Recap

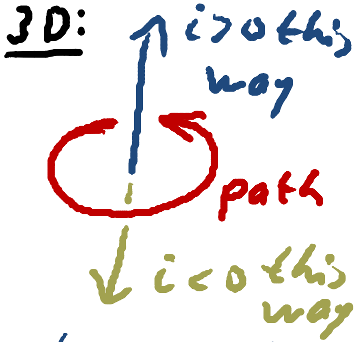
Lecture 19

- Ampere's Law: relates current to magnetic field it produces

$$\oint \vec{B}\cdot d\vec{s} = \oint B\cos\theta\, ds = \oint B_{\parallel \text{ to path}}\, ds = \mu_0\, i_{\text{enc, net}}$$

closed path

integration path can have any shape, but must be closed.

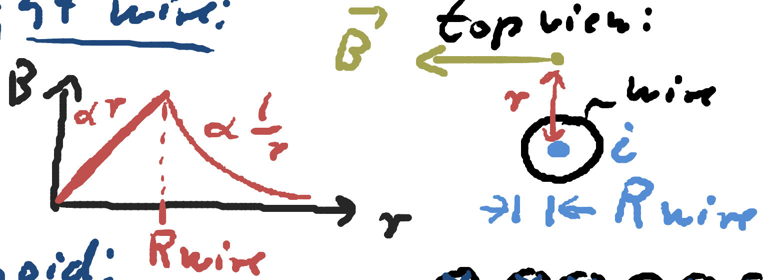


- watch out for correct sign of current (use right-hand rule)
- Only include currents completely enclosed by the integration path

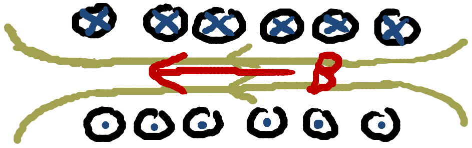
- Magnetic field by a long, straight wire:

$|B| = \dfrac{\mu_0 i}{2\pi R^2}\, r$ for $r < R_{\text{wire}}$

$|B| = \mu_0/2\pi\ {}^1/_r$ for $r > R_{\text{wire}}$



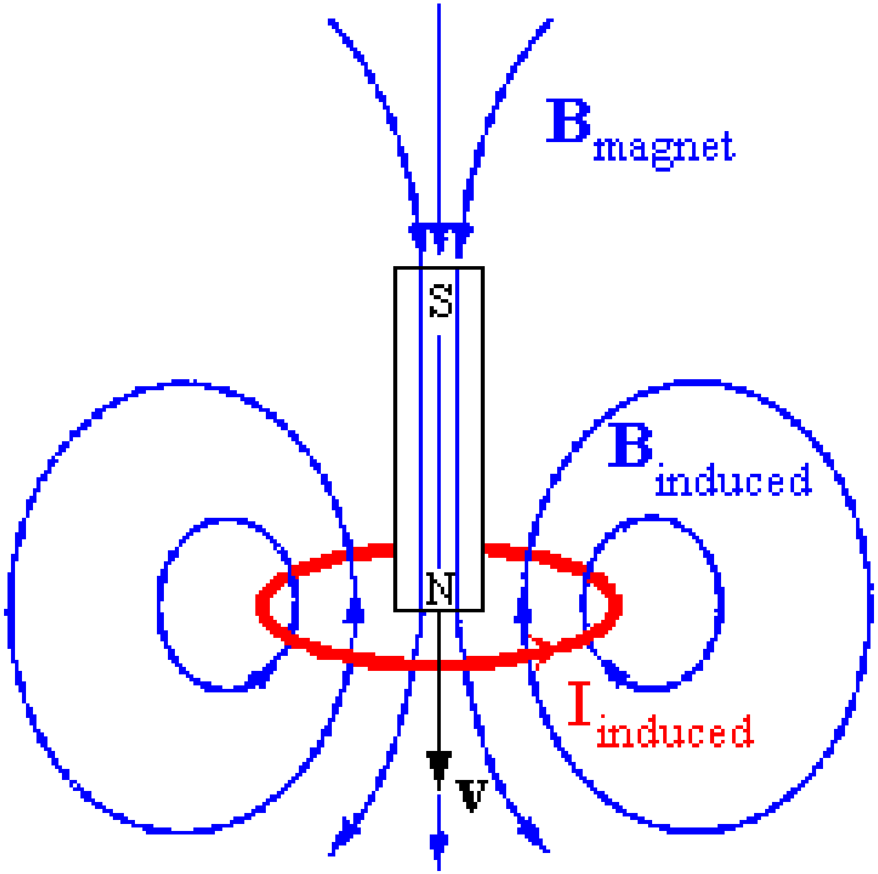
- Magnetic field by a long solenoid:



