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Electronic Devices and Analog Circuits

- **Lecture 7**
  - Inductors
  - DC motors
  - Inductive power generation
  - Diodes for rectification
  - DC regulator circuits

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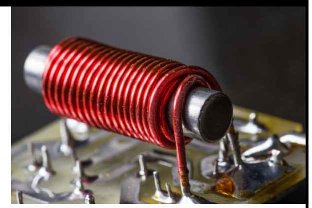
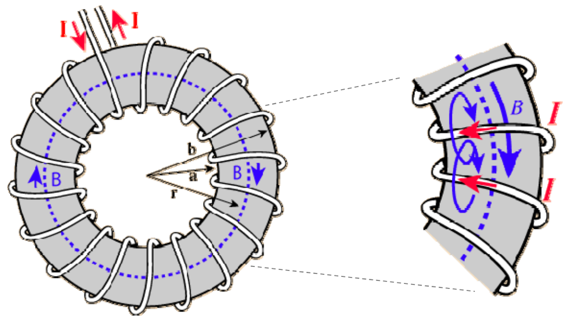
Objectives of this Lecture

- **Introduce inductor elements**
- **Describe inductance, and how it is used to create motors and generators**
- **Cover the basics regarding DC regulators and rectification**
- **Describe a DC-DC conversion circuit for use in Lab 2**

Inductors

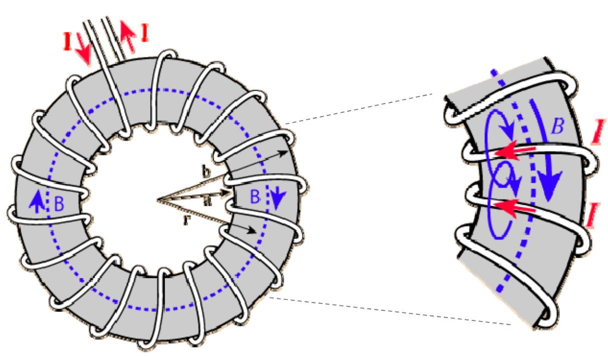
- Inductor elements are created for use in filter circuits and for energy storage
- Often formed around materials with high permability, μ, so that the flux lines are well contained





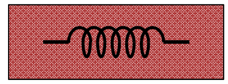
Inductors

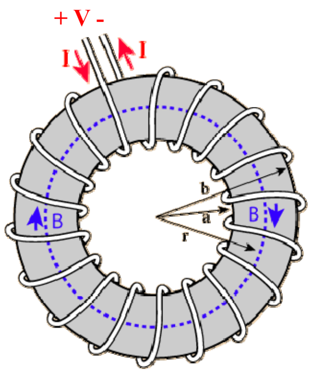
- When we make inductors we often try to contain the magnetic fields by wrapping wires around a magnetic core
- A core is also used to precisely specify the number of loops
  - Example: Toroidal inductor where overall inductance is increased by the number of loops that are coupled



Toroidal Inductor

- **Represented as a lumped circuit element** ***if flux is well contained***





- **From Maxwell: Flux Density**

Permeability is measure of material's ability to support the formation of a magnetic field within itself. The degree of magnetization that a material obtains in response to an applied magnetic field [Henrys/meter]

Number of turns

$$B(t) = \frac{\mu \cdot N \cdot i(t)}{l(t)}$$

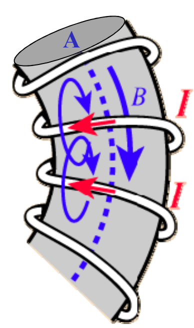
Length around core

Flux

- **Flux through each turn (loop) is the integral of the flux density through the cross section of the core**

