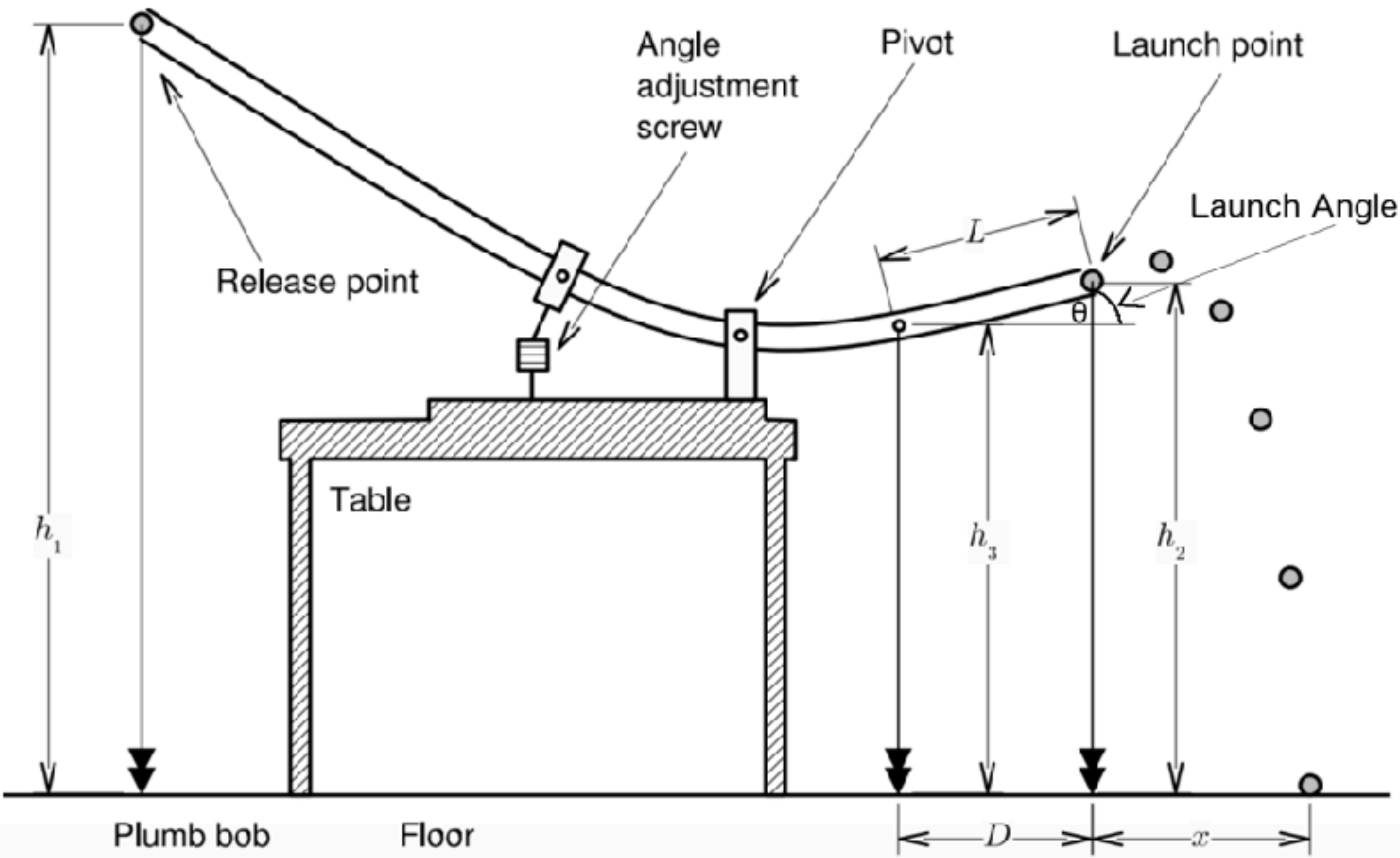

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Experiment 3: Magnetic Fields

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Office Hour: Mondays, 5:30PM-6:30PM @ Pupin 1216

INTRO TO EXPERIMENTAL PHYS-LAB
1494/2699

Outline

- Today we will deal with magnetic fields only
- The <u>physics of interest</u> to understand the experiment is:
  - Interplay between electric currents and magnetic fields:
    - Currents experience magnetic force (Lorentz law)
    - Current generate magnetic fields (Biot-Savart law)
- The <u>experiment</u> will be mainly focused on:
  - Determining the magnetic field of an electromagnet using the Lorentz force
  - Study the induced e.m.f. of a magnetic field through a coil of known geometry

Magnetic fields

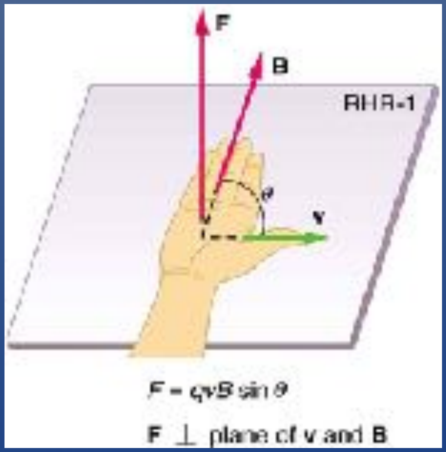
- What creates a magnetic field?

  <u>Answer:</u> Moving charges!

- **Question:** How do we <u>define</u> the magnetic field?
- While the electric field has a nice definition that only involves its sources ($\vec{E} = (kq/r^2)\hat{r}$), this is not the case for magnetic fields
- They can only be defined operatively through the force they exert on a moving charge (**<u>Lorentz force</u>**):

$$\vec{F} = q\vec{v} \times \vec{B}$$

- Right-hand rule:



Given a charge *q* moving with velocity ***v***, the **magnetic field** is whatever we have to plug into this equation to find the right magnitude and direction of the exerted force

