SECTION 1: ELECTRICAL FUNDAMENTALS

ENGR 201 – Electrical Fundamentals I

Introduction

Electricity – what is it?

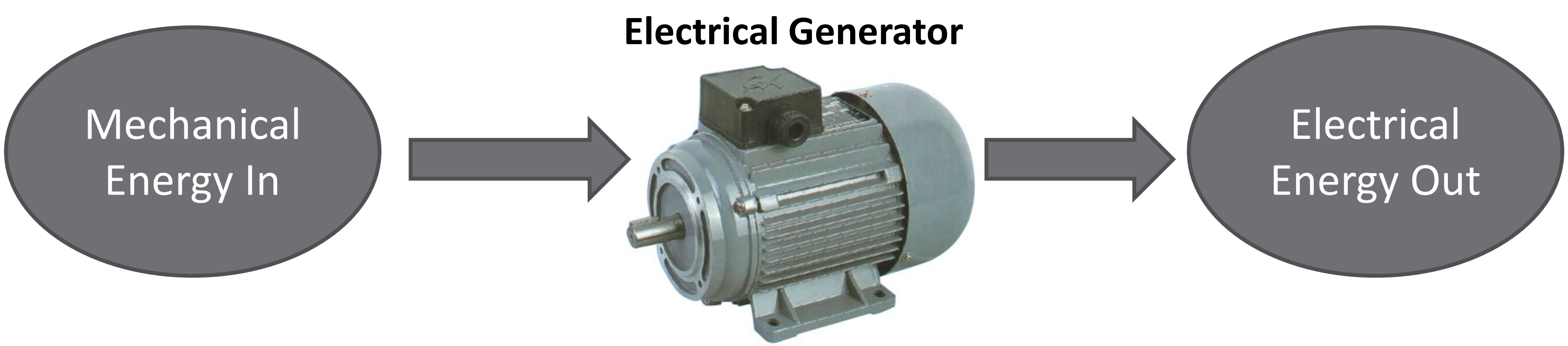
- Fundamental form of ***energy***
  - Resulting from charge differentials
- ***Electrons*** are the carriers of electrical charge
  - Electron is negatively charged
  - ***Hole*** – absence of an electron – is positively charged
- May occur naturally
  - Lightning, static electricity
- May be produced by conversion from other forms of energy
  - Generator, battery, solar panel

Electricity – why do we care?

- Electricity can do *work* for us
  - Mechanical, heat, light, etc.
- Efficient means of *energy transmission*
  - Large regions supplied by a single power plant
- Used to process and transmit *information*
  - Computers, mobile phones, TV, radio, etc.
  - Instrumentation and measurement

Electrical Energy

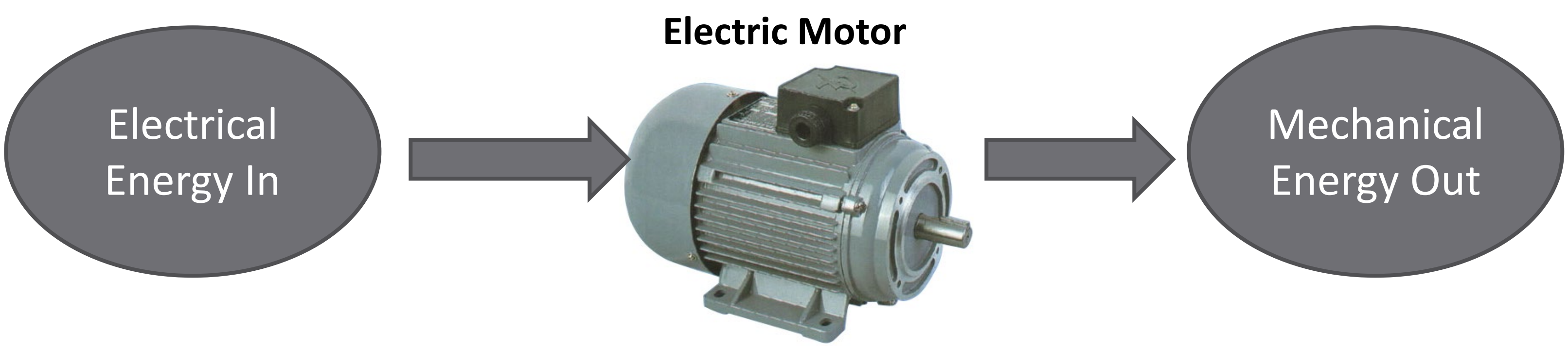
- Energy is conserved, but may be converted from one form to another
- Electrical energy – charge differentials – produced from other forms of energy
  - Generator – mechanical energy
  - Battery – chemical energy



