PHYS 1441 – Section 001
Lecture #21

Monday, Nov. 27, 2017

*Dr. **Jaehoon Yu***

- Chapter 29:EM Induction & Faraday's Law
  - Induced EMF and EM Induction
  - Faraday's Law of Induction
  - Lenz's Law
  - Generation of Electricity
  - Transformer

Today's homework is homework #12, due 11pm, Monday, Dec. 4!!

Announcements

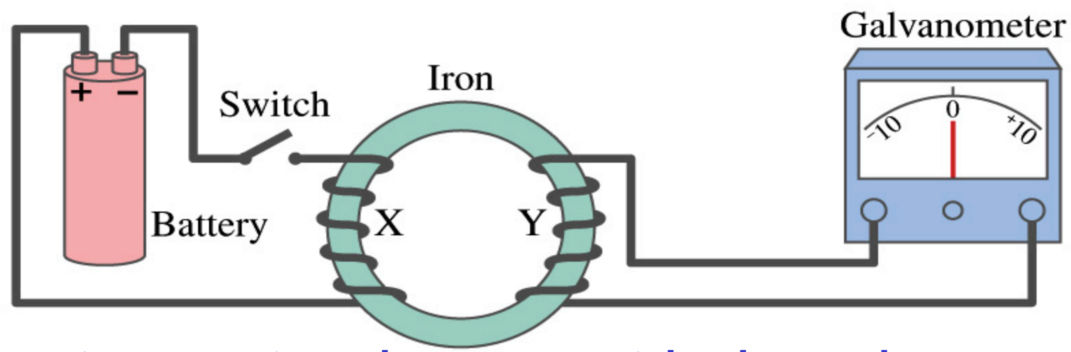
- Bring your planetarium extra credit sheet by the beginning of the class this Wednesday, Nov. 29!
  - Be sure to tape one end of the ticket stub on a sheet of paper with your name on it
- Term 2 results
  - Class average: 68.3/96
  - Equivalent to 74.2/100
    - Previous exams: 51/100 and 71/100
  - Top score:94/96
- Quiz #4
  - This Wednesday, Nov. 29 at the beginning of the class
  - Covers CH28.4 through what we finish Monday, Nov. 27
  - BYOF
- Final exam
  - Date and time: 11am, Monday, Dec. 11 in class
  - Comprehensive exam: covers CH21.1 through what we fisish next Wednesday, Dec. 6
  - BYOF

Induced EMF

- It has been discovered by Oersted and company in early 19^{th} century that
  - Magnetic field can be produced by the electric current
  - Magnetic field can exert force on the electric charge
- So if you were scientists at that time, what would you wonder?
  - Yes, you are absolutely right! You would wonder if the magnetic field can create the electric current.
  - An American scientist Joseph Henry and an English scientist Michael Faraday independently found that it was possible
    - Though, Faraday was given the credit since he published his work before Henry did
      - He also did a lot of detailed studies on magnetic induction

