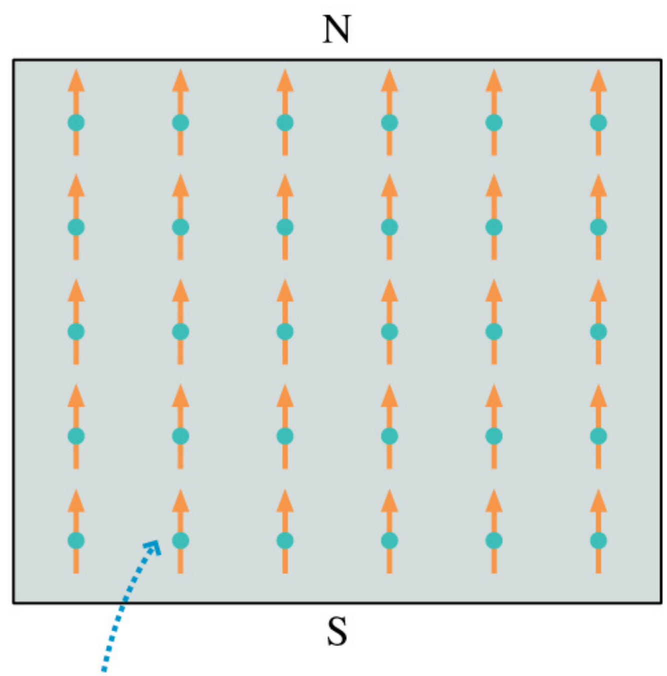
Announcements

- Help room hours (1248 BPS)
  - Ian La Valley(TA)
  - Mon 4-6 PM
  - Tues 12-3 PM
  - Wed 6-9 PM
  - Fri 10 AM-noon
- LON-CAPA #7 due Oct. 25
- Final Exam Tuesday Dec 11 7:45-9:45 AM

Ferromagnetism

- What makes a permanent magnet?
- Depends on crystalline structure of material
- Pure iron does not make a good magnet because it's easy to get the domains to un-align themselves
  - we saw that with the propane torch on Thursday
- But an alloy of steel with 51% iron, 24% cobalt, 14% nickel, 8% aluminum and 3% copper has permanent magnetic properties and is used to make permanent magnets
- Most stainless steels, with chromium and nickel, have virtually no magnetic properties

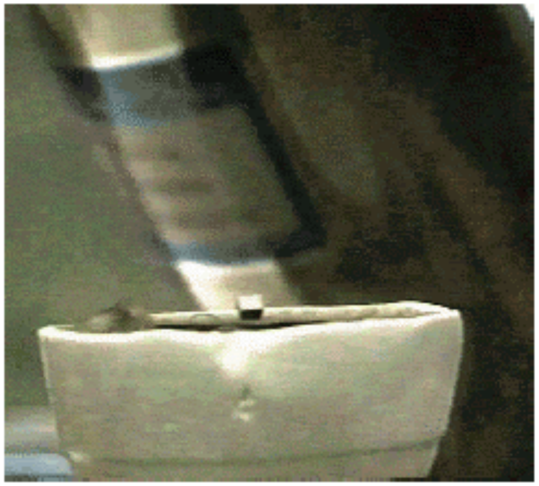


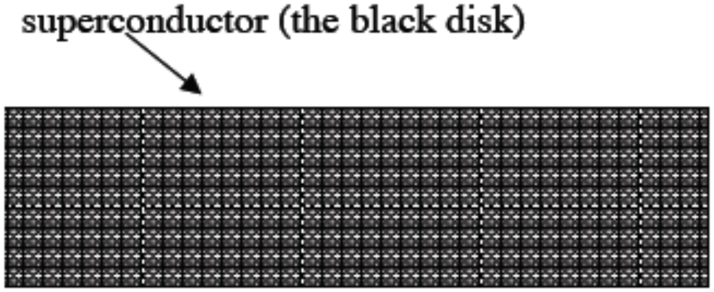
The atomic magnetic moments are aligned.
The sample has a north and south magnetic pole.

Diamagnetism in superconductors

Ferromagnetism isn't the only kind of magnetism. Also paramagnetism and diamagnetism.

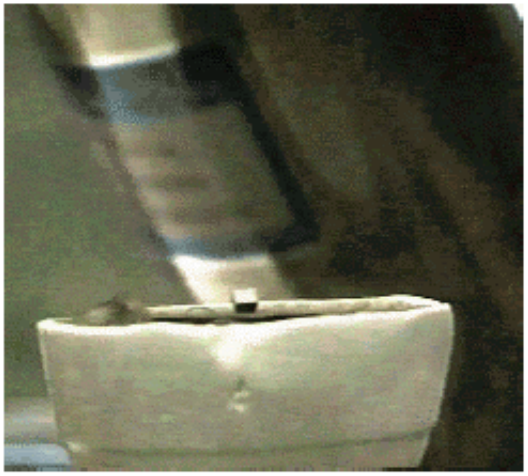
- How does this work?
  - superconductors hate magnetic fields
  - they want to push them away
  - you can push a magnet away by creating another magnetic field
  - a current loop produces a magnetic field
  - current loops can easily form in superconductors

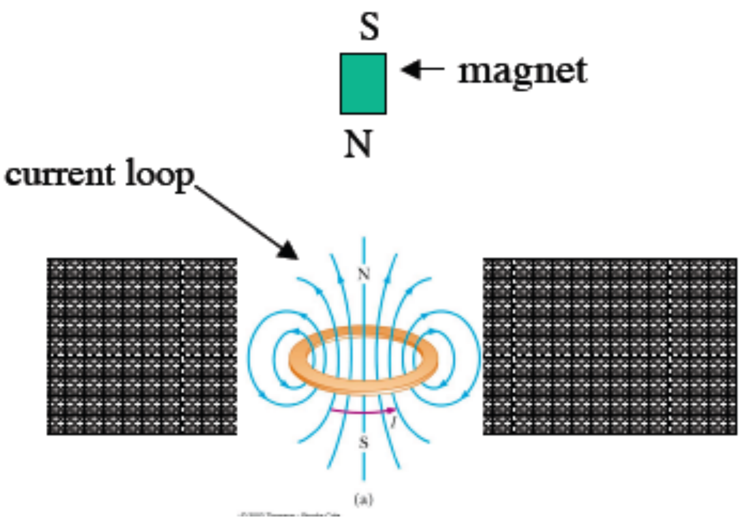




Diamagnetism

- How does this work?
  - superconductors hate magnetic fields
  - they want to push them away
  - you can push a magnet away by creating another magnetic field
  - a current loop produces a magnetic field
  - current loops can easily form in superconductors
  - voila, current loops form in superconductors when a magnet is nearby





Meissner effect

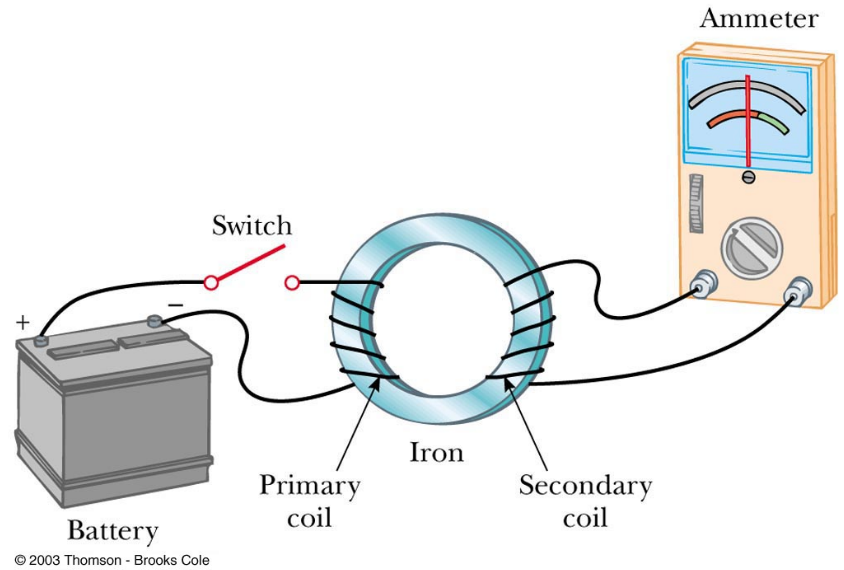
Magnetic induction

- We talked about Faraday before
  - 1791-1867
- Little formal education; almost entirely self-taught
  - he was apprenticed as a book-binder and ended up reading most of the books he was supposed to bind

An important experiment

- This is his most famous experiment
- In the early 1800's he was where we are now in this course
  - strong electric fields create magnetic fields (by creating currents)
  - from symmetry it seemed that strong magnetic fields should be able to create electric fields (and currents)