$B_{\text{inside solenoid}} = \mu_0 i n$ ← n = # of turns of solenoid per length

Today:

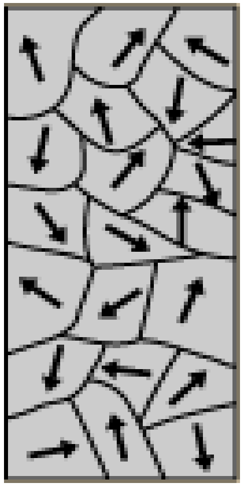
- **Magnetic materials**
- **Change in magnetic flux and Faraday's law of induction**
- **Lenz's law**



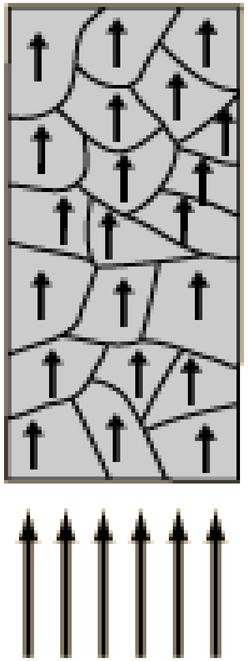
Magnetic Materials

- **Ferromagnetic:**
- Examples: Iron, nickel…
- Divided into regions ("domains") in which atomic magnetic dipoles line up
- If placed in an external magnetic field: dipoles of domains line up in direction of magnetic field