Electromagnetic Induction

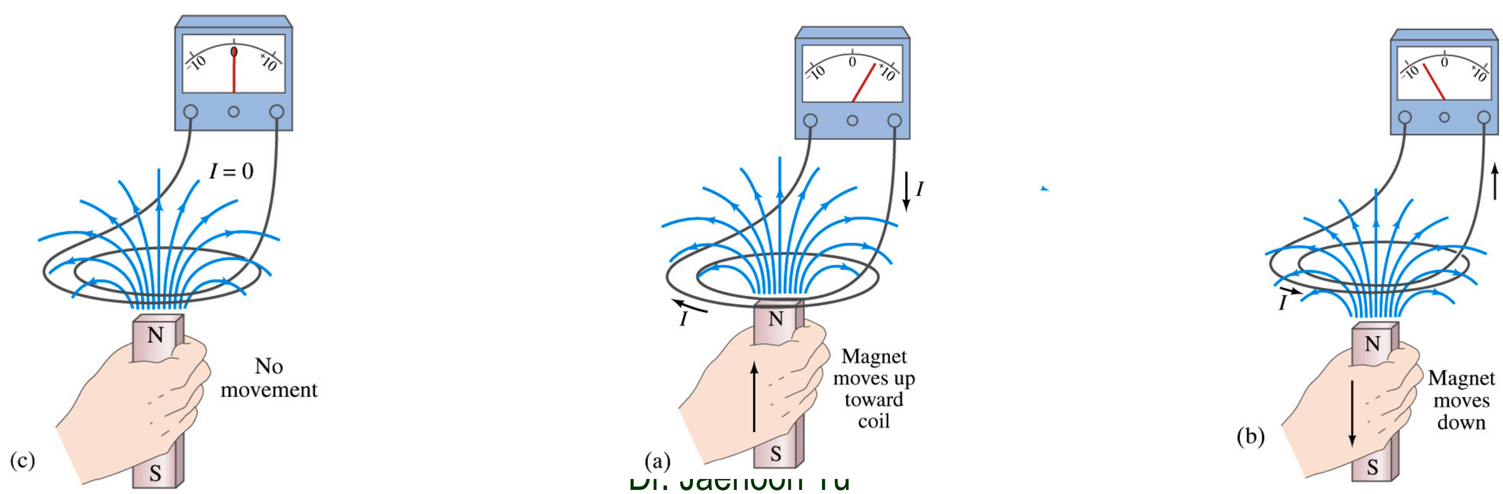
- Faraday used an apparatus below to show that magnetic field can induce current



- Despite his hope he did not see steady current induced on the other side when the switch is thrown
- But he did see that the needle on the Galvanometer turns strongly when the switch is initially thrown and is opened
  - When the magnetic field through coil Y changes, a current flows as if there were a source of emf
- Thus he concluded that **<u>an induced emf is produced by a changing magnetic field</u>** ➔ **<u>Electromagnetic Induction</u>**

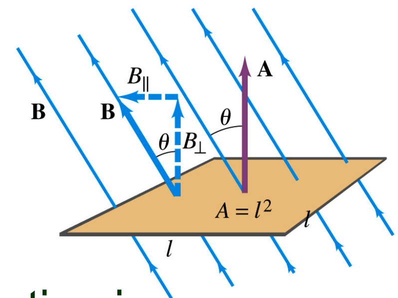
Electromagnetic Induction

- Further studies on electromagnetic induction taught
  - If a magnet is moved quickly into a coil of wire, a current is induced in the wire.
  - If a magnet is removed from the coil, a current is induced in the wire in the opposite direction
  - By the same token, the current can also be induced if the magnet stays put but the coil moves toward or away from the magnet
  - Current is also induced if the coil rotates.
- In other words, it does not matter whether the magnet or the coil moves. It is the relative motion that counts.



Magnetic Flux

- So what do you think is the induced emf proportional to?
  - The rate of changes of the magnetic field?
    - the higher the changes the higher the induction
  - Not really, it rather depends on the rate of change of the **magnetic flux**, Φ_B.
  - Magnetic flux is defined as (just like the electric flux)



  - $\boxed{\Phi_B = B_{\perp} A = BA\cos\theta = \vec{B}\cdot\vec{A}}$
    - θ is the angle between **B** and the area vector **A** whose direction is perpendicular to the face of the loop based on the right-hand rule
  - What kind of quantity is the magnetic flux?
    - Scalar. Unit?
    - $T \cdot m^2$ or weber $\boxed{1Wb = 1T \cdot m^2}$
- If the area of the loop is not simple or B is not uniform, the magnetic flux can be written as $\boxed{\Phi_B = \int \vec{B}\cdot d\vec{A}}$

