

Today:

Chapter 25 (Magnetic Induction)

Final Exam

Tue Dec 20, 11.30am—1.30pm

- Cumulative, multiple-choice, 2-3 qns per chapter up to Ch 22, and 5-6 qns per chapter after that.
- All questions you will have seen before on lecture slides, midterms, or review sessions (inc. final review session)

Electromagnetic Induction

- **Voltage can be induced (created) by a changing magnetic field.**
- *C.f.* last chapter: currents produce magnetic field, i.e. electricity produces magnetic fields.
The reverse is true too! Magnetic fields can produce electricity.

(Exploited today in effective electricity transmission across world)

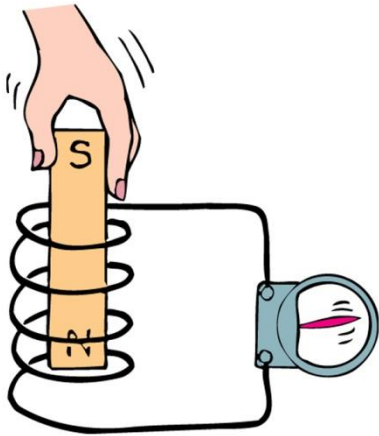
Electromagnetic Induction

- Moving a magnet in and out of a wire loop creates a current (Faraday and Henry) :

- **DEMO -**

<http://micro.magnet.fsu.edu/electromag/java/faraday2/>

Or, <http://www.youtube.com/watch?v=hajlIGHPeuU>

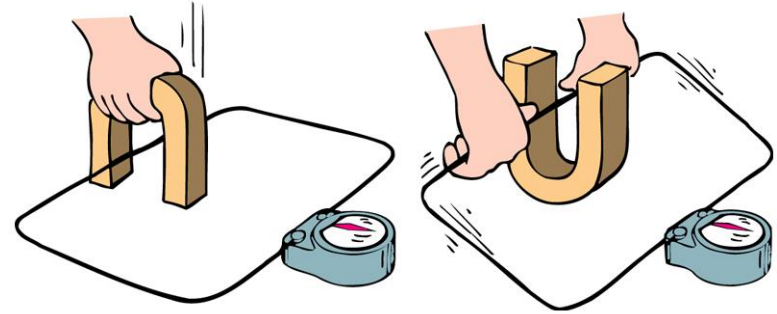


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- Don't need any battery/voltage source – just need *relative motion between magnet and coil*.
- Moving magnet in vs moving out: current induced in opposite directions.
- If magnet is stationary, there is no current.
- The greater the number of loops, the greater the voltage induced

Electromagnetic induction cont.

- **Relative motion is needed:** Voltage is induced either
 - if magnet is moved near stationary conductor, *or*
 - if conductor is moved near stationary magnet



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The key point is that the conductor lies in a region where the magnetic field changes

- The faster the motion, the greater the voltage. If move too slowly, hardly any voltage.
- The voltage induced creates a current that in turn, has a magnetic field – this *repels* the original magnet that induced the voltage

Recall ch. 24

Electromagnetic induction cont.

Eg. **DEMO**: Drop a magnet down a copper or aluminum pipe. It takes longer to fall down than an unmagnetized object !

<http://www.youtube.com/watch?v=sPLawCXvKmg>

As a magnet falls down into a coil of many loops → large voltage induced → large current induced → large associated magnetic field → large repulsion with original magnet.

Faraday's Law

- **The induced voltage in a coil is proportional to the product of the number of loops and the rate at which the magnetic field changes within those loops.**
- The amount of resulting *current* depends on the induced voltage but also on the resistance of the coil and the nature of the circuit (a property called *inductance*, not covered in this course).
- Many applications: e.g. Credit cards (see book for more), airport security systems, tape recorders...
- **Eg. Traffic lights:**
Consider embedding a wide, closed loop of wire in a road surface. The Earth's magnetic field goes through this loop. Now, if when a metal (iron) car passes by, it momentarily increases the field in the loop, triggering a current pulse, that is then detected to trigger traffic lights !
- Other than relative motion b/n magnets and conductors, can also *induce voltage in some loop by changing the current in another nearby loop.* (since this changes the mag field near the 1st loop)

Clicker Question

Can current flow around a wire loop which is not connected to any battery or power source?