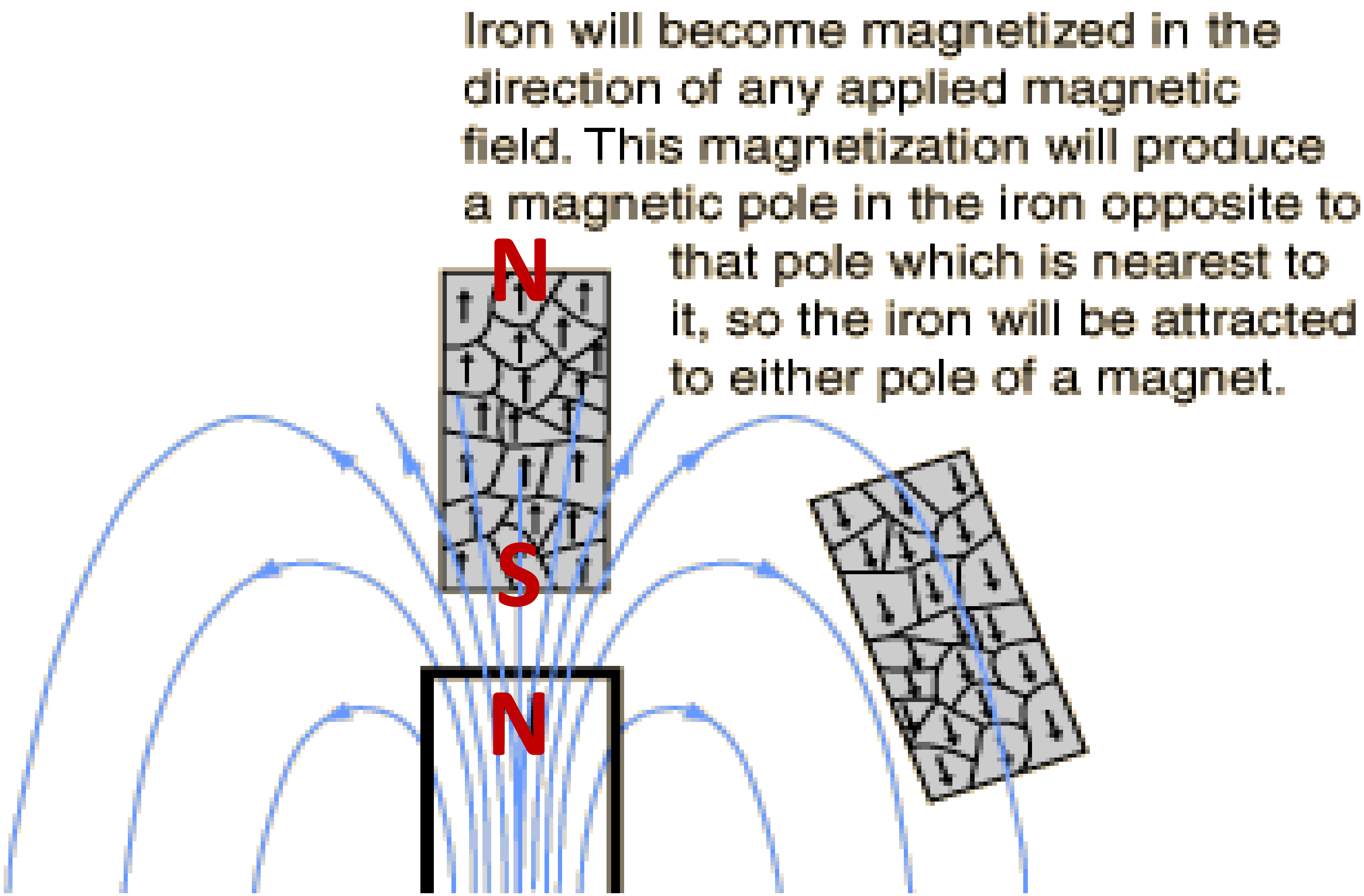
  -> material develops a strong magnetic dipole moment in direction of the applied external magnetic field
- The dipole moment alignment ("magnetization") partially persists when the external field is removed -> permanent magnet



In bulk material the domains usually cancel, leaving the material unmagnetized.



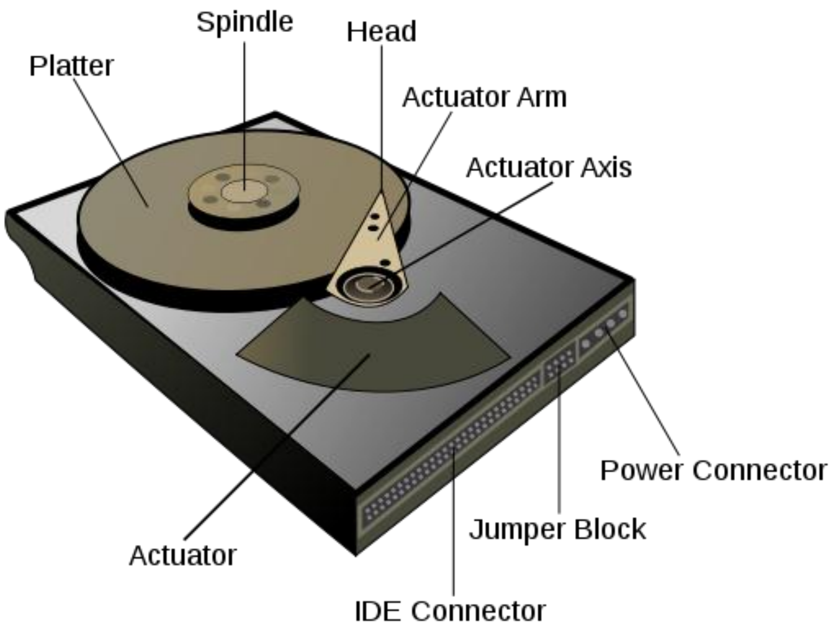
Externally applied magnetic field.