$$\phi(t) = \int B \cdot dA = A \cdot B(t)$$

- **Total flux is then:**



$$\lambda(t) = N \cdot \phi(t) = N \cdot A \cdot B(t) \quad \text{Webers [Wb]}$$

$$B(t) = \frac{\mu \cdot N \cdot i(t)}{l}$$

$$\therefore \lambda(t) = \frac{\mu \cdot N^2 \cdot A}{l} \cdot i(t)$$

$$\lambda(t) = L \cdot i(t)$$

$$\therefore L = \frac{\mu \cdot N^2 \cdot A}{l} \quad \text{Wb/A [H]}$$

Inductor Equation

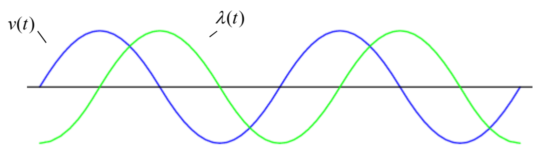
- Results in the simple expression for voltage and current relationship for a linear time-invariant inductor

$$L = \frac{\mu \cdot N^2 \cdot A}{l} \quad \text{Wb/A [H]}$$

$$\lambda(t) = L \cdot i(t)$$

$$v(t) = \frac{d\lambda(t)}{dt} = \frac{d[L \cdot i(t)]}{dt} = L\frac{di(t)}{dt}$$

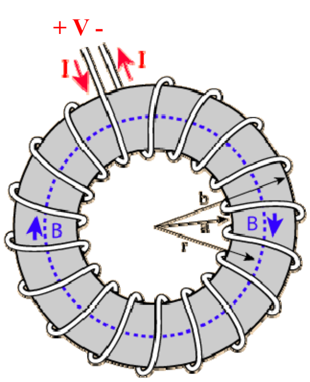
- For a sine wave voltage there is a phase shift with respect to the magnetic flux (hence the current)

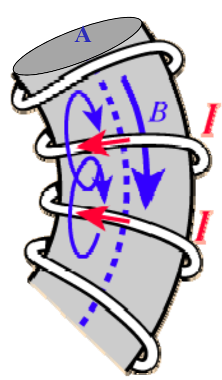


Stored Energy

- Ignoring coil resistance, core loss and inter-turn capacitance for our linear time invariant toroidal inductor:

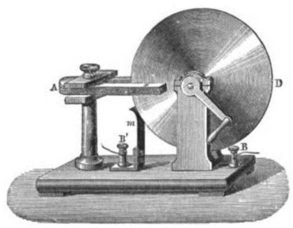
$$E = \frac{L \cdot i(t)^2}{2}$$

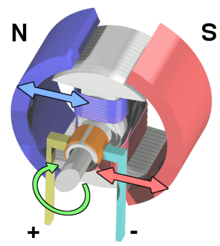




Inductance and Electric Motors and Generators

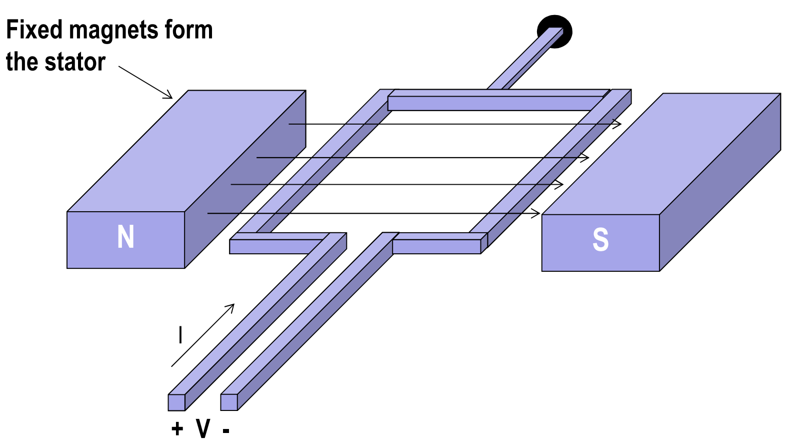
- Faraday showed that a force is produced on a current by a magnetic field
  - Faraday disk converts electrical energy into mechanical energy
  - Two interacting magnetic fields -- one stationary, and another attached to a part that can move
- Modern DC motors and generators are based on the same principals