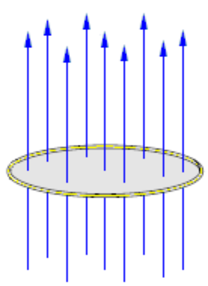
this is the experiment that he set up

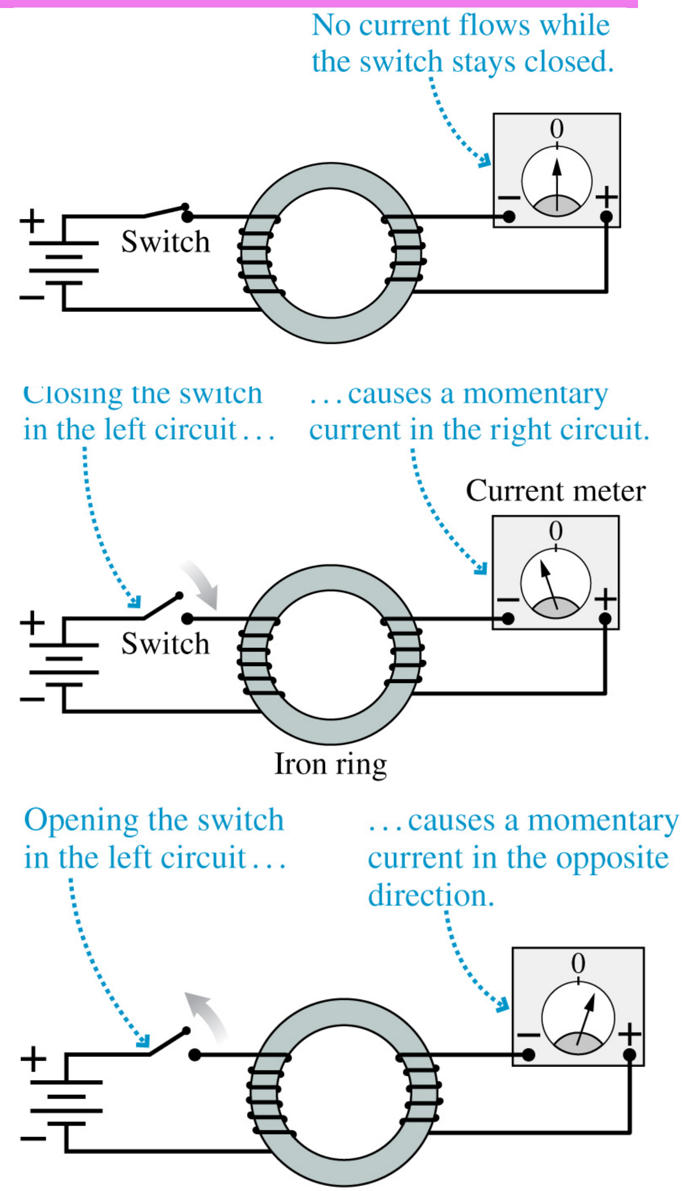


what did he find?

What he found

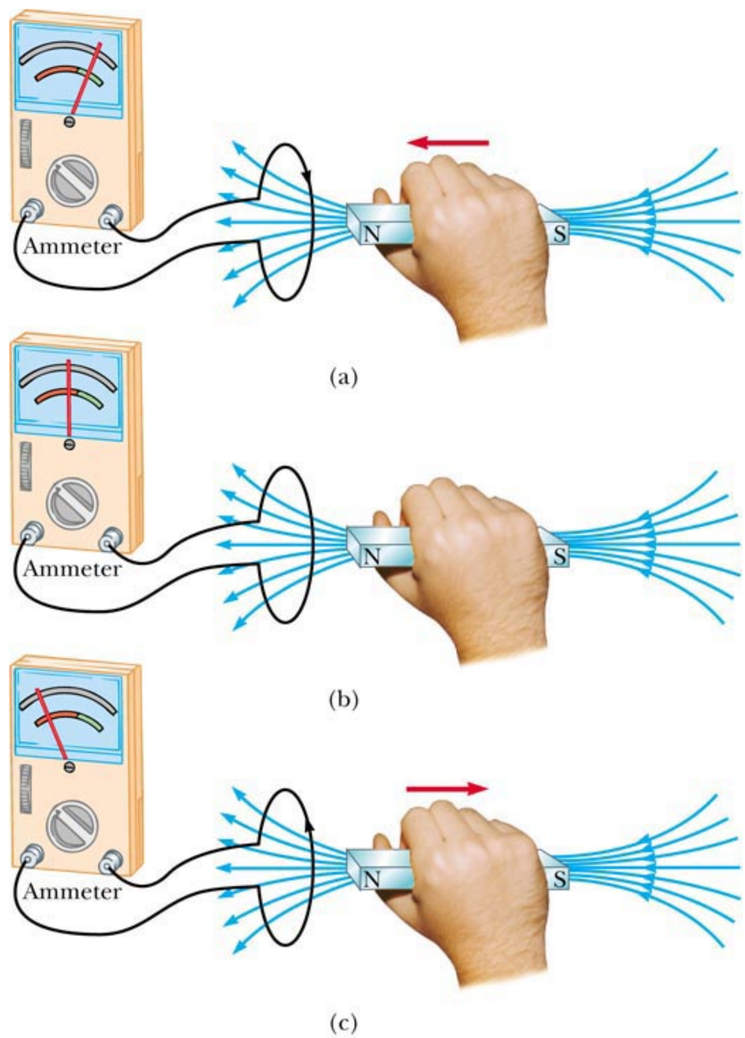
- A strong magnetic field does not create an electric current
- But he did notice a current in the meter when he first closed the switch and just after he opened it again
- So it's not a magnetic field that creates an electric current; it's a changing magnetic field
- And not the magnetic field per se, but the magnetic flux
  - just think of the flux as the number of magnetic field lines going through a loop





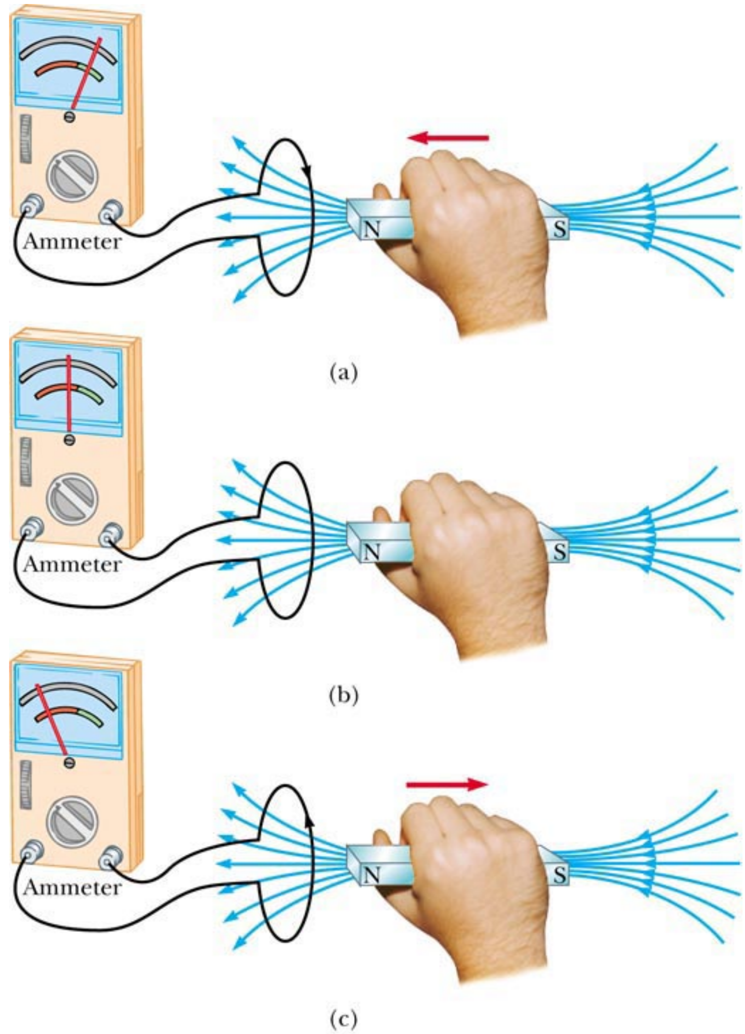
Faraday's law of induction

- We saw one way of changing the magnetic flux
  - here's another



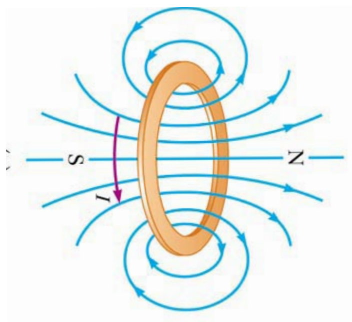
Notice the direction of the current flow

- The direction of the induced voltage (sometimes termed an emf as we did for a battery) is such that it tries to produce a current whose magnetic field opposes the change in flux thru the loop
- Lenz's law
  - any change is resisted no matter what the direction (- sign)

