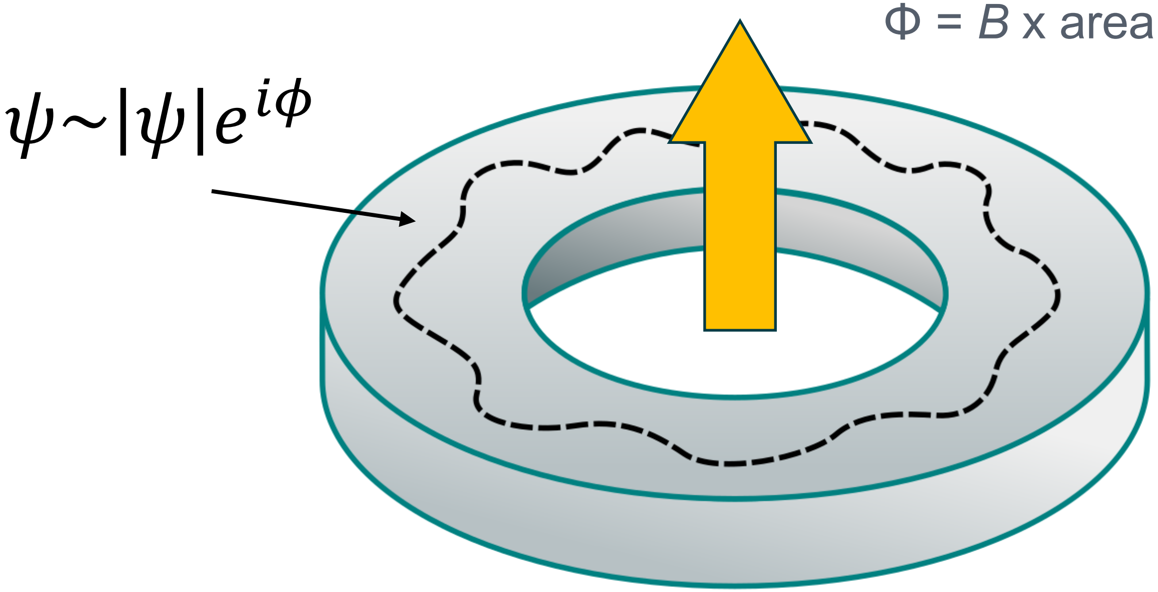
Tinkham, Introduction to Superconductivity, 2nd ed, Dover Publications (2005)

https://en.wikipedia.org/wiki/Cooper_pair#/media/File:Cooper_pairs.jpg

Macroscopic quantum coherence

$$\Psi_{\mathrm{BCS}} = \prod_k \psi_k$$

- The BCS wavefunction is a product of all Cooper pair states
- All pair states are coherent in phase
- Overall wavefunction must be single valued at all locations (think of the hydrogen atom)
- Wavefunction is coherent across entire superconductor



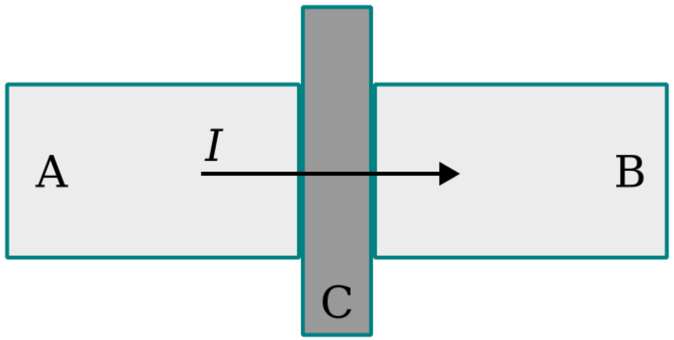
From London equations, any magnetic flux threading a superconductor must be **quantised** in units of Φ_0

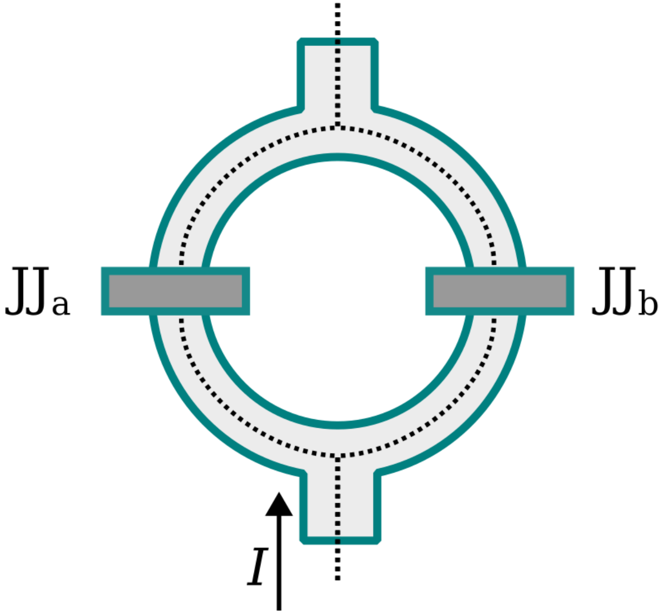
$$\Phi = \oint A.dl = n\Phi_0 \qquad \Phi_0 = \frac{h}{2e}$$