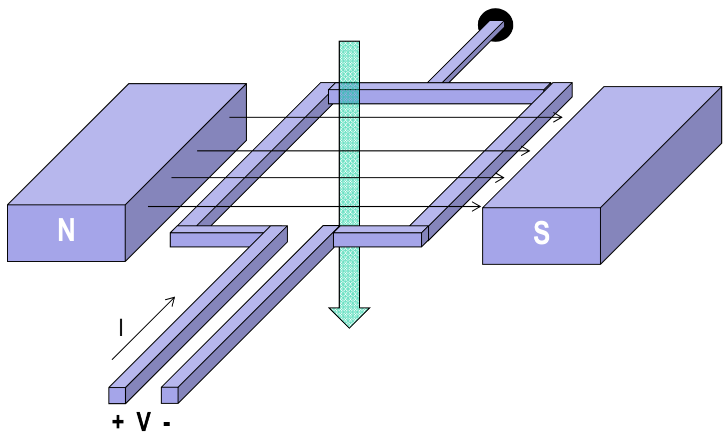
Fundamentals of a DC Motor

- Insert a current-carrying loop between two fixed magnets
- Connect the loop to a pivot point along its axis



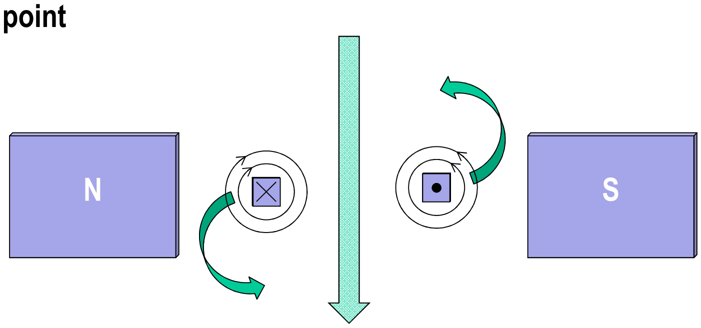
Fundamentals of a DC Motor

- Rotor loop establishes a magnetic field direction due to DC current flow direction



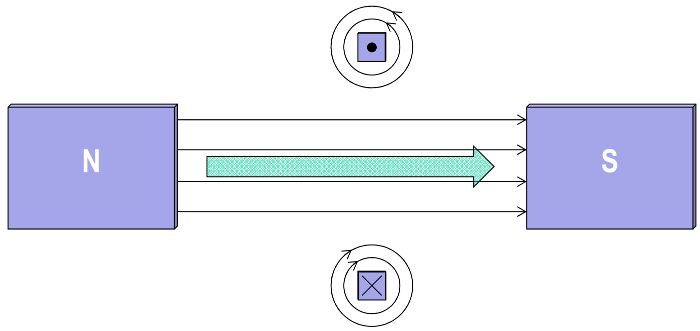
Torque

- The magnetic field applies a torque to both sides of the metal loop
- The combined torque causes the loop to rotate about its pivot point



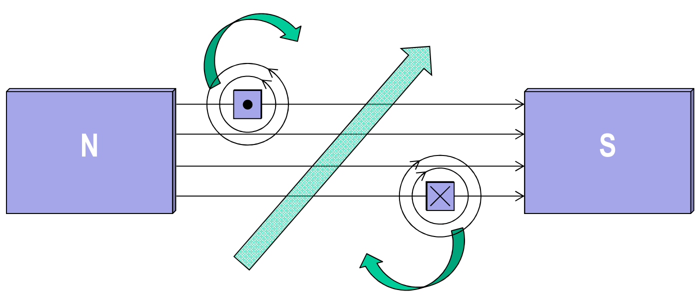
Torque

- There is no torque at the neutral plane point, but inertia keeps the loop rotating