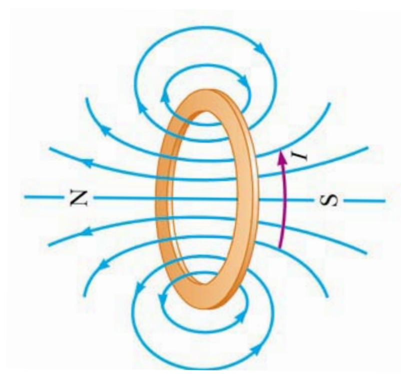


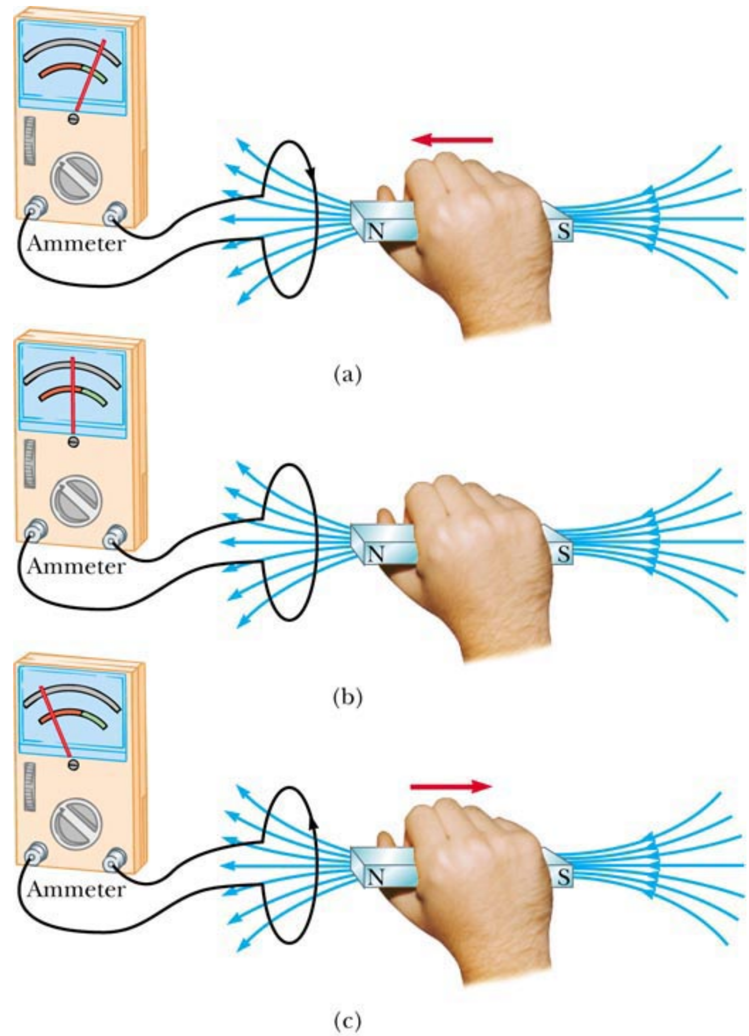
Notice the direction of the current flow

I push the magnet in; the coil is pushing back



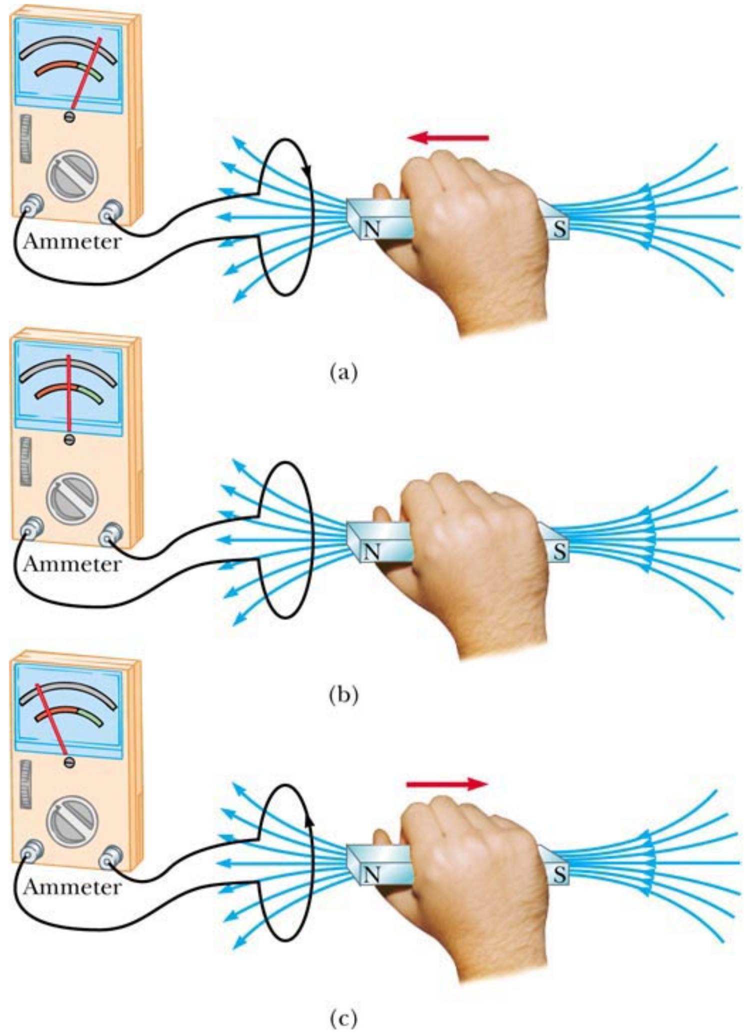
I pull the magnet out; the coil is pulling back





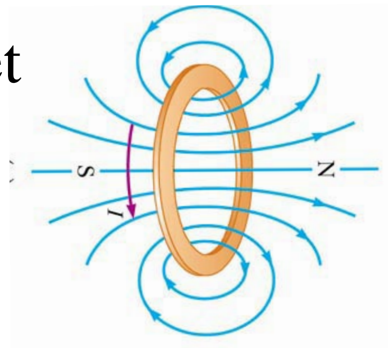
Change of flux

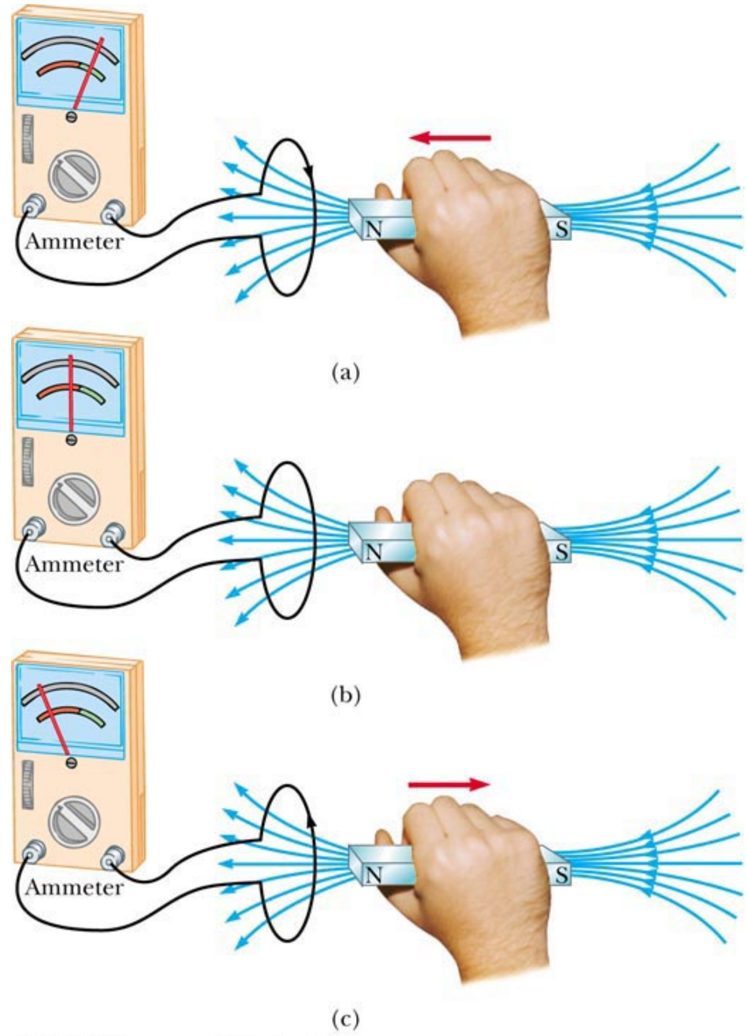
- From careful experimentation I find that I can create a larger current by moving the magnet more quickly into and out of the coil
- It's not the change in magnetic flux per se that's important, but the change of flux per time



Direction of current flow

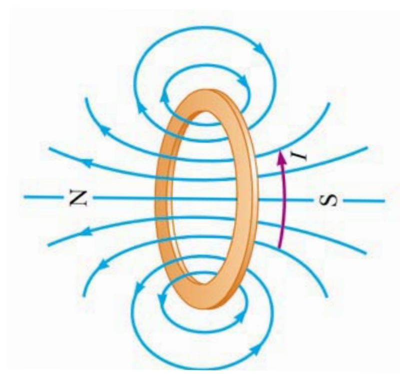
I push the magnet in; the coil is pushing back





What can I say about the work I have to do moving the magnet in and out?