http://www.trimainternational.com/Products/de.htm

Electrical Energy

- Electrical energy can be converted into other useful forms of energy
  - Motor – mechanical energy
  - Heater – thermal energy
  - Charged battery – chemical energy



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Energy Transmission

- Electricity is an efficient means of ***energy transmission***
  - Energy is transmitted broadly from a single power plant
  - No longer need to grind our wheat at the windmill

- Imagine other modes of energy transmission
  - Hydraulic, pneumatic, cables, rotating shafts
  - Pneumatic was used in some European cities and was proposed for transmission of energy from Niagara to Buffalo in late 19th century

Relevance for ***ALL*** Engineers

- ***Energy***
  - Efficient means of transmission & distribution
  - Efficient conversion
    - Efficiency of motors vs. engines
- Very few engineered systems without electronics
  - Aircraft, automobiles, robotics, etc.
- ***Instrumentation and measurement***
  - All engineered products and systems must be tested, measured, and evaluated
  - Electronic measurements are fast, accurate, repeatable, and can be automated

What is Electrical Engineering?

- Many categories of electrical engineers
- Most fall into one of two areas:
  - ***Electronics***
    - Computers
    - Communications
    - Instrumentation and measurement
    - Controls/robotics
    - Energy systems
  - ***Power systems***
    - Power generation, transmission, distribution, storage
    - Electric drives
    - Controls/robotics
    - Energy systems

Where We Are Going

ENGR 201/202

- ENGR 201 – Electrical Fundamentals I
  - DC circuits

- ENGR 202 – Electrical Fundamentals II
  - AC circuits

- ***Objectives*** of these courses:
  - Develop an ***understanding of electrical circuit theory***
  - To prepare you for courses in:
    - Energy conversion systems – ESE 450
    - Electrical power systems – ESE 470
    - Energy storage systems – ESE 471
    - Electronics/circuit design
    - System dynamics and Controls
    - Robotics

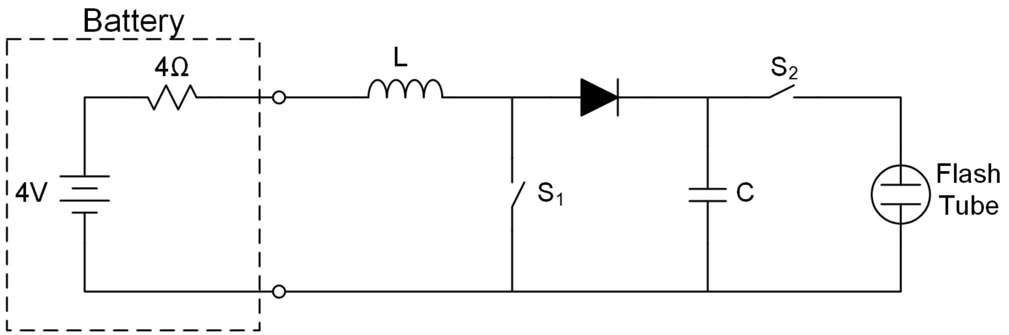
ENGR 201 – Course Overview

- ***ENGR 201 – Electrical Fundamentals I***
  - DC circuit analysis

- **Section 1**: Electrical Fundamentals
- **Section 2**: Resistive Circuit Analysis I
  - Fundamental laws
- **Section 3**: Resistive Circuit Analysis II
  - Circuit analysis methods
- **Section 4**: Operational Amplifiers
- **Section 5**: Capacitance and Inductance

