Phys 102 – Lecture 14

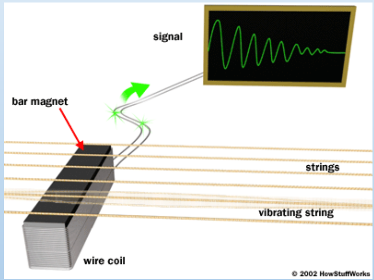
Faraday's law of induction

Today we will...

- Continue our discussion of electromagnetic induction unifying electricity & magnetism
  - Last time: Lenz' law for EMF *direction*
  - Today: Faraday's law for EMF *magnitude*
- Apply these concepts
  - Lenz' & Faraday's law are basis for electrical generators & transformers, and much more

Power plant

Credit card reader



Guitar pickup

Faraday's law of induction

Change in flux Φ through a loop induces an EMF ε

Induced EMF ε →

$$\boxed{\varepsilon = -\frac{\Delta\Phi}{\Delta t}}$$

← Rate of change of flux Φ

Magnitude

Induced EMF ε = rate of change of flux Φ

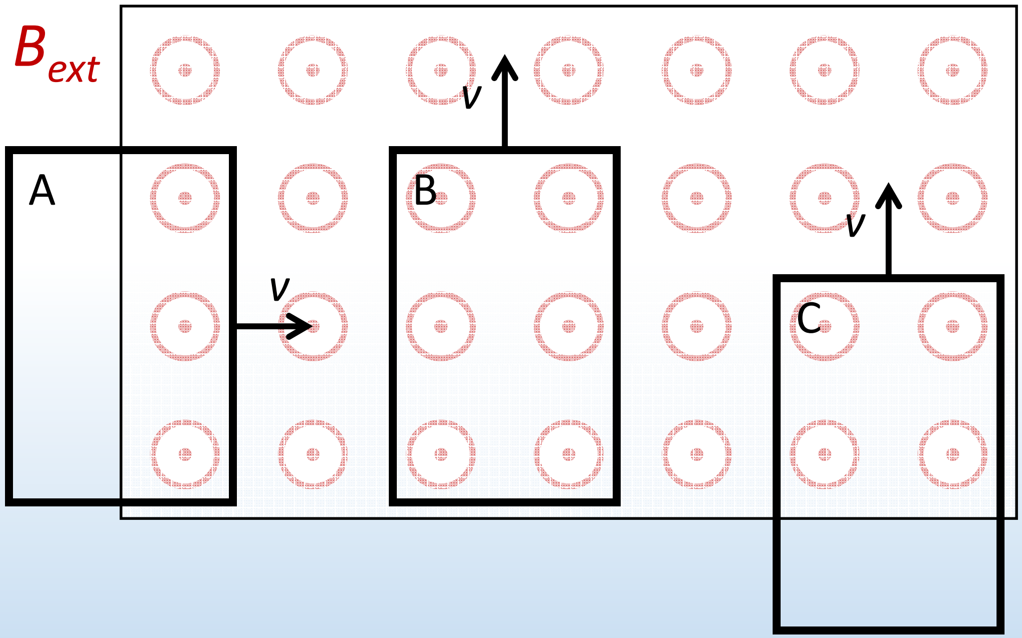
$$|\varepsilon| = \left|\frac{\Delta\Phi}{\Delta t}\right|$$

Direction

Lenz' law: EMF ε *opposes* change in flux Φ

ACT: moving loops

Three loops are moving at the same speed *v* in a region containing a uniform *B* field. The field is zero everywhere outside.



In which loop is |ε| greatest at the instant shown?

A. Loop A

B. Loop B

C. Loop C

Faraday's Law of Induction

"Induced EMF" = rate of change of magnetic flux

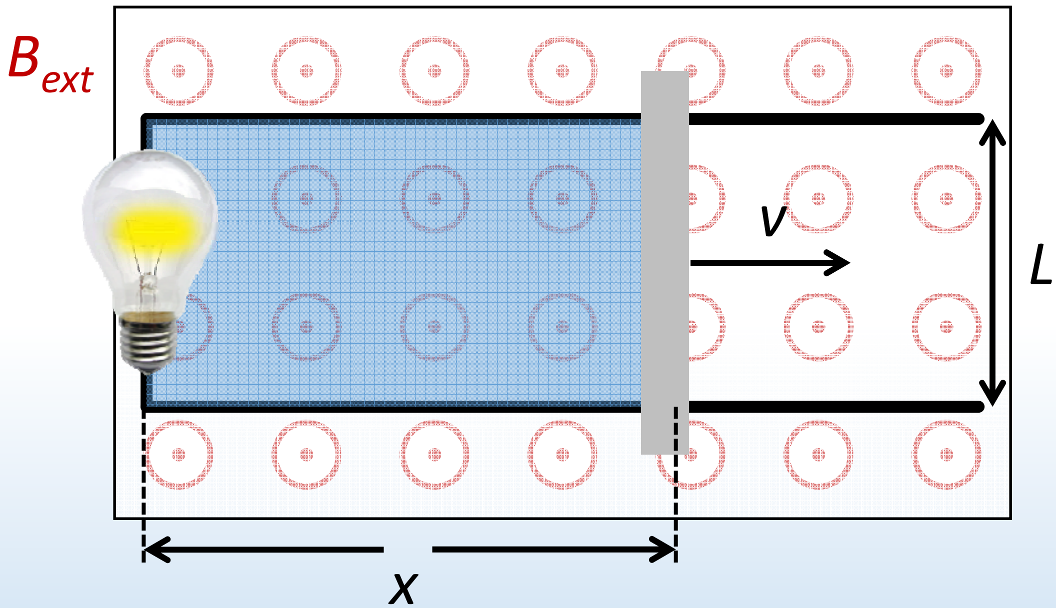
$$\varepsilon = -\frac{\Delta\Phi}{\Delta t}$$