I pull the magnet out; the coil is pulling back



Faraday's law

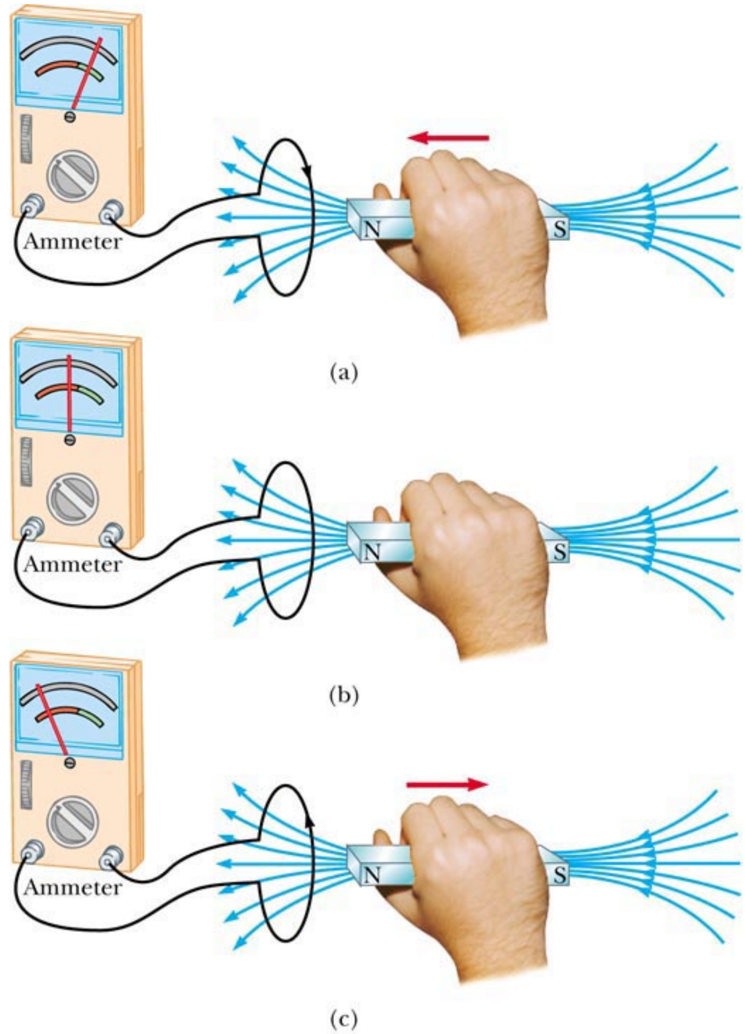
- The voltage induced by a changing magnetic flux is equal to rate at which the flux is changing

emf

$$\varepsilon = -\frac{\Delta\phi}{\Delta t} = -\frac{\Delta(BA\cos\theta)}{\Delta t}$$

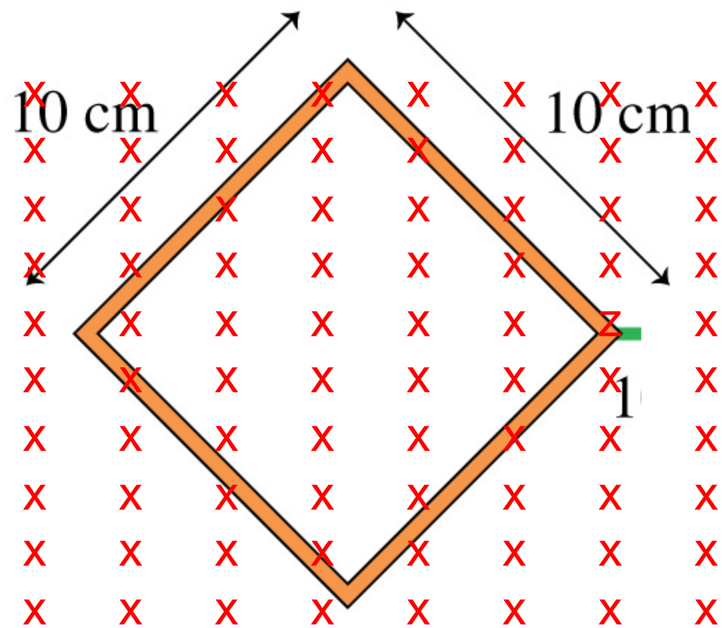
Lenz's law

- B can change, A can change, or the angle between B and A can change
- ε is a voltage so has to have units of volts



Faraday's law

- I have a flexible wire loop in a region of uniform magnetic field B = 1.0 T into the plane of the page
- I push in on the two sides of the loop so that the loop collapses to zero area in 0.25 s
- What is the emf ε induced in the loop?
- First, what is the initial magnetic flux ($\phi = BA\cos\theta$)
  - $\phi = (1.0T)(0.1m)^2 = 0.01T.m^2$
  - number of magnetic field lines inside the loop
- What is the final magnetic flux?
  - 0

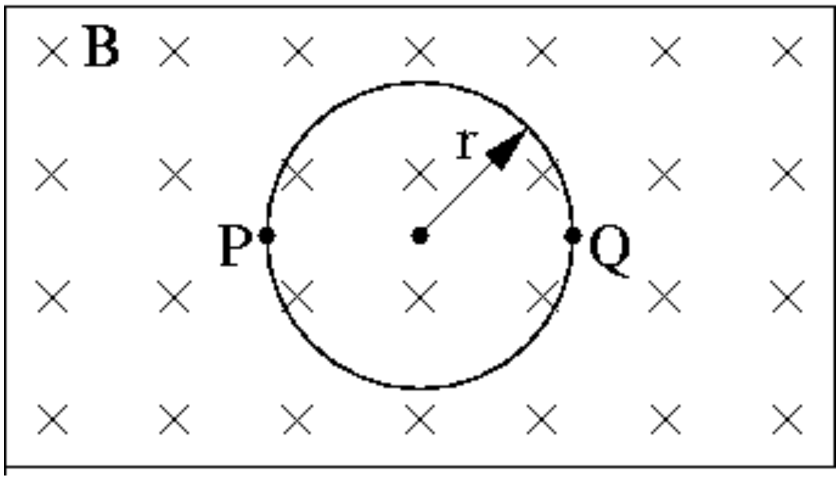


$$\varepsilon = -\frac{\Delta\phi}{\Delta t} = -\frac{0.01T \bullet m^2}{0.25s} = 0.04T \bullet m^2/s = 0.04V$$

What direction is the current induced?

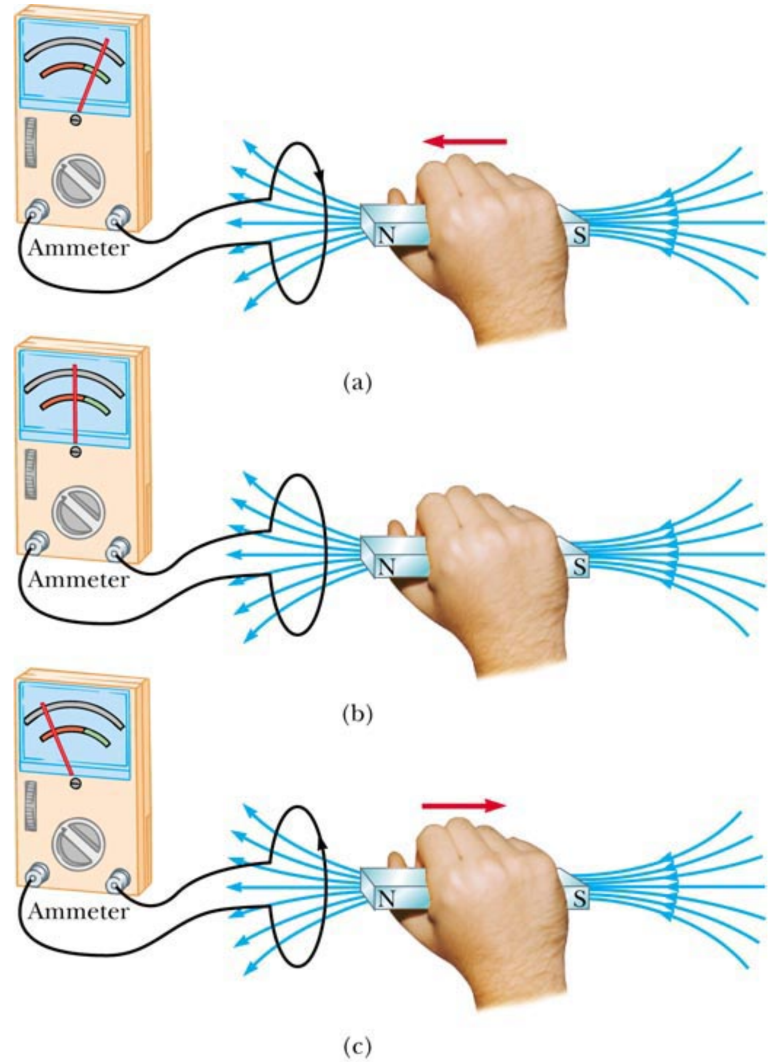
LON-CAPA problem

- The loop initially has a number of magnetic field lines passing through it
- After it is collapsed, it has none
- This problem can be solved in the same way



Clicker question

- The force on the bar magnet resulting from the current induced in the coil
  - A) opposes the motion causing the change in flux
  - B) is in the same direction as the motion causing the change in flux
  - C) is independent of the motion causing the change in flux



