Cryogenics Hands-on Training

Part 2: Liquid Oxygen/Eddy Current/Electrical Properties

The 7th Asian School on Superconductivity and Cryogenics for Accelerator

Feb 1—9, 2026

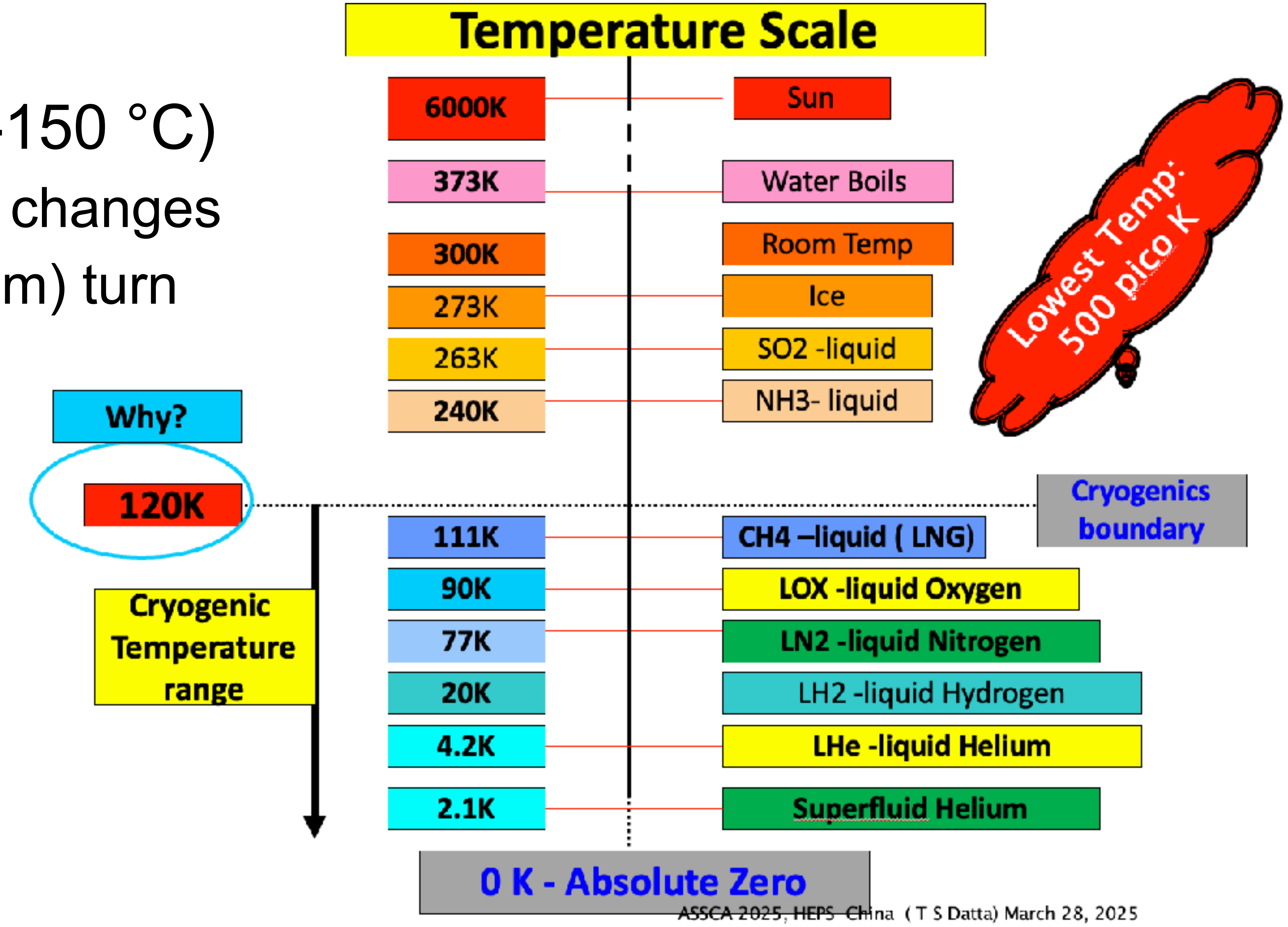
Soohyung Lee (Korea University)

What is Cryogenics?

- Cryogenics is a branch of physics that studies what happens to things at very low temperature.

- Cryogenic temperature: < 123 K (or < -150 °C)
  - "Normal" behavior of materials drastically changes
  - Gases (oxygen, nitrogen, hydrogen, helium) turn into liquids

- Many lectures in ASSCA2026
  - Cryogenics I (Prof. Sangkwon Jeong)
  - Cryogenics II (Prof. Rui Ge)
  - Cryogenics III (Prof. Hirotaka Nakai)
  - Cryogenics IV (Prof. Xilong Wang)
  - Cryogenics V (Dr. Seo Jung Kim)



Prof. T. S. Datta (ASSCA2025)

SAFETY WARNINGS

- We are using LN_2 today
  - Very common (78% of air, cheap) → good for simple coolings
- It's **VERY COLD** (77 K = -196 °C). **Be aware all the time, wear protection gears** (gloves and glasses)