Since $\Phi = BA\cos\varphi$, 3 things can change Φ

1. Area of loop covered by flux
2. Magnetic field *B*
3. Angle *φ* between normal and *B*

Calculation: changing area

A bar slides with speed *v* on a conducting track in a uniform *B* field



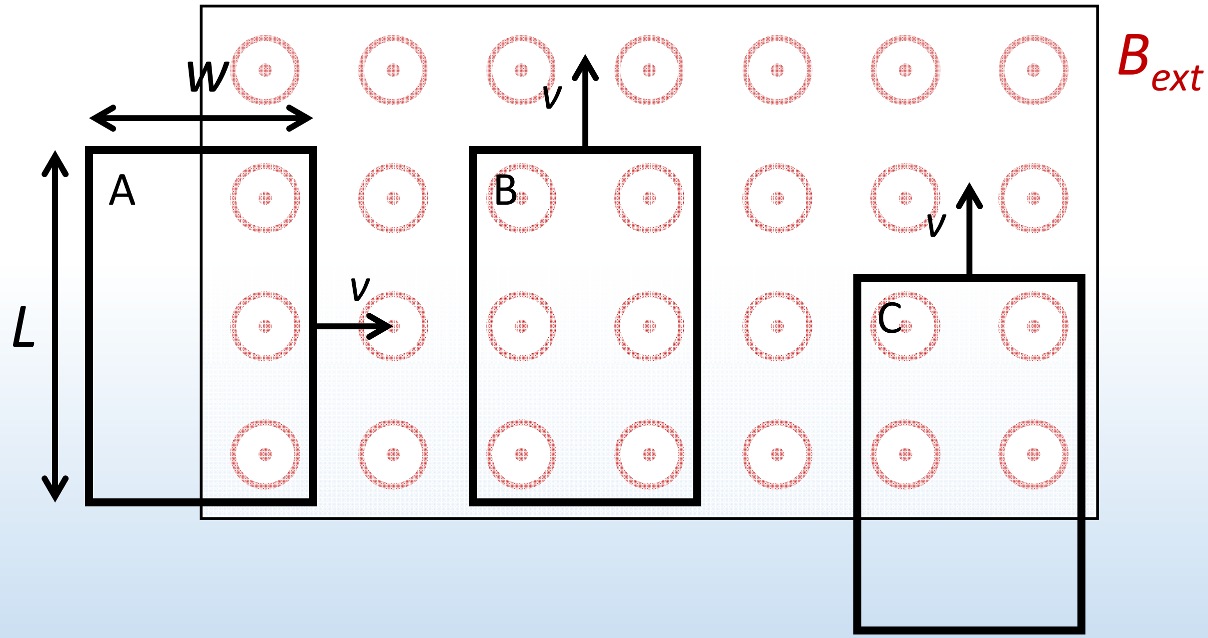
What is the magnitude of the EMF induced in the circuit?

$$|\varepsilon| = \left|\frac{\Delta\Phi}{\Delta t}\right| \qquad \Phi = B_{ext}Lx \quad \text{and only } x \text{ is changing}$$

$$= \frac{\Delta(B_{ext}Lx)}{\Delta t} = B_{ext}L\frac{\Delta x}{\Delta t} = B_{ext}Lv$$

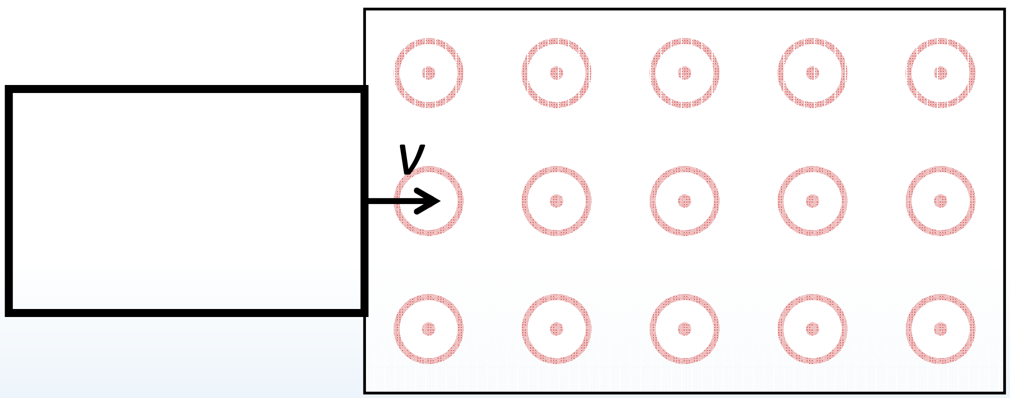
Moving loops revisited

Three loops are moving at the same speed *v* in a region containing a uniform *B* field. The field is zero everywhere outside.