- A) Yes, generally current will flow
- B) Yes, if the loop lies in a magnetic field
- C) Yes, if the loop lies in a changing magnetic field
- D) No, never, as this would violate energy conservation.
- E) No, never as this would violate charge conservation.

Answer: C

Faraday's law: Voltage, and therefore current, is induced by a changing magnetic field

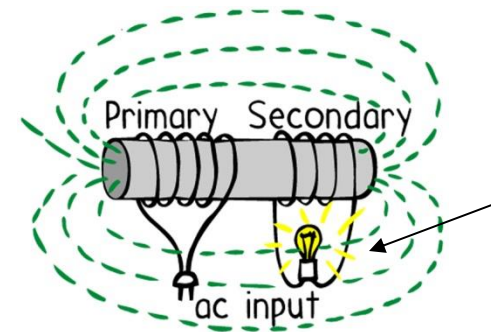
A Question

How could a light bulb near, but not touching, an electromagnet be lit? Is ac or dc required?

← recall, a current-carrying coil

If the bulb is connected to a wire loop that intercepts changing magnetic field lines from an electromagnet, voltage will be induced that can illuminate the bulb. Need ac, since need changing fields.

Eg. Idea behind transformers, see shortly:



Even just 1 loop here will work.

Clicker Question

Consider a closed loop made of rubber and a closed loop made of copper. If a magnet is plunged in and out of each at the same rate, which gets the larger voltage induced? Which gets the larger current induced?

- A) Larger voltage and larger current induced in the copper loop
- B) Larger voltage and larger current induced in the rubber loop
- C) Same voltage and same current induced in both
- D) Same voltage induced in both, larger current induced in copper
- E) Larger voltage induced in copper, same current in both
- F) None of the above

Answer: D

Both get same induced voltage (Faraday's law), but the current is larger in the copper since it has less resistance. Electrons in the rubber feel the same electric field, but cannot move easily in response.

Generators and Alternating Current

- Recall that induced voltage (or current) *direction* changes as to whether magnetic field is increasing or decreasing (eg magnet being pushed in or pulled out). In fact:

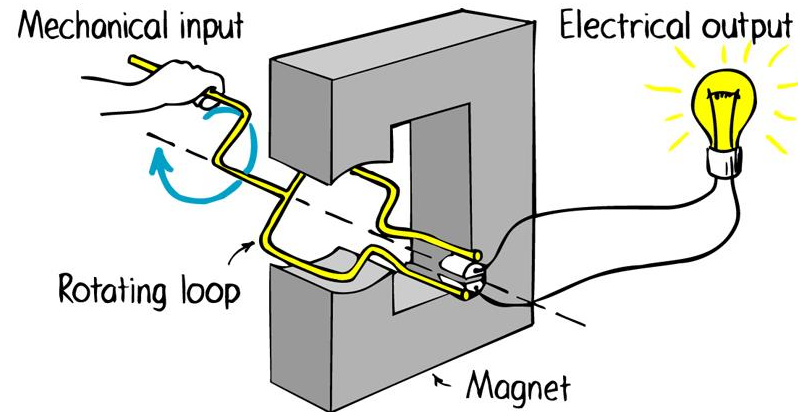
frequency of the alternating voltage = frequency of changing magnetic field.

Generator: when coil is rotated in a stationary magnetic field: ac voltage induced by the changing field within the loop.