Electronic Photo Flash Circuit

- ***Electronic photo flash circuit***
  - Simple, yet very interesting circuit example
  - Preview of what you will learn in ENGR 201



- The problem:
  - Use small, rechargeable battery to fire the camera flash
- The details:
  - 4 V battery – maximum output power: ~1 W
  - Flash tube requires 100s of volts, ~1000 W
- By the end of ENGR 201, you'll understand:
  - How this works – how the required voltage and power are supplied
  - How we determine the appropriate model for the battery
  - How long the battery will last – how many flashes

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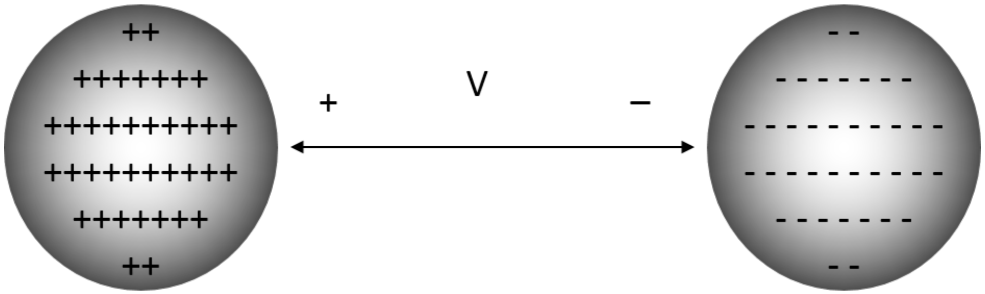
Electrical Fundamentals

Electrical Potential



- ***Potential*** or ***voltage*** or ***electromotive force*** (emf)
  - A measure of electrical energy
  - The energy required to move one unit of electrical charge from one point to another
    - Units of potential: volts (V)
    - Units of electrical charge: coulombs (C)
    - Units of energy: joules (J)

$$1V = 1\frac{J}{C}$$

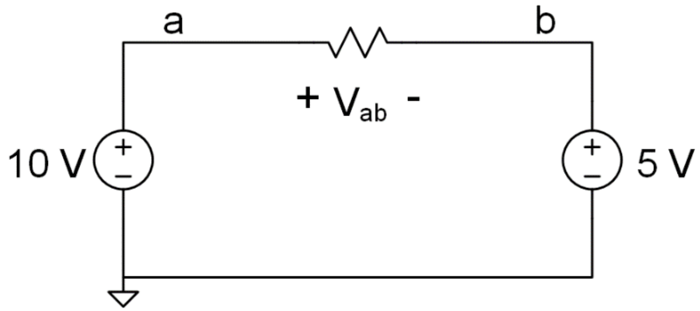
Electrical Potential

- Electrical potential is a ***differential quantity***
  - Voltage ***between*** two points in a circuit
  - Voltage between a point and a ***ground reference***
- No such thing as an *absolute* voltage at a location, but…
  - We do talk about ***node voltages***
    - Always referenced to ground
  - For example,
    - Node voltages:

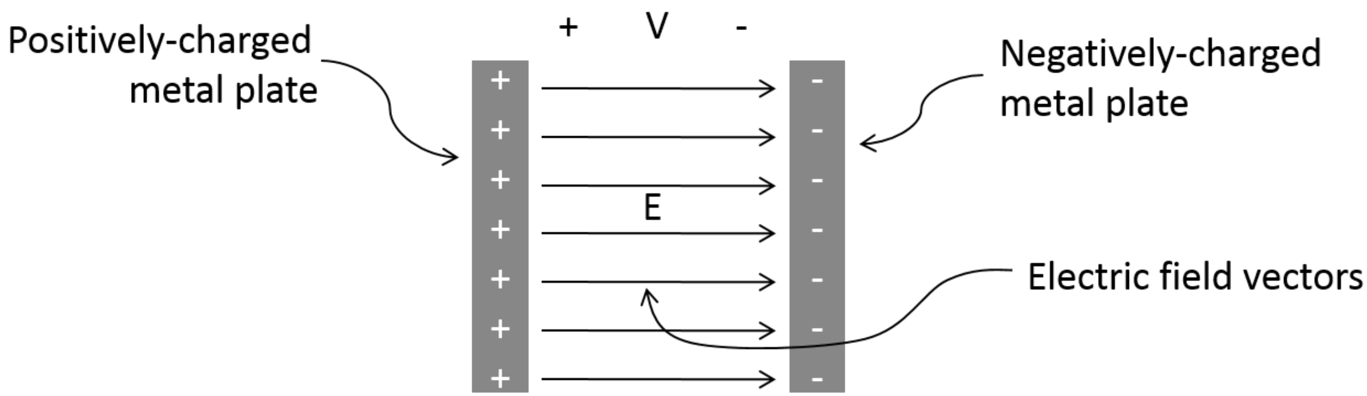
$$V_a = 10\,V, \quad V_b = 5\,V$$

    - Differential voltage:

$$V_{ab} = V_a - V_b = 5\,V$$

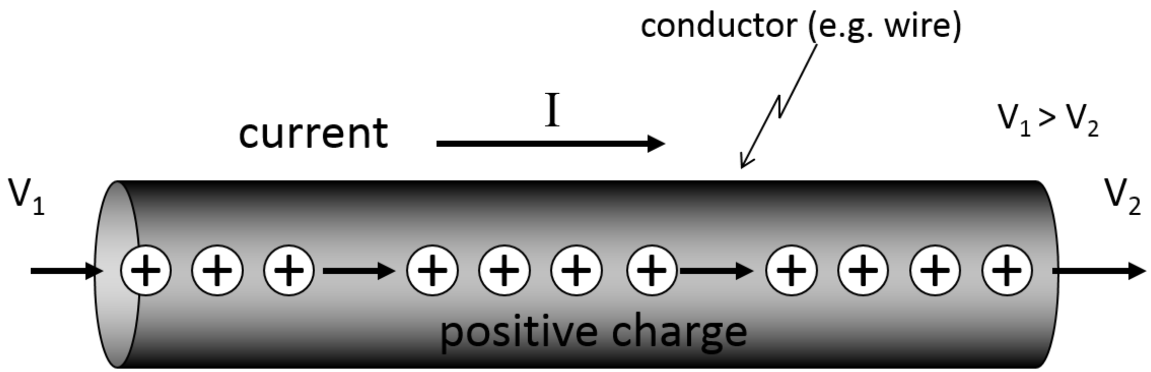


Electric Field



- ***Electric field***
  - A field of force experienced by positively-charged particles
  - Points from positive to negative charge (positive to negative potential)
  - Positive charge wants to move in the direction of the E-field, toward negative charge
  - Units: newtons per coulomb (N/C) or volts per meter (V/m)
  - The negative gradient of the potential
  - Electrical energy is stored in the electric field