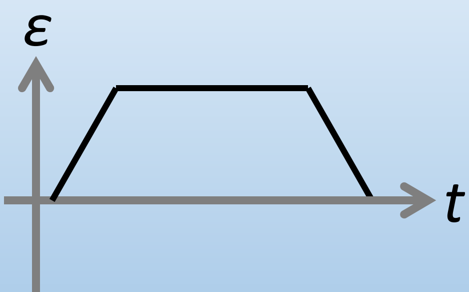
ACT: Moving loop

A loop moves through a region with a uniform *B* field at a constant speed *v.* The field is zero outside.

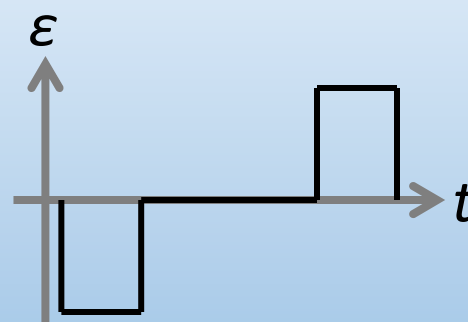


Which diagram best represents the EMF *ε* in the loop vs. time?

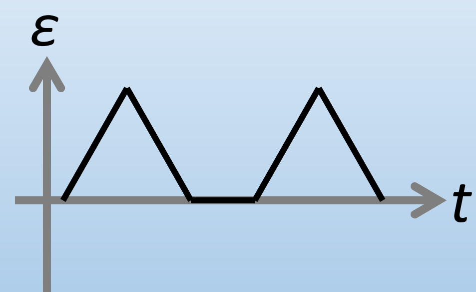
A.



B.



C.



Calculation: solenoid cannon

A loop of radius r_{loop} = 11 cm is placed around a long solenoid. The solenoid has a radius r_{sol} = 4.8 cm and n = 10,000 turns/m of wire. The current I through solenoid increases at a rate of 1.5 A/s.

EXAM 2, FA13

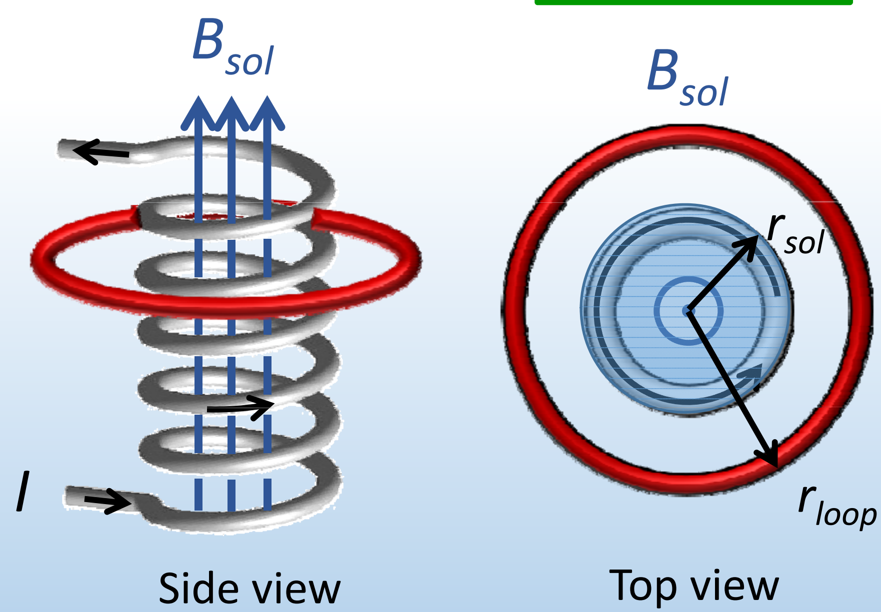
What is the EMF $|\varepsilon|$ in the loop?

$$|\varepsilon| = \left|\frac{\Delta\Phi}{\Delta t}\right| \qquad \Phi = B_{sol}A_{sol}\cos\varphi$$

B field is changing, area is constant

$$B_{sol}(t) = \mu_0 n I(t)$$

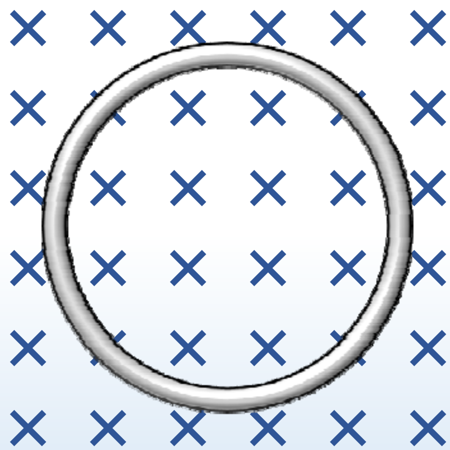
$$|\varepsilon| = \frac{\Delta B_{sol}}{\Delta t}A_{sol} = \mu_0 n \frac{\Delta I}{\Delta t}A_{sol}$$

