PHYS 1444 – Section 002
Lecture #22

Wednesday, Apr. 29, 2020
Dr. Jaehoon Yu

CH 29:EM Induction & Faraday's Law

- Transformer
- Electric Field Due to Changing Magnetic Flux

Chapter 30: Inductance

- Inductance
- Mutual and Self Inductance
- Energy Stored in the Magnetic Field

Announcements

- Reading assignments: CH30.7 – 30.11 & CH31.6 – 10
- Final comprehensive exam: 1:00 – 2:20pm ext Wed. May 6
  - Covers CH21.1 through what we finish Monday, May 4+ math refresher
  - BYOF
- Planetarium Extra Credit: Due 1pm, May 6
  - Send me the photos of the sheet with the front of the ticket stubs and of the sheet with them flipped over, showing the back of them
  - Email subject line must be: SP-Planetarium
- Special project #6: Fill out the survey at
  - https://s.surveyplanet.com/mw8bpHPyb
  - 15 points total for 7 questions
  - Deadline: End of the day, Wednesday, May 6
- Course evaluation now for 10 min

Reminder: Special Project #5 – COVID-19

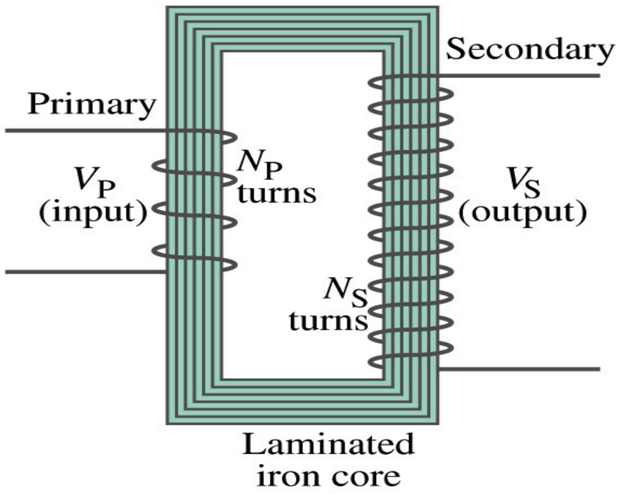
- Make comparisons of COVID-19 statistics between the U.S., South Korea and Germany from https://coronaboard.com on spreadsheet
  - Total 27 points: 1 point for each of the top 15 cells and 2 points for each of the 6 cells for testing
- Make a timeline from Jan. 15, 2020 through Apr. 15 for The World Health Organization (WHO), U.S.A. and South Korea in their actions in response to COVID-19: One in Jan., one in Apr. and two each in Feb. and Mar.
  - 2 points each, totaling 30 points
- What are the 3 most fundamental requirements for opening back up (2 points each, total 6 points)? Identify the two of these U.S. is ready (1 point each, total 2 points; do NOT just take politician's words!) for opening.
  - **Must be quantitative!**
- Due: 1pm Monday, May 4
  - Scan all pages of your special project into the pdf format, including the spreadsheet
  - Save all pages into **one file** with the filename SP5-YourLastName-YourFirstName.pdf
- Spreadsheet has been posted on the class web page. Download ASAP.

PHYS1442-002, Spring 20, Special Project #5, COVID-19

	Name:		Date of COVID-19 Data:	
Items		**U.S.A**	**South Korea**	**Germany**
Total Population				
COVID-19 Confirmed cases	Number			
	Cases per 1M people			
COVID-19 Deaths	Number			
	Death per 1M people			
COVID-19 Testing to date	Number			
	Per 1M people			

Transformer

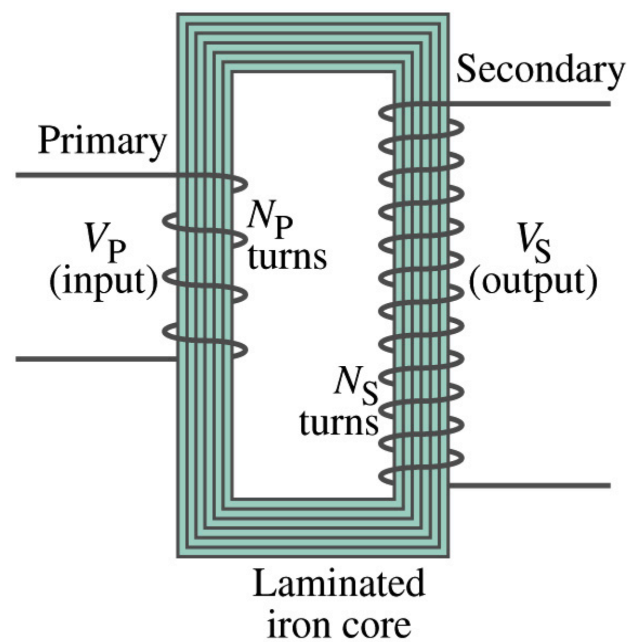
- What is a transformer?
  - A device for increasing or decreasing an AC voltage
  - A few examples?
    - TV sets to provide the high voltage to picture tubes, portable electronic device converters, transformers on the pole, etc
- A transformer consists of two coils of wires known as the primary and the secondary
  - The two coils can be interwoven or linked by a laminated soft iron core to reduce losses due to Eddy current
- Transformers are designed so that all magnetic flux produced by the primary coil pass through the secondary



How does a transformer work?