Today's Hands-on Trainings

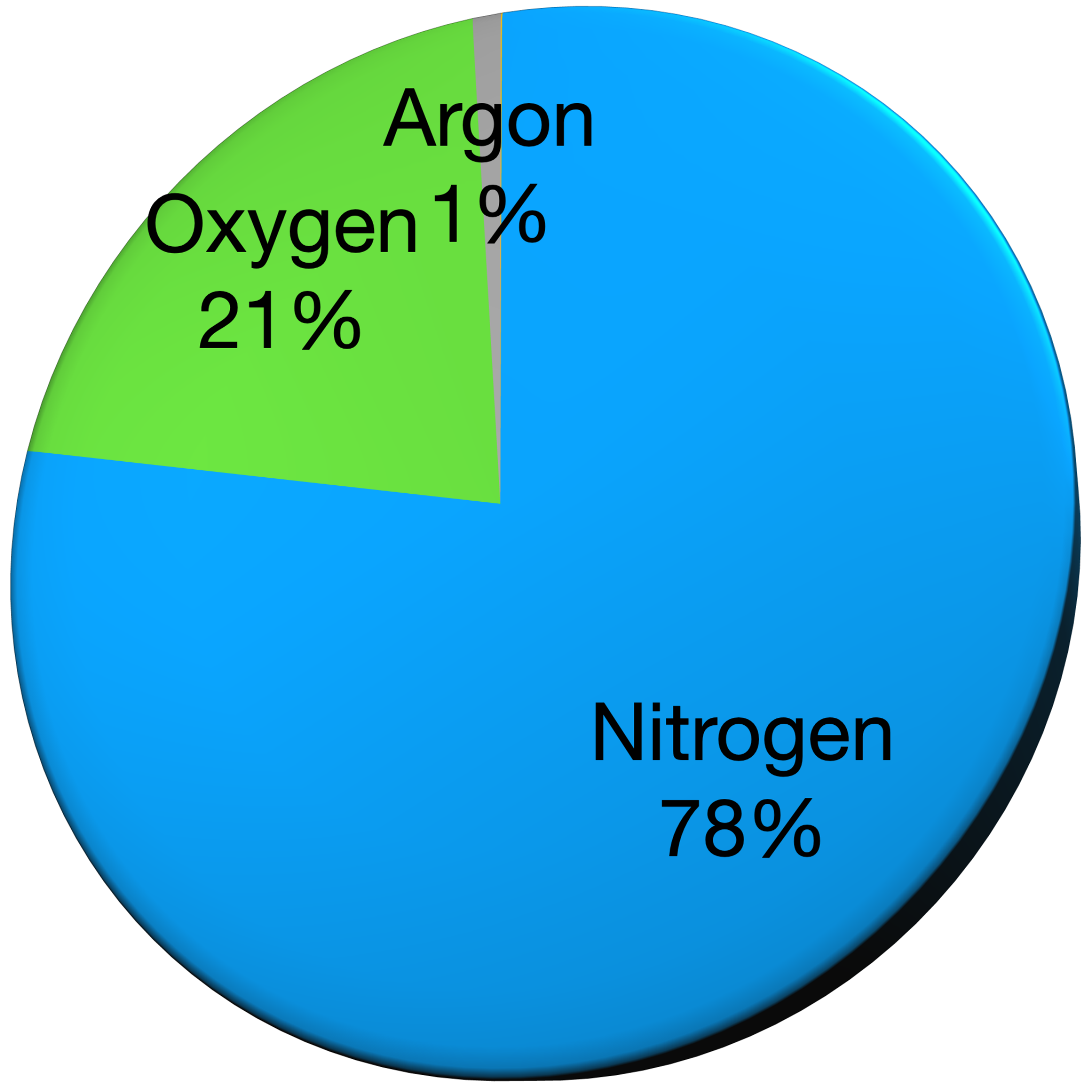
- #1: Liquid oxygen
  - Producing some liquid oxygen and confirming it
- #2: Eddy current
  - Feeling the effects of eddy current with various materials
- #3: Temperature coefficients of resistance and capacitance
  - Measuring resistance and capacitance and obtaining temperature coefficients of resistance and capacitance
- We'll do those in the accelerator lab (1st floor)