$$\nabla \times A = B$$

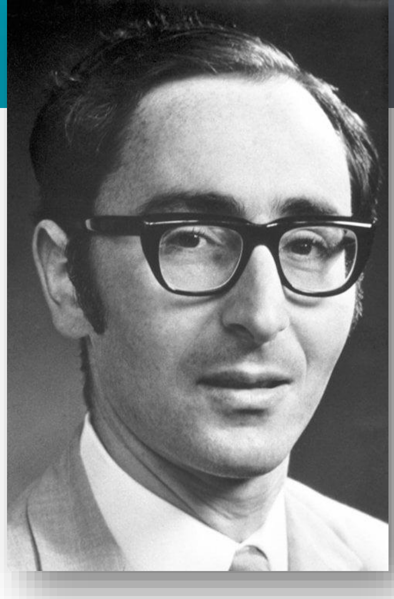
Josephson effects

$\psi_A \sim |\psi| e^{i\phi_A}$ $\psi_B \sim |\psi| e^{i\phi_B}$

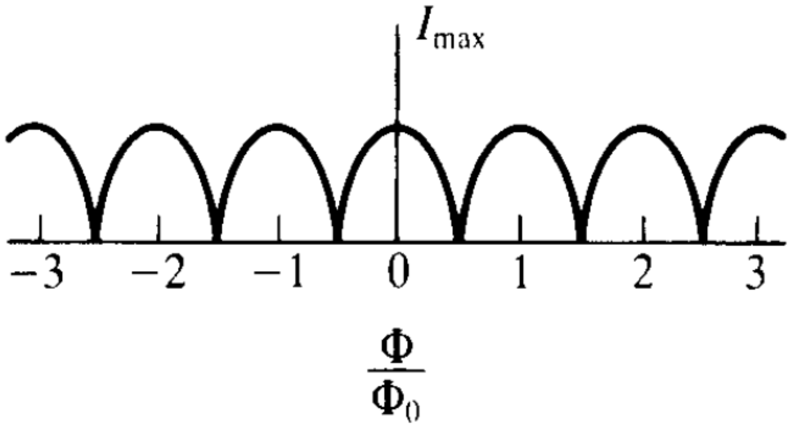




Brian Josephson
Nobel Prize Winner 1973
for predicting tunnelling
effects now known as
'Josephson effects'



Tinkham, Introduction to Superconductivity, 2nd ed, Dover Publications (1996)



- ❑ Cooper pairs can tunnel from superconductor A to B through a "weak link" (C) – a **Josephson junction**
- ❑ If there is a difference in phase ΔΦ, a spontaneous current will flow (DC Josephson effect)

$$J = J_0 \sin(\Delta\phi)$$

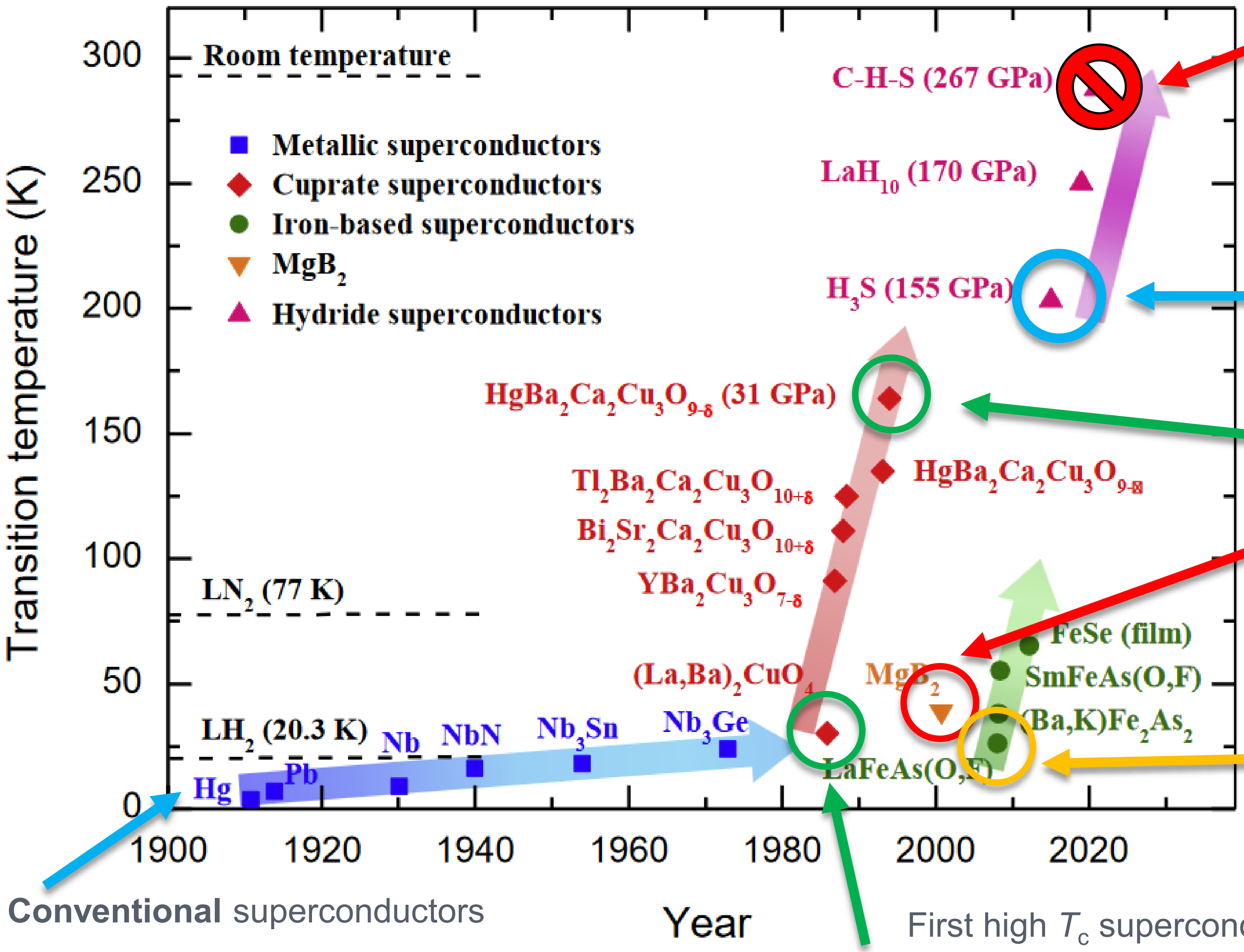
- ❑ Two Josephson junctions (JJ) in parallel form a Superconducting Quantum Interference Device (SQUID)
- ❑ Magnetic flux threading the junction causes interference of the two wavefunctions