Rotation

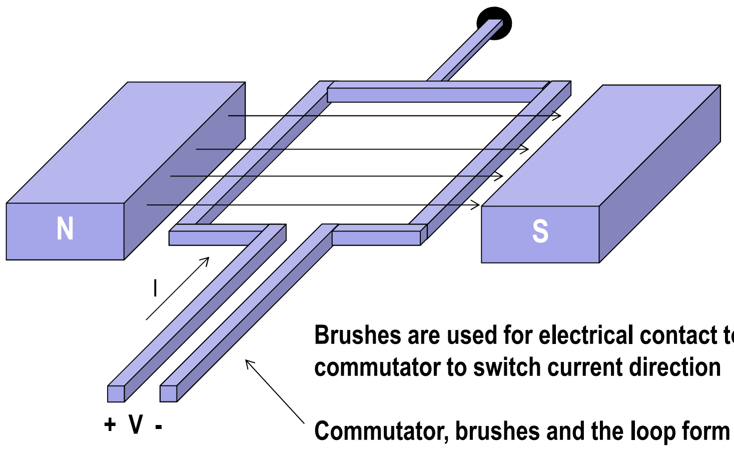
- If the currents remained in the same direction, the fields would now oppose this direction of rotation



- And an oscillating motion would be produced for the loop about its pivot axis

Brushes and Commutators

- But instead, a commutator switches the direction of current when the loop passes through the neutral plane

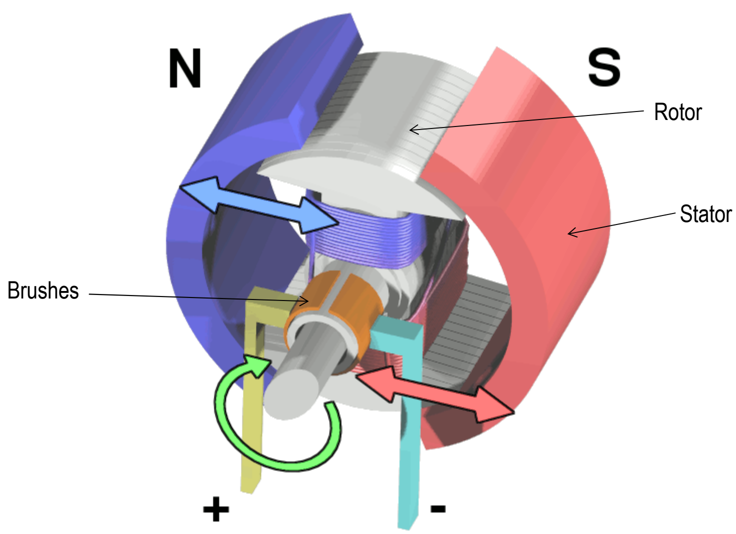


Brushes are used for electrical contact to the commutator to switch current direction

Commutator, brushes and the loop form the armature of the motor/generator

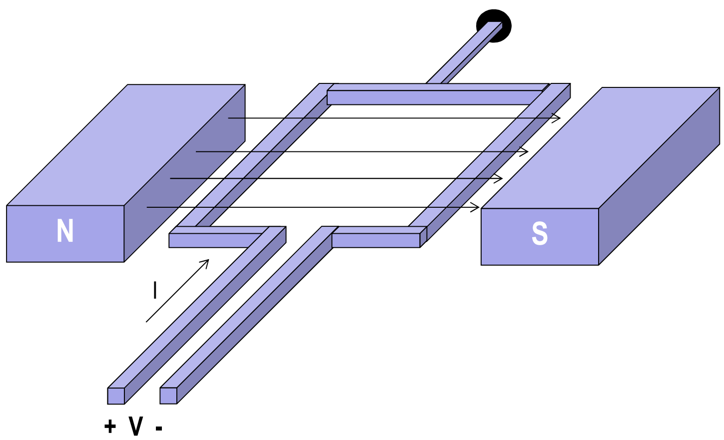
dc Motor

- Rotor can generate more flux coupling with wound wire



Brushless dc Motors and Generators

- Brushes wear out, and can slow down the rotor assembly
- Inexpensive silicon chips and power transistors have enabled switching the current direction to be done electronically