Lorentz Force

- From the previous slide, a charged particle entering a magnetic field with some velocity will feel a Lorentz force:

$$\vec{F} = q\vec{v} \times \vec{B}$$

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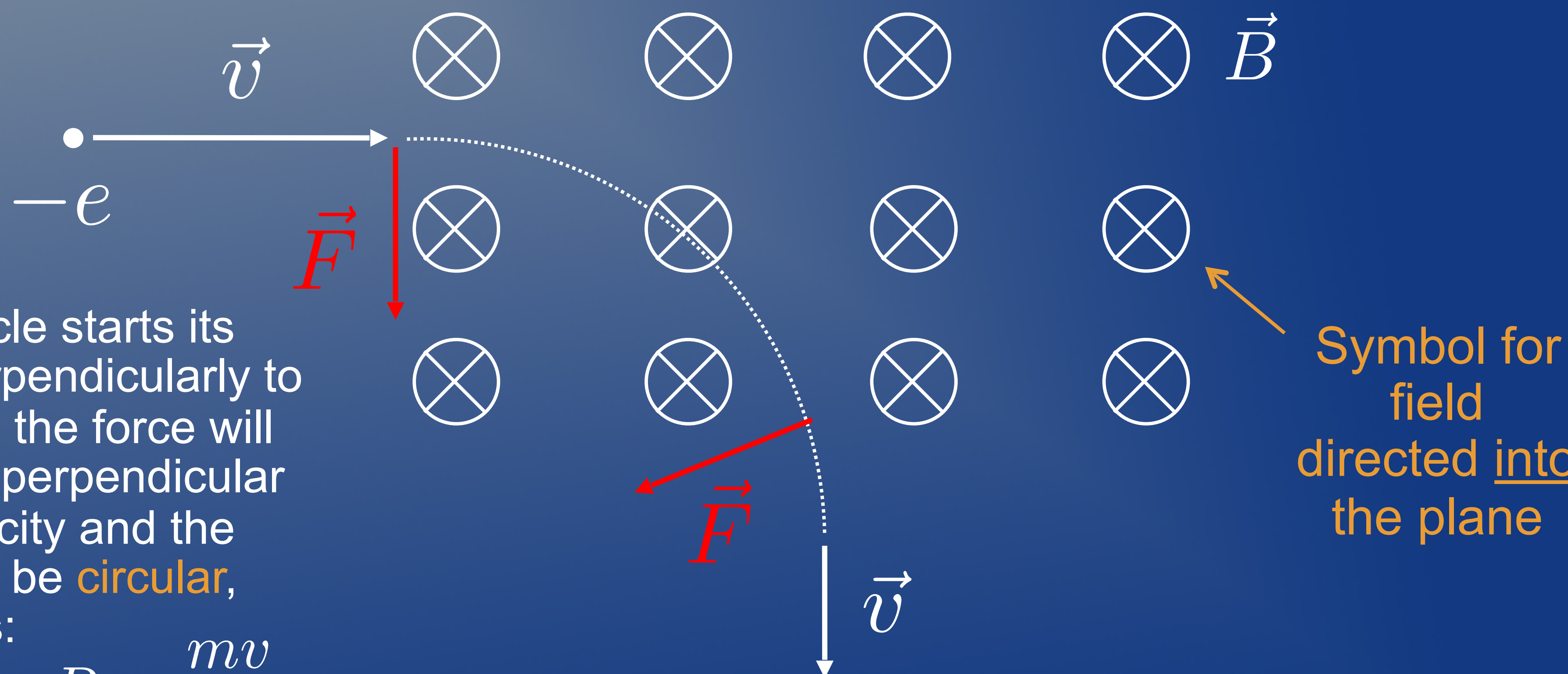


If the particle starts its motion perpendicularly to the B field, the force will always be perpendicular to the velocity and the motion will be circular, with radius:

$$R = \frac{mv}{qB}$$

Current carrying rod under magnetic field

- Since current = many moving charges ⟶ wire/rod carrying a current will experience the Lorentz force as well!
- Let's consider a <u>small</u> moving charge (*dq*) contained in a <u>small</u> piece of wire (*dx*). The <u>small</u> Lorentz force exerted on this charge by an external field *B* is then:

$$d\vec{F} = dq\,\vec{v} \times \vec{B} = dq\frac{d\vec{x}}{dt} \times \vec{B} = \frac{dq}{dt}d\vec{x} \times \vec{B}$$

$$= I\,d\vec{x} \times \vec{B}$$

- Integrating over the all wire, the total force is:

$$\vec{F} = I\,\vec{L} \times \vec{B}$$

Force exerted on the wire

External B field

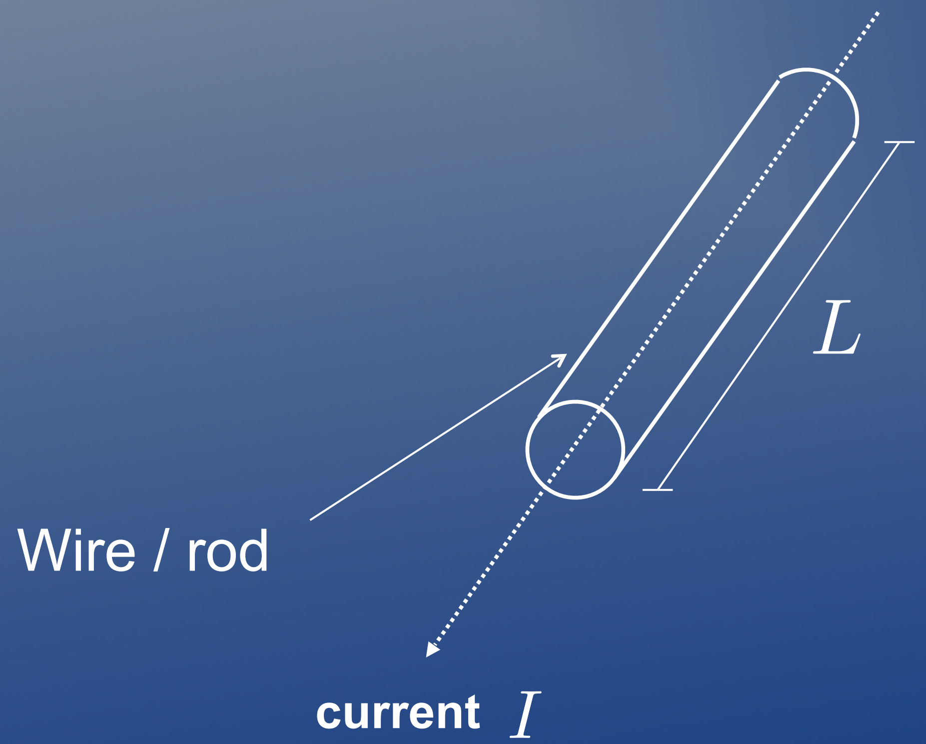
Current flowing through the wire

Vector with magnitude given by the length of the wire and direction parallel to the current