$$\Phi_0 = \frac{h}{2e}$$

- ❑ The critical current I_c of the SQUID is extremely sensitive to the contained flux
- ❑ Basis for high-sensitivity magnetometers

T_c over the years

This is not an exhaustive list – many, many more superconductors out there



Retracted!

Allegations of fraud committed by Ranga Dias!

Hydrogen-rich compound synthesised under extreme pressure. Not stable at ambient pressure. Likely a conventional superconductor.

Pressure can have strong effect on superconductivity.

Conventional superconductor with multiple superconducting gaps

Beginning of the iron age of superconductors.
Iron is usually magnetic, which would be detrimental to superconductivity, but not so here.
Also, unconventional superconductors.

Conventional superconductors

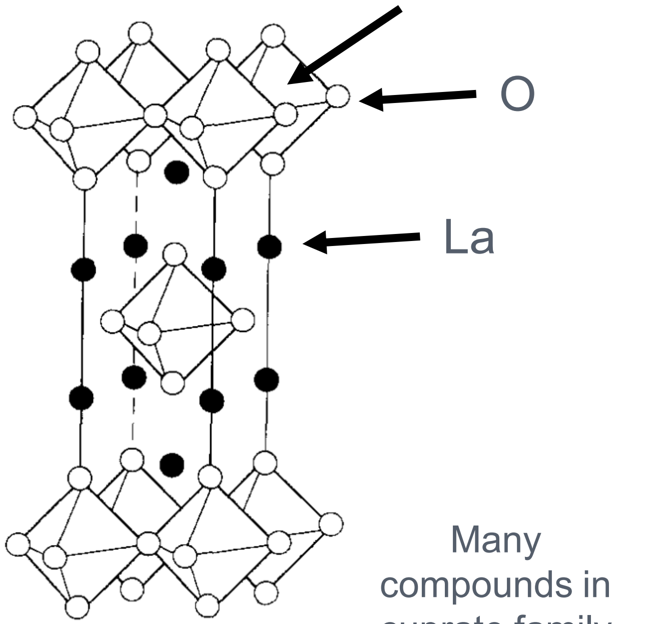
First high T_c superconductor –
also, an **unconventional** superconductor

C. Yao and Y. Ma, iScience **24**, 102541 (2021)

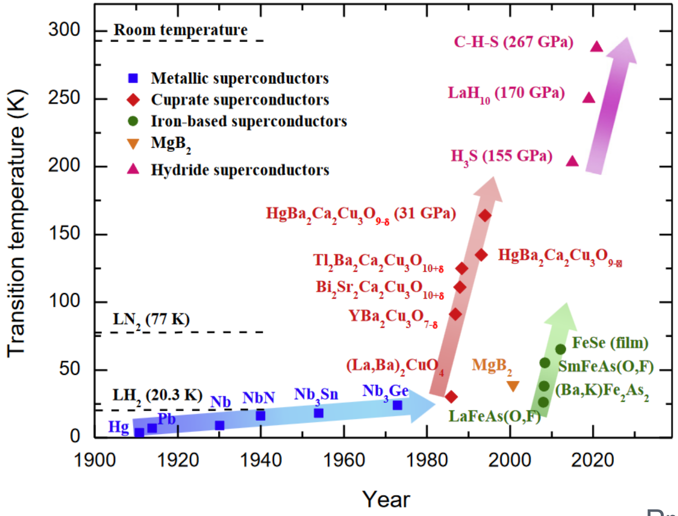
Cuprates – the first high T_c superconductors