Faraday's Law of Induction

- In terms of magnetic flux, we can formulate Faraday's findings
  - The emf induced in a circuit is equal to the rate of change of magnetic flux through the circuit

$$\varepsilon = -\frac{d\Phi_B}{dt}$$

Faraday's Law of Induction

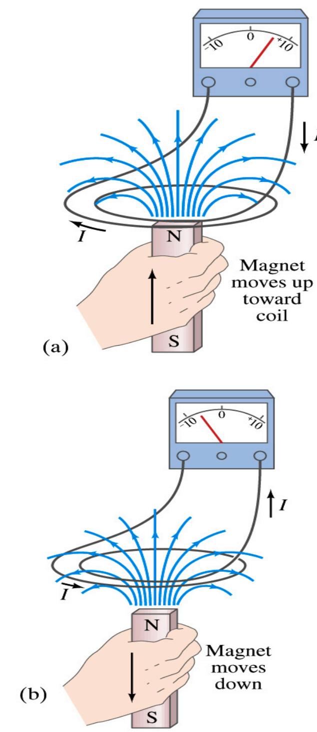
- If the circuit contains N closely wrapped loops, the total induced emf is the sum of emf induced in each loop

$$\varepsilon = -N\frac{d\Phi_B}{dt}$$

  - Why negative?
    - Has got a lot to do with the direction of induced emf…

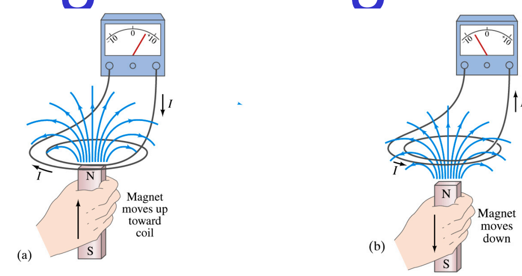
Lenz's Law

- It is experimentally found that
  - An induced emf gives rise to the current whose magnetic field opposes the original change in flux ➔ This is known as **Lenz's Law**
  - In other words, an induced emf is always in the direction that opposes the original change in flux that caused it.
  - We can use Lenz's law to explain the following cases in the figures
    - When the magnet is moving into the coil
      - Since the external flux increases, the field inside the coil takes the opposite direction to minimize the change and causes the current to flow clockwise
    - When the magnet is moving out
      - Since the external flux decreases, the field inside the coil takes the opposite direction to compensate the loss, causing the current to flow counter-clockwise
- Which law is Lenz's law result of?
  - Energy conservation. Why?

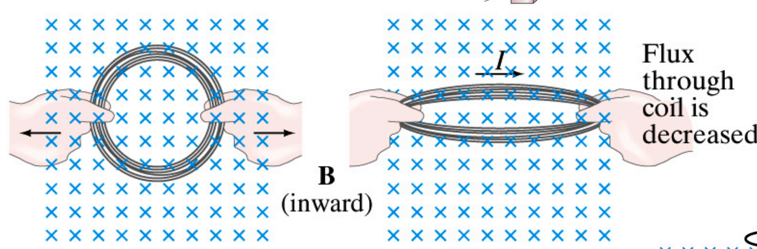


Induction of EMF

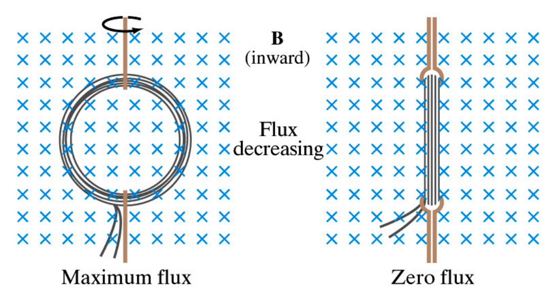
- How can we induce emf?
- Let's look at the formula for the magnetic flux
- $\Phi_B = \int \vec{B} \cdot d\vec{A} = \int B \cos\theta \, dA$
- What do you see? What are the things that can change with time to result in change of magnetic flux?
  - Magnetic field