#1: Liquid Oxygen

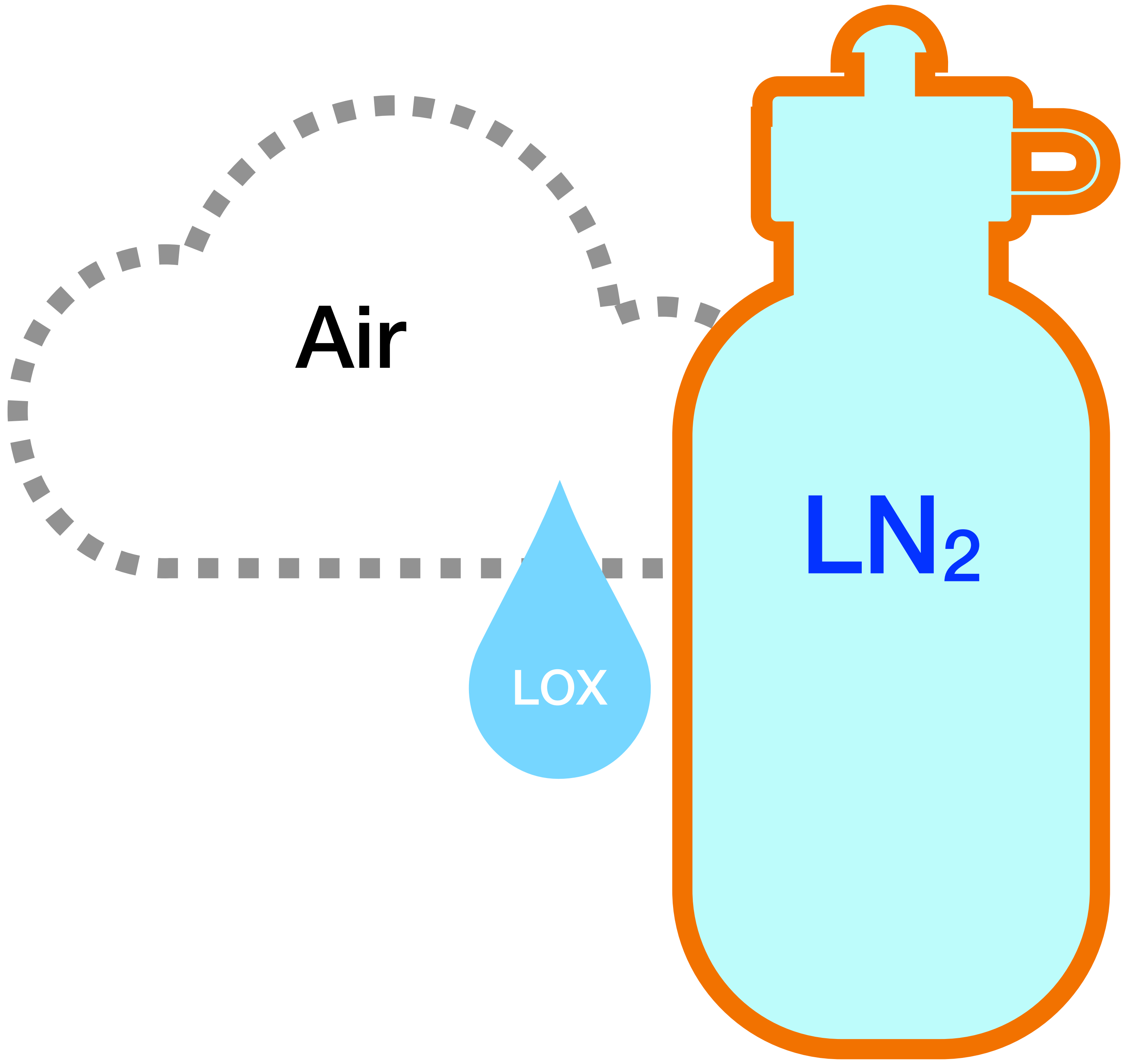
Liquid Oxygen

- Oxygen is the 2nd most common element in the air

Element	Portion [%]	Boiling Point [K]
Nitrogen (N_2)	78.084	**77.4**
Oxygen (O_2)	20.946	**90.2**
Argon (Ar)	0.9340	87.3
Carbon dioxide (CO_2)	0.04	194.7



- Liquid nitrogen (LN_2) will provide a lower temperature than the boiling point of oxygen
  - Oxygen in the air will condense to a liquid (LOX) at the temperature
  - LOX can be confirmed by its properties:
    - Pale blue
    - Paramagnetic: weakly attracted by a magnet
    - Oxidant: Don't do this…



Liquid Oxygen

- What we are going to do:
  - Pouring an amount of LN_2 into a copper cone
  - Wait for a while until the copper cone is cooled down enough
  - At some point, you'll see some liquid drops from the bottom
  - Place a magnet if the liquid is affected by the magnetic

#2: Eddy Current

Eddy Current

- Varying magnetic field induces a current inside a conductor → “Eddy current”
  - Eddy current generates a secondary magnetic field against the varying magnetic field (Lenz’s law)

- Many applications in our real-life

Eddy Current

- Maxwell's equation (in vacuum)

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0} \qquad \nabla \cdot \vec{B} = 0$$

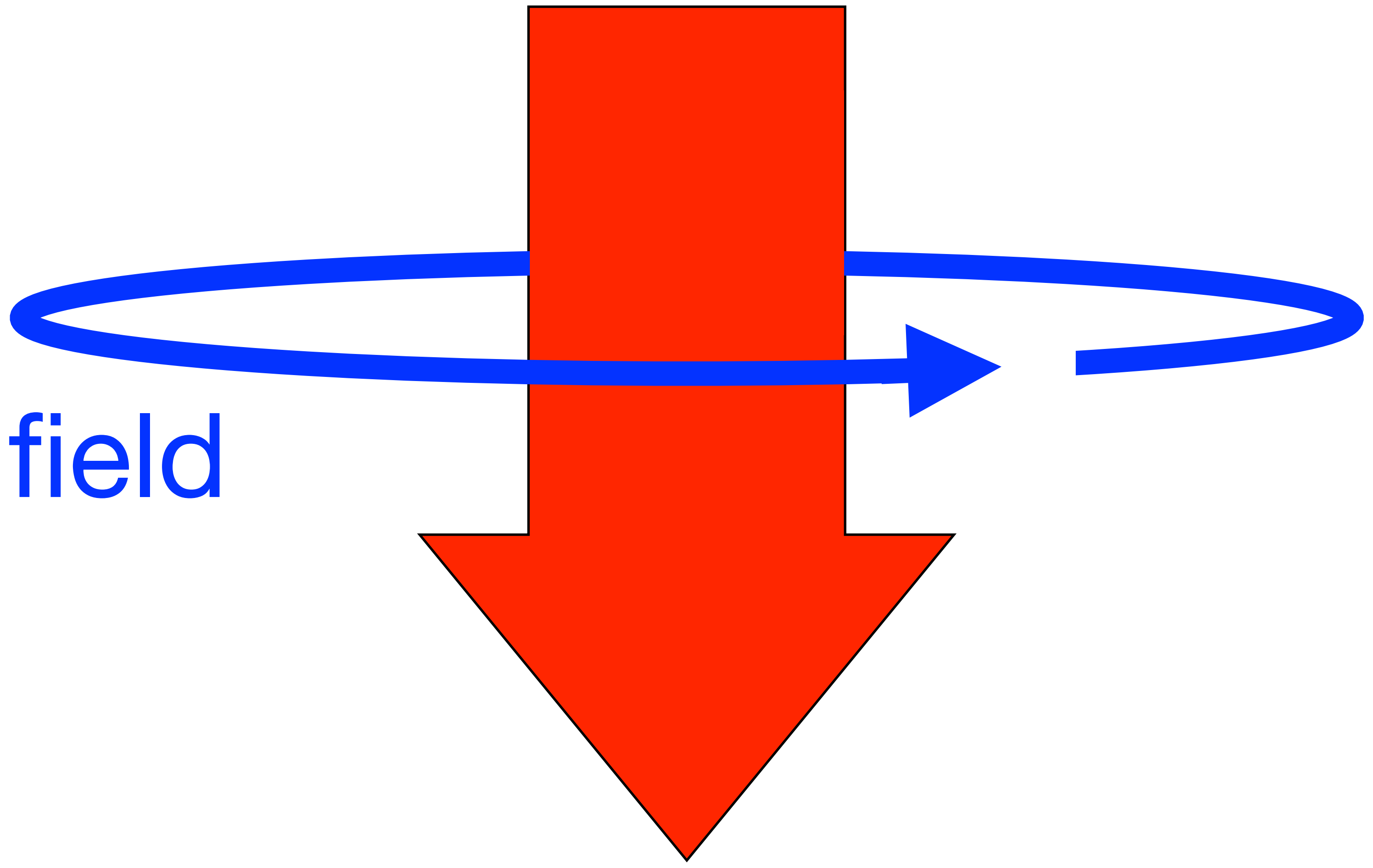
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