Cheong, Physica C **158**, 109 (1989)

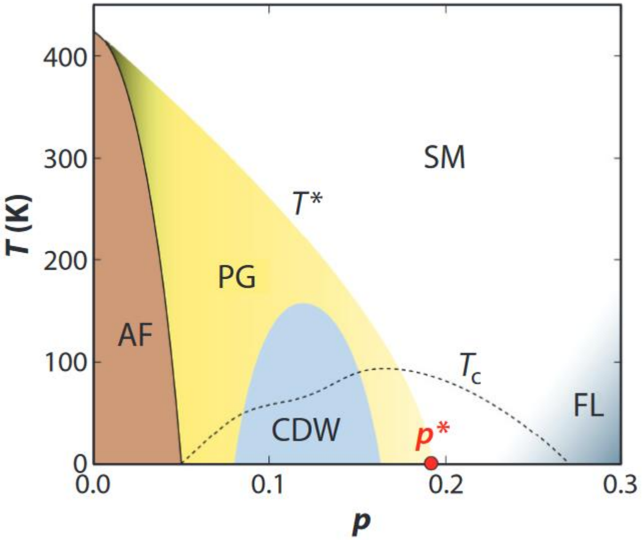
$LaCu_2O_4$



Many compounds in cuprate family



- High T_c superconductivity discovered in a **ceramic** compound, T_c ~ 30 K
- Common to all cuprates is the Cu-O planes
- Normal state conduction is very bad
- Very complex phase diagram – antiferromagnetism (AF), charge density wave (CDW), strange metal (SM), pseudogap (PG) …
- Lots of interesting many-body physics!



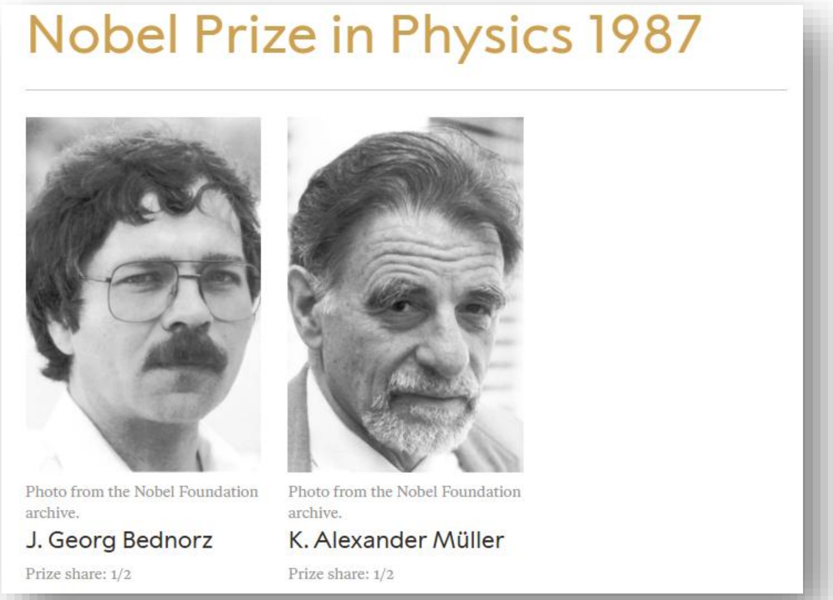
Proust and Taillefer, Annual Review of Condensed Matter Physics **10**, 409 (2019)

Prize awarded very rapidly!

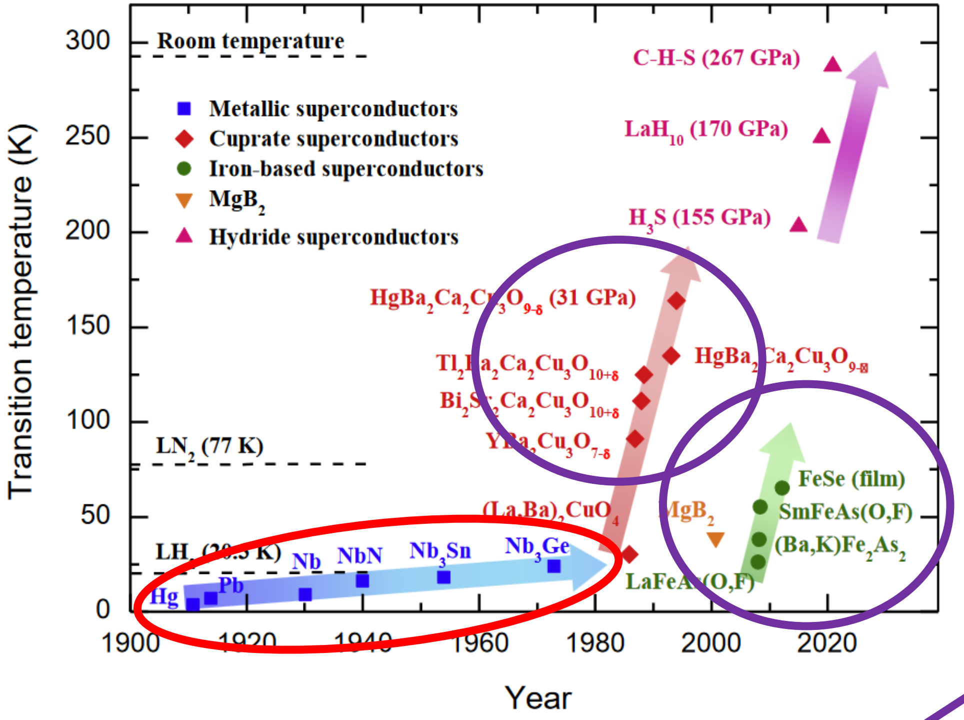
Possible High T_c Superconductivity in the Ba – La – Cu – O System