  - The area of the loop

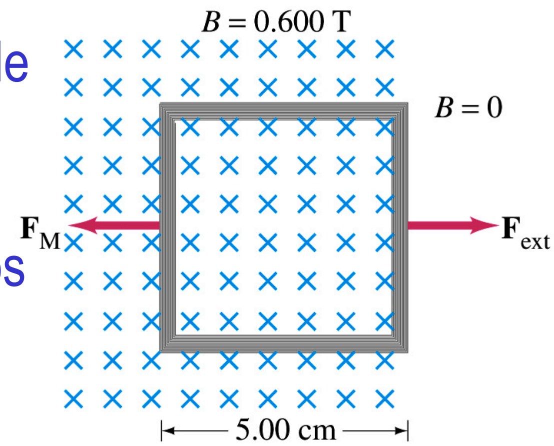


  - The angle θ between the field and the area vector



Example 29 – 5

Pulling a coil from a magnetic field. A square coil of wire with side 5.00cm contains 100 loops and is positioned perpendicular to a uniform 0.600-T magnetic field. It is quickly and uniformly pulled from the field (moving perpendicular to B) to a region where B drops abruptly to zero. At t=0, the right edge of the coil is at the edge of the field. It takes 0.100s for the whole coil to reach the field-free region. Find (a) the rate of change in flux through the coil, (b) the emf and the current induced, and (c) how much energy is dissipated in the coil if its resistance is 100Ω. (d) what was the average force required?



What should be computed first? The initial flux at t=0.

The flux at t=0 is $\Phi_B = \vec{B}\cdot\vec{A} = BA = 0.600T\cdot\left(5\times10^{-2}m\right)^2 = 1.50\times10^{-3}Wb$

The change of flux is $\Delta\Phi_B = 0 - 1.50\times10^{-3}Wb = -1.50\times10^{-3}Wb$

Thus the rate of change of the flux is

$$\frac{\Delta\Phi_B}{\Delta t} = \frac{-1.50\times10^{-3}Wb}{0.100s} = -1.50\times10^{-2}\,Wb/s$$

Example 29 – 5, cnt'd

Thus the total emf induced in this period is

$$\varepsilon = -N\frac{d\Phi_B}{dt} = -100\cdot\left(-1.50\times10^{-2}\,Wb/s\right) = 1.5V$$

The induced current in this period is

$$I = \frac{\varepsilon}{R} = \frac{1.5V}{100\Omega} = 1.50\times10^{-2}\,A = 15.0mA$$

Which direction would the induced current flow? Clockwise

The total energy dissipated is

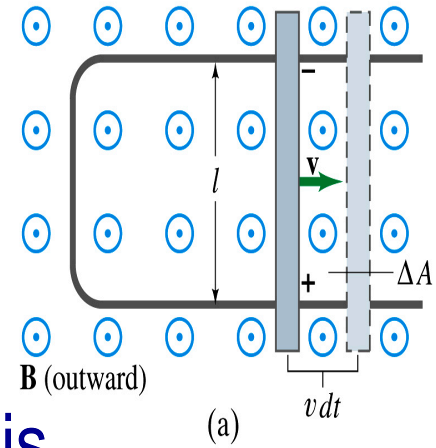
$$E = Pt = I^2Rt = \left(1.50\times10^{-2}\,A\right)^2\cdot100\Omega\cdot0.100s = 2.25\times10^{-3}\,J$$

Force for each coil is $\vec{F} = I\vec{l}\times\vec{B}$ Force for N coil is $\vec{F} = NI\vec{l}\times\vec{B}$

$$\left|F\right| = NIlB = 100\cdot\left(1.50\times10^{-2}\,A\right)\cdot\left(4\times5\times10^{-2}\right)\cdot0.600T = 0.045N$$

EMF Induced on a Moving Conductor

- Another way of inducing emf is using a U shaped conductor with a movable rod resting on it.
- As the rod moves at a speed v, it travels $v$dt in time dt, changing the area of the loop by dA=lvdt.