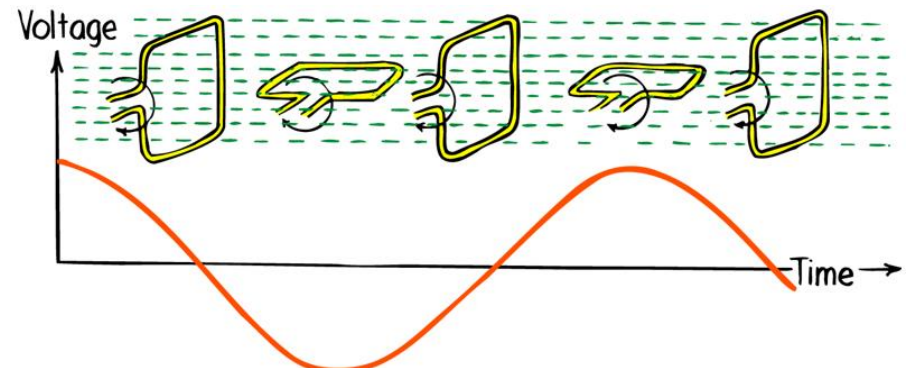
Note similarity to motor from Ch. 24: the only difference is that in a generator, the input is the mechanical energy, the output is electrical.

(other way around for motor).

Note, change in # field lines intersecting the loop area, as it rotates.



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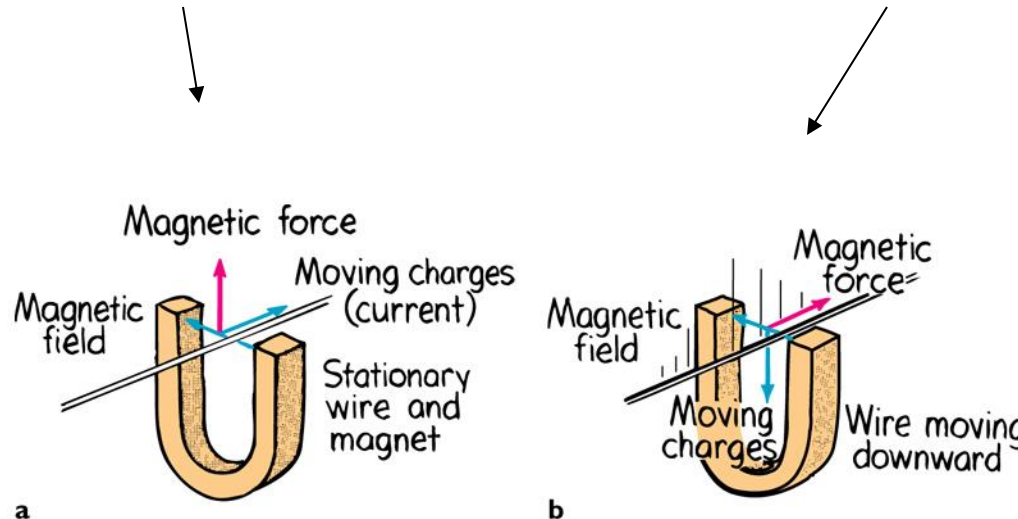


Generators cont.

Fundamentally, induction arises because of the force on moving charges in a magnetic field (recall Ch.24):

Compare *motor effect* to *generator effect*

Motor: current along wire, means moving charges in mag field. So experience force perp. to motion and to field, ie. upward.



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Generator: wire (no initial current) moved downward, so electrons are moving down in field, so feel force perp. to motion and to field i.e. along wire, i.e. a current.

(+ ions also feel force, in opp dir. but not free to move).