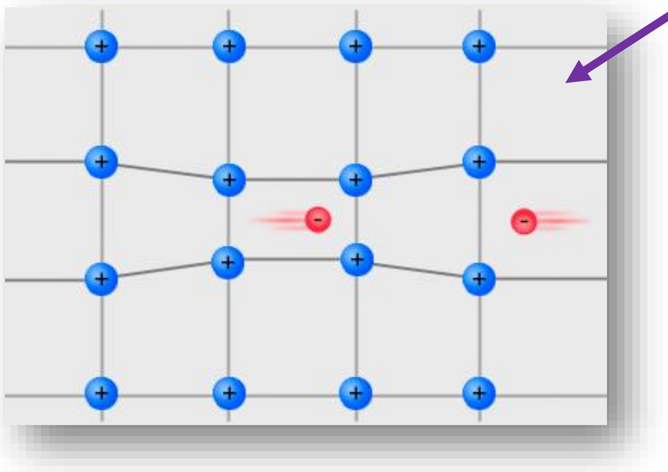
J.G. Bednorz and K.A. Müller
IBM Zürich Research Laboratory, Rüschlikon, Switzerland

Received April 17, 1986

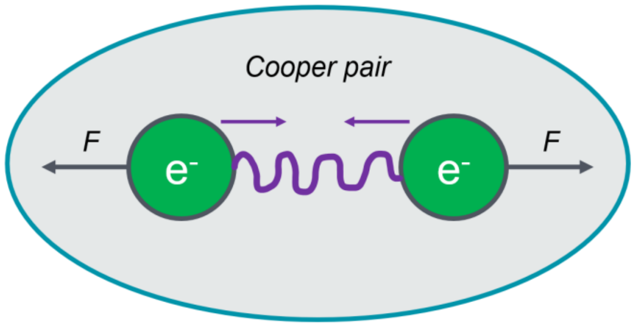


Conventional vs Unconventional Superconductivity



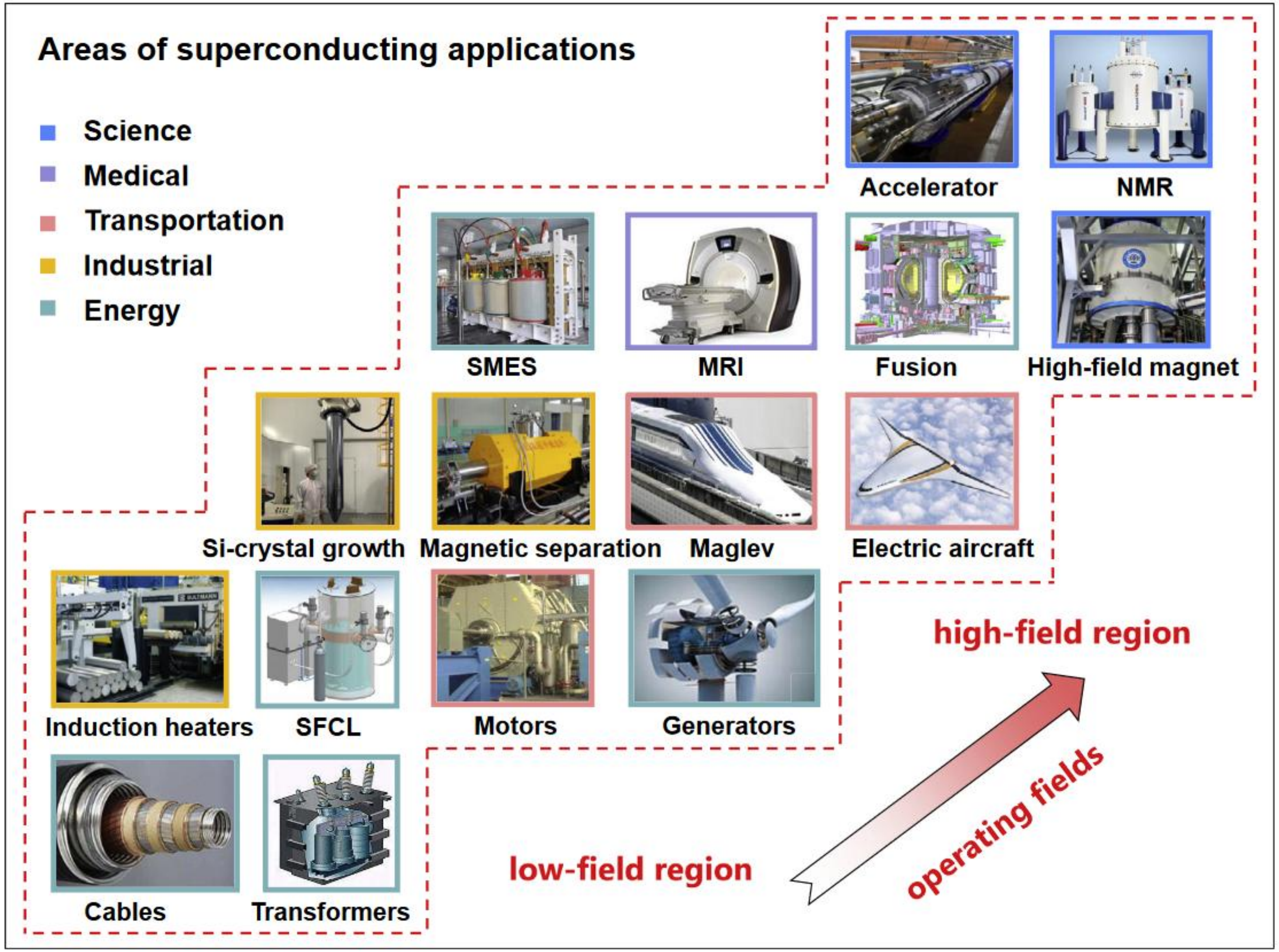


All superconductors seem to contain Cooper pairs and have similar phenomenology, i.e. Meissner state, gap in DOS, Josephson effects…



- ❑ Conventional superconductors : pairing is due to electron phonon coupling (i.e. lattice vibrations)
- ❑ Pairing mechanism is not known for unconventional superconductors! Still an open question.
- ❑ Most high T_c SCs are unconventional e.g. cuprates, iron-based (but probably not hydrides)
- ❑ Many low T_c unconventional SC's as well, e.g. heavy fermion compounds like $CeCu_2Si_2$, UPt_3
- ❑ Whoever figures it out will certainly win a Nobel Prize!

Applications I – High current-capacity conductors



C. Yao and Y. Ma, iScience **24**, 102541 (2021)

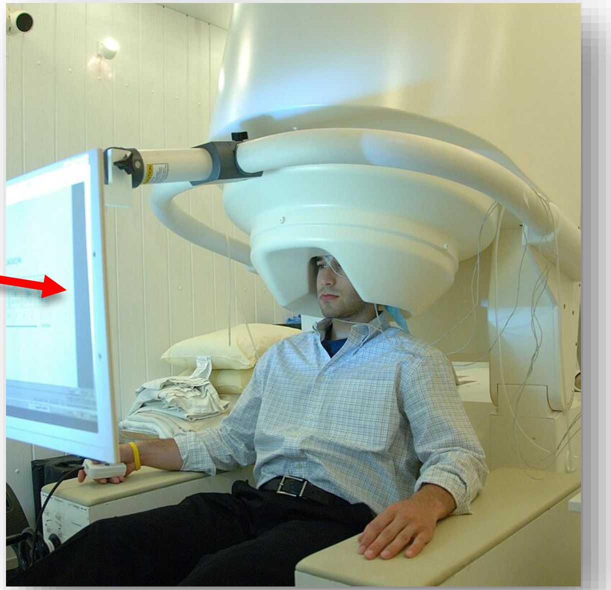
- ❑ Main use of superconductors is to carry high density of electrical current
- ❑ Simply not possible with normal metals, e.g. copper, due to heat dissipation
- ❑ Substantial engineering challenges to fabricate long cables with uniform properties
- ❑ Cuprates a popular choice, but ceramic-nature mean difficult to bend etc
- ❑ Iron-based materials also popular – cheaper, more ductile, more forgiving properties, but not as performant (yet)
- ❑ Specific application determines required properties
- ❑ Cryogenic cooling a further engineering challenge & cost (e.g. helium scarcity)

Applications II – Electronic & Quantum Technologies

Unique properties of superconductors can be exploited in many novel technologies, e.g. :

- SQUID magnetometers – used from research to medical settings (e.g. magnetoencephalography)
- Superconducting diodes – non-linear electronic components with zero resistance 'on' state
- Rapid single flux quantum (RSFQ) electronics – classical computing architecture based on SC's, very fast
- Superconductor-based particle and single-photon detectors
- Josephson-junction-based transmon qubits (amongst others) – foundation of many quantum computer architectures
- Superconducting resonators for detecting galactic axions
- Probably a lot more I don't know about (not my area of expertise 😅)