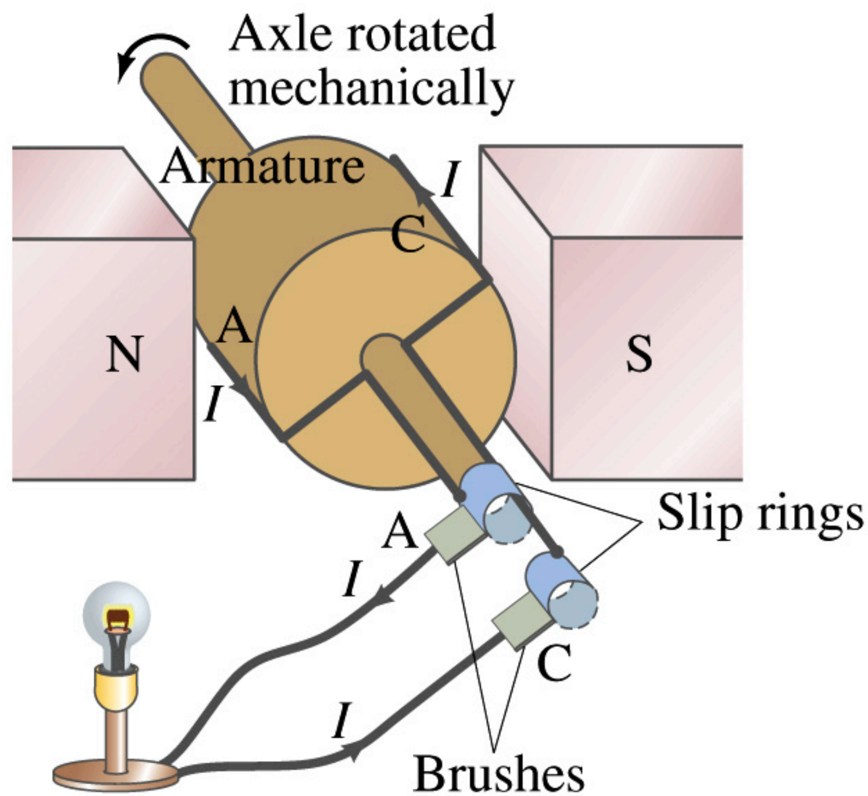
- Using Faraday's law, the induced emf for this loop is

$$|\varepsilon| = \frac{d\Phi_B}{dt} = \frac{BdA}{dt} = \frac{Blvdt}{dt} = Blv$$

  - This equation is valid as long as B, l and v are perpendicular to each other. What do we do if not?
    - Use the scalar product of vector quantities
- An emf induced on a conductor moving in a magnetic field is called a **motional emf**

Electric Generators

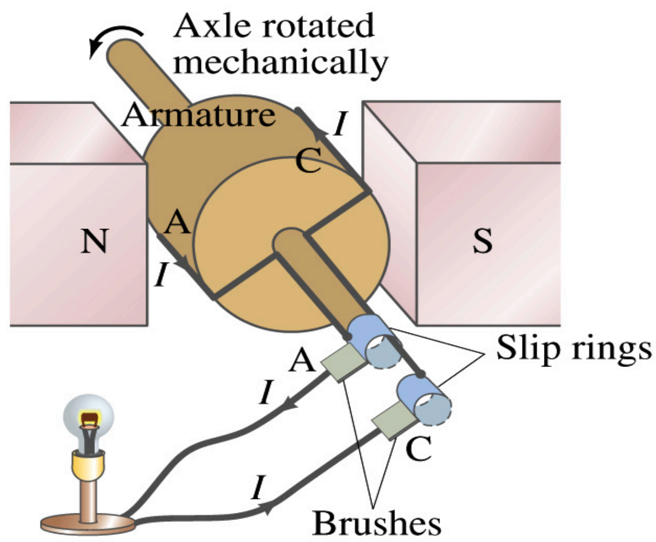
- What does a generator do?
  - Transforms mechanical energy into the electrical energy
  - What does this look like?
    - An inverse of an electric motor which transforms electrical energy to mechanical energy
  - An electric generator is also called a dynamo



- Whose law does the generator based on?
  - Faraday's law of induction

How does an Electric Generator work?