Faraday's law

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \epsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t}$$

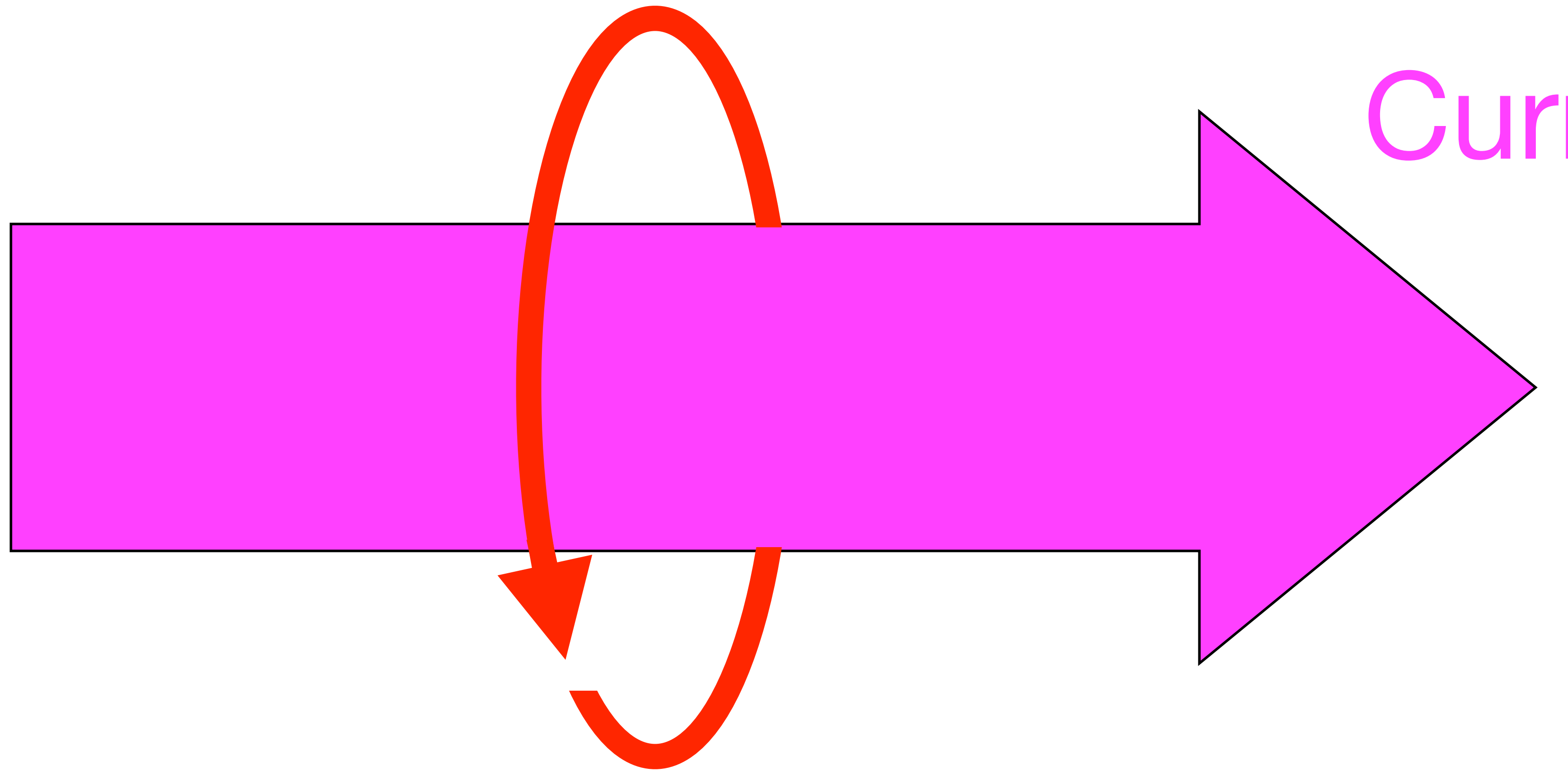
Ampere's law

Varying (increasing) magnetic field



Electric field

Current



Induced magnetic field

Eddy Current

- If the varying magnetic field is surrounded by a conductor,

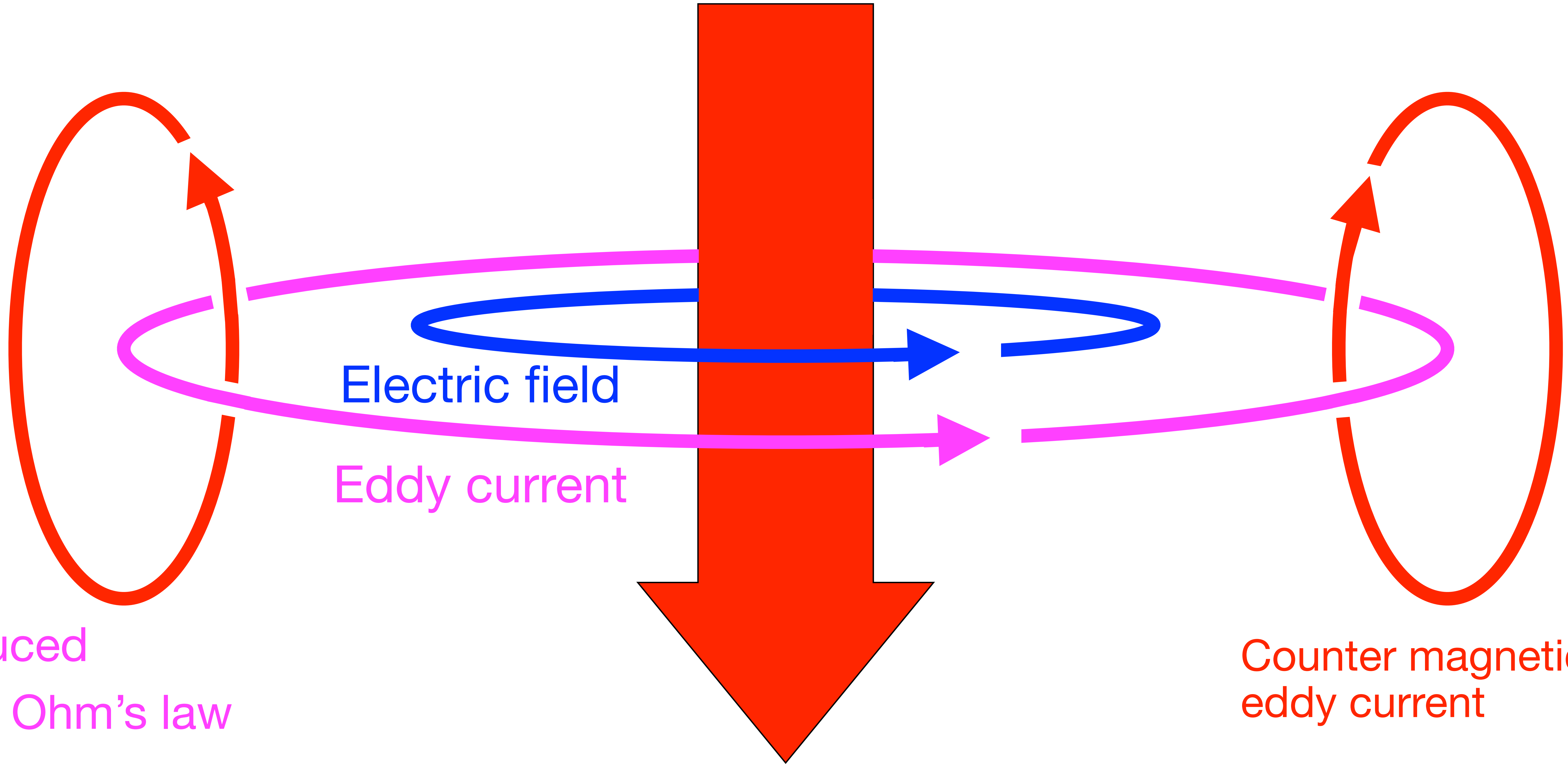
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

Faraday's law

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \epsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t}$$

Ampere's law

Varying (increasing) magnetic field



$$\vec{J} = \sigma \vec{E}$$

Ohm's law

Eddy current is induced
in the conductor by Ohm's law

Counter magnetic field is induced by the eddy current

Eddy Current

- Ohm's law tells us that a material with a higher conductivity (=less resistance) yields a higher eddy current with a given electric field

$$\vec{J} = \sigma \vec{E}$$

- Resistivity of metal usually decreases as the temperature decreases
    - e.g. Copper: $\rho_{300\,\mathrm{K}} / \rho_{77\,\mathrm{K}} \simeq 8$