https://en.wikipedia.org/wiki/Magnetoencephalography#/media/File:NIMH_MEG.jpg



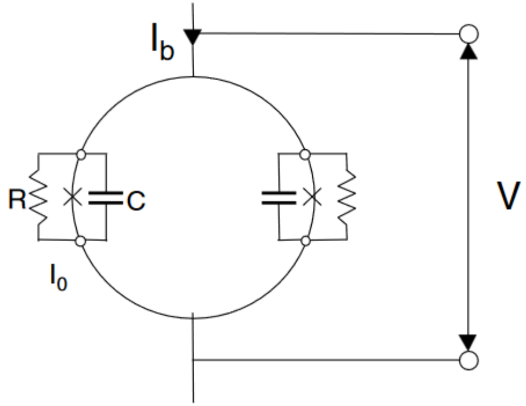
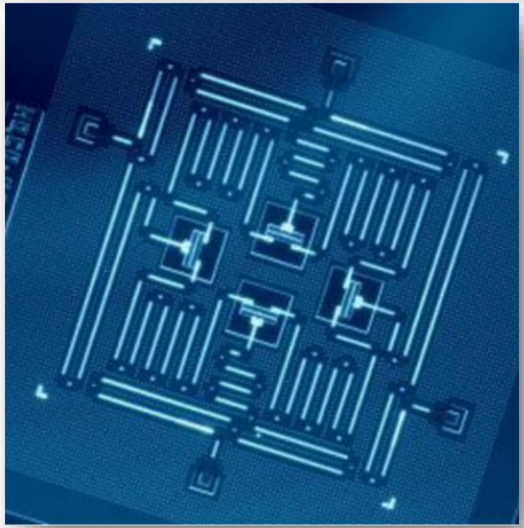
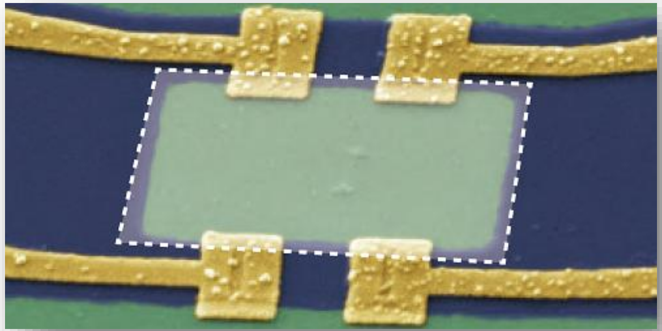


Figure 5. Schematic diagram of a dcSQUID.

Pizzella et al., Superconductor Science and Technology **14**, R79 (2001)



Gambetta et al., npj Quantum Information **3**, 2 (2017)



https://physics.aps.org/articles/v18/s12

Assignment

- See "Guidelines for technical report" on Moodle for full details
- In brief, maximum 3000 words (8 or so pages) technical report on a topic of your choosing*, that is written at a technical level understandable by a final year Physics / Nat Sci undergraduate
- *The topic needs to be on current research on superconductivity. Can be theory, experiment, materials, applications, devices etc, but **must focus on superconductivity!** Choose something that interests you.
- Please discuss with me if you have picked something tangential!
- You will need to read old as well as new publications to put research into context, but the emphasis should be on what is the current state of the research topic, i.e. what is the status? what direction will it go next? Why?
- There is a detailed mark scheme on Moodle – it is slightly different depending on whether you are Physics (32044) or Nat Sci (40044)
- PH30044 is the old name for PH32044
- There is also a document from Dr. Habib Rostami provided for last year's course – contains useful advice and suggestions

Assignment

- Superconductivity is a well-established research field, with links to lots of other aspects of physics and science
- This is good – you should be able to find a topic that interests you
- Any ideas already?
- This presentation will be on Moodle for you to refer back to
- I’ve also collated some hopefully useful resources & jumping-off points
- Watch out for inaccurate websites / documents that aren’t peer reviewed or possibly written by a crackpot – there are lots out there! Double check the “facts” / expertise of the author
- Peer-reviewed papers should be your primary source of information, textbooks can also supplement this

Resources

Magazines / Popular reading (for initial inspiration, not a primary source)

- Physics World
  https://www.physicsworld.com
- Scientific American
  https://www.scientificamerican.com
- New Scientist
  https://www.newscientist.com
- APS Physics
  https://physics.aps.org/
- AIP Physics Today
  https://pubs.aip.org/physicstoday

  https://pubs.aip.org/physicstoday/article/63/9/38/386608/The-discovery-of-superconductivityA-century-ago
- Quanta Magazine
  https://www.quantamagazine.com
- E.g. https://www.quantamagazine.org/room-temperature-superconductor-discovery-meets-with-resistance-20230308/

Audio

- In Our Time
  https://www.bbc.co.uk/programmes/m001hfpc

Books (be aware of date of most recent edition – things change quickly!)

- Stephen Blundell – “Superconductivity: A Very Short Introduction” (OUP, 2009) https://academic.oup.com/book/830
- Antonio Badía-Majós – “Macroscopic Superconducting Phenomena: An Interactive Guide” (IoP, 2021) https://iopscience.iop.org/book/mono/978-0-7503-2711-4
- Richard Feynman – “Feynman Lectures on Physics” #21 https://www.feynmanlectures.caltech.edu/III_21.html
- James Annett – “Superconductivity, Superfluids and Condensates” (OUP, 2004) https://academic.oup.com/book/54744
- Charles Poole et al. – “Superconductivity” (3rd ed, Elsevier, 2014) https://www.sciencedirect.com/book/9780124095090/superconductivity
- Michael Tinkham – “Introduction to Superconductivity” (2nd ed, Dover Publications Inc, 1996)
- Anant Narlikar – “Frontiers in Superconducting Materials” (Springer Nature, 2005) https://link.springer.com/book/10.1007/b138883

Resources

Journals (not an exhaustive list!)