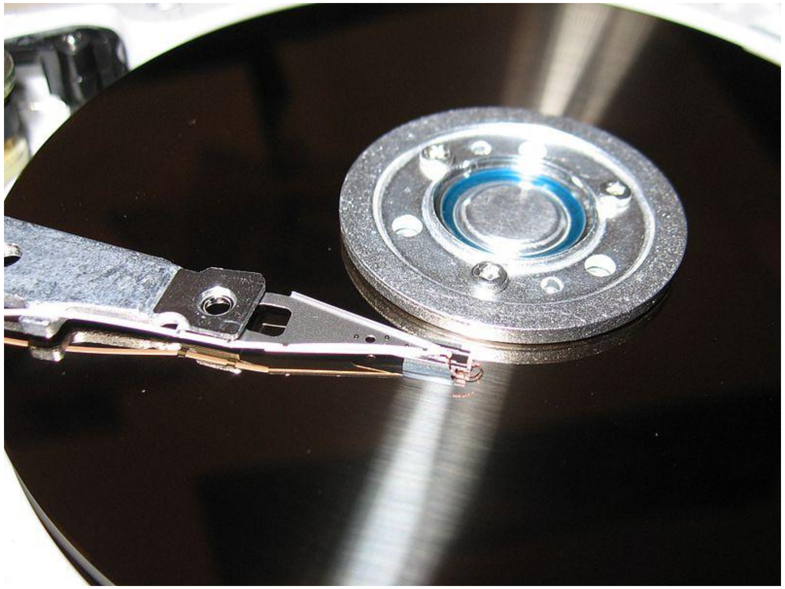


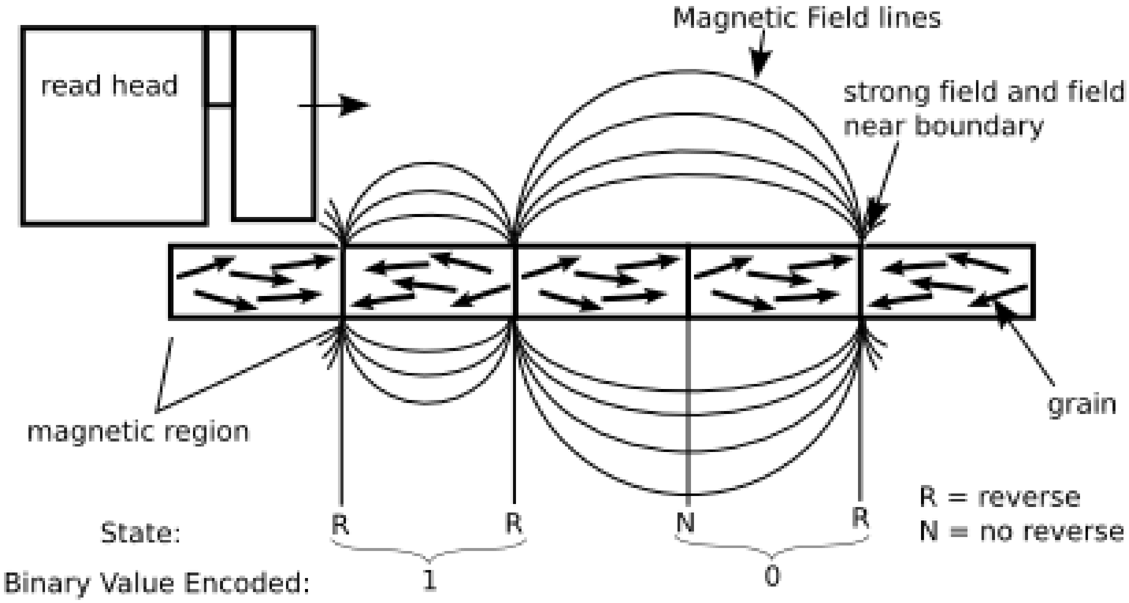
Iron will become magnetized in the direction of any applied magnetic field. This magnetization will produce a magnetic pole in the iron opposite to that pole which is nearest to it, so the iron will be attracted to either pole of a magnet.