Current carrying rod under magnetic field

- Let's see how the force works:

$$\vec{F} = I\,\vec{L} \times \vec{B}$$



Current carrying rod under magnetic field

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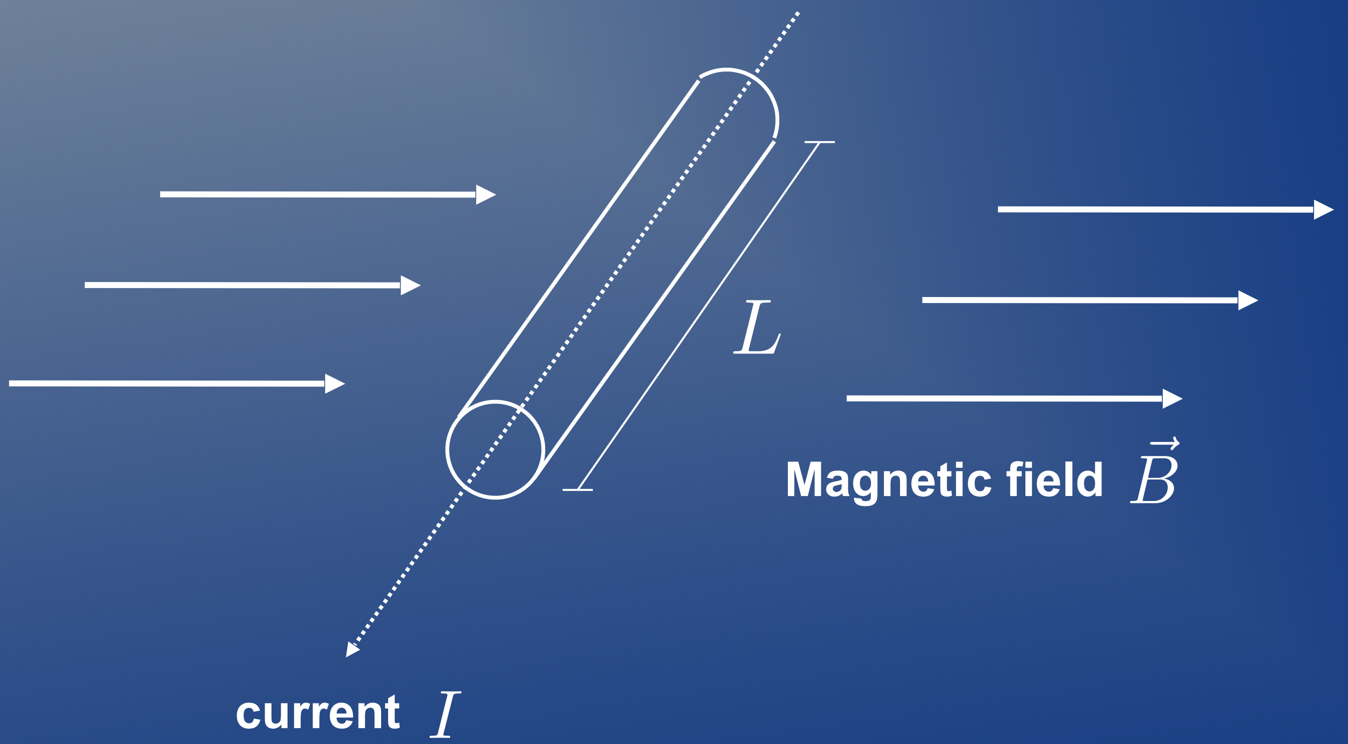

Current carrying rod under magnetic field

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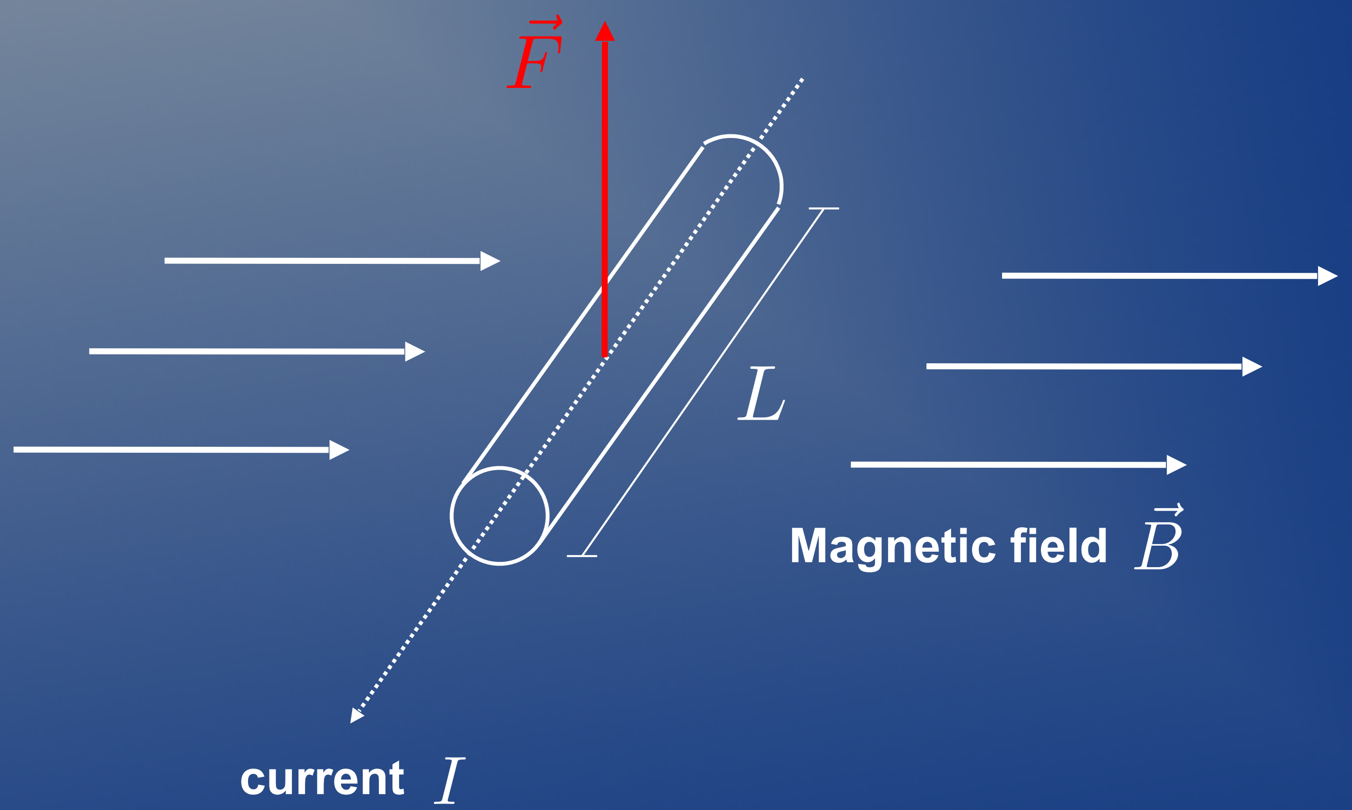
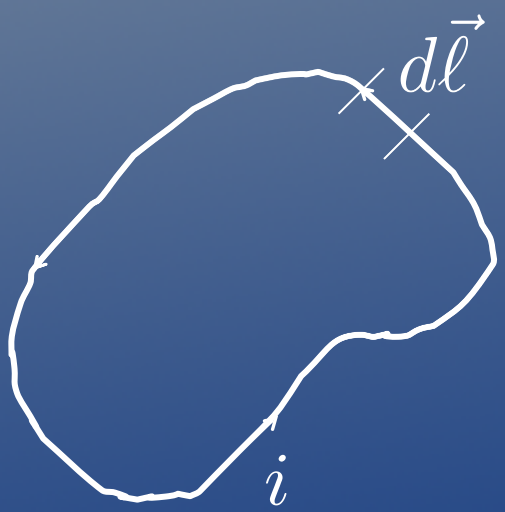
$$\vec{F} = I\,\vec{L} \times \vec{B}$$