Brushless dc Motors and Generators

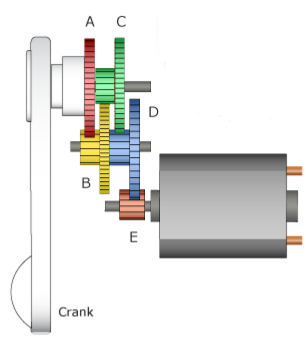
- Can put the fixed magnets on the stator, or put them on the rotor and switch the stator electromagnetically
- Apply a dc voltage to a dc motor to form a current in the loop that causes the axis to spin
  - Moves a wheel, or a propeller, etc.
- Or, turn a crank to spin the loop and generate a voltage at the voltage leads
  - Is the voltage AC or DC?
  - Does it have a commutator or is it brushless?

Brushless dc Motors and Generators

- **Depending on the switching method used by the controller, the current will be some time-varying (ac) signal**
  - The frequency of this current signal will be related to the RPMs of the motor

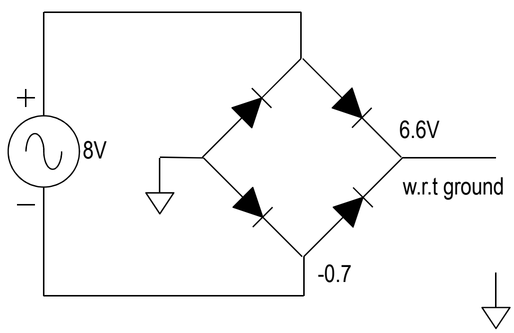
Lab 2: Hand Cranked Cellphone Charger

- **You will use a DC motor with a built-in gearbox**
- **Turning the crank through the gearbox will generate a time varying output voltage/current**
- **The voltage polarity will depend on which way we spin the rotor**
- **Use a full wave rectifier to extract the DC component for either polarity**



Full-Wave Rectifier

- Full-wave rectifiers are most commonly used to generate dc voltages from ac power outlets
- Extracts the dc component from a positive or negative voltage signal

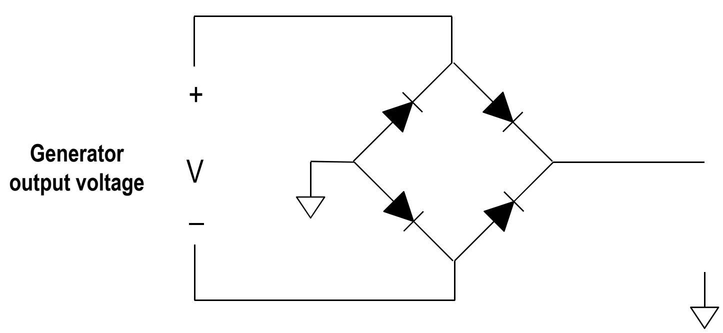


EXERCISE:

Confirm that the output voltage is the same w.r.t. ground for an input voltage of -8V

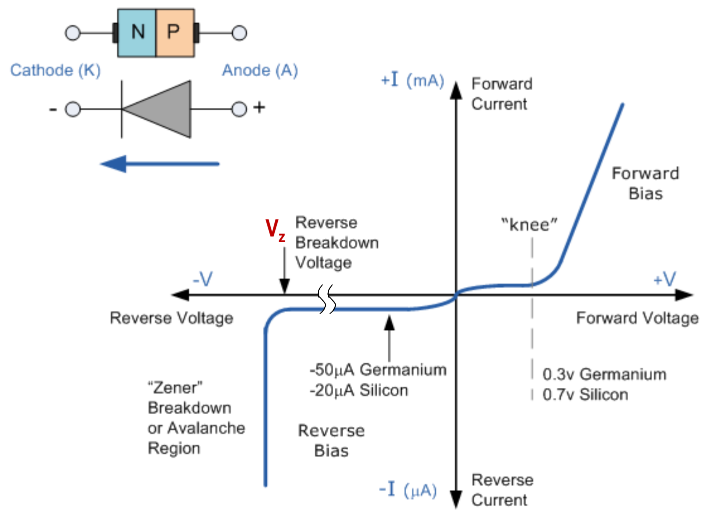
Full-Wave Rectifier

- The diodes ensure that the time-varying positive or negative voltage from the generator produces a positive dc output