Clicker question

- The force on the bar magnet resulting from the current induced in the coil
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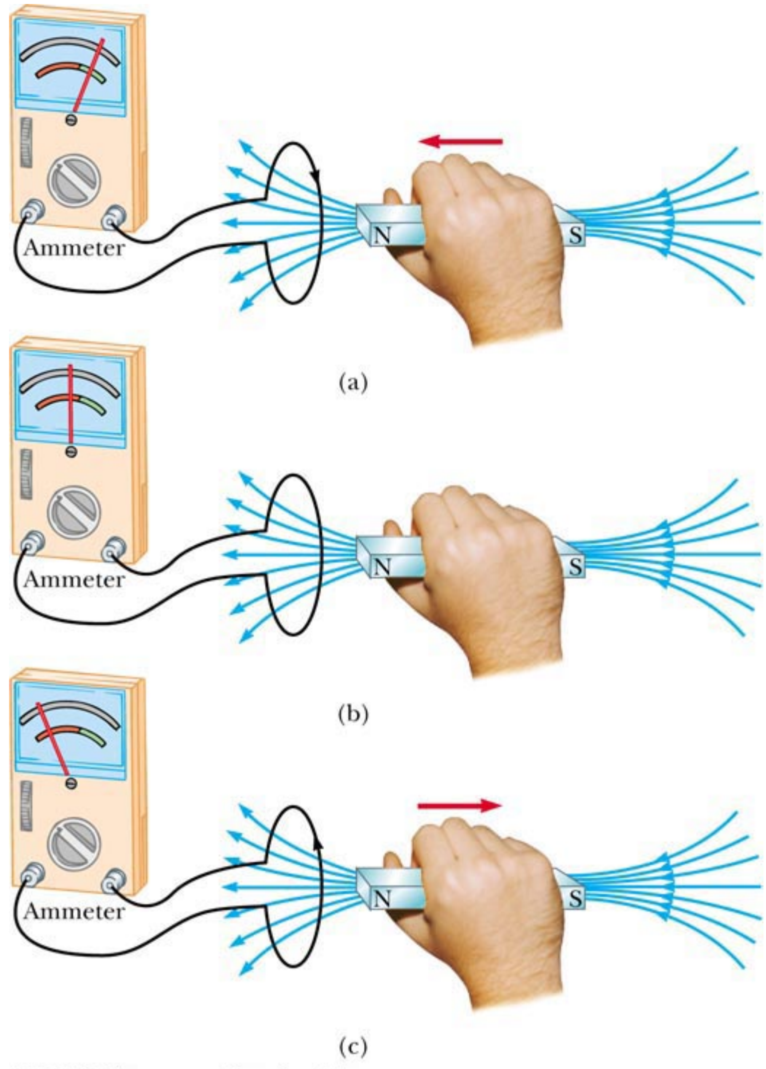
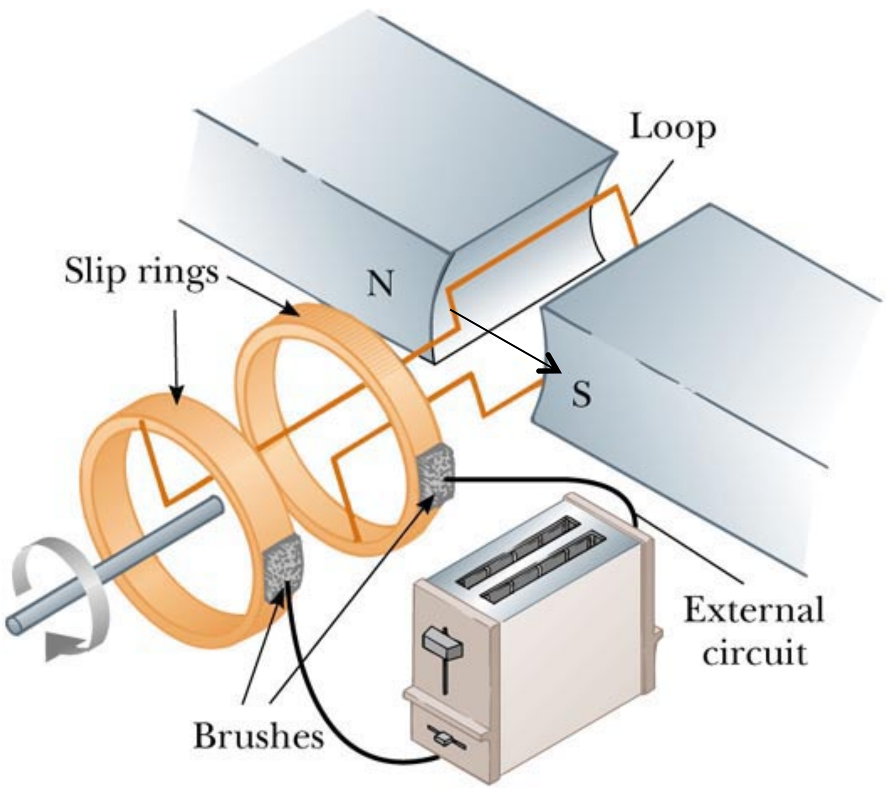
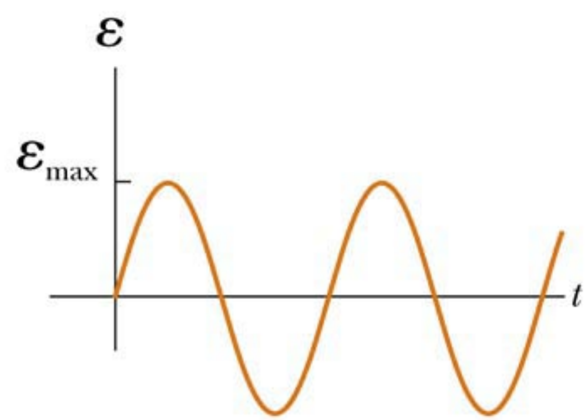


A case where B and A stay the same but θ changes



(a)

an electrical generator consists of a coil rotating inside of a constant magnetic field



(b)

it produces an emf that varies sinusoidally with time

Lenz's law

voltage from a generator

$\varepsilon = -N\,\Delta\Phi_B/\Delta t$ Faraday's law

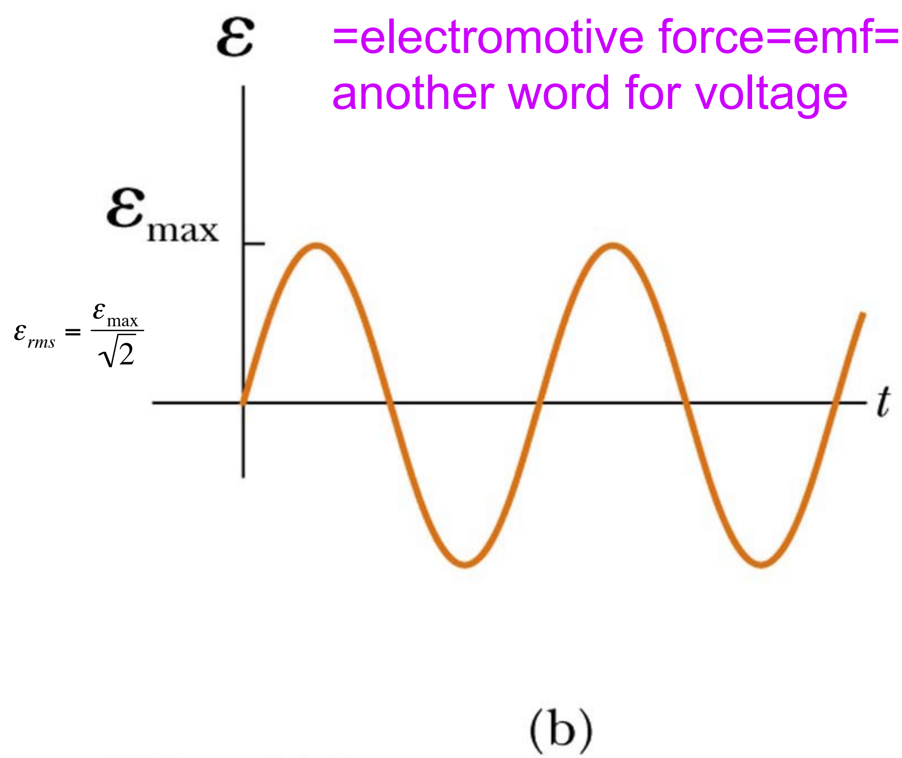
$= -N\,B\,A\,\omega\cos\omega t$

and $\omega = 2\pi f$

$\varepsilon_{max} = N\,B\,A\,\omega$

$T = 2\pi/\omega$

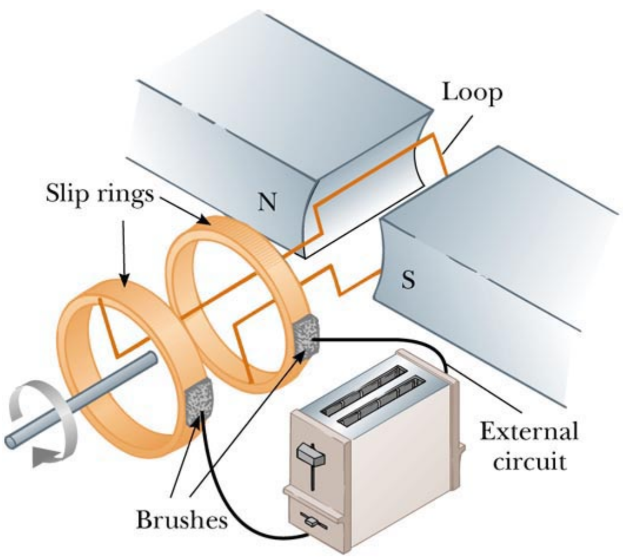
$$\varepsilon_{rms} = \frac{\varepsilon_{max}}{\sqrt{2}}$$



For example, when we say the voltage coming from an electrical outlet is 120 V, we are referring to the rms value. The peak value is 170 V.