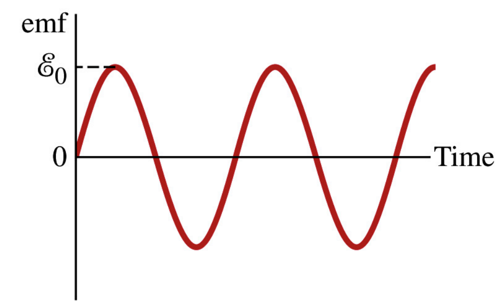
- An electric generator consists of
  - Many coils of wires wound on an armature that can rotate by mechanical means in a magnetic field
- An emf is induced in the rotating coil
- Electric current is the output of a generator



- Which direction does the output current flow when the armature rotates counterclockwise?
  - The conventional current flows outward on wire A toward the brush
  - After half the revolution the wire A will be where the wire C is and the current flow on A is reversed
- Thus the current produced is alternating its direction

How does an Electric Generator work?

- Let's assume the loop is rotating in a uniform B field w/ a constant angular velocity ω. The induced emf is
- $$\varepsilon = -\frac{d\Phi_B}{dt} = -\frac{d}{dt}\int \vec{B}\cdot d\vec{A} = -\frac{d}{dt}\left[BA\cos\theta\right]$$
- What is the variable that changes above?
  - The angle θ. What is dθ/dt?
    - The angular speed ω.
  - So $\theta = \theta_0 + \omega t$
  - If we choose $\theta_0 = 0$, we obtain
  - $$\varepsilon = -BA\frac{d}{dt}\left[\cos\varpi t\right] = BA\varpi\sin\varpi t$$
  - If the coil contains N loops: $\varepsilon = -N\frac{d\Phi_B}{dt} = NBA\varpi\sin\varpi t = \varepsilon_0\sin\varpi t$
  - What is the shape of the output?
    - Sinusoidal w/ the amplitude $\varepsilon_0 = NBA\omega$



- USA frequency is 60Hz. Europe is at 50Hz
  - Most the U.S. power is generated at steam plants

Example 29 – 9

An AC generator. The armature of a 60-Hz AC generator rotates in a 0.15-T magnetic field. If the area of the coil is $2.0 \times 10^{-2} m^2$, how many loops must the coil contain if the peak output is to be ε_0=170V?