Broad interest / high impact

- *Nature family:* Nature, Nature Physics, Nature Materials, Nature Communications
- *Science family:* Science, Science Advances

More physics-specialised, but still broader interest

- *Physical Review family:* Physical Review (older papers), Physical Review Letters, Physical Review X, Physical Review Applied, Physical Review Research

  Collection on SC: https://journals.aps.org/prl/heating-up-of-superconductors
- Applied Physics Letters, APL Materials
- ACS Nano, Nano Letters
- Communications Materials, Communications Physics, Scientific Reports, npj Quantum Materials
- Materials Today, Materials Today Physics, Advanced Materials, Journal of Applied Physics, Advances in Physics

Specialised, superconductor / condensed matter focused

- Superconductivity (Elsevier), Superconductor Science and Technology (IoP), Physica C: Superconductivity and its Applications (IoP), Physical Review B (APS), Journal of Physics: Condensed Matter (IoP)

Review Journals (make sure to look at primary sources)

- Reviews of Modern Physics, Nature Reviews Physics, Nature Reviews Materials, Annual Review of Condensed Matter Physics, Applied Physics Reviews

Further thoughts

- Be careful of MDPI-affiliated journals – reports of predatory behaviour and poor-quality peer-review process. However, some work is still very good quality – hard to tell apart!
- arXiv https://arxiv.org/list/cond-mat.supr-con/recent
  This is a preprint server – papers are not (yet) peer-reviewed, but there are new additions daily. You can often find interesting results here months before they are published. But you have to take them with a pinch of salt.
- Many, many more. I recently counted 150+ different journals in my collection on superconductivity & condensed matter physics.
- Use e.g. *Web of Science* and *Google Scholar* etc to help find related / interesting papers

Resources

Video (for inspiration, mostly – may contain errors)

- Mark Transtrum – a good introduction to concepts in SC (RF stuff not essential)
  https://www.youtube.com/watch?v=S0w8273i5uM

- Domain of Science – good overview, not completely up to date / accurate
  https://www.youtube.com/watch?v=bD2M7P6dTVA

- Steven Kivelson – an authority in condensed matter physics
  https://www.youtube.com/watch?v=Yx666k2XH8E
  https://www.youtube.com/watch?v=ROwLS0cKUN4

- Andrew Boothroyd – also well known in the field
  https://www.youtube.com/watch?v=NzzchLXdGmE

- Sean Hartnoll – discussing connections with black holes
  https://www.youtube.com/watch?v=L5WY9xGPjS4
  https://www.youtube.com/watch?v=RIrZnhHTBS8

- Cambridge lectures on superconductivity – looks a bit dated, but accurate
  https://www.ascg.msm.cam.ac.uk/lectures/introduction.html

- CERN Introduction to Superconductivity – also looks a bit dated
  https://cds.cern.ch/record/396936?ln=en

- Greg Stewart – very knowledgeable, video not great quality
  https://www.youtube.com/watch?v=KZRIonT6p7Q
  https://www.youtube.com/watch?v=W-rgcLxFgpM

- Veritasium "World's Strongest Magnet" – superconductivity adjacent, entertaining
  https://www.youtube.com/watch?v=g0amdIcZt5I

- PBS Spacetime – a little sensationalist, wouldn't trust entirely
  https://www.youtube.com/watch?v=npynpWkUSYw

- Tout est Quantique – fun quantum-related animations
  https://toutestquantique.fr/

Possible Topics

UNIVERSITY OF BATH

- Unconventional superconductivity – are all unconventional superconductors the same? Is there a common mechanism?
- Origin of high temperature superconductivity in cuprates – what is the relation of SC to other ordered phases, i.e. charge density waves, antiferromagnetic mott insulator, strange metal …
- Is room temperature superconductivity possible? Under what circumstances?
- Multi-gap superconductors – how does this affect SC properties, theories etc
- SC in twisted bilayer graphene
- Carbon-based superconductors
- Organic superconductors
- Hydride superconductors (watch out for Ranga Dias / retractions)
- Nickelate superconductors
- Pressure-induced superconductivity (not hydrides)
- LK-99 controversy – was it even a superconductor?
- 3D printed superconductors – additive manufacturing
- SC-based particle / photon detectors
- SC electronics (rapid single flux quantum logic)
- Iron-based superconductors
- Magnetic superconductors (i.e. coexisting SC and long-range magnetism)
- Exotic superconductors, e.g. UTe_2, Sr_2RuO_4, Kagome materials
- Majorana bound states in SC
- Pair density wave SC
- Hunt for finite-momentum / FFLO states
- Light-induced / transient superconductivity
- Connection between black holes and high Tc superconductivity
- Superconductivity in neutron stars
- State of the art superconductor-based qubits
- High-current capacity SC wires for e.g. MRI (MgB_2?)
- Magnetic confinement in fusion applications (irradiation damage)
- Aviation / transport / Maglev trains
- Energy storage
- Magnetic imaging in the body (using e.g. SQUIDs)
- Anything else you think is interesting!