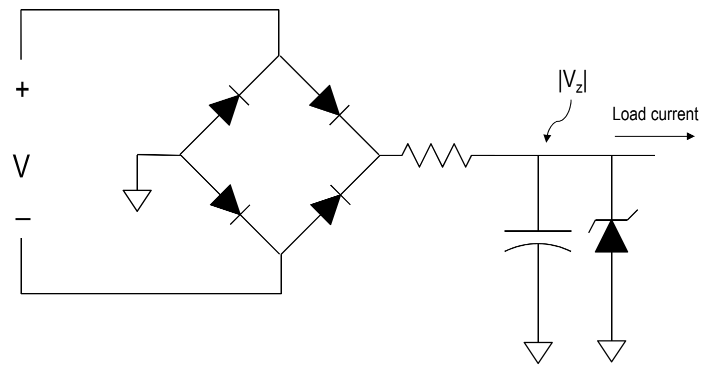
Diode Models

- Diode reverse characteristic can be utilized as well



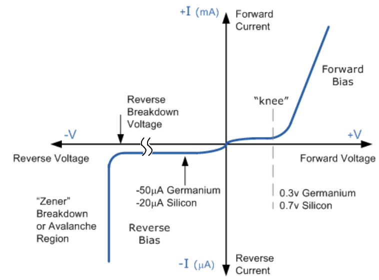
Full-Wave Rectifier

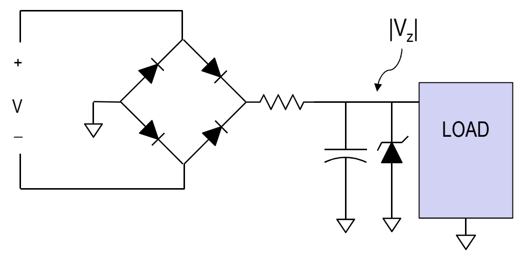
- Use Zener diode to clamp the dc to a fixed value
- RC is used to smooth out the ripple
- The resistor also limits the current into the Zener diode, but thereby limits the maximum possible load current



Regulator Efficiency

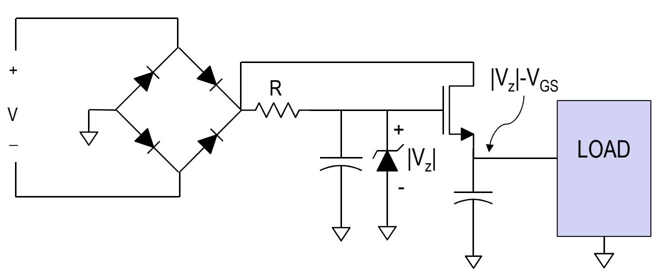
- Load current will vary, but *near maximum* power is burned even for minimum loading condition





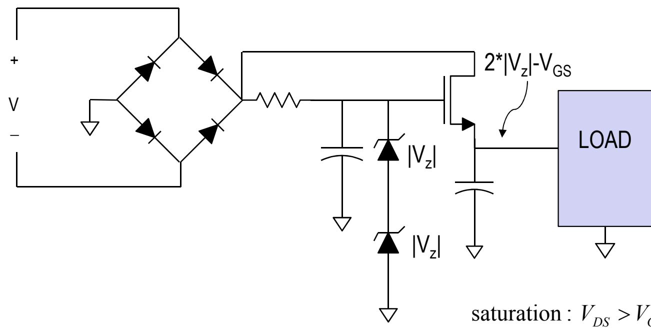
More Efficient Regulator

- We can add a transistor to improve the efficiency
- R can now be larger without limiting maximum loading current
- But the DC voltage to the load now depends on the V_{GS} of the MOSFET