Extra Reading, i.e. Non-Examinable

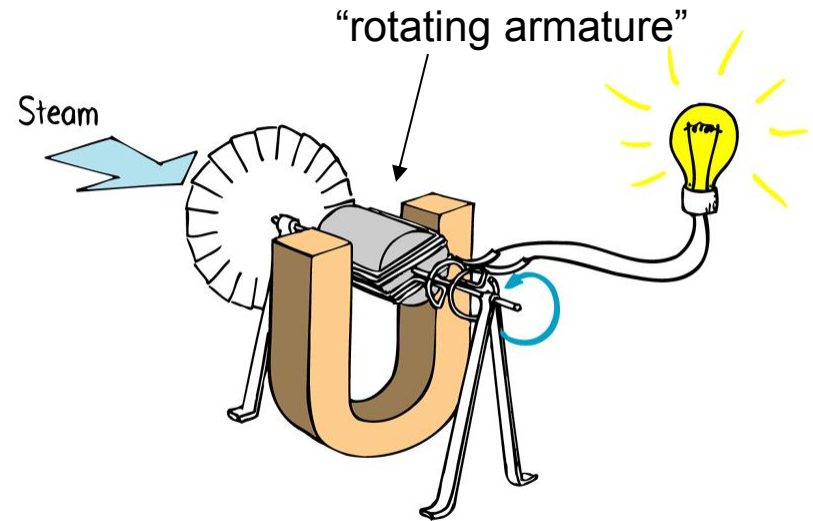
Power production

Turbogenerator power

(Original idea was Tesla (late 1800's))

Steam (or falling water) used to drive turbine that rotates copper coils in a strong magnetic field. Hence ac voltage/current induced.

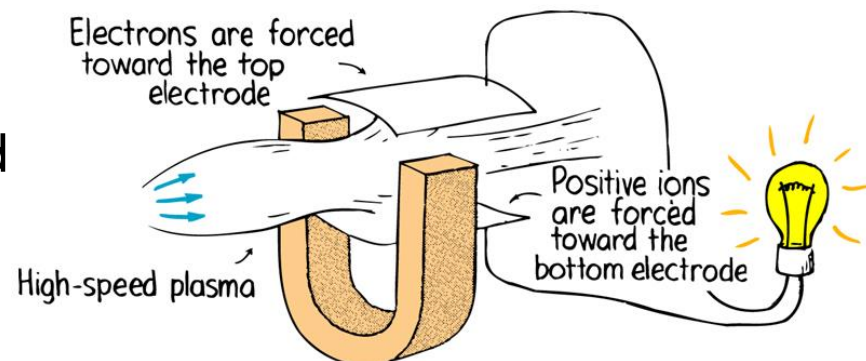
Iron core placed in center of copper coil to strengthen the field.



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Magnetohydrodynamic power (MHD)

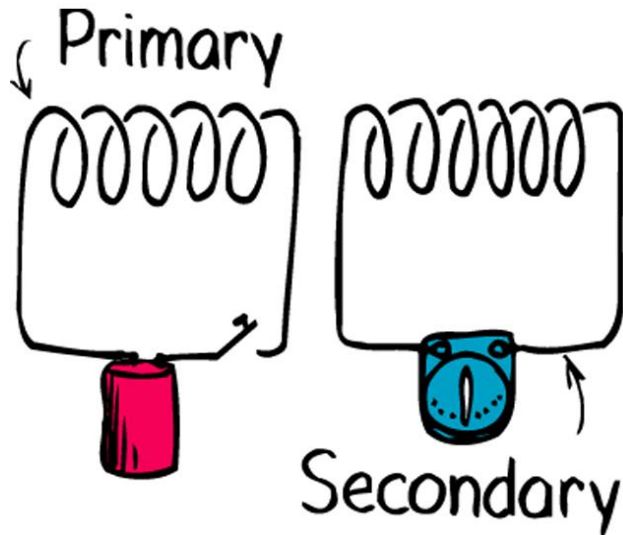
Instead of the rotating armature, use supersonic plasma sent through mag field
Positive ions and electrons deflect to opposite sides – collected by “electrodes” (ie conducting plates), giving them a voltage difference.



Relatively new technology, since not easy to produce high speed plasmas.

Transformers

Consider first the following arrangement of side-by-side coils:



The primary coil has a battery, so when switch is closed, current flows in it, creating a sudden magnetic field that threads the secondary coil – inducing current pulse in it too. *(Note no battery in secondary coil).*

Only brief though, since current in secondary only flows at the time the switch in primary is opened or shut.