- Thus, stronger counter magnetic field at lower temperatures

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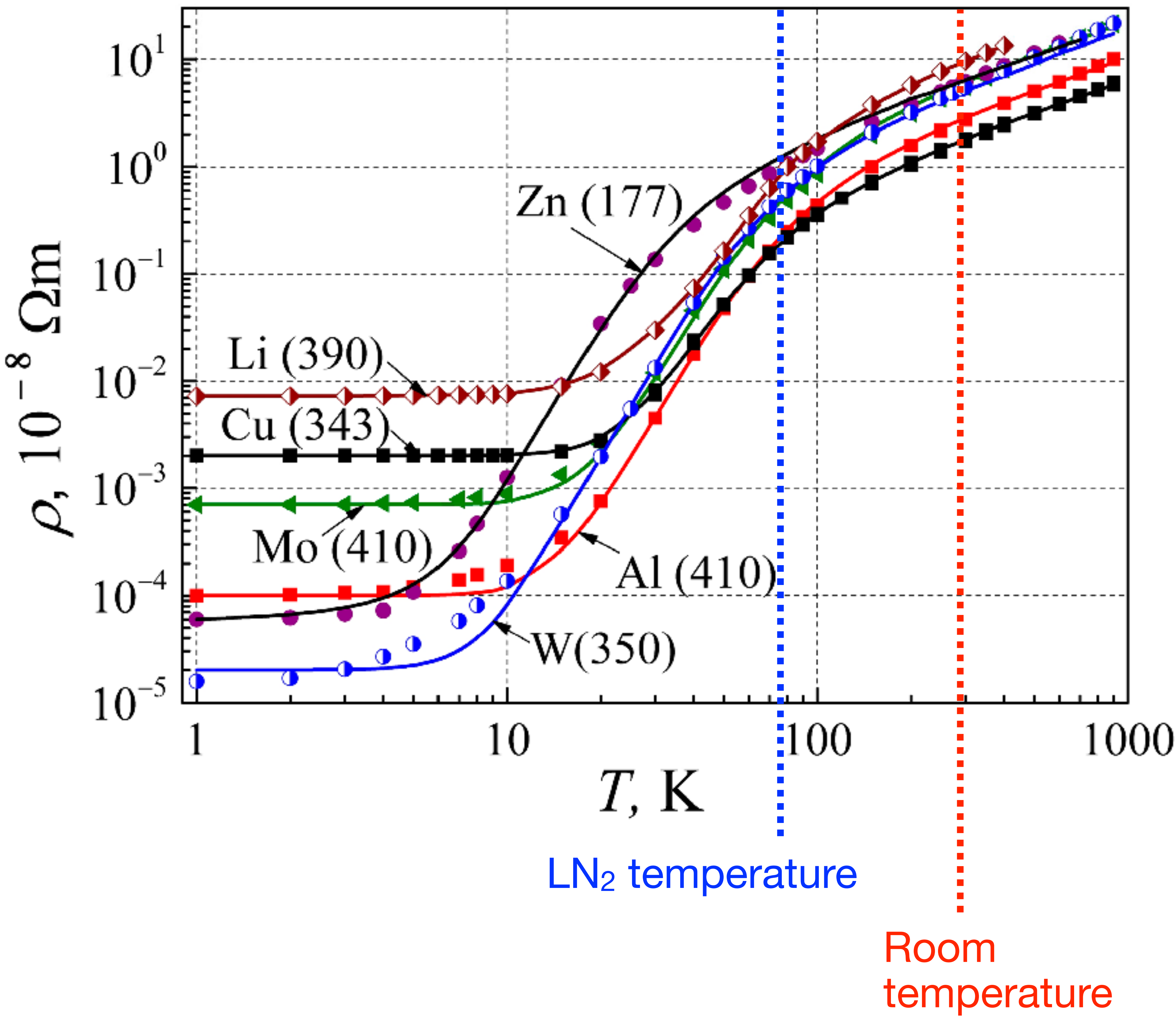
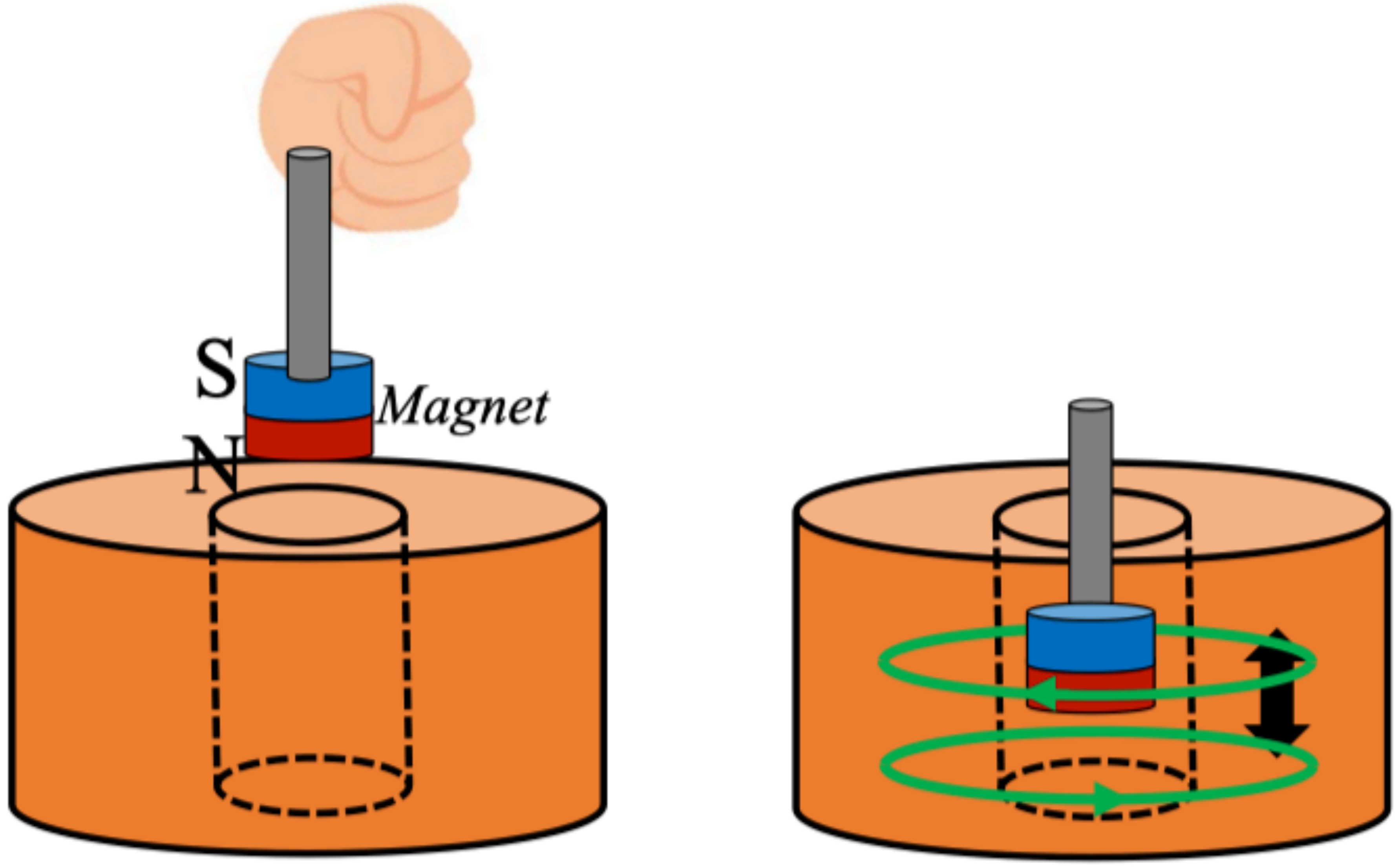
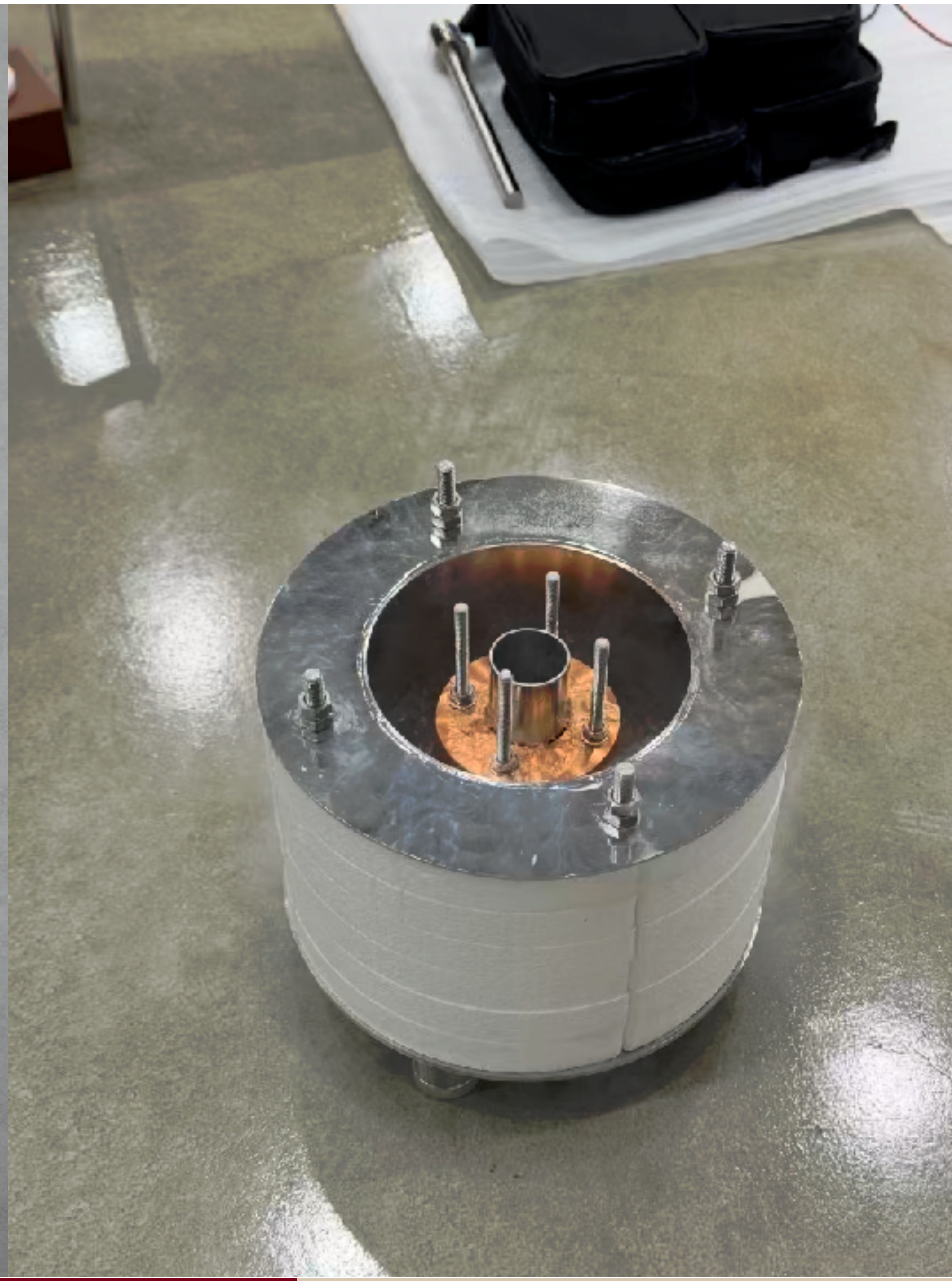