Electrical Current

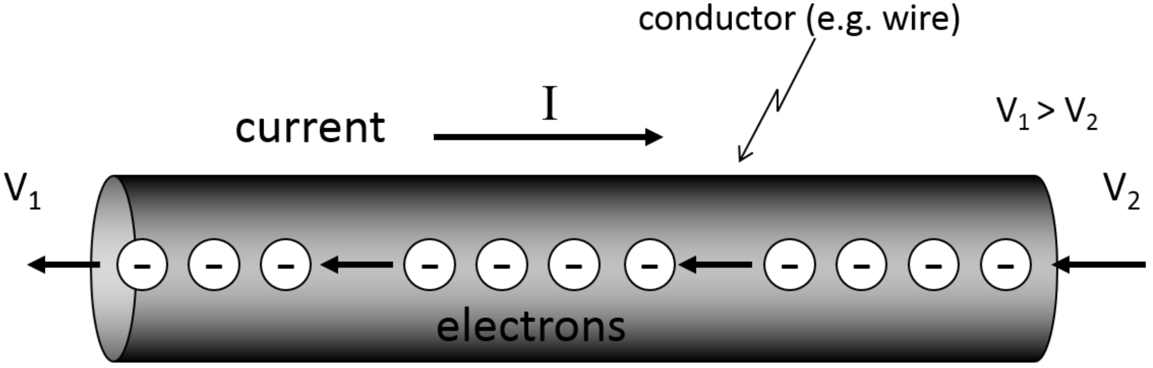


- Electrical current (I) is the flow of positive charge
  - Voltage is the driving potential
  - Units: amperes or amps (A) – coulombs per second (C/s)
    - A ***rate*** of charge flow:

$$1A = 1\frac{C}{s}$$

  - Current wants to flow from high to low potential
  - Analogous to fluid flow or heat flow
    - Fluid flows from high to low pressure
    - Heat flows from high to low temperature

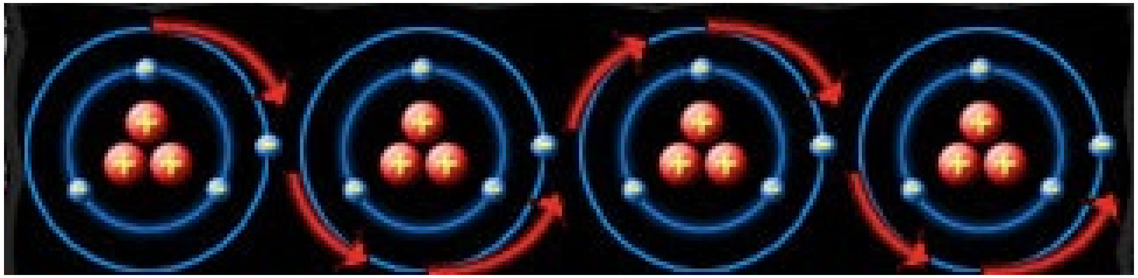
Current – what's really flowing?



- Current is defined as the ***flow of positive charge***
- Really, current is the ***flow of negatively-charged electrons in the opposite direction***
  - Electrons flow from low potential to high potential
  - Negative charge flow in one direction is equivalent to positive charge flow in the opposite direction

Conductors and Insulators

- Electrical current flows more easily in some materials (***conductors***) than in others (***insulators***)
- Good conductors:
  - Copper
  - Aluminum
  - Gold
  - Silver



http://elpaso.apogee.net/foe/fbbr.asp

- All have a single valence electron
  - Easy for electrons to move from one atom to the next
- Good insulators have full valence bands

Electrical-Mechanical Analogies

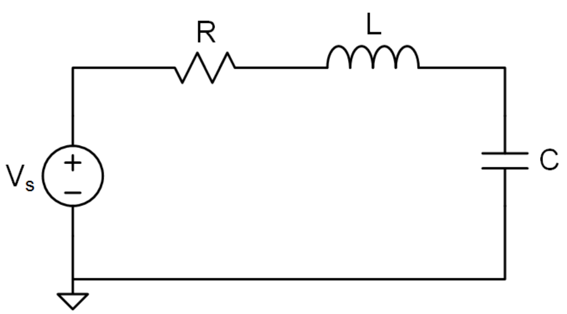
- Electrical systems are analogous to:
  - ***Fluid systems***
  - ***Thermal systems***

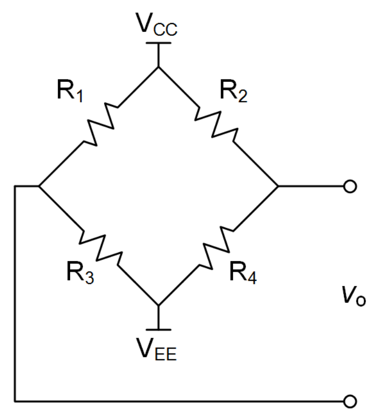
Domain	Driving potential	Flowing quantity	Flow	(units)
Electrical	Voltage	Positive charge	Current	(A)
Fluid	Pressure	Fluid	Flow rate	(m^3/s)
Thermal	Temperature	Heat	Heat flux	(W)