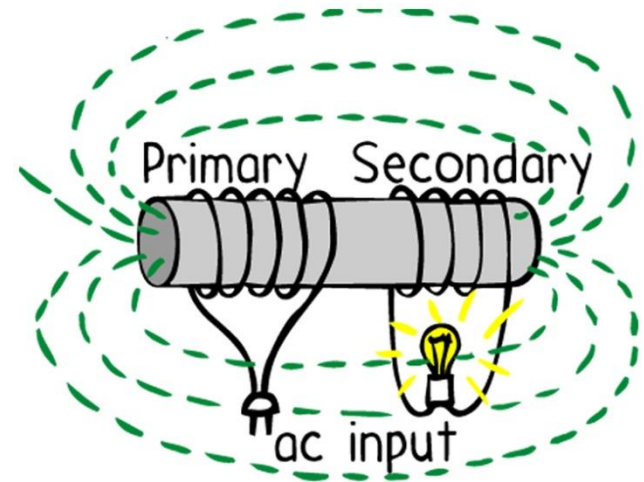
Question: Say the switch in primary coil is closed at time 0 and then opened again after 5 seconds. What is (roughly) the behavior of the current in the primary coil? the secondary coil?

Primary: current begins at time 0, is constant for 5 sec, then drops to zero.

Secondary: current pulse at time 0 flows in one direction, then goes to zero while the primary current is constant. Then pulse flows in opposite dir. when the switch is opened, and again goes to zero afterwards.

Transformers cont.

- To maintain current flow in the secondary coil, need always **changing magnetic field**, i.e. always changing current in the primary coil – **use ac**.
- Moreover, can put an **iron core** through the coils, as this intensifies the field (recall Ch.24) and so amplifies the current through the secondary, i.e. simple transformer looks like:



- Recall dependence on # coils (called # *turns*):
 - the field generated by the primary coil is greater if there are more loops in it (Ch24, property of electromagnets)
 - the voltage induced in the secondary coil is greater if there are more loops in it (Faraday's law)
- So.....

Transformers cont.

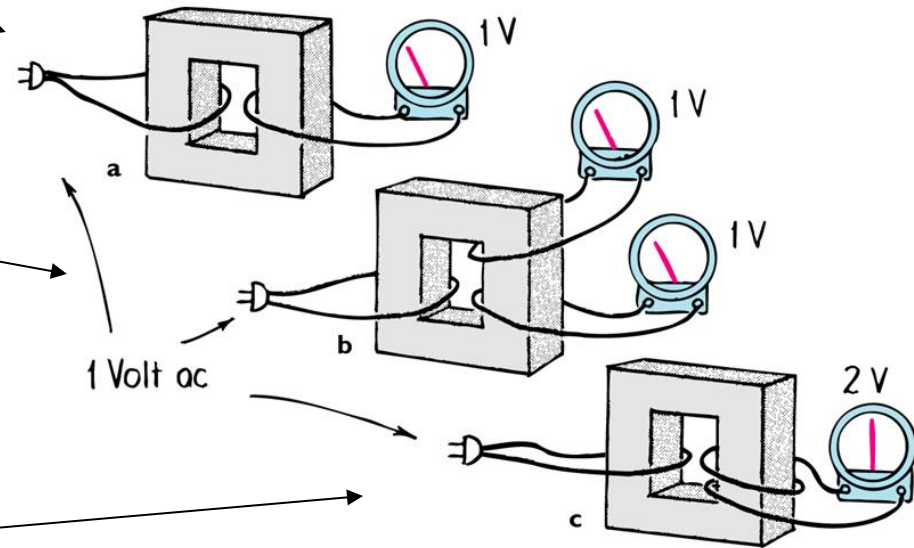
...Leads to the following relationship:

$$\frac{\text{Primary voltage}}{\text{\# of primary turns}} = \frac{\text{Secondary voltage}}{\text{\# of secondary turns}}$$

Eg. If both coils have same # turns, then voltage induced in secondary is equal to that in the primary.

Eg. If secondary has more turns than primary, then voltage is *stepped up* i.e. greater in the secondary than in the primary.