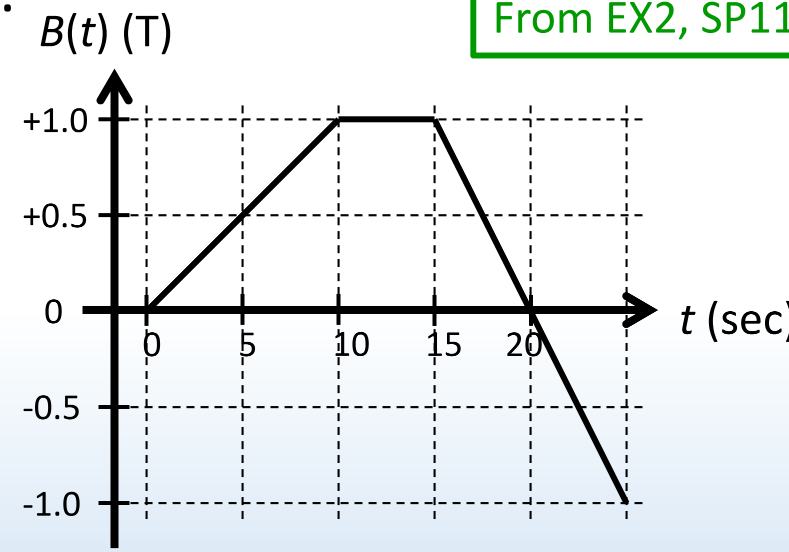


ACT: time-varying B field

A circular loop is placed in a uniform *B* field that varies in time according to the plot on the right.

From EX2, SP11





At which time is the EMF magnitude $|\varepsilon|$ in the loop largest?

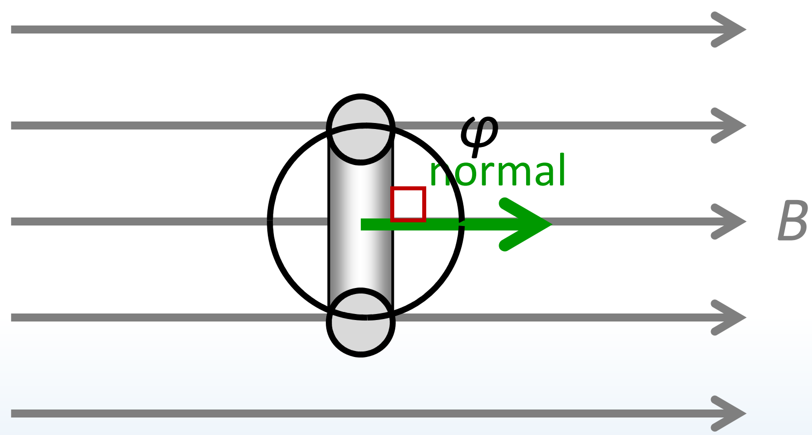
A. $t = 5$ s

B. $t = 12$ s

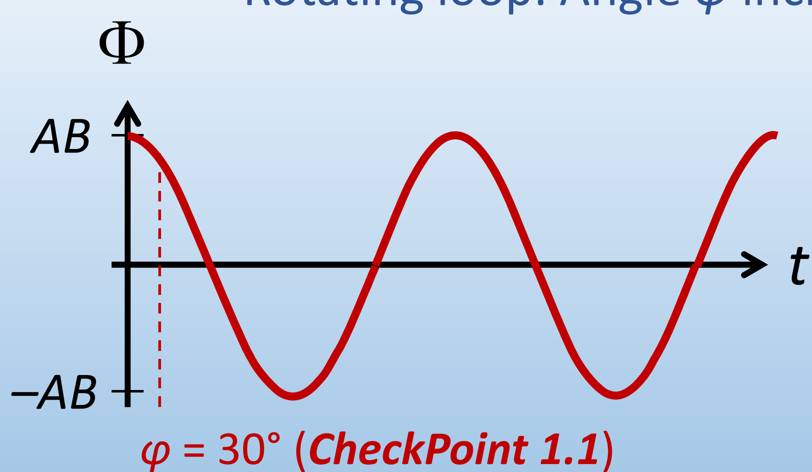
C. $t = 20$ s

Changing φ

EMF can be induced by changing angle φ between loop normal and B field



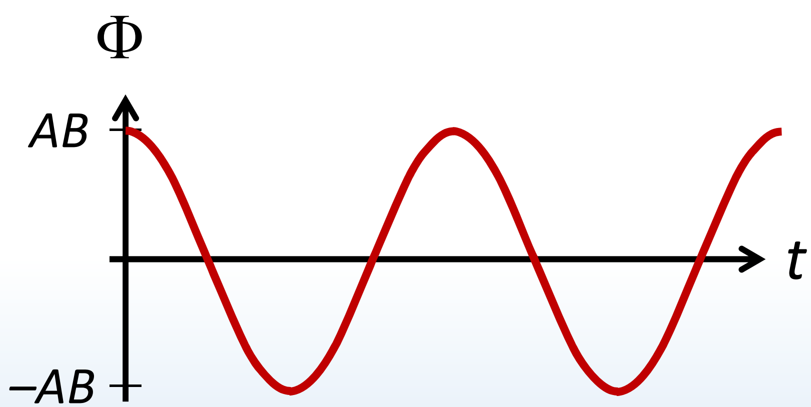
Rotating loop: Angle φ increases at a rate ω (in rad/s)