Current generating a magnetic field

- We just saw that a current can “feel” a magnetic field by experiencing the Lorentz force
- However, it turns out that currents also **generate magnetic fields**
- The law describing the small magnetic field generated by a small piece of wire with a current is the **Biot-Savart law**:



$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{i\,d\vec{\ell}\times\hat{r}}{r^2}$$

Current in the wire

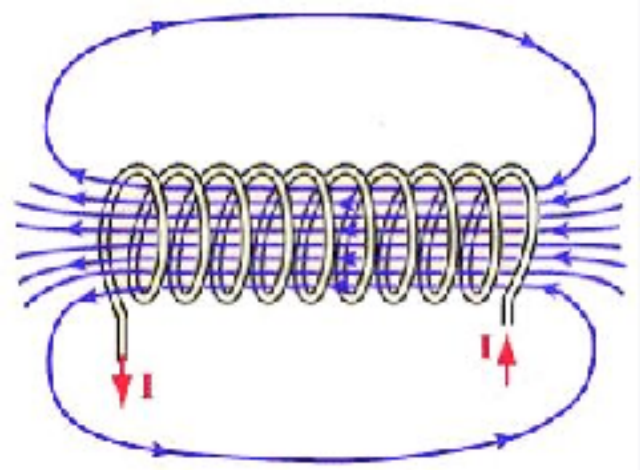
Vector with length as the small piece and direction as the current

Position of the point where we are observing the B field

$$\mu_0 = 4\pi\times 10^{-7}\ \mathrm{N/A^2}$$

Magnetic field from a solenoid

- The only case of some interest for this weekly experiment is that of many consecutive loops. Such a system is called a solenoid
- Without showing the (boring) details of the calculation, if we have many consecutive loops carrying a current *i*, then the field is approximately:



$$B = \begin{cases} \mu_0 \frac{Ni}{L} & \text{inside} \\ 0 & \text{outside} \end{cases}$$

N = number of turns;

L = length of the solenoid

- In our case, we also will not be in vacuum and hence we will have $\mu_0 \longrightarrow \mu_0 \mu_r$

Average induction

- As we know, **Faraday's law for induction** states that the change in time of the magnetic flux through a surface generates an e.m.f.:

Total flux — Total number of turns — Flux through the single loop

$$\mathcal{E} = -\frac{d\Phi_{\text{coil}}}{dt} = -N\frac{d\Phi_{\text{loop}}}{dt}$$

- If the area of each loop is constant with time and the field changes by *ΔB* over a time *Δt*, then the e.m.f. can be simply computed as:

$$\mathcal{E} = -NA\frac{\Delta B}{\Delta t}$$

- This is what you will use for the experiment

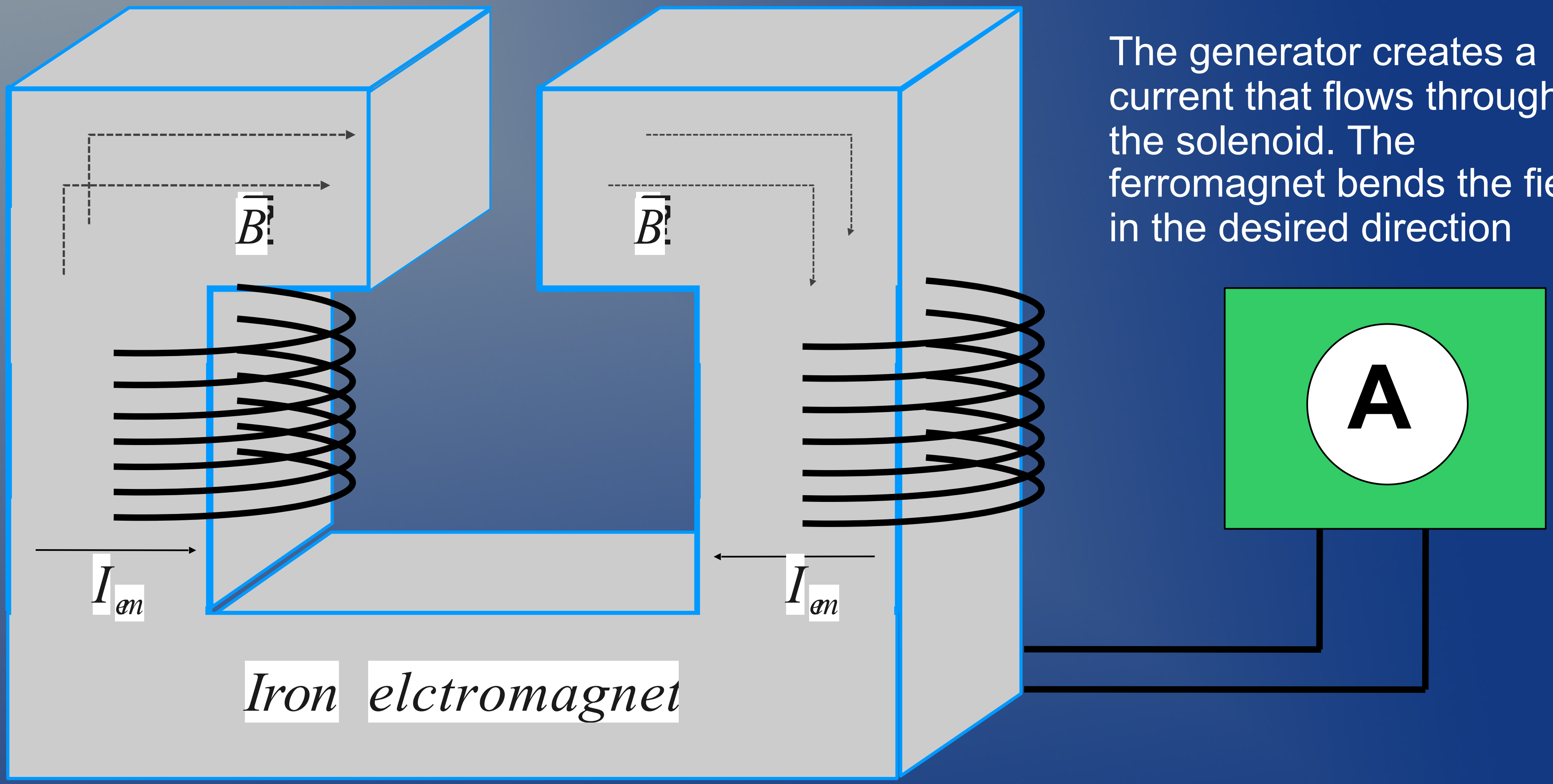
The Experiment

Main goals

- In this experiment we will study magnetic field through the analysis of Lorentz force and Faraday's law.
- The main goals are:
- **Part 1:** to measure the magnetic field in an electromagnet by balancing the Lorentz force with gravitational force
- **Part 2:** to verify Faraday's (and Lenz) law of induction by observing the e.m.f. generated in a coil subject to a varying magnetic field