Here, twice as many, and each loop intercepts the same mag field change, same voltage. Join them → add voltages



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Eg. If secondary has less # turns than first (not shown), the voltage induced will be less, ie. *stepped down*.

Transformers and Power Transmission

- Because of energy conservation, **if the voltage in the secondary is stepped up, the current must be correspondingly lower:**

Recall: rate of energy transfer → Power into primary = power out of secondary, so

$$(\text{voltage} \times \text{current})_{\text{primary}} = (\text{voltage} \times \text{current})_{\text{secondary}}$$

- Transformers are behind the main reason why most electric power is ac rather than dc: easy way of stepping up and down.
- To transmit across large distances (i.e. cities...), want to minimize energy loss due to wire heating i.e. want *low currents*, so correspondingly *high voltages* **i.e. step up for transmission**
- Power usually generated at 25 000 V, stepped up to 750 000V near the power station for long-distance transmission, then stepped down in stages to voltages needed in industry (eg 440 V) and homes (120 V).
- EM induction thus is method for transferring energy between conducting wires. In fact, this is also behind radiant energy in the sun! (see later...)

Questions

- (1) If 120 V is put across a 50-turn primary, what will be the voltage and current output if the secondary has 200 turns, and is connected to a lamp of resistance 80 Ω ?

$$(120 \text{ V})/50 = (?V)/(200), \text{ so } ? = \underline{480 \text{ V}}$$

$$\text{Current} = \text{voltage/resistance} = 480/80 = \underline{6 \text{ A}}$$

- (2) What is the power in the secondary coil?

$$\text{Power} = \text{voltage} \times \text{current} = 480 \text{ V} \times 6 \text{ A} = \underline{2880 \text{ W}}$$

- (3) Can you determine the current drawn by the primary coil? If so, what is it?

$$\text{current} = \text{power/voltage}, \text{ and power input} = \text{power out} = 2880 \text{ W}$$

$$\text{so, current} = 2880/120 = \underline{24 \text{ A}}$$

Clicker Question

A step-up transformer increases

- A) Power
- B) Energy
- C) Voltage
- D) Current
- E) Some of the above

Answer: C, voltage

Power and energy are conserved, current is decreased

Self-induction

- Current-carrying loops in a coil interact with magnetic fields of loops of other coils, but also with fields from loops of the same coil – called *self-induction*
- Get a self-induced voltage, always in a direction *opposing* the changing voltage that creates it. - called *back emf* (= back electromotive force)
- We won't cover this much, except to say that this is behind the sparks you see if you pull a plug out from socket quickly, while device is on:

Consider here a long electromagnet powered by a dc source. So have strong mag field through coils. If suddenly open a switch (e.g. pulling the plug), the current and the large field go to zero rapidly. Large change in field → large induced voltage (back emf) – this creates the spark (zap!).



Field Induction

- Fundamentally, a changing mag field produces an *electric field*, that consequently yields voltages and currents.
- You don't need wires, or any medium, to get fields induced.
- Generally, Faraday's law is

An electric field is created in any region of space in which a magnetic field is changing with time. The magnitude of the induced electric field is proportional to the rate at which the magnetic field changes. The direction of the induced electric field is perpendicular to the changing magnetic field.

Complementary to Faraday's law (due to Maxwell): *just interchange "electric" and "magnetic" in the law above!* i.e.

A magnetic field is created in any region of space in which an electric field is changing with time. The magnitude of the induced magnetic field is proportional to the rate at which the electric field changes. The direction of the induced magnetic field is perpendicular to the changing electric field.

- This beautiful symmetry is behind the physics of light and electromagnetic waves generally!

Clicker Question

Voltage can be induced in a wire by

- A) moving the wire near a magnet.
- B) moving a magnet near the wire.
- C) changing the current in a nearby wire.
- D) Choices A, B, and C are all true.
- E) None of the above choices are true.

Answer: D

Electromagnetic induction: a voltage is induced in a wire when it lies in a region where the magnetic field is changing in time.