$$\Phi(t) = BA\cos\omega t$$

Calculation: EMF from changing φ

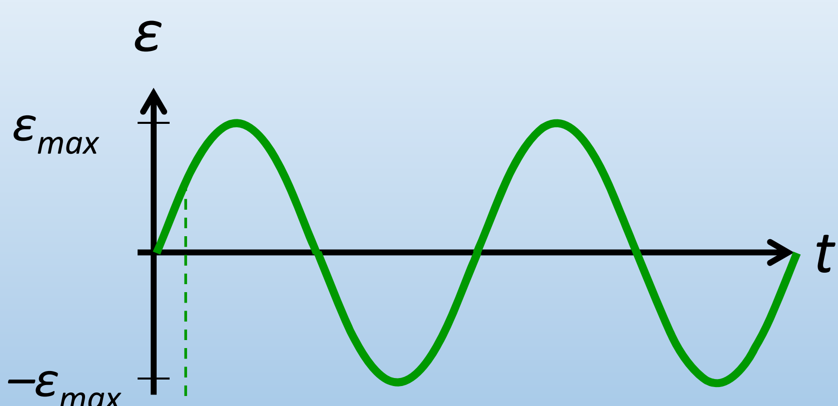
What is the EMF induced by changing angle *φ* between loop normal and *B* field?



$$\Phi(t) = BA\cos\omega t$$

$$\varepsilon = -\frac{\Delta\Phi}{\Delta t}$$

ΔΦ/Δt represents rate of change or *slope* of Φ vs. *t* at that particular time



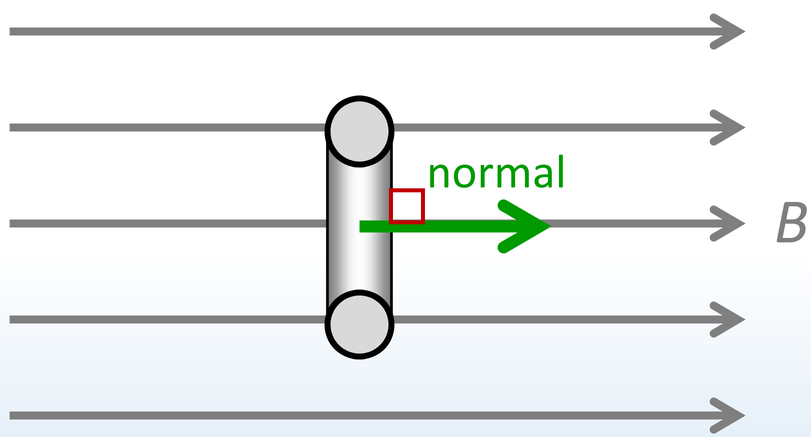
φ = 30° (***CheckPoint 1.2-1.3***)

$$\varepsilon(t) = \varepsilon_{\max}\sin\omega t$$

EMF is a sine wave!

ACT: Rotating loop

The loop below rotates in a uniform *B* field. Which of the following factors can increase the EMF in the loop?



DEMO

A. Increasing the rotation rate ω

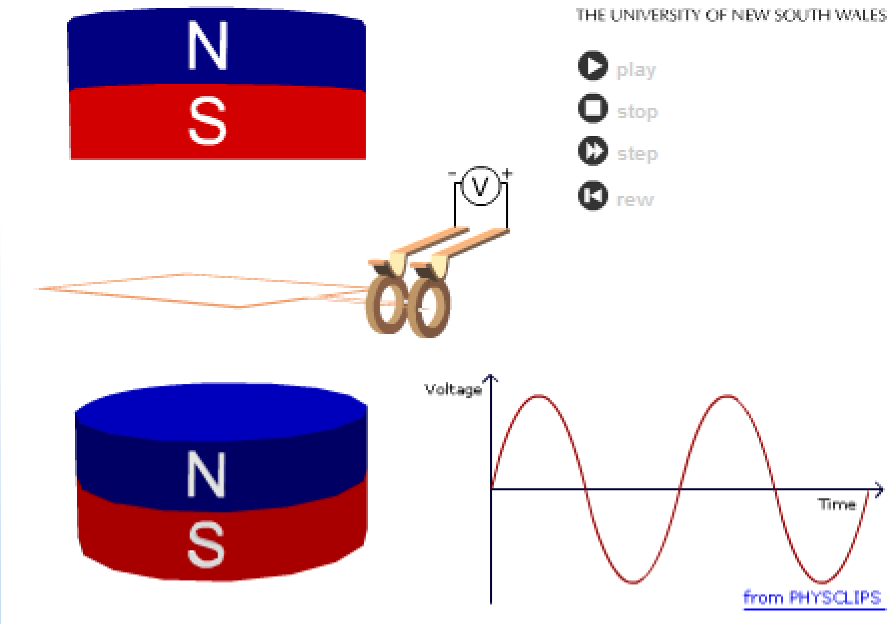
B. Wrapping more turns of wire around the loop