Eddy Current

- What we are going to do:
  - Pushing and pulling a magnet inside conductors at a room-temperature
    - Copper and aluminum
  - Do the same with cryogenic copper
  - Feel the resistive force





#3: Temperature Coefficients of Resistance and Capacitance

Temperature Coefficients of Resistance and Capacitance

- As seen, resistivity of a material changes over its temperature
  - Extreme example: superconductors ($\rho_{\text{Nb}} = 0$ at $T_c < 9.25$ K)
- Temperature coefficient of resistance (TCR)

$$R = R_0 \left[1 + \alpha(T - T_0)\right]$$

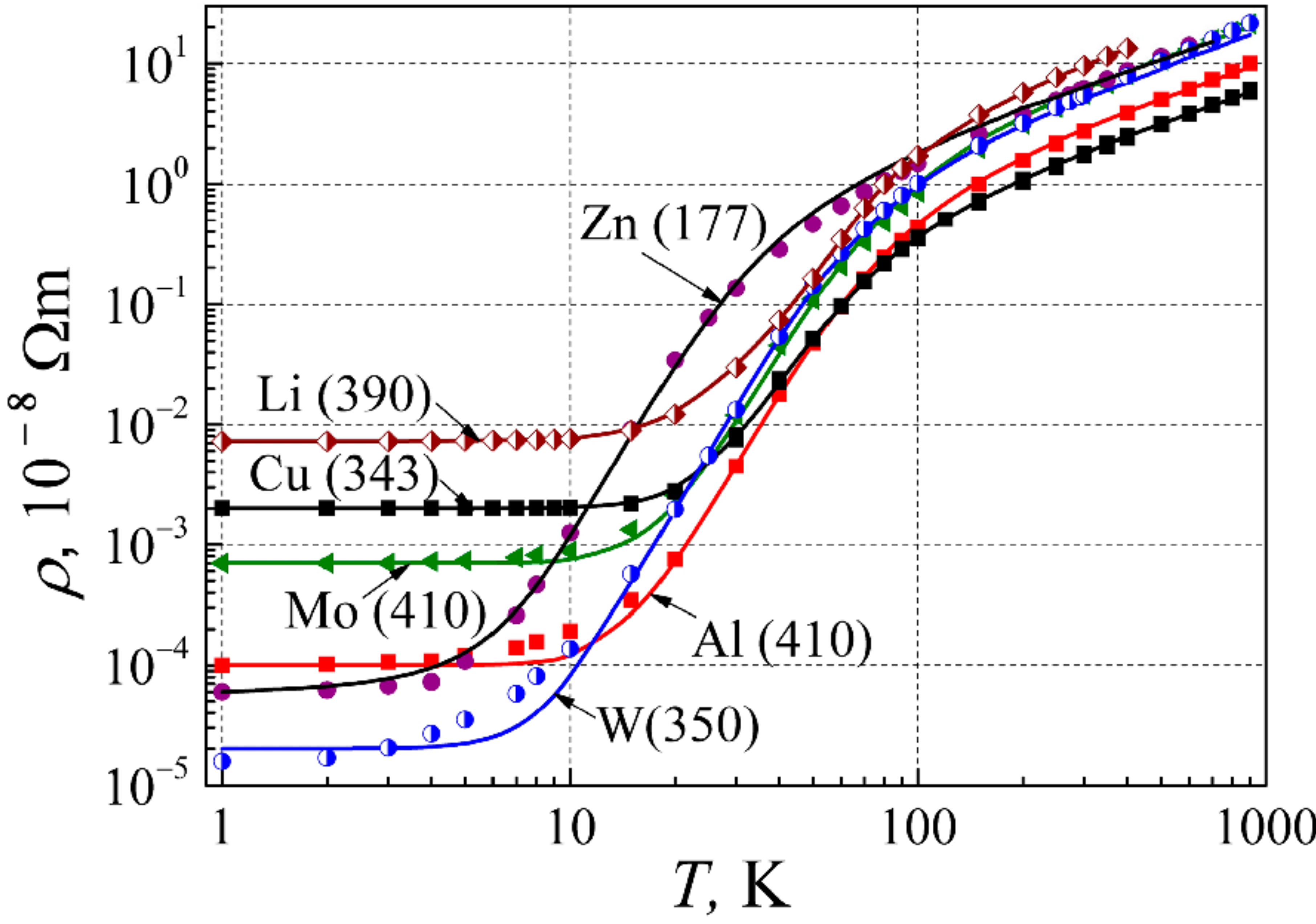
R: resistance at a temperature T
R_0: resistance at a reference temperature T_0
α: temperature coefficient of resistance