Generators and motors

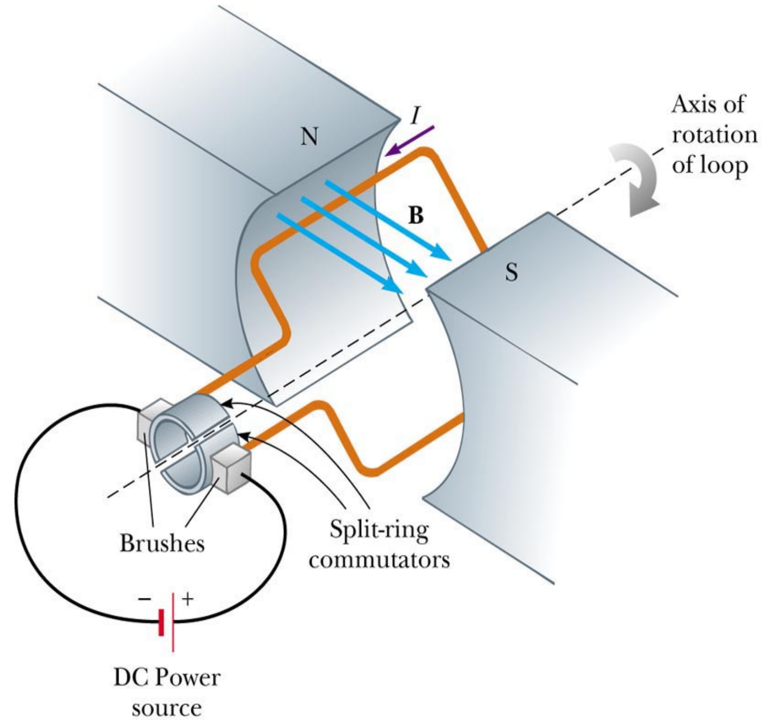
What's the difference between them?



(a)

$\mathcal{E}_{ma}$

–



A generator turns mechanical work into electrical energy.
A motor turns electrical energy into mechanical work.
A motor is a generator run in reverse.

Demo

Maxwell's equations

- Maxwell was the first to assemble the 4 equations that describe electromagnetism
- He presented his paper "On Faraday's Lines of Force" when he was 24

$$\oint_{surface} \vec{E} \cdot d\vec{A} = \frac{Q_{in}}{\varepsilon_o}$$

$$\oint_{surface} \vec{B} \cdot d\vec{A} = 0$$

$$\oint_{curve} \vec{E} \cdot d\vec{s} = -\frac{d\Phi_B}{dt}$$

$$\oint_{curve} \vec{B} \cdot d\vec{s} = \mu_o \left(I_{through} + \varepsilon_o \frac{d\Phi_E}{dt} \right)$$

Maxwell's laws

$$\oint_{surface} \vec{E} \cdot d\vec{A} = \frac{Q_{in}}{\varepsilon_o}$$

$$\oint_{surface} \vec{B} \cdot d\vec{A} = 0$$

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$$\oint_{curve} \vec{B} \cdot d\vec{s} = \mu_o \left(I_{through} + \varepsilon_o \frac{d\Phi_E}{dt} \right)$$

- Gauss' law for electric fields: charged particles create an electric field
- Gauss' law for magnetic fields: there are no magnetic monopoles
- Faraday's law: an electric field can also be created by a changing magnetic field
- Ampere-Maxwell law: a magnetic field can be created either by an electric current or by a changing electric field

Electromagnetic waves

- Working with Maxwell's equations in free space, i.e. no charges or currents

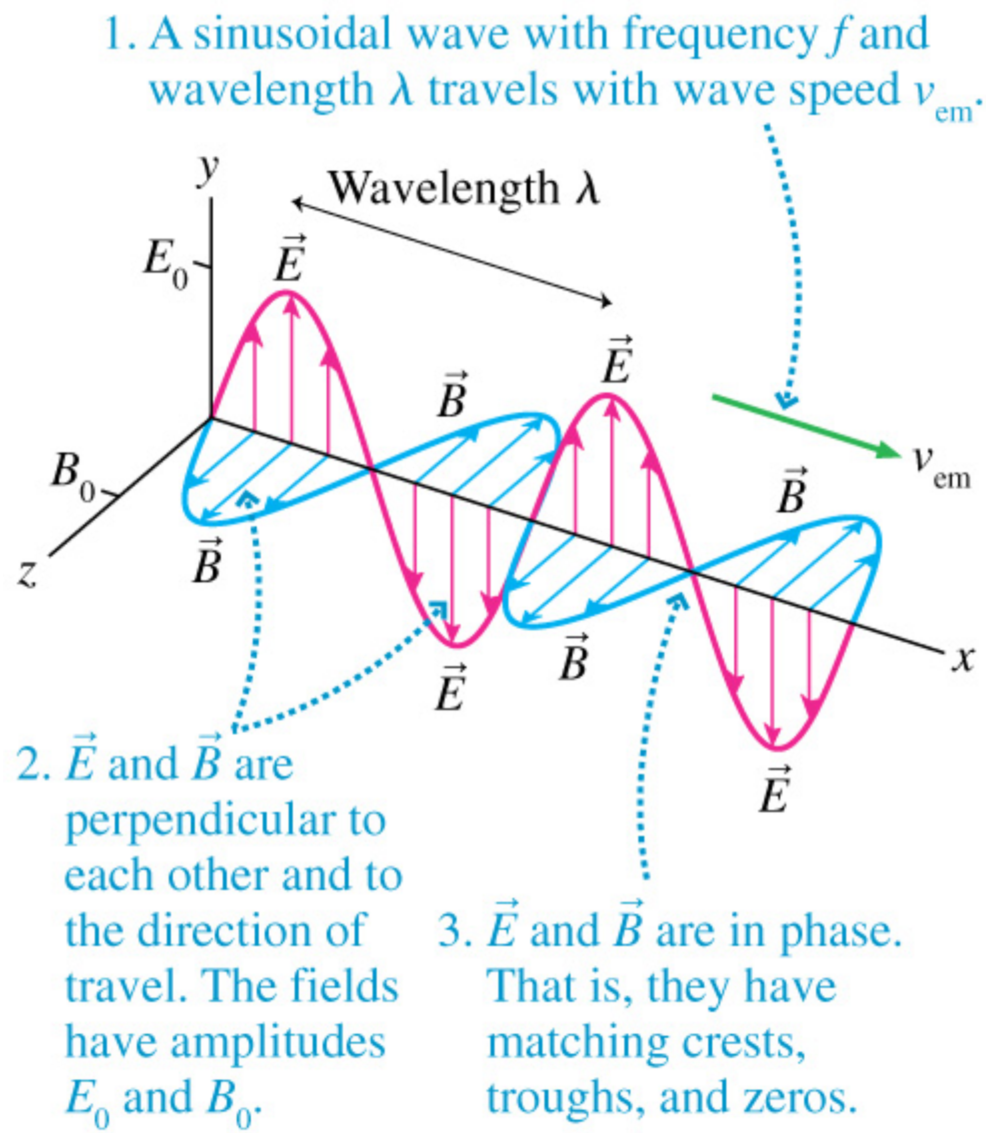
$$\oint_{surface} \vec{E} \cdot d\vec{A} = 0$$

$$\oint_{surface} \vec{B} \cdot d\vec{A} = 0$$

$$\oint_{curve} \vec{E} \cdot d\vec{s} = -\frac{d\Phi_B}{dt}$$

$$\oint_{curve} \vec{B} \cdot d\vec{s} = \mu_o \varepsilon_o \frac{d\Phi_E}{dt}$$

- …it can be shown that light consists of oscillating electric and magnetic fields



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- …it can be shown that light consists of oscillating electric and magnetic fields

$$\frac{\partial^2 E_y}{\partial x^2} = \varepsilon_o \mu_o \frac{\partial^2 E_y}{\partial t^2}$$

$$\frac{\partial^2 E_y}{\partial x^2} = \frac{1}{c^2} \frac{\partial^2 E_y}{\partial t^2}$$

- You end up with a wave equation where the speed of the wave depends on two constants of nature: ε_o and μ_o
  - ε_o comes in when we talk about electric fields
  - μ_o comes in when we talk about magnetic fields
  - $c = \frac{1}{\sqrt{\mu_o \varepsilon_o}} = 3X10^8 m/s$

You can put the equations on a t-shirt

- …in this case, the equations are in differential form, rather than integral form