Part 1: the electromagnet

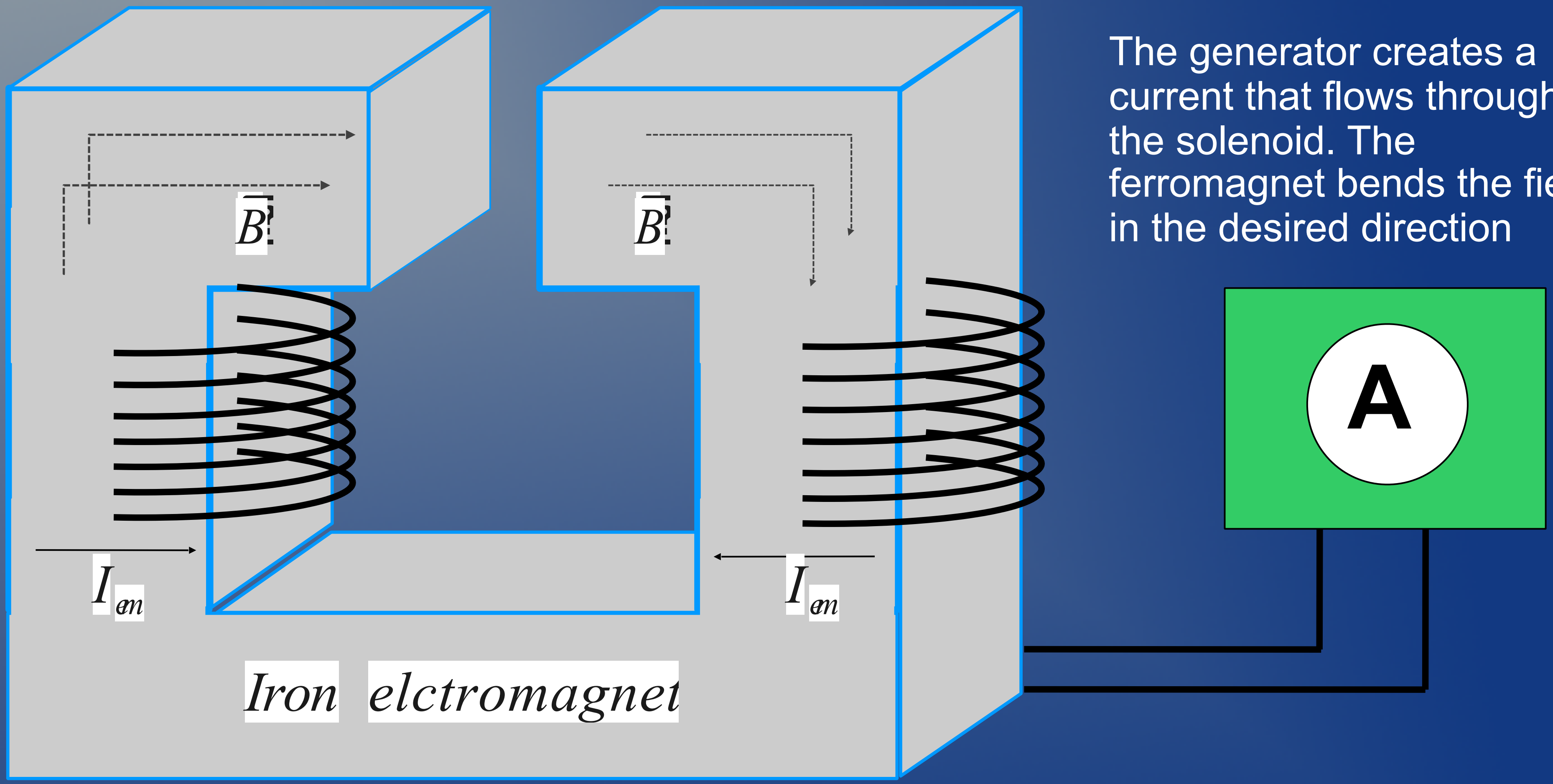
- We will have a big ferromagnet with a solenoid around it



The generator creates a current that flows through the solenoid. The ferromagnet bends the field in the desired direction

Part 1: the electromagnet

- Current carrying coils create magnetic field in magnet!



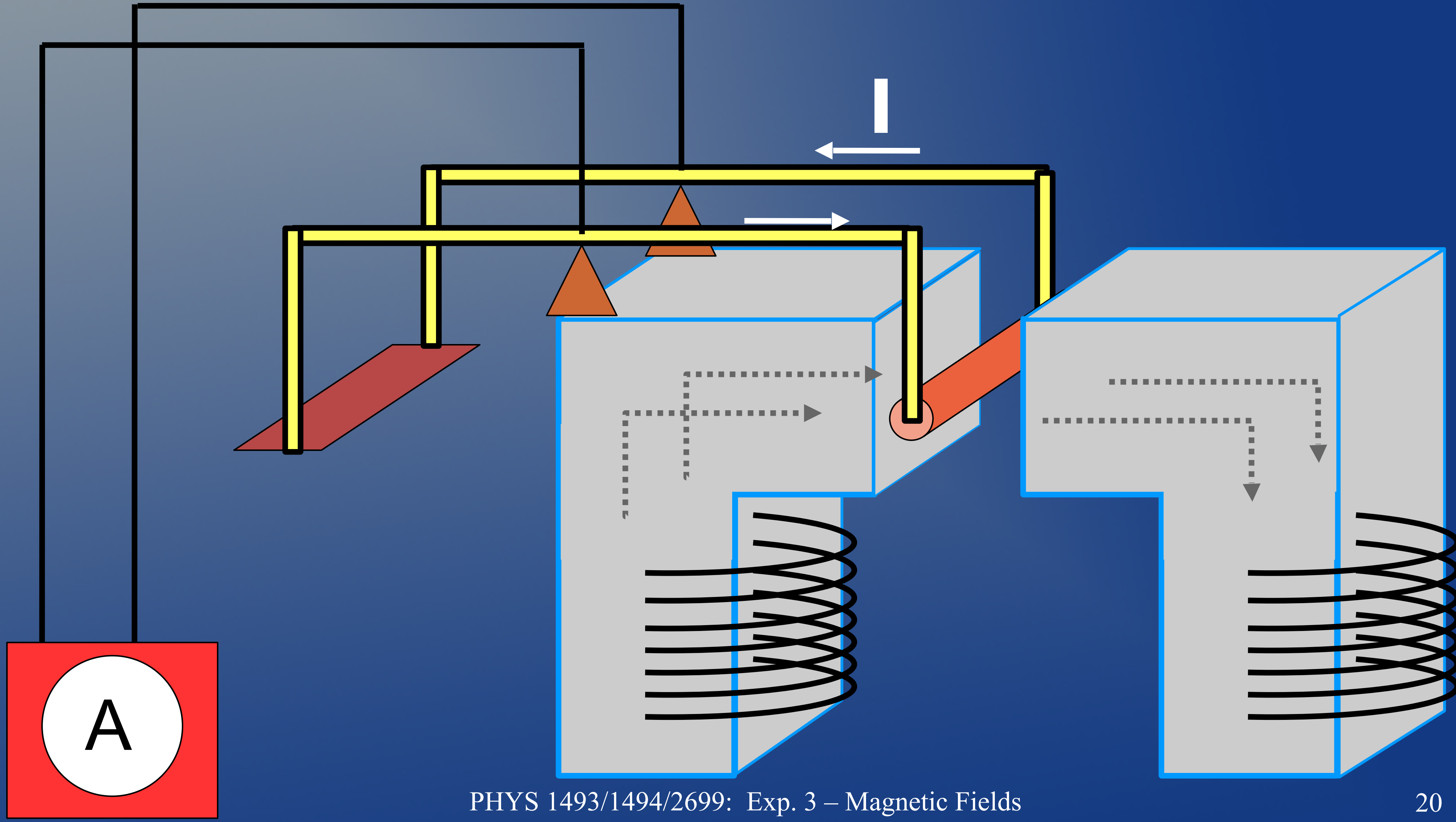
The generator creates a current that flows through the solenoid. The ferromagnet bends the field in the desired direction