That’s why a magnet sticks to a steel refrigerator door…

Example: Hard disk drive







A hard disk drive records data by magnetizing a thin film of ferromagnetic material on a disk.

- **Diamagnetic:**
  - Atoms have no permanent dipole moments, but weak magnetic dipole moments are produced in the atoms when placed in an external magnetic field

    ->Create a very weak magnetic dipole field in opposition to an externally applied magnetic field
  - Dipole moments and net field disappear when external magnetic field is removed
- **Paramagnetic:**
  - Atoms have permanent dipole moments, but are randomly oriented
  - When placed in an external magnetic field, dipoles partially align in direction of the field

    ->Create a net magnetic dipole field in direction of the externally applied magnetic field
  - Alignment and net field disappear when external magnetic field is removed

Example: Levitation of a Frog on a strong Magnetic Field

- **A live frog levitates inside a 32 mm diameter vertical bore of a solenoid in a magnetic field of about 16 T.**
- **Why?**
  - **Diamagnetism of the frog**
  - **Magnetic dipole moment of frog opposes B_{ext} -> repulsive force!**

Magnetic Induction:

↝ **so far:**

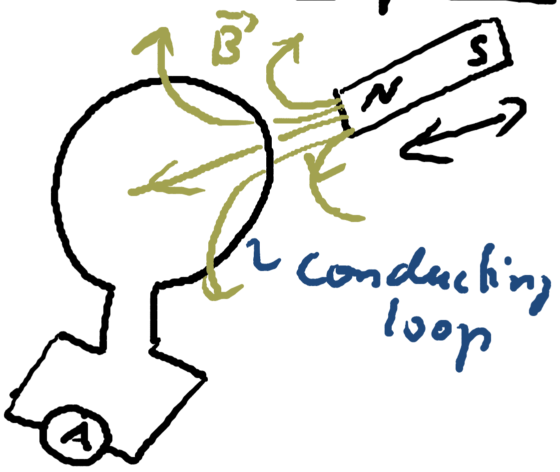
- electric charge moving in a magnetic field ⇒ force $\vec{F} = q\,\vec{v} \times \vec{B}$
- moving electric charge ⇒ produces a magnetic field around itself
  $$d\vec{B} = \frac{\mu_0}{4\pi}\, i\, \frac{d\vec{s} \times \hat{r}}{r^2}$$

↝ **now:**

changing magnetic field (magnetic flux Φ_B) through a conducting loop ⇒ produces a current ("induced current") in the conducting loop ⇔ produces / induces an emf that makes the current flow ⇔ induces an electric field in the loop

Examples of Magnetic Induction:

I



ammeter → current

moving magnet

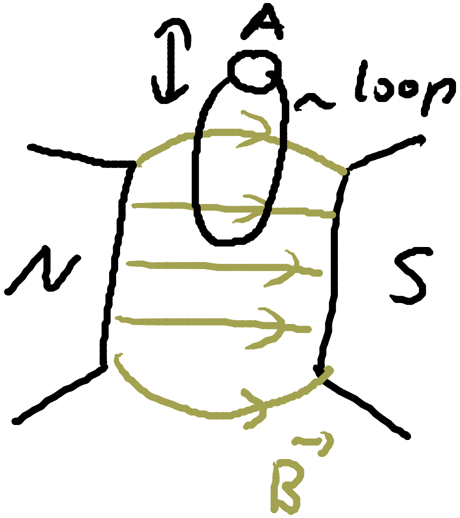
$\Downarrow$

<u>change</u> in magnetic flux going through the loop

$\Downarrow$

induces emf/current in the loop

II



moving coil of wire through localized magnetic field

$\Downarrow$

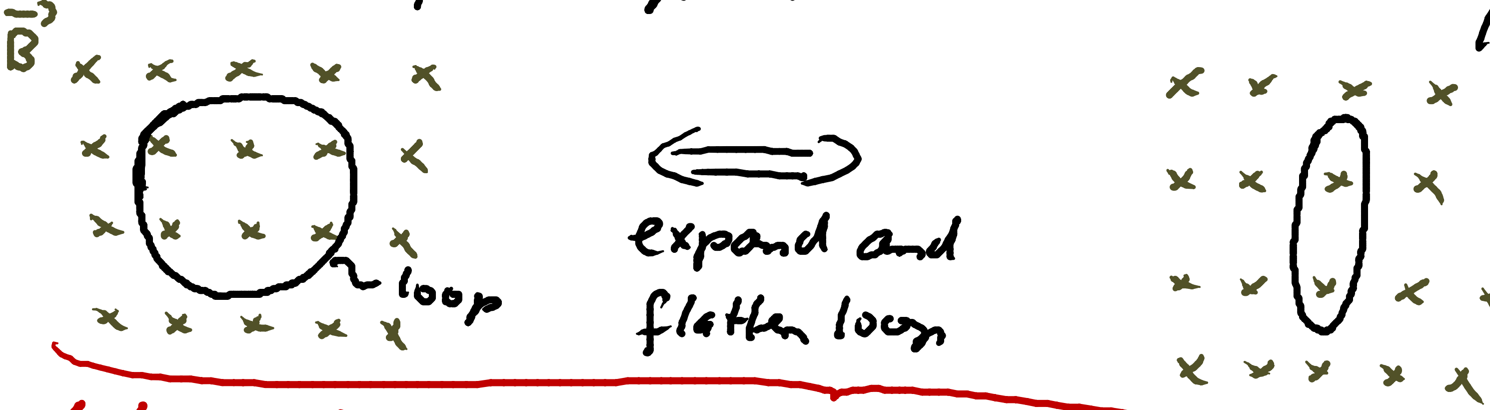
change in magnetic flux through the loop

$\Downarrow$

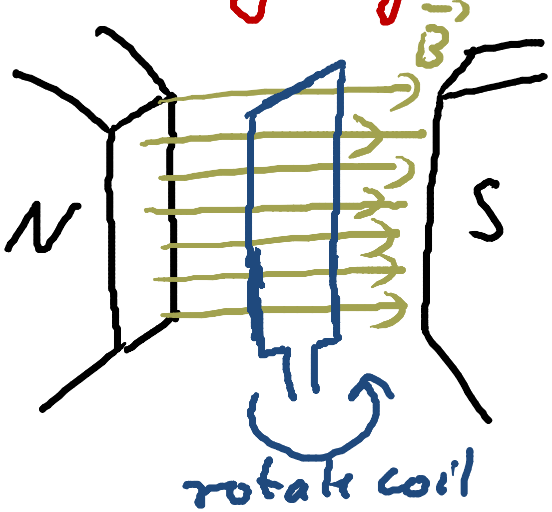
induces emf/current in the loop

III changing flux through loop

by changing area or orientation of the loop in B-Field ⇒ induces emf/current in the loop