More Efficient Regulator

- Would probably need more gate voltage for this to work
- But V_{GS} is still a function of the MOSFET (hence load) current
  - We don't want the voltage to change significantly with loading

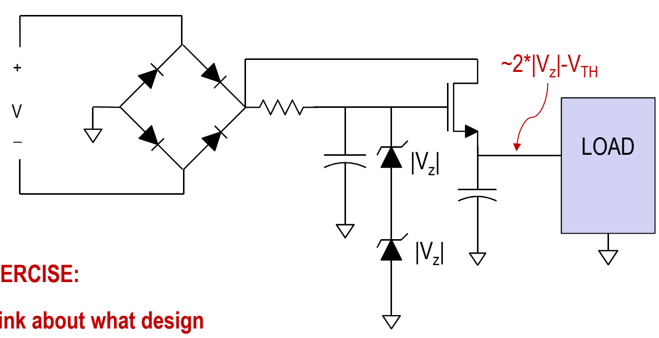


$$\text{saturation}: V_{DS} > V_{GS} - V_{TH}$$

$$I_D = \frac{1}{2}\mu_n C_{ox} \frac{W}{L'}(V_{GS} - V_{TH})^2$$

More Efficient Regulator

- How could you select a MOSFET to make the load voltage no longer a function of V_{GS}, and approximately a function of V_{TH}?



EXERCISE:

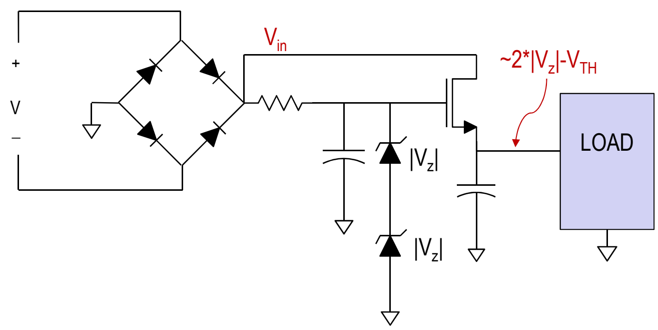
Think about what design parameters you would change, such as MOSFET size, to accomplish this

$$\text{saturation}: V_{DS} > V_{GS} - V_{TH}$$

$$I_D = \frac{1}{2}\mu_n C_{ox} \frac{W}{L'}(V_{GS} - V_{TH})^2$$

More Efficient Regulator

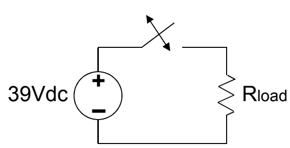
- But for large Vin the voltage drop across the MOSFET will dissipate a lot of unused power

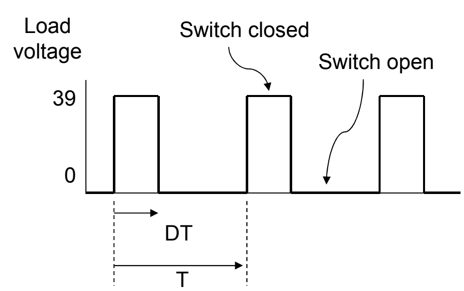


- There are more efficient ways of doing DC-DC conversion

Low Loss Conversion

- Switch the large voltage into pulses of voltage
- Based on the duty cycle, D, the average voltage delivered to the load is reduced
  - Still need a low pass filter to convert AC pulses to DC value

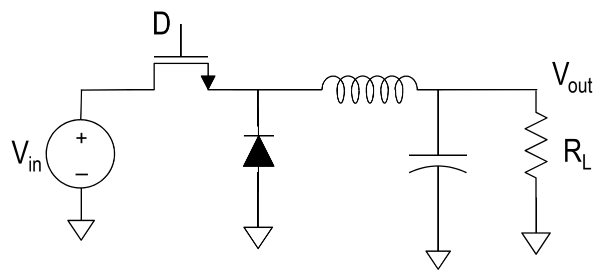




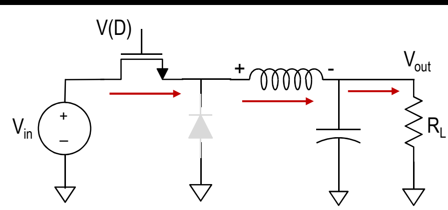
If the duty cycle D of the switch is 0.33, then the average voltage to the load is13Vdc