C. Increasing the *B* field

D. All of the above

Application: generators ∿

Electrical generators use external energy source (gas, steam, water, wind, nuclear, etc) to spin loop in *B* field



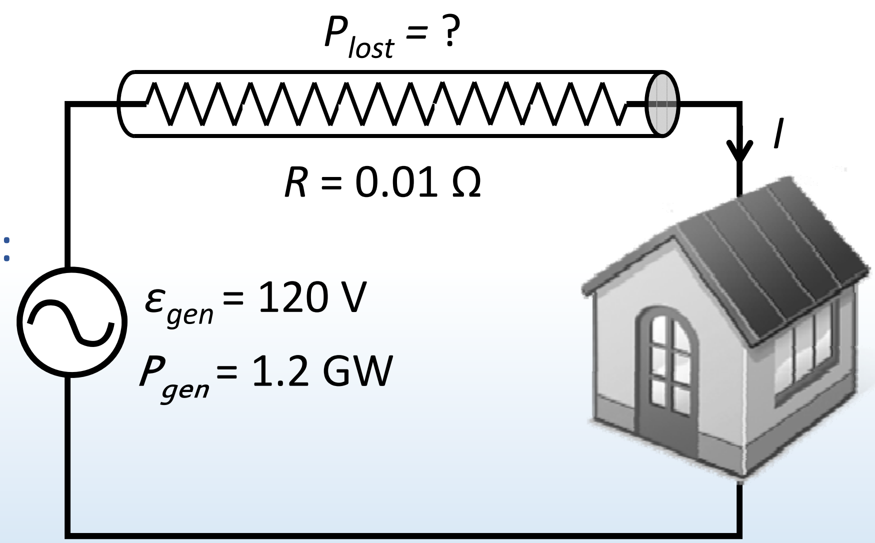
Why electrical current from outlets is alternating current (AC)

In US, current oscillates at a frequency of 60 Hz (cycles/s)

Calculation: CheckPoint 2

A generator produces 1.2 Giga Watts of power, which it transmits to a town through power lines with total resistance 0.01 Ω.

How much power is lost in the lines if it is transmitted at 120 V?