Notice: changes "number of field lines" ∝ magnetic flux Φ_B going through the conducting loop



rotating coil

⇓

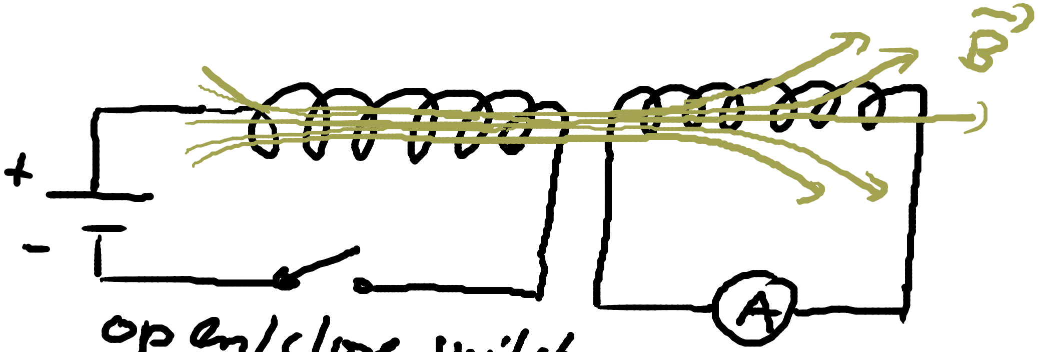
magnetic flux through coil changes with time

⇓

induces emf/current in coil

⇒ electric generator!

IV



open/close switch

$\Rightarrow$ <u>changing</u> magnetic field $\vec{B}$

$\Rightarrow$ changing magnetic flux through coil on the right side

$\Rightarrow$ emf/current is induced in coil on the right side

Notice:

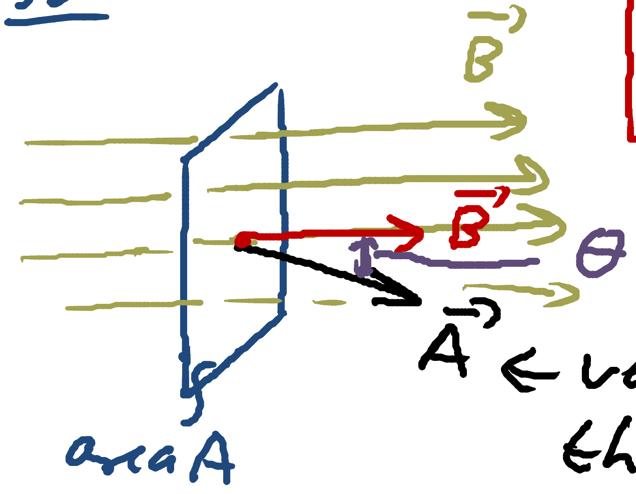
- emf/current is only induced if magnetic flux Φ_B through the loops is changing with time!
  $\Rightarrow$ need $d\Phi_B/dt \neq 0$
- Direction of current is different for $d\Phi/dt > 0$ (increase in flux with time) and $d\Phi_B/dt < 0$ (decrease in flux with time)

Quantitative Treatment: Define magnetic flux Φ_B

(magnetic flux through area A) $\propto$ (number of field lines going through area A)

⇝ for uniform magnetic field and flat area:

3D:



$\vec{A}$ ← vector of magnitude A, that is perpendicular to area A

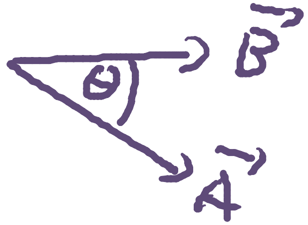
$$\boxed{\Phi_B = \vec{B}\cdot\vec{A} = B\,A\cos\theta}$$

} can be >0 or <0

↖ angle between $\vec{B}$ and $\vec{A}$

$$\Phi_B = B_{\parallel \text{ to } \vec{A}}\,A$$

(i.e. ⊥ to area A)



Units: $[\Phi_B] = T\,m^2 = 1$ weber $= 1$ Wb

⇝ for more general case:

non-flat surface and/or non-uniform field:

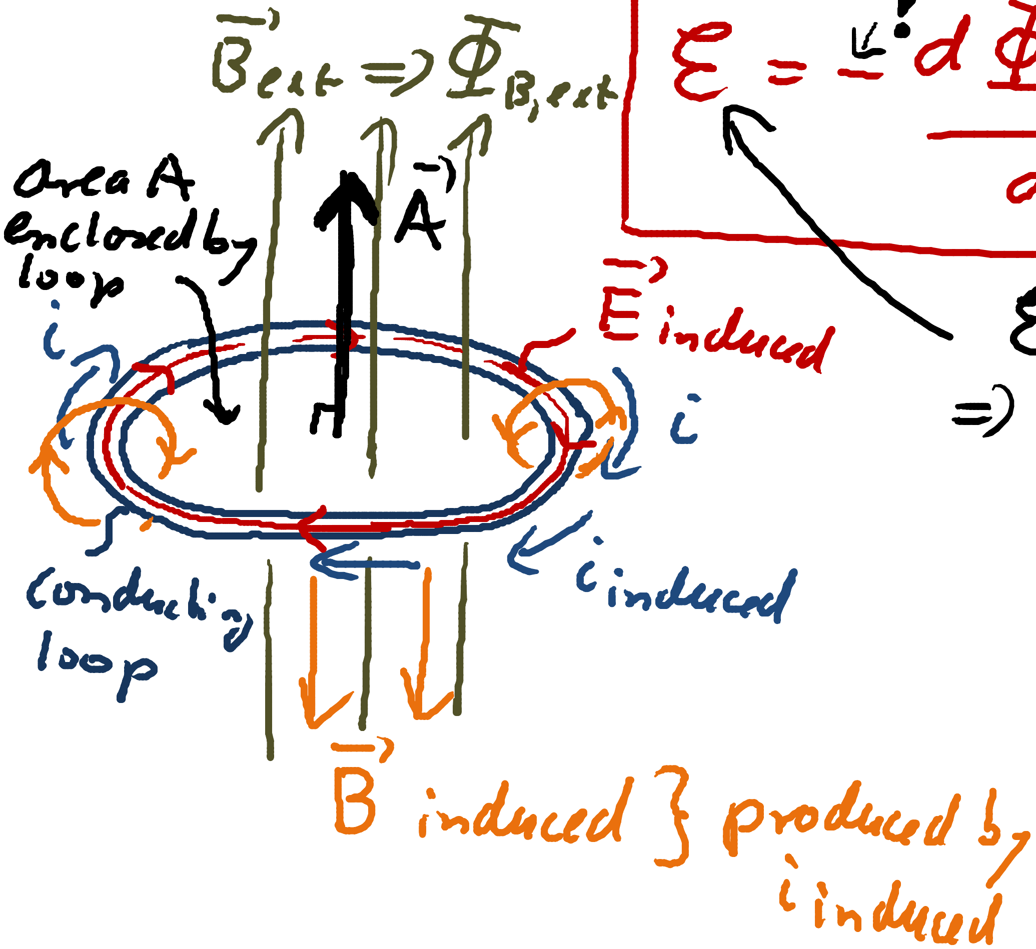
break area into small sections with $\vec{B} \approx$ const and sum up/integrate over all contributions to the total flux:

$$\boxed{\Phi_B = \sum_i \vec{B}_i \cdot \Delta\vec{A}_i = \int_{\text{area}} \vec{B} \cdot d\vec{A}}$$

Faraday's Law of Induction:

(emf induced in a conducting loop) = − (rate at which the external magnetic flux $\Phi_{B,ext}$ through that loop changes with time)

3D: Assume ext $\vec{B}_{ext}$ increases with time



$$\boxed{\mathcal{E} = \overset{!}{-}\frac{d\Phi_{B,ext}}{dt}}$$

$[\mathcal{E}] = \text{volts}$

$\mathcal{E}$ can be positive or negative

⇒ sign tells you which way current flows in the loop:

⇒ see Lenz's Law

for coil with N turns:

$$\boxed{\mathcal{E} = -N\, d\Phi_B/dt}$$