- Capacitance also changes over temperature
  - Changing of dielectric material behavior in capacitors
    - e.g. electrolytic capacitors: electrolytes are frozen → drastically decreasing capacitance
- Temperature coefficient of capacitance (TCC)

$$C = C_0 \left[1 + \alpha(T - T_0)\right]$$

C: resistance at a temperature T
C_0: resistance at a reference temperature T_0
α: temperature coefficient of capaciitance

V. Palenskis, Metals ***2024****, 526 (2024)*

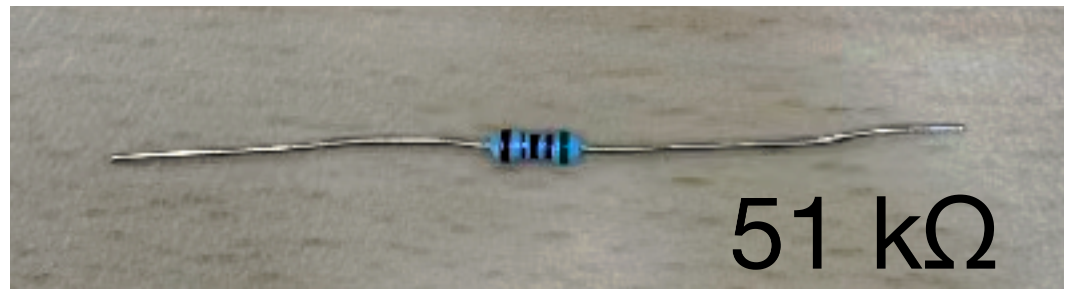


By measuring resistances (or capacitances), you can extract TCR (or RCC)

Temperature Coefficients of Resistance and Capacitance

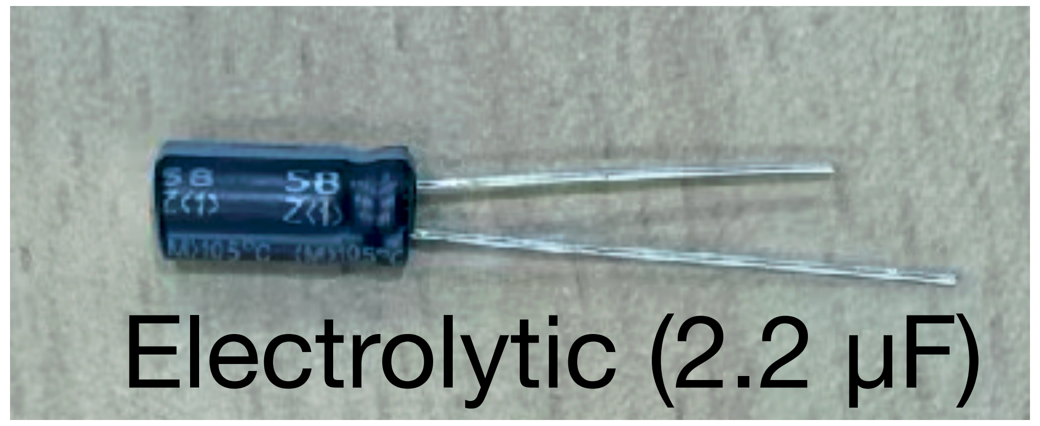
- What we are going to do: Obtaining TCR and TCC of various resistors/capacitors

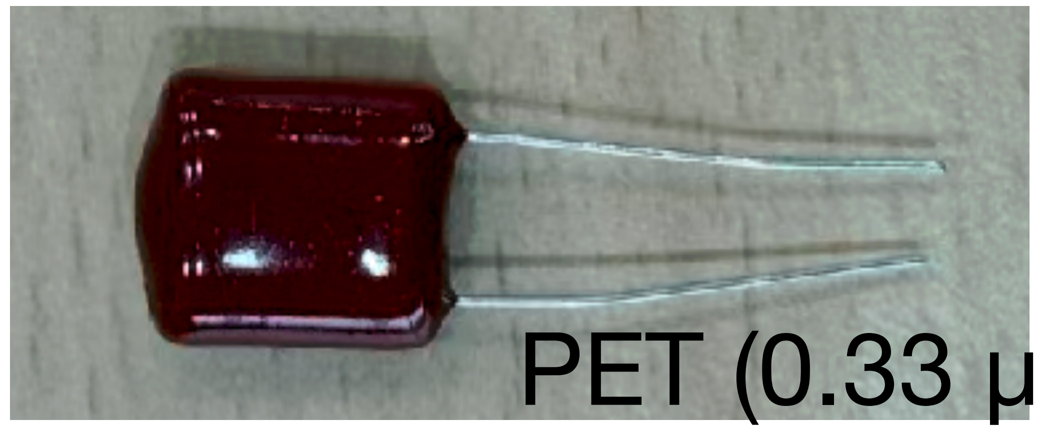
- Resistors
  - Metal film resistors



  - Measure the resistance of them at a room-temperature and a cryogenic temperature
  - Estimate TCR and interpret the measurement

- Capacitors
  - Electrolytic capacitor (aluminum)
  - Metallized polyester capacitor (PET)





  - Measure the capacitance of them at a room-temperature and a cryogenic temperature
  - Estimate TCC and interpret the measurement

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