Part 1: current carrying balance

- Given a magnetic field and a current carrying rod, we know how the force exerted on the rod looks like (Lorentz force) from electromagnetic theory
- **Question:** can we use this to compute the magnetic field of the electromagnet?
- **Idea:** We can use known weight to balance the Lorentz force and hence find its magnitude. Once this is known (and given the current flowing through the rod) we can easily compute the magnetic field!

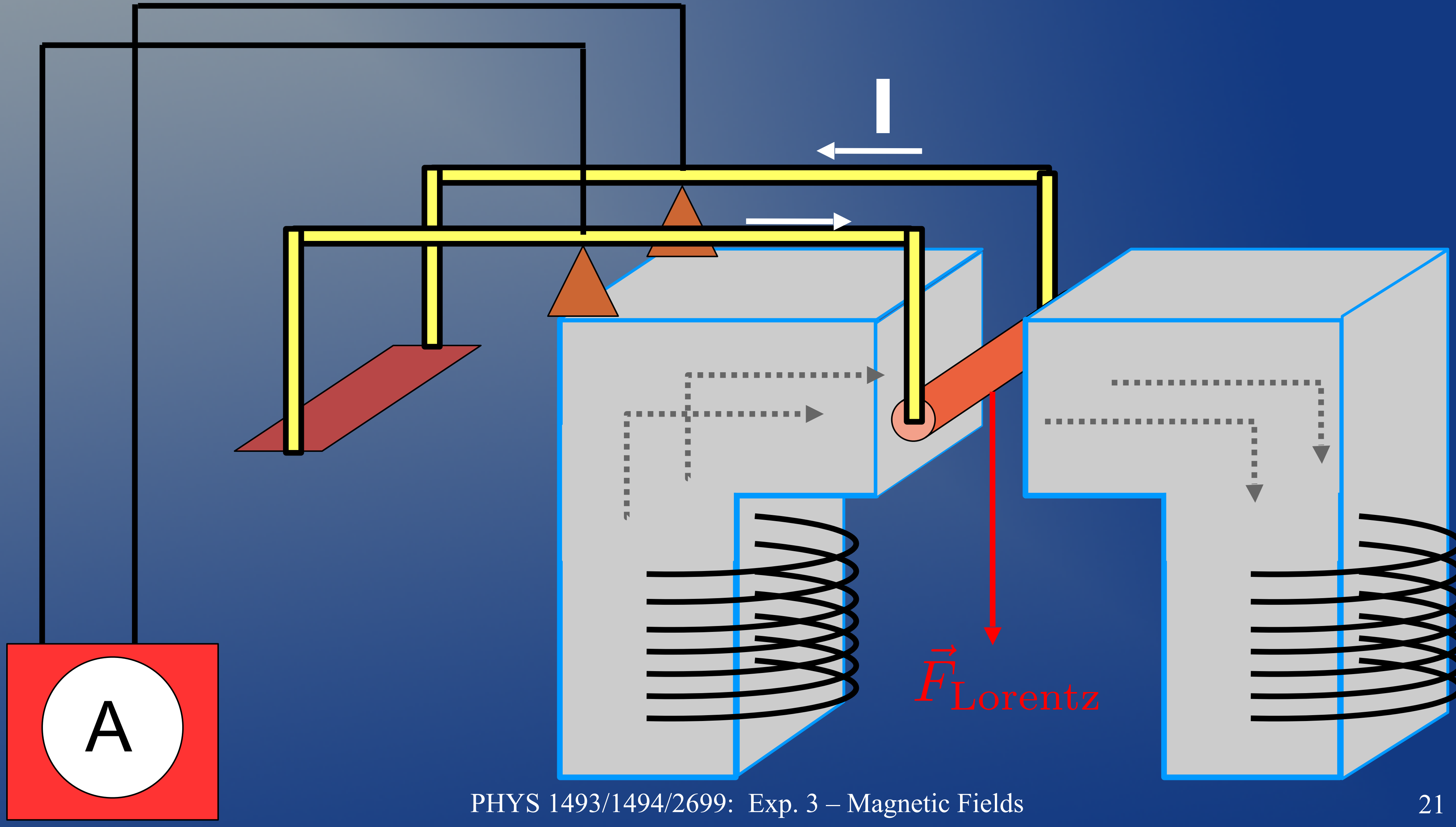
Part 1: measuring *B*

- We let a known current go through the balance and hence to the rod.