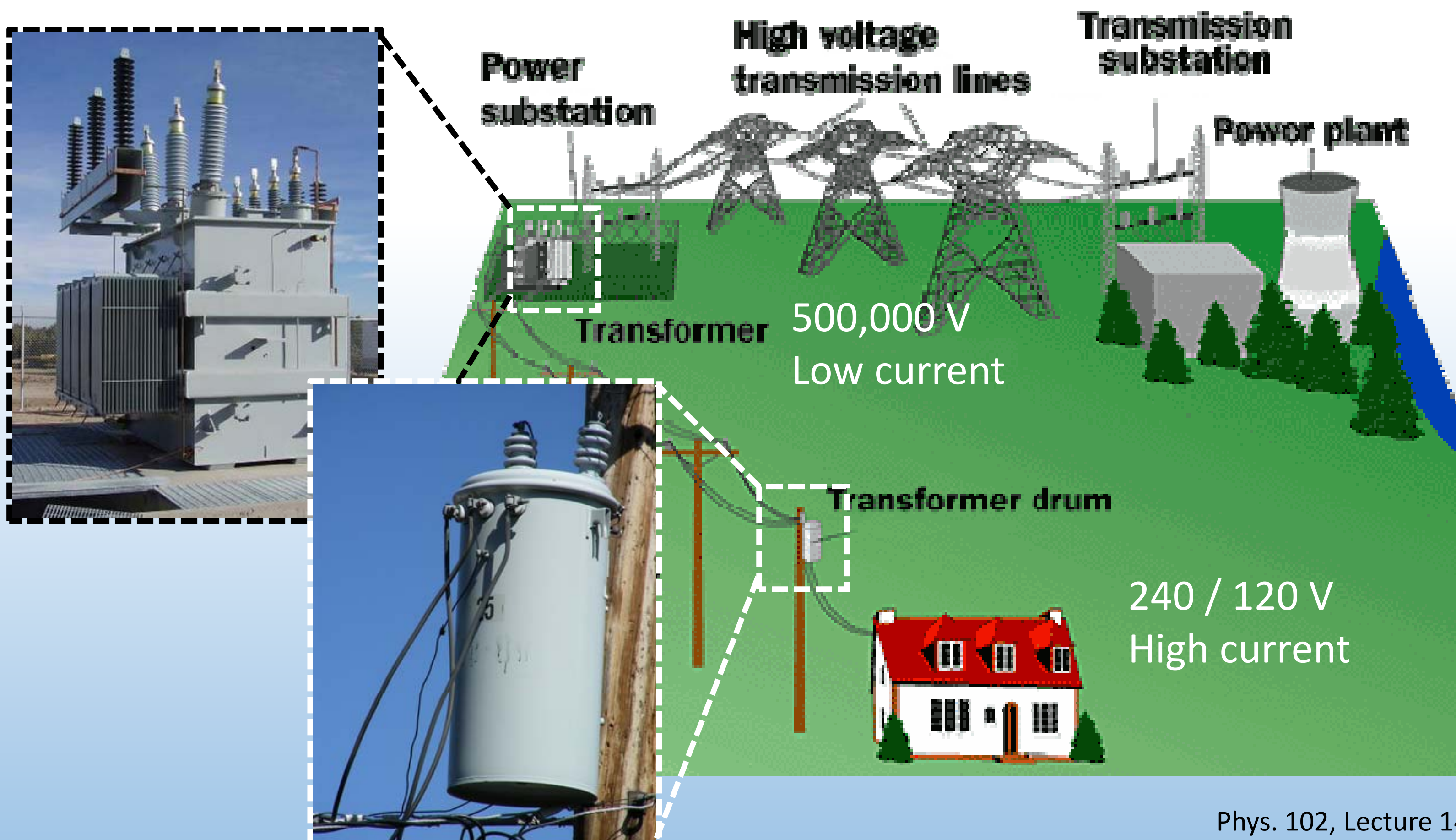


Power delivered by generator through lines:

Power lost in lines:

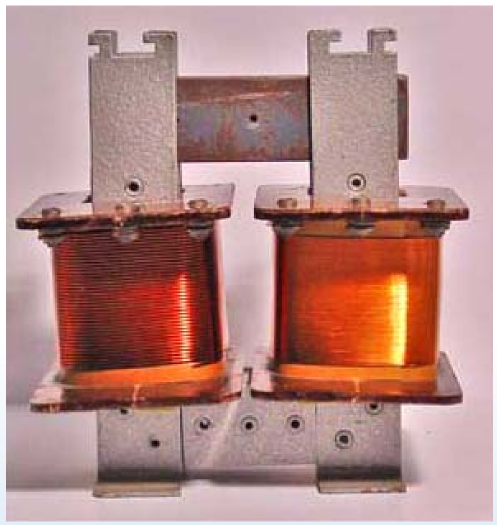
Electrical power distribution

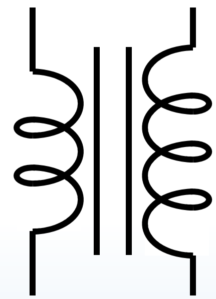
Transformers make it possible to distribute electrical power at high voltage and “step-down” to low voltage at your house.



Transformers

Transformers are made of two coils wound around a common iron core





- Key to modern electrical system
- Transform between high and low voltages
- Very efficient

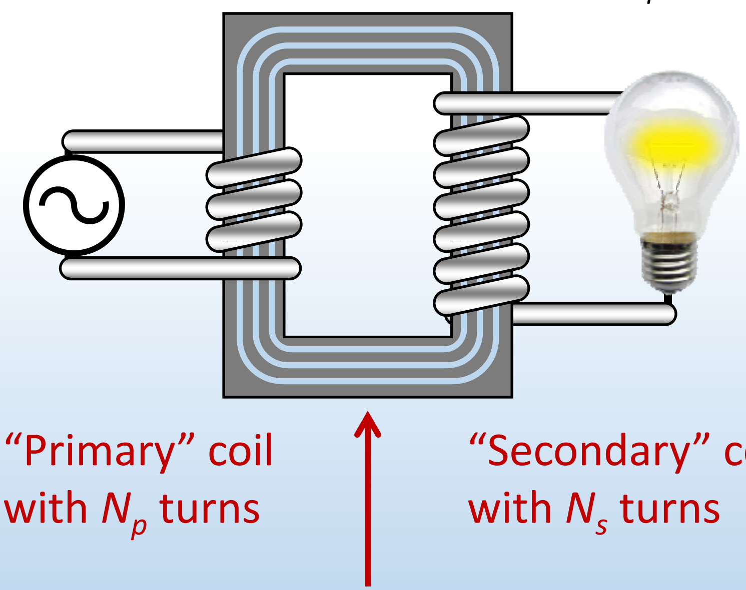
Principles of transformers

Transformers work by Faraday's law. Changing current in "primary" creates changing flux in primary and "secondary"

"Step-up" transformer: $N_s > N_p$

$$V_p = -N_p \frac{\Delta\Phi}{\Delta t} \qquad V_s = -N_s \frac{\Delta\Phi}{\Delta t}$$