- When an AC voltage is applied to the primary, the changing B it produces will induce the voltage of the same frequency in the secondary wire
- So how would we make the voltage different?
  - By varying the number of loops in each coil
  - From Faraday's law, the induced emf in the secondary is
  - $V_S = N_S \frac{d\Phi_B}{dt}$
  - The input primary voltage is
  - $V_P = N_P \frac{d\Phi_B}{dt}$
  - Since $d\Phi_B/dt$ is the same, we obtain
  - $\boxed{\frac{V_S}{V_P} = \frac{N_S}{N_P}}$

Transformer Equation



The Transformer Equation

- The transformer equation does not work for DC current
  - Since there is no change of magnetic flux!!
- If $N_S > N_P$, the output voltage is greater than the input so it is called a step-up transformer while $N_S < N_P$ is called step-down transformer
- Now, it looks like energy conservation is violated since we can get more emf from smaller ones, right?
  - Wrong! Wrong! Wrong! Energy is always conserved!
  - A well designed transformer can be more than 99% efficient
  - The power output is the same as the input:
  - $V_P I_P = V_S I_S$
  - $$\boxed{\frac{I_S}{I_P} = \frac{V_P}{V_S} = \frac{N_P}{N_S}}$$

The output current for a step-up transformer will be lower than the input, while it is larger for a step-down x-former than the input.

Example for A Transformer

Portable radio transformer. A transformer for home use of a portable radio reduces 120-V AC to 9.0V AC. The secondary contains 30 turns, and the radio draws 400mA. Calculate (a) the number of turns in the primary (b) the current in the primary and (c) the power transformed.

(a) What kind of a transformer is this? A step-down x-former

Since $\frac{V_P}{V_S}=\frac{N_P}{N_S}$ We obtain $N_P = N_S\frac{V_P}{V_S} = 30\frac{120V}{9V} = 400turns$

(b) Also from the transformer equation $\frac{I_S}{I_P}=\frac{V_P}{V_S}$ We obtain

$$I_P = I_S\frac{V_S}{V_P} = 0.4A\frac{9V}{120V} = 0.03A$$

(c) Thus the power transformed is

$$P = I_S V_S = (0.4A)\cdot(9V) = 3.6W$$

How about the input power? The same assuming 100% efficiency.

Example 29 – 13: Power Transmission

Transmission lines. An average of 120kW of electric power is sent to a small town from a power plant 10km away. The transmission lines have a total resistance of 0.4Ω. Calculate the power loss if the power is transmitted at (a) 240V and (b) 24,000V.

We cannot use $P=V^2/R$ since we do not know the voltage along the transmission line. We, however, can use $P=I^2R$.

(a) If 120kW is sent at 240V, the total current is $I=\frac{P}{V}=\frac{120\times10^3}{240}=500A.$

Thus the power loss due to transmission line is

$$P=I^2R=(500A)^2\cdot(0.4\Omega)=100kW$$

(b) If 120kW is sent at 24,000V, the total current is $I=\frac{P}{V}=\frac{120\times10^3}{24\times10^3}=5.0A.$

Thus the power loss due to transmission line is

$$P=I^2R=(5A)^2\cdot(0.4\Omega)=10W$$

The higher the transmission voltage, the smaller the current, causing less loss of energy. This is why power is transmitted w/ HV, as high as 170kV.

Electric Field due to Magnetic Flux Change

- When the electric current flows through a wire, there is an electric field in the wire that moves electrons
- We saw, however, that changing magnetic flux induces a current in the wire. What does this mean?
  - There must be an electric field induced by the changing magnetic flux.
- In other words, a changing magnetic flux produces an electric field
- This result applies not just to wires but to any conductor or any region in space

Generalized Form of Faraday's Law

- Recall the relationship between the electric field and the potential difference $V_{ab} = \int_a^b \vec{E} \cdot d\vec{l}$
- Induced emf in a circuit is equal to the work done per unit charge by the electric field
- $\varepsilon = \int_a^b \vec{E} \cdot d\vec{l}$
- So we obtain

$$\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt}$$

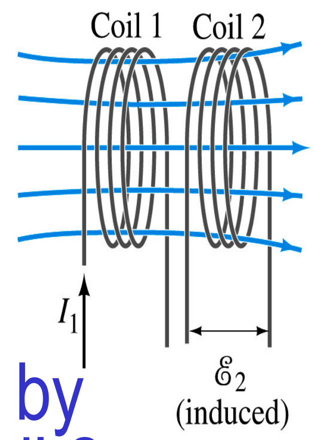
- The integral is taken around the path enclosing the area through which the magnetic flux Φ_B is changing.