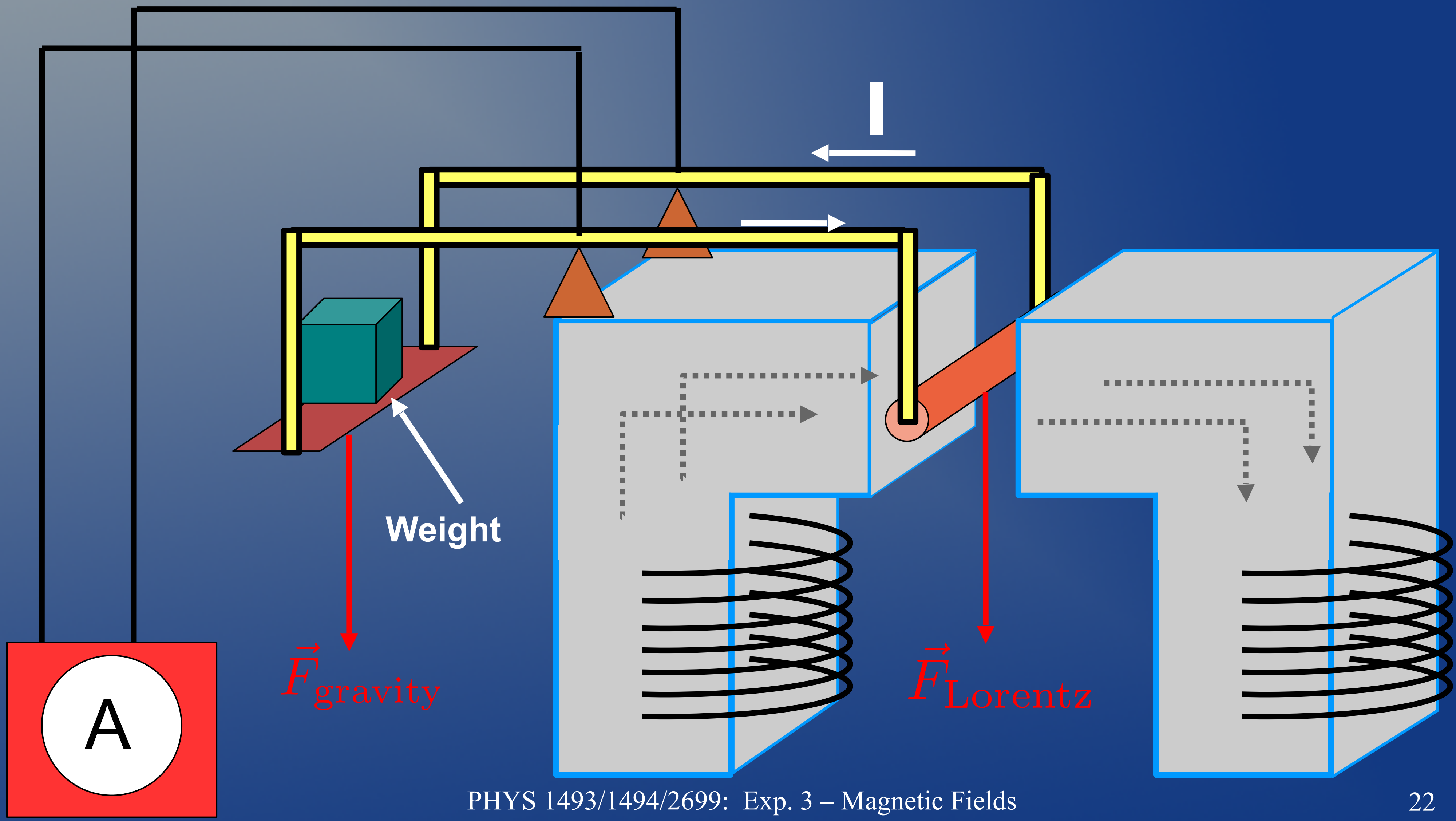
Part 1: measuring *B*

- This generates a magnetic force that wants to push the rod downward



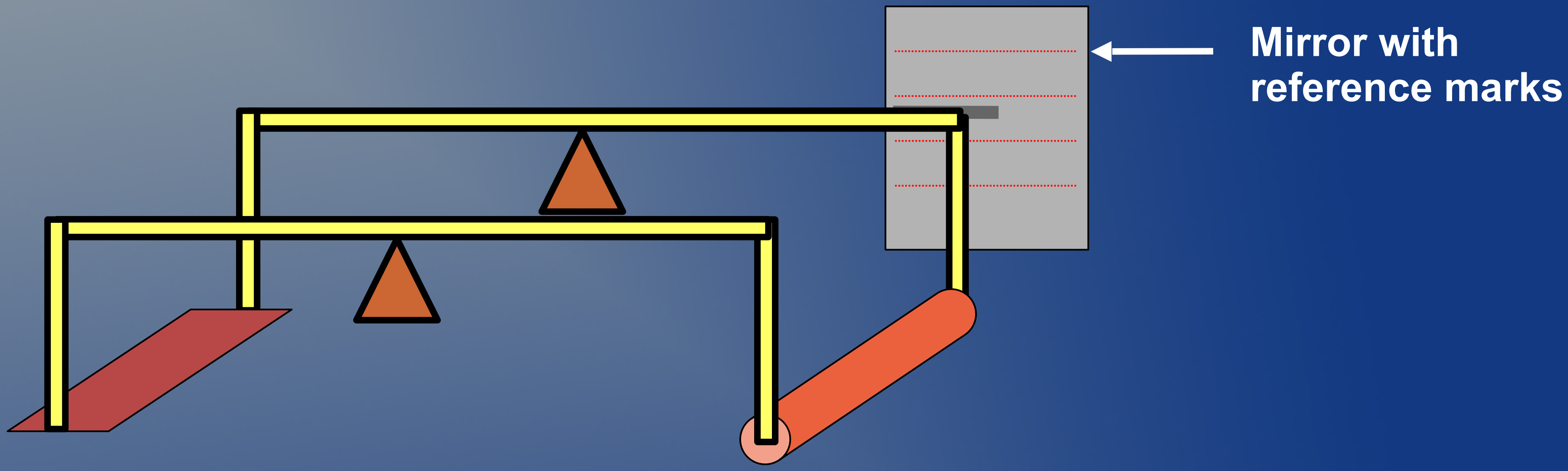
Part 1: measuring *B*

- We can oppose this force by adding weight on the other side



Part 1: measuring *B*

- **Before turning any of the currents on**, balance rod using mirror.



- Once found reference, use it for rest of current balance measurements!
- **Warning:** This part of the experiment will be vulnerable to parallax errors. (*i.e.* angle that you line up your eyes to the reference marks). Try to be as careful as possible

Part 1: data taking

- Set the electromagnet current I_{em} to 5 Amps.
- Take 5 balance current measurements as follows:
  1) Set the mass (*m*) on the scale
  2) Using the mirror, determine the current (*i*) needed to balance gravity with the Lorentz force
  3) For a fixed value of I_{em} collect 5 pairs *(m, i)*
- Repeat everything for I_{em} = 4 A, 3 A, and 2 A.

Total of 20 measurements!