video

You can sit in Maxwell's chair

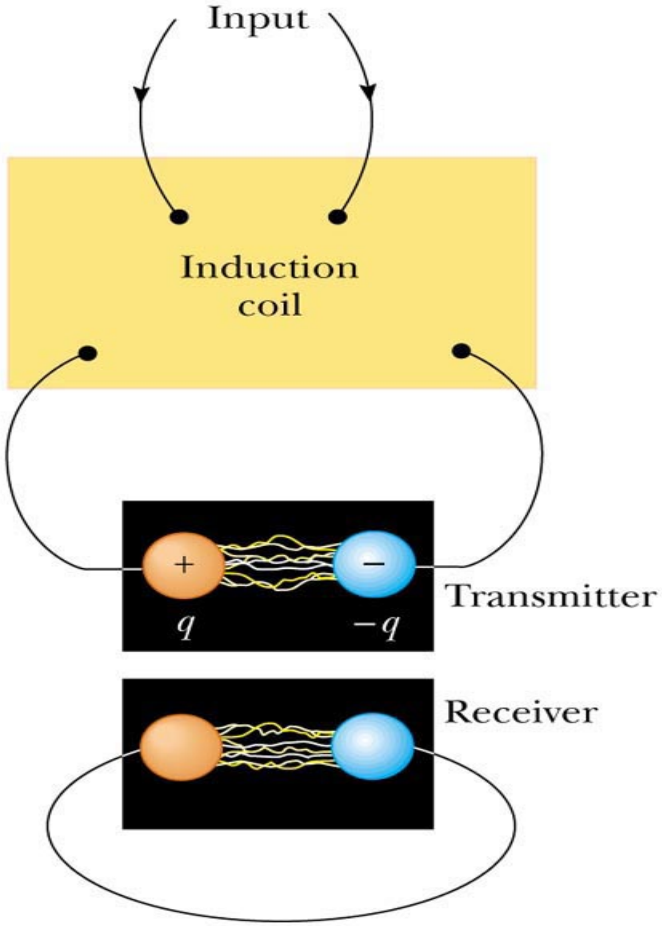
You can sit in Maxwell's chair

…or at least I can

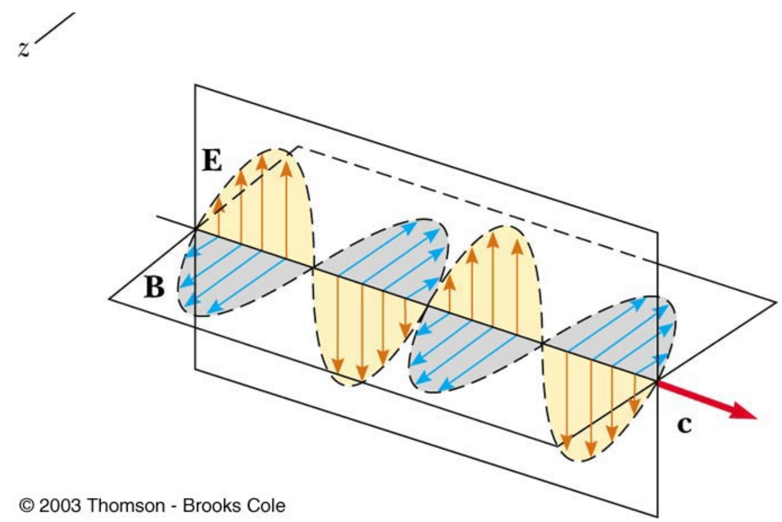
at the Cavendish Laboratory at the University of Cambridge

What we know

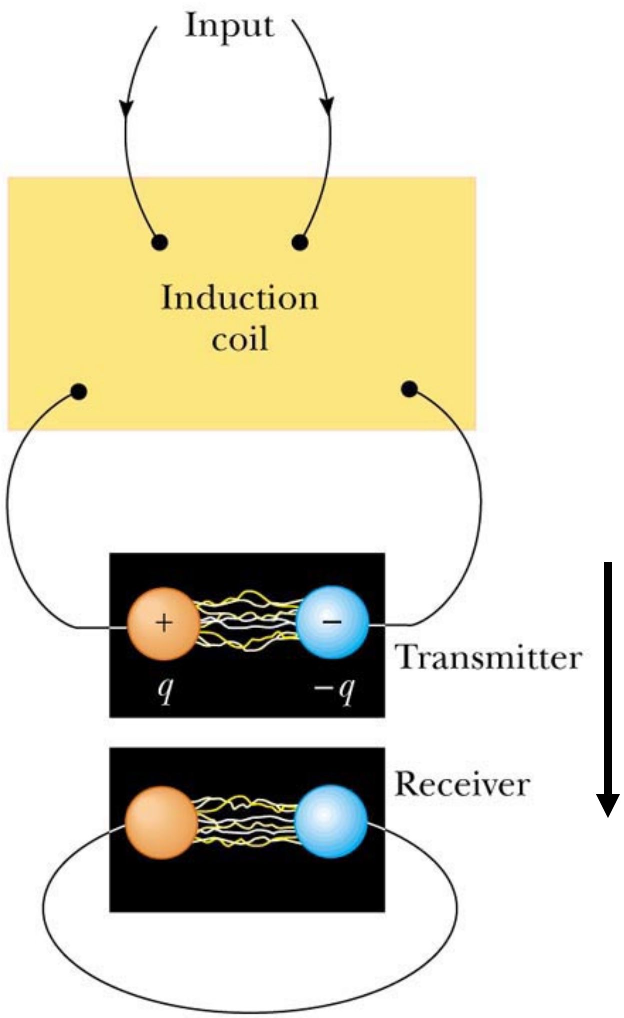
- Stationary electric charges produce electric fields
- Electric charges in uniform motion (currents) produce electric and magnetic fields
- Accelerated electric charges produce electric fields, magnetic fields, and electromagnetic waves