Inductance

- A changing magnetic flux through a circuit induces an emf in that circuit
- An electric current produces a magnetic field
- From these, we can deduce
  - A changing current in one circuit must induce an emf in a nearby circuit ➔ Mutual inductance
  - Or induce an emf in itself ➔ Self inductance

Mutual Inductance

- If two coils of wire are placed near each other, a changing current in one will induce an emf in the other.



- What is the induced emf in coil 2, ε_2, proportional to?
  - Rate of the change of the magnetic flux passing through it
- This flux is due to current I_1 in coil 1
- If Φ_{21} is the magnetic flux in each loop of coil 2 created by coil1 and N_2 is the number of closely packed loops in coil 2, then $N_2\Phi_{21}$ is the total flux passing through coil 2.
- If the two coils are fixed in space, $N_2\Phi_{21}$ is proportional to the current I_1 in coil 1, $N_2\Phi_{21} = M_{21} I_1$.
- The proportionality constant for this is called the Mutual Inductance and defined as $\boxed{M_{21} = N_2\Phi_{21}/I_1}$.
- The emf induced in coil 2 due to the changing current in coil 1 is

$$\boxed{\varepsilon_2 = -N_2 \frac{d\Phi_{21}}{dt} = -\frac{d\left(N_2\Phi_{21}\right)}{dt} = -M_{21}\frac{dI_1}{dt}}$$

Mutual Inductance

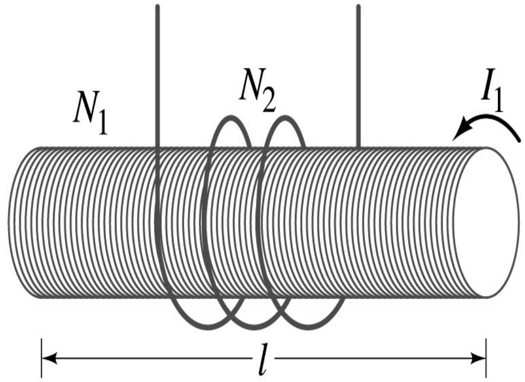
- The mutual induction of coil 2 with respect to coil 1, M_{21},
  - is a constant and does not depend on I_1.
  - depends only on "geometric" factors such as the size, shape, number of turns and the relative position of the two coils, and whether a ferromagnetic material is present

    What? Does this make sense?

    - The farther apart the two coils are the less flux can pass through coil, 2, so M_{21} will be less.
  - In most cases the mutual inductance is determined experimentally
- Conversely, the changing current in coil 2 will induce an emf in coil 1
- $$\varepsilon_1 = -M_{12}\frac{dI_2}{dt}$$
  - M_{12} is the mutual inductance of coil1 with respect to coil2 and $M_{12} = M_{21}$
  - We can put $M=M_{12}=M_{21}$ and obtain $$\varepsilon_1 = -M\frac{dI_2}{dt} \text{ and } \varepsilon_2 = -M\frac{dI_1}{dt}$$
  - SI unit for mutual inductance is Henry (H) $$1H = 1V \cdot s/A = 1\Omega \cdot s$$

Example 30 – 1

Solenoid and coil. A long thin solenoid of length ℓ and cross-sectional area **A** contains **N_1** closely packed turns of wire. Wrapped around it is an insulated coil of **N_2** turns. Assuming all the flux from coil 1 (the solenoid) passes through coil 2, calculate the mutual inductance.



First, we need to determine the flux produced by the solenoid.

What is the magnetic field inside the solenoid? $B = \dfrac{\mu_0 N_1 I_1}{l}$

Since the solenoid is closely packed, we can assume that the field lines are perpendicular to the surface area of the coils. Thus the flux through coil 2 is

$$\Phi_{21} = BA = \frac{\mu_0 N_1 I_1}{l} A$$

Thus the mutual inductance of coil 2 is

$$M_{21} = \frac{N_2 \Phi_{21}}{I_1} = \frac{N_2}{I_1} \frac{\mu_0 N_1 I_1}{l} A = \frac{\mu_0 N_1 N_2}{l} A$$

Note that M_{21} only depends on geometric factors!