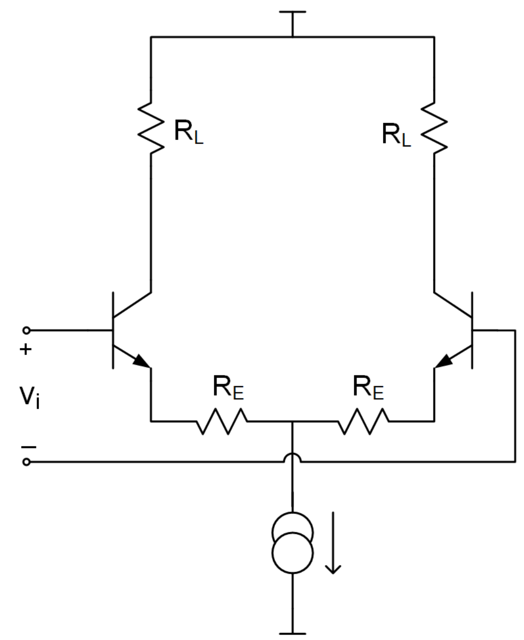
Electrical Circuits

Electrical Networks – Schematics

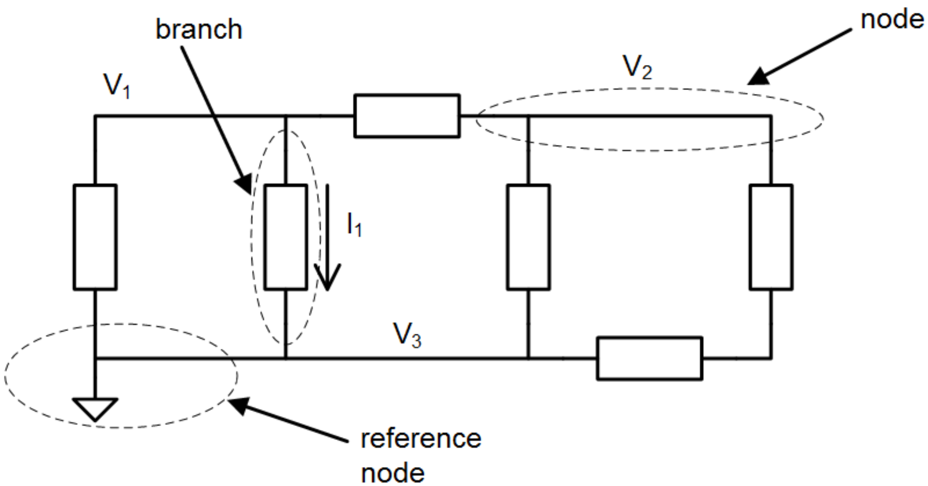
- Electrical circuits represented graphically with ***schematics***
  - Schematic symbols represent circuit elements
  - Schematics detail connections between circuit elements
  - Schematics describe paths for the flow of electrical current
- Some examples:







Electrical Networks – Branches & Nodes



- ***Nodes***
  - Connection points for circuit elements
  - Node voltages given with respect to a reference node (0 V, ground)
    - E.g. V_3 = 0 V, here
  - Current flows into and out of nodes

- ***Branches***
  - Paths for current to flow
  - Connections between nodes
  - Branches are the components that comprise the circuit
  - Voltage across a branch is the difference between node voltages at either end