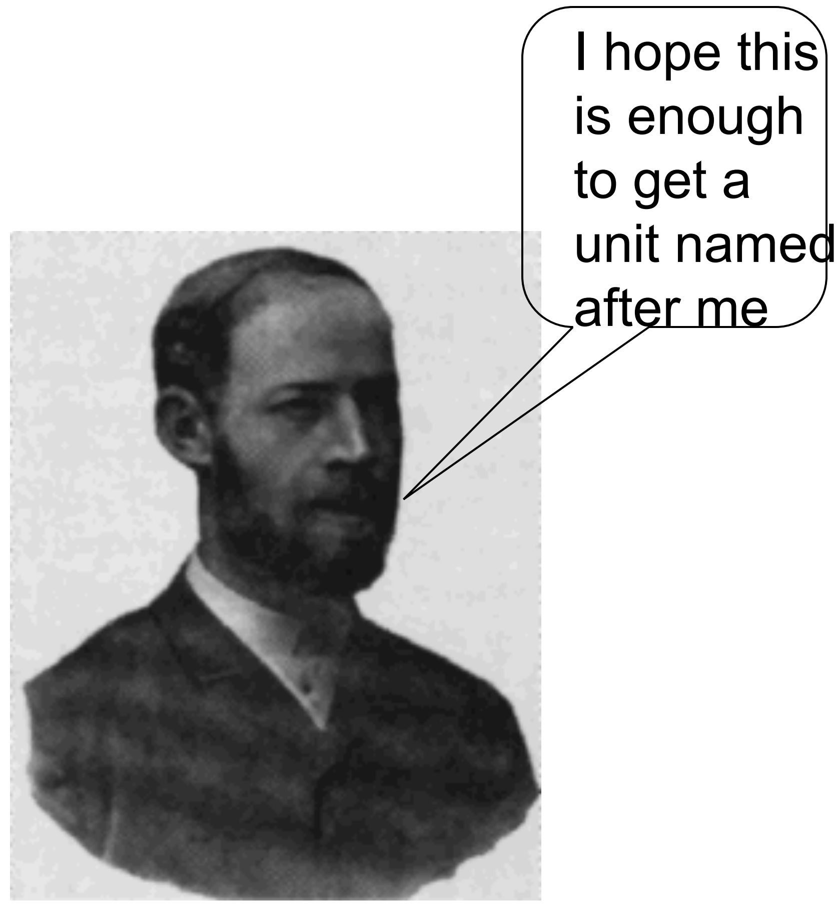
EM waves



It was left to Heinrich Hertz to verify EM waves



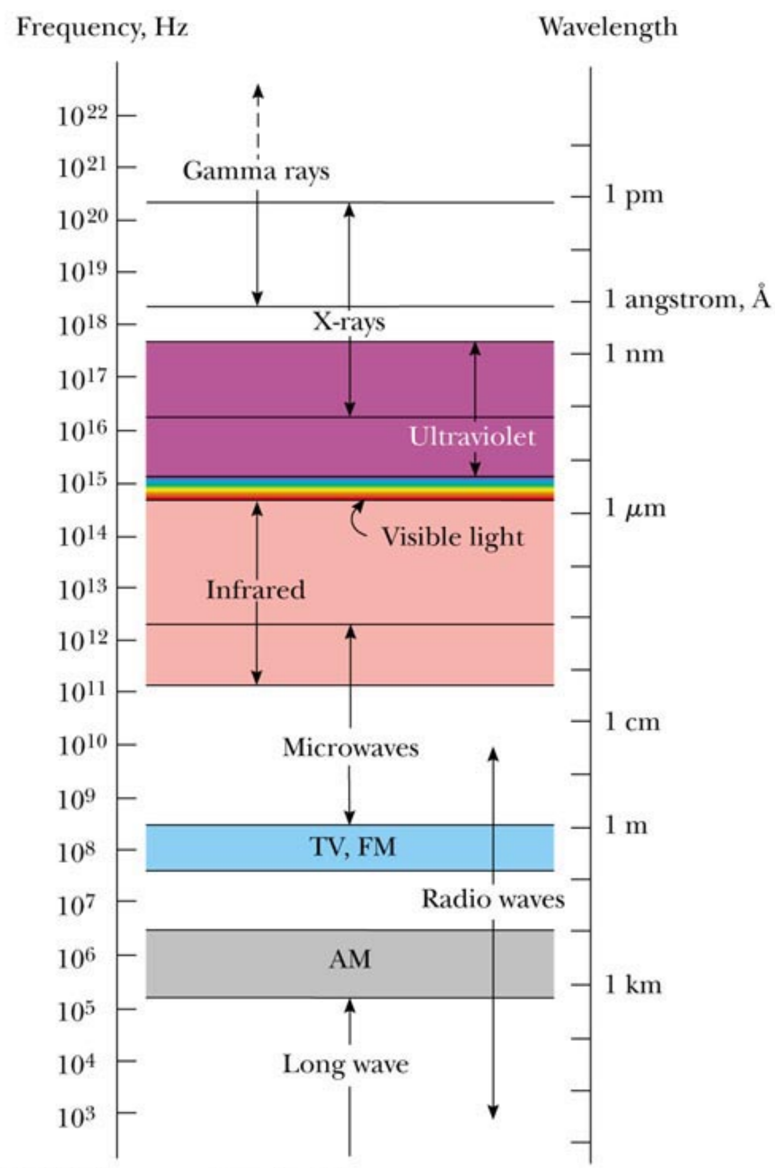
EM waves



…and of course the unit for frequency is Hertz

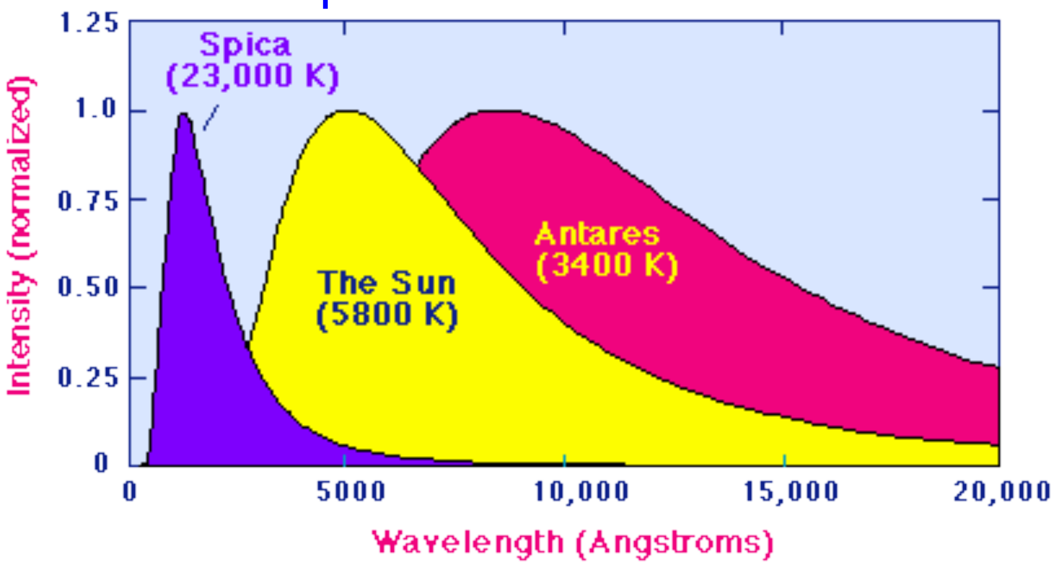
Electromagnetic spectrum

- All electromagnetic waves travel through vacuum with a speed c (3×10^8 m/s)
- For all EM waves, $c=\lambda f$ (true for any type of wave)
- $\lambda = c/f$
- The visible portion of the spectrum forms a tiny portion of the total EM spectrum

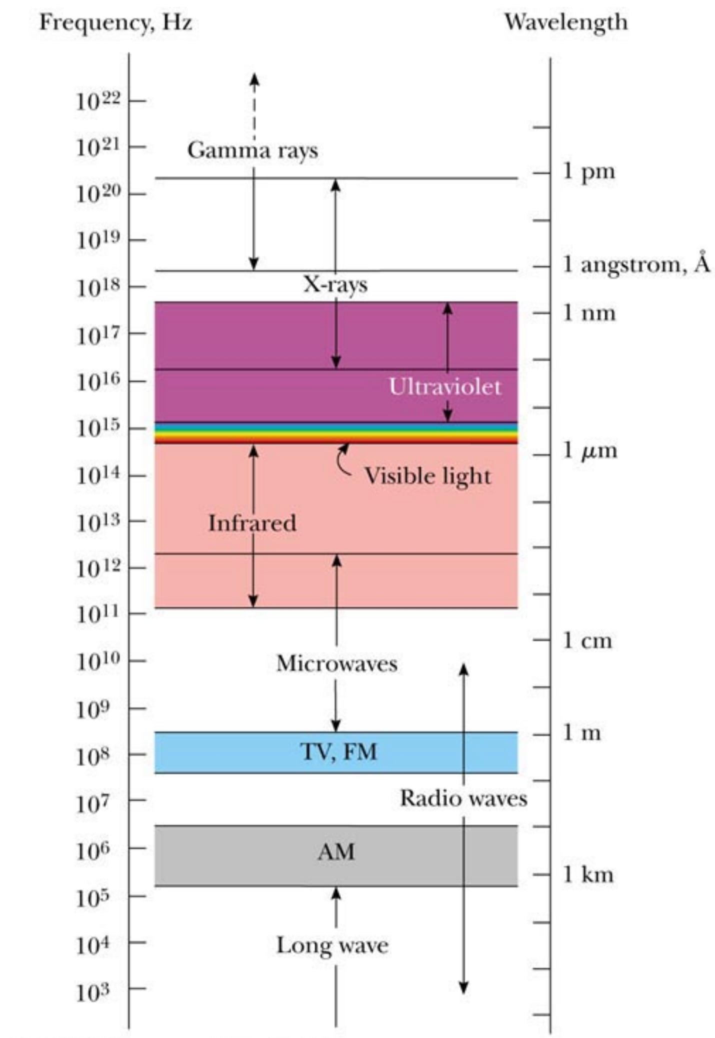


Electromagnetic spectrum and the sun

- As we've said before, the electromagnetic waves coming from the sun peak in the yellow portion of the visible spectrum

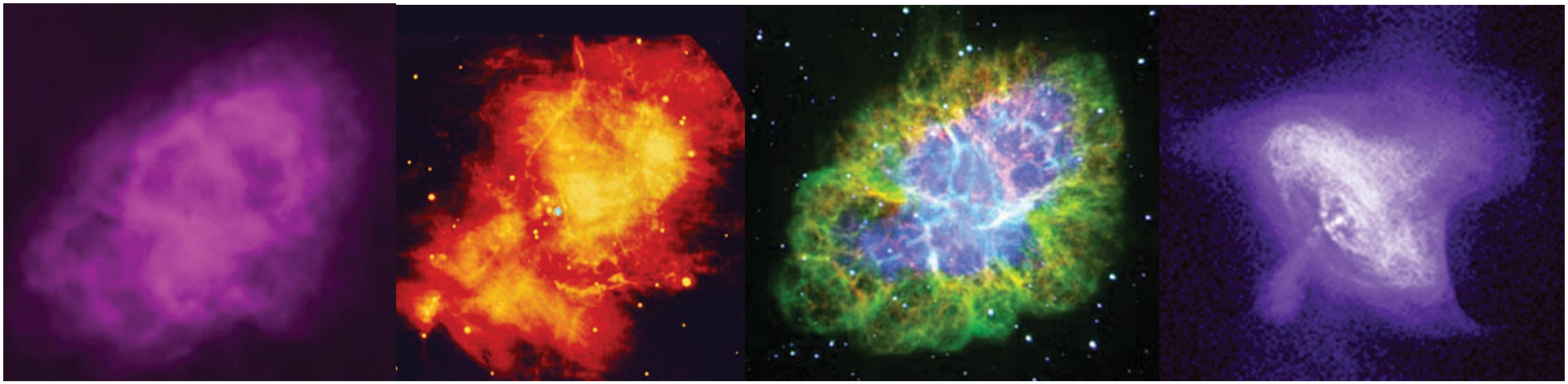


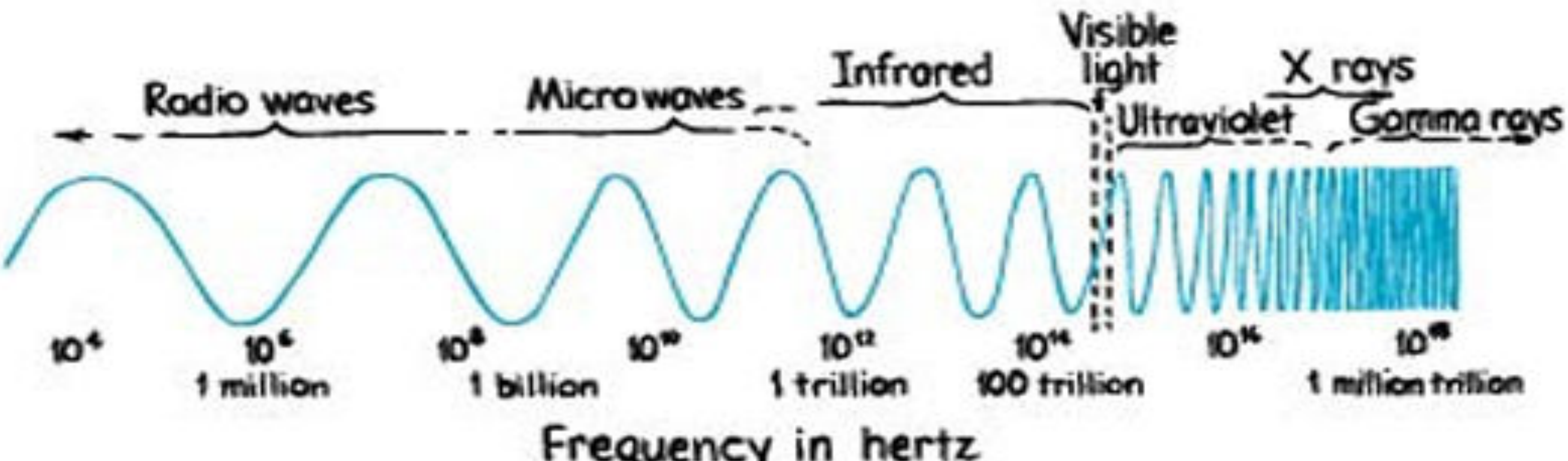
- The light from other stars may peak at different wavelengths, depending on their surface temperature



Views of Crab Nebula

radio infra-red optical X-ray





Increasing wavelength