Buck Converter

- Buck converter – voltage step down, current step up
- An inductor and a capacitor form a lossless low-pass filter
- A MOSFET serves as the switch
- The diode serves as a current flow path when the switch is open



Buck Converter



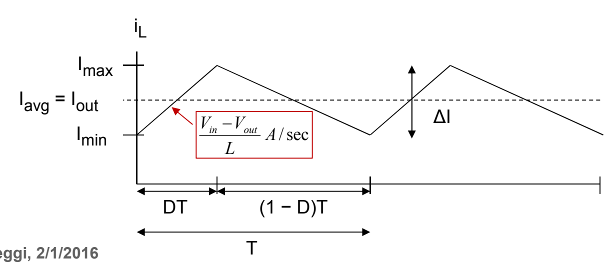
Switch closed:

$$v_L = V_{in} - V_{out}$$

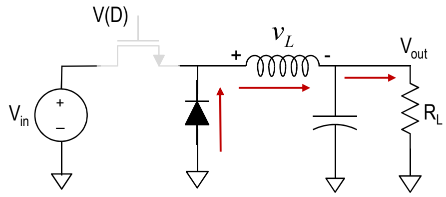
Diode is "off"

$$\frac{di_L}{dt} = \frac{V_{in} - V_{out}}{L}$$

- Inductor current increases which produces a voltage that opposes input voltage
- V_{out} is less than V_{in} based on drop across inductor
- D and T are chosen so that switch is opened while the inductor current is still changing, and energy is stored in the inductor of 0.5*L*i²



Buck Converter

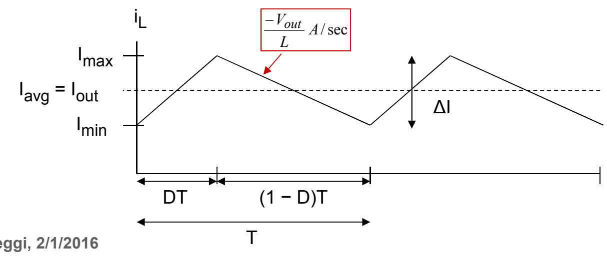


Switch open:

$$v_L = -V_{out}$$

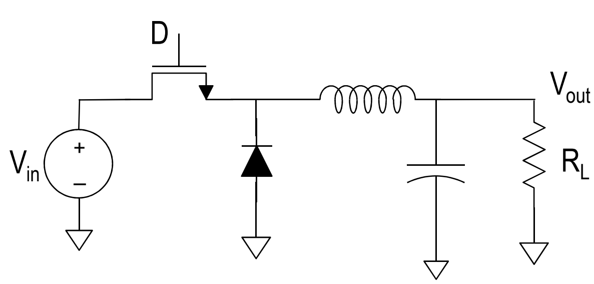
$$\frac{di_L}{dt} = \frac{-V_{out}}{L}$$

- Inductor current decreases, which causes its voltage to change sign and now aid in the direction of supplying the load
- Inductor is delivering its stored energy to supply the load while switch is open
- Switch closes again while current is decreasing and inductor voltage is non-zero



Buck Converter

- **Capacitor helps to smooth out the voltage ripple**
- **LC filter effect will be covered in future lectures**
- **Time domain understanding of inductors should enable you to build a Buck Converter for your cellphone charger**



Take Aways from this Video

- Understand the basics of forming an inductor element
- Have some idea of how you would calculate the inductance for a wound toroid
- Some basics regarding the operation of a DC motor
- A good start toward building your own Buck Converter in the lab