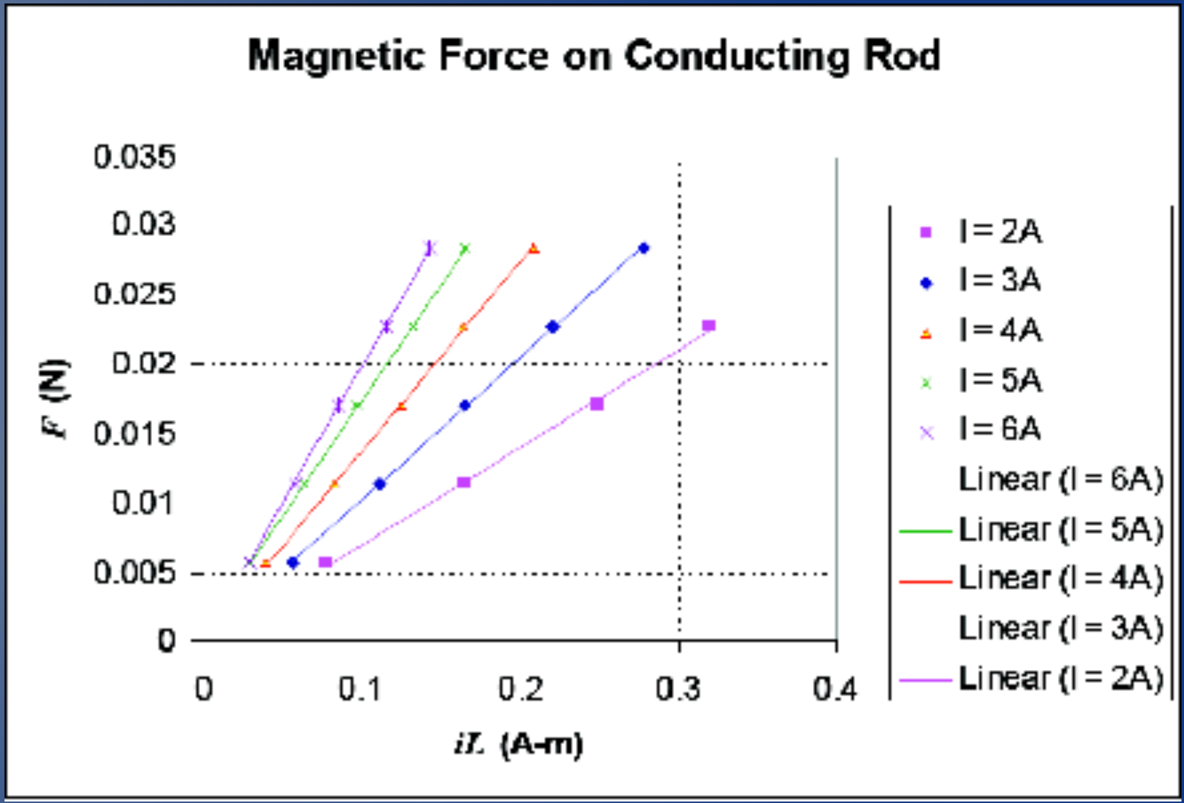
Part 1: tips

- Balancing Act:
  - Scale will oscillate when balancing force on current rod with weights.
  - ***Wait until the balance stops oscillating to determine whether or not the net force is zero.***
  - Tip: Vary current in rod slowly to prevent large balance oscillations.
- Uncertainties in rod current:
  - Uncertainties are ***not*** necessarily given by the ammeter of current carrying rod.
  - A possible way to estimate the error on current: change the current until the rod is clearly out of equilibrium. Record the minimum and maximum currents for which it looks horizontal. Half the difference between them will be your error

Part 1: analysis

- For every value of the current flowing through the electromagnet, I_{em}, plot the magnitude of the Lorentz force ($F = mg$) vs. iL
- The magnitude of the Lorentz force is given by:

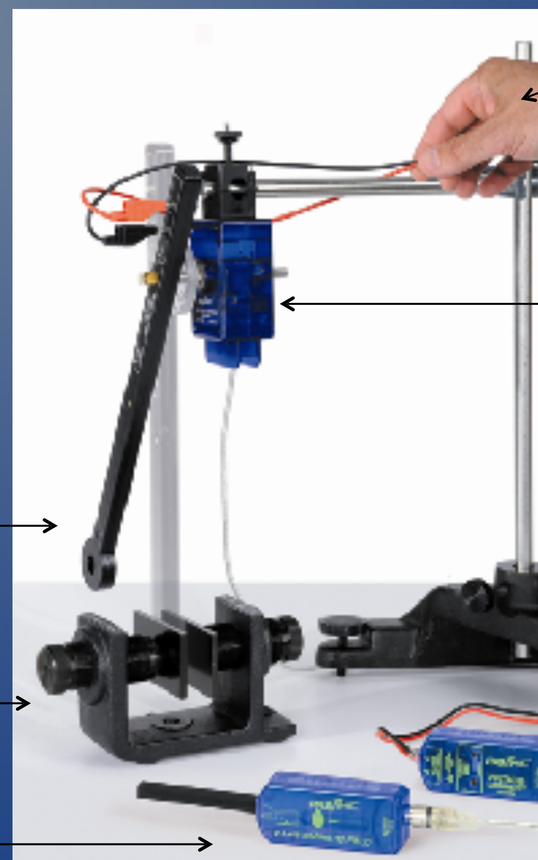
$$F = iLB$$



- From the **slope** of each line (for a given I_{em}) one can then compute the ferromagnet magnetic field $B \pm \sigma_B$
- Once this is done for all four values of I_{em}, plot B vs. I_{em} and observe their relation. Is that what you expected?

Part 2: the swinging coil

- In this part of the experiment you will observe the voltage induced in a coil by a changing magnetic field
- The whole apparatus looks like:



Thing! From the Addams family…

Rotary motion sensor

Small coil (feels the induction)

Magnet

Voltage sensor (measures the induced e.m.f.)

Magnetic field sensor (allows to measure the field generated by the magnet)

Part 2: preliminary data

- Before measuring the actual induced e.m.f. you will need to take some preliminary data
- Place the magnetic field sensor in between the two poles of the magnet and measure the field for 5-6 seconds
- From the points obtained in this way compute and record $B \pm \sigma_B$ of the magnet
- This value will be used later on in the experiment
- Repeat the same procedure but now with the sensor 1 cm and 2 cm away from the axis of the magnet

Part 2: data taking

- Now swing the coil ***once*** through the magnet and **observe the peak in the induced voltage** due to the changing flux of the magnetic field
- Using the "smart tool" on Data Studio compute the average e.m.f. (including all the points of the voltage peak) and the time interval *Δt* (from the beginning to the end of the peak) over which the magnetic flux changed
- The expected average e.m.f. is given by the formula found in slide 13:

Number of turns of the swinging coil (*N = 200*)

Area of the coil (d_{outer} = *3.1* cm)

Field measured in the **preliminary part**

$$\mathcal{E} = -NA\frac{\Delta B}{\Delta t}$$

Time interval

- Compare the expected average with the measured one

Part 2: tips

- This second part is fairly easy since the software does most of the work for you!
- The main part of the lab this week will be on data analysis therefore be very careful to:
  - Take all the data you need before leaving the lab. You will not have the chance to take them again!
  - Try to understand exactly what is going on in your experiment. Do not blindly take data or you will have problems interpreting them later in the week