The maximum emf of a generator is $\varepsilon_0 = NBA\varpi$

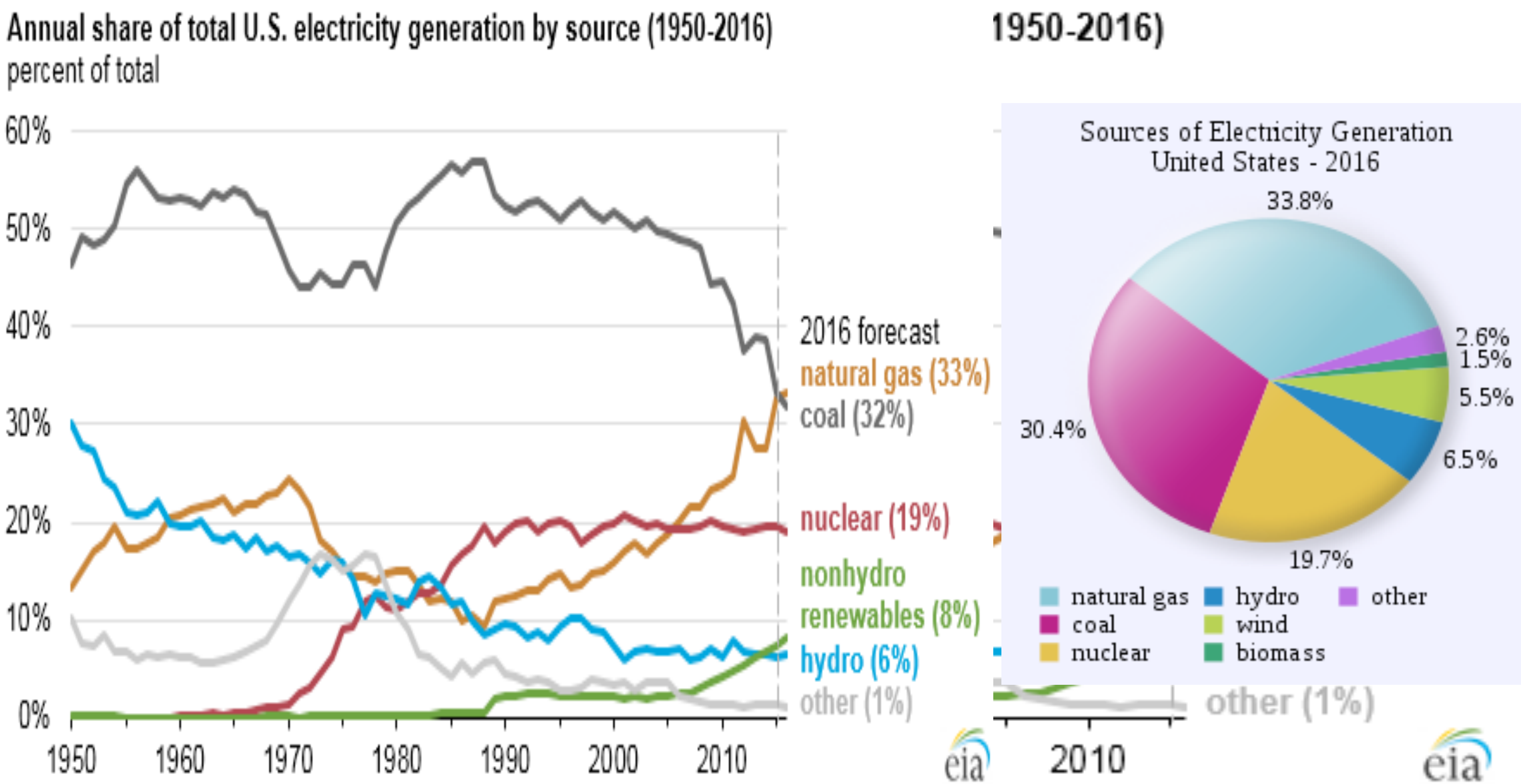
Solving for N

$$N = \frac{\varepsilon_0}{BA\varpi}$$

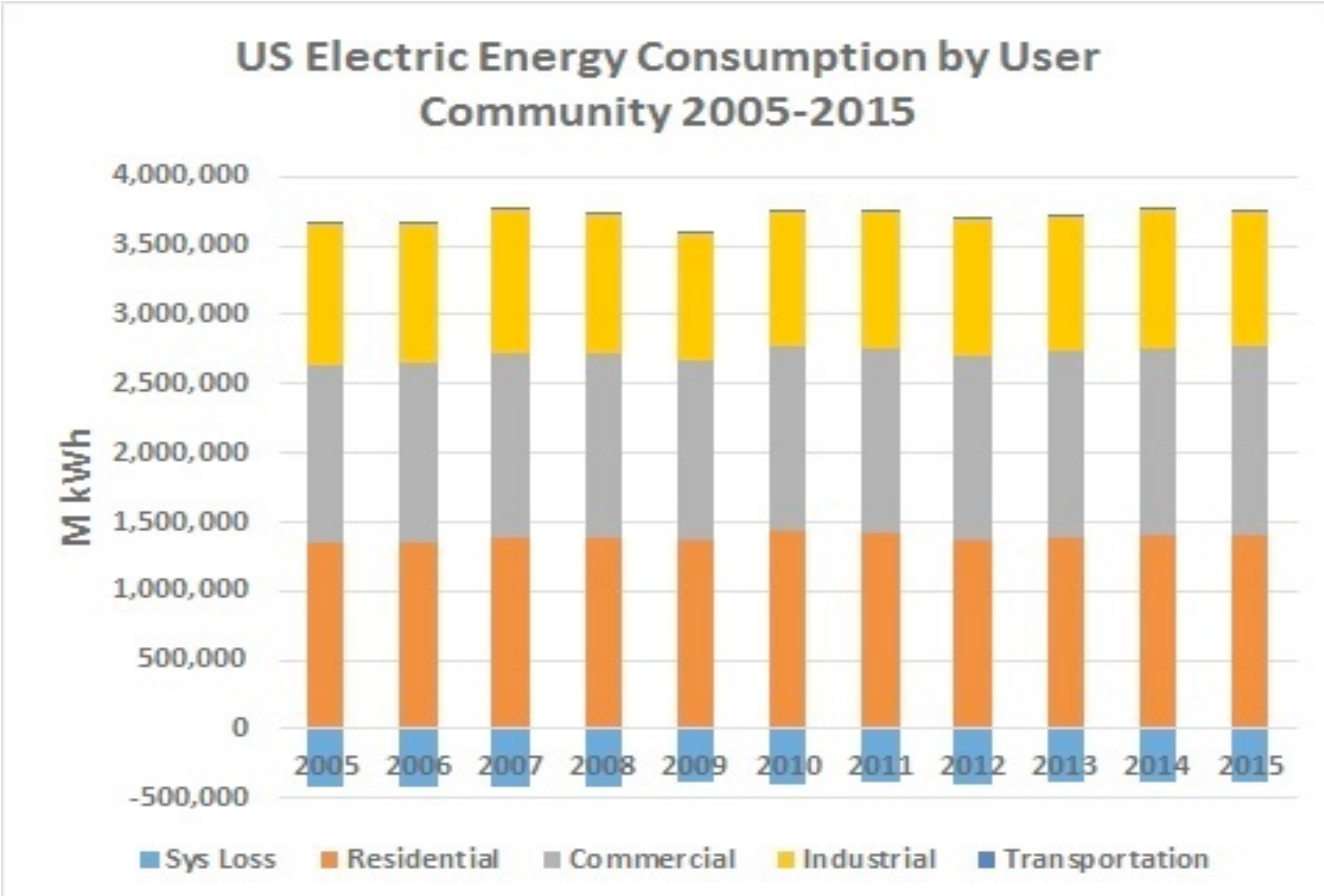
Since $\varpi = 2\pi f$ We obtain

$$N = \frac{\varepsilon_0}{2\pi BAf} = \frac{170V}{2\pi \cdot (0.15T) \cdot \left(2.0 \times 10^{-2} m^2\right) \cdot \left(60 s^{-1}\right)} = 150 turns$$

US Electricity Sources



US Electric E Consumption by Users



US Energy Information Administration http://www.eia.gov/electricity/

The World Energy Consumption

- In 2013, total worldwide energy consumption was 567 EJ (567×10^{18} J=157 PWh)➔ expected >1000EJ by 2050
  - Equivalent to an average energy consumption rate of 18 terawatts (1.8×10^{13} W)
  - US uses 39.1 PWh (1.38kWh/person, as of 2014)
- The potential for renewable energy
  - solar energy 1600 EJ (444,000 TWh)
  - wind power 600 EJ (167,000 TWh)
  - geothermal energy 500 EJ (139,000 TWh),
  - biomass 250 EJ (70,000 TWh)
  - hydropower 50 EJ (14,000 TWh) an
  - ocean energy 1 EJ (280 TWh)
  - Read this paper if you want to learn more