$$\boxed{\frac{V_s}{V_p} = \frac{N_s}{N_p} = \frac{I_p}{I_s}}$$



"Primary" coil with N_p turns

"Secondary" coil with N_s turns

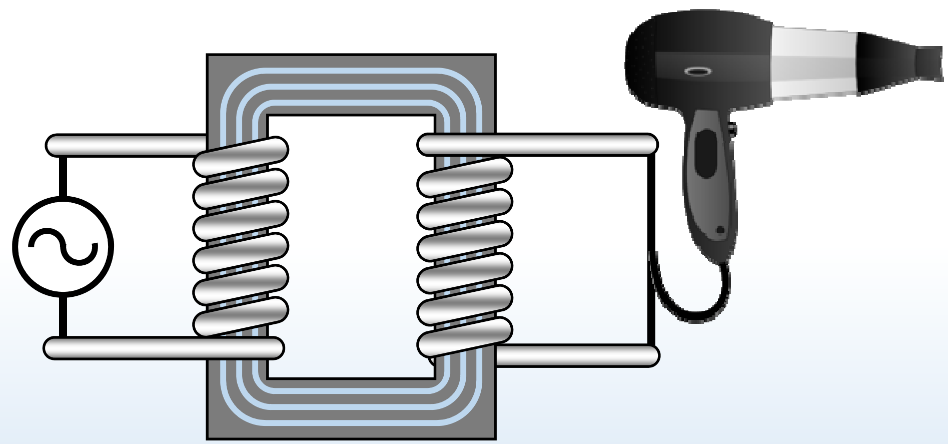
Core ensures *B* field of primary passes through secondary

Energy is conserved

$$P_p = I_p V_p = I_s V_s = P_s$$

ACT: CheckPoint 3.1

You are going on a trip to France where the outlets are 240 V. You remember from PHYS 102 that you need a transformer, so you wrap 100 turns of a *primary*.

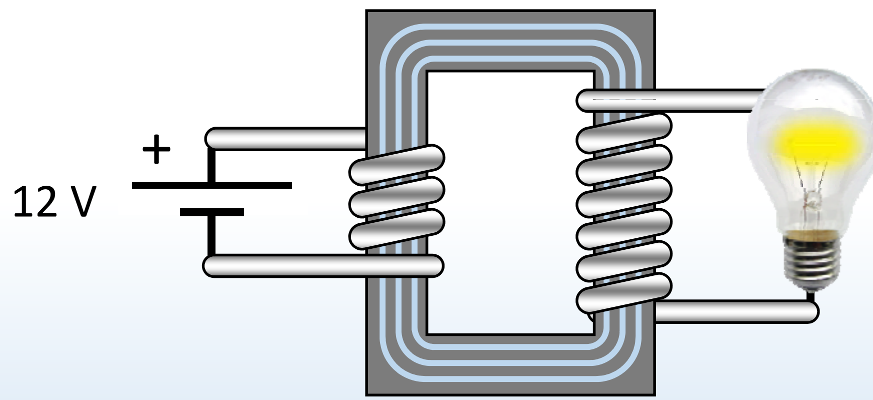


How many turns should you wrap around the *secondary* to get 120 V out to run your hair dryer?

A. 50　　B. 100　　C. 200

ACT: Transformers

A 12 V battery is connected to a transformer that has a 100 turn primary coil and 200 turn secondary coil.



What is the voltage across the secondary after the battery has been connected for a long time?

A. $V_s = 0$ V B. $V_s = 6$ V C. $V_s = 12$ V D. $V_s = 24$ V

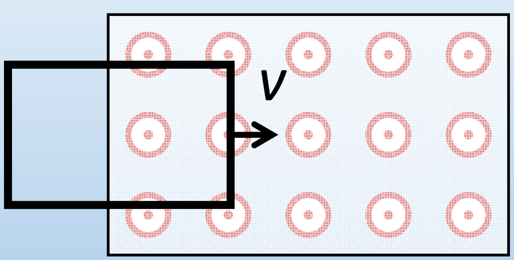
Summary of today's lecture

Faraday's law: "Induced EMF" = rate of change of magnetic flux

$$\varepsilon = -\frac{\Delta\Phi}{\Delta t}$$

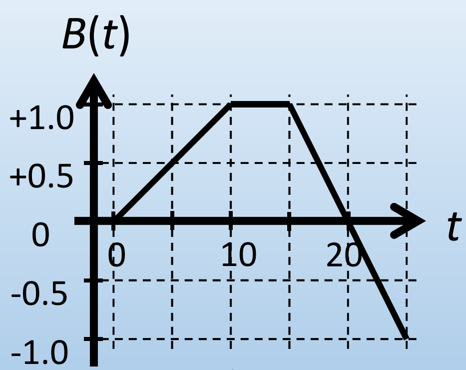
Since $\Phi = BA\cos\varphi$, 3 things can change Φ

1. Area of loop



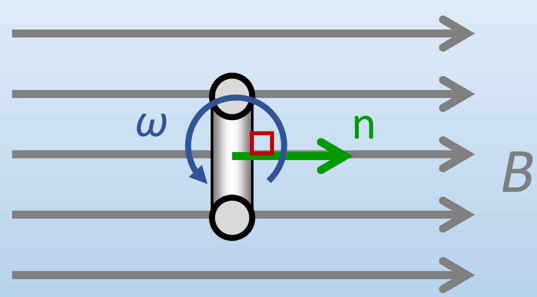
$$\varepsilon = BLv$$

2. Magnetic field *B*



$$\varepsilon = -\frac{\Delta B}{\Delta t}A$$

3. Angle *φ*



$$\varepsilon(t) = \omega NBA\sin\omega t$$