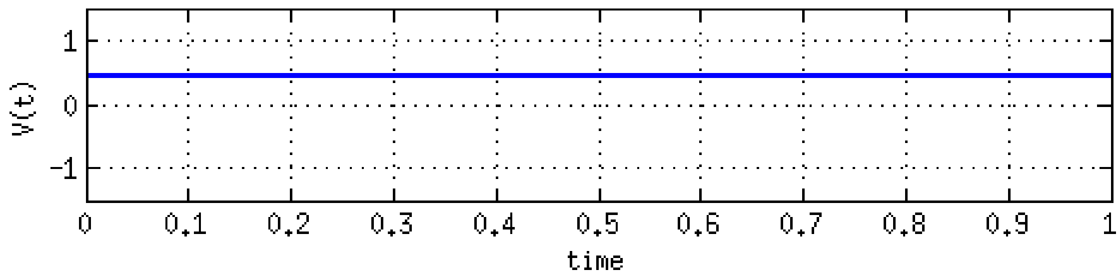
Electrical Signals & Waveforms

Electrical Signals

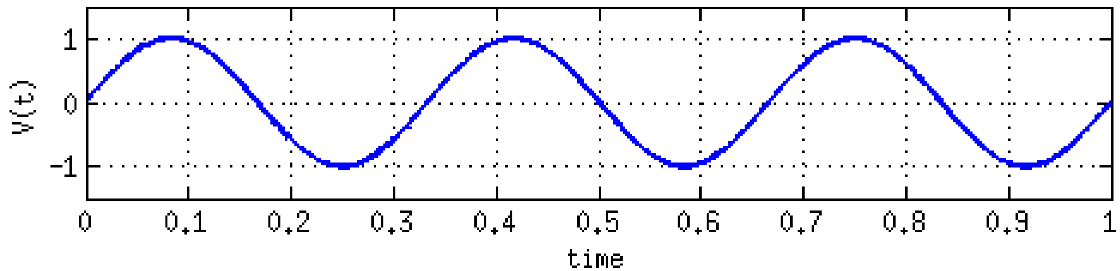
- ***Voltage*** and ***current*** are the two properties of electrical circuits that we are most often concerned with
  - Voltages and currents may be ***constant as functions of time***
    - Direct current, ***DC***
  - Or they may be ***time-varying***
    - Alternating current, ***AC***
  - We can refer to these quantities as electrical ***signals***
    - They carry information
    - More appropriate terminology in the world of electronics than power systems
- Voltages and currents can be plotted as functions of time – ***waveforms***

DC vs. AC

- ***DC*** (direct current) electrical signals (voltages, currents) are ***time-invariant***
  - In ENGR 201, we will primarily focus on DC signals

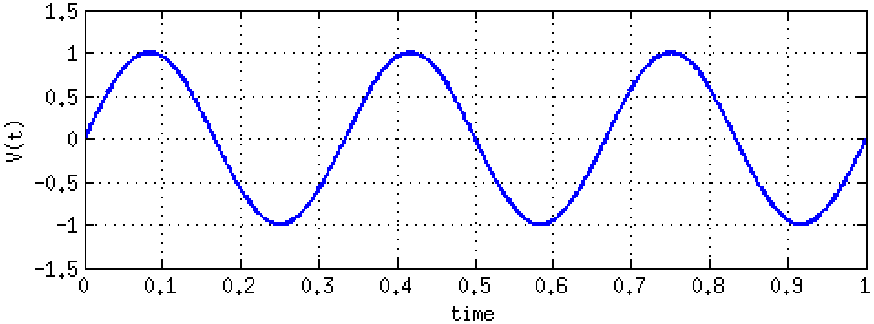


- ***AC*** (alternating current) electrical signals are ***time-varying***
  - Possibly ***periodic***

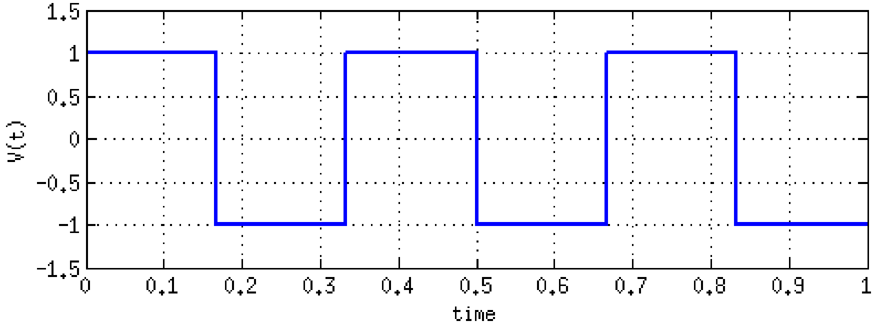


Some Typical Waveforms

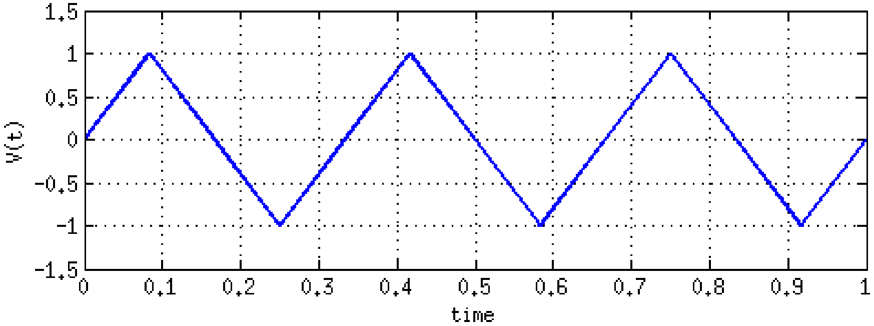
Sinusoid:



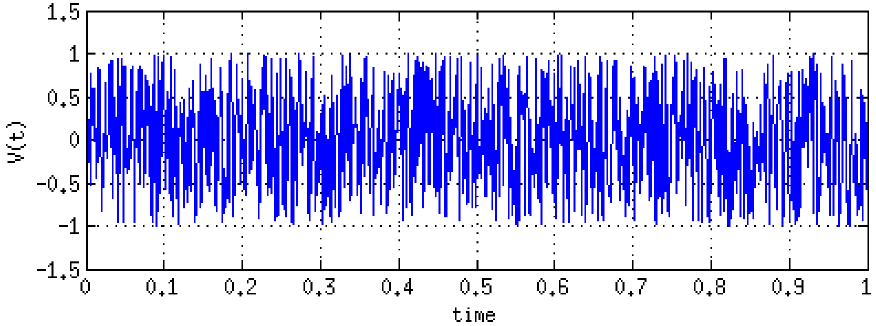
Square wave:



Triangle wave:

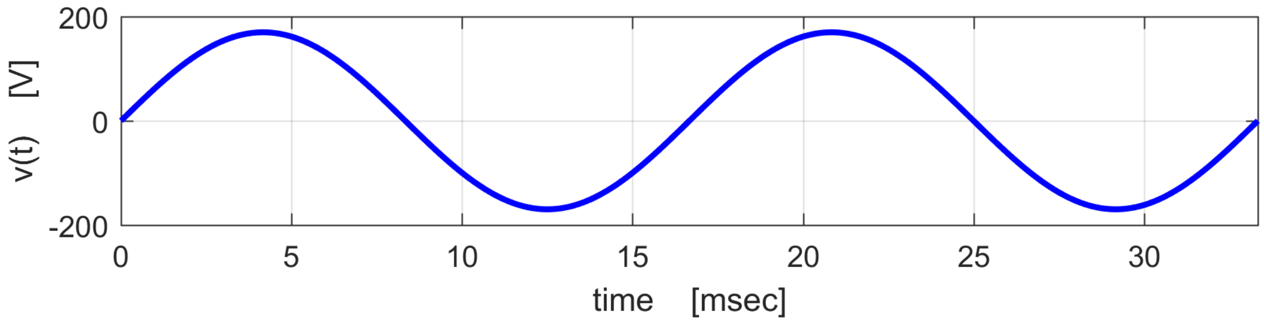


Noise:



Sinusoidal Signals

- In ENGR 202, we will see that ***sinusoidal*** signals are of particular interest in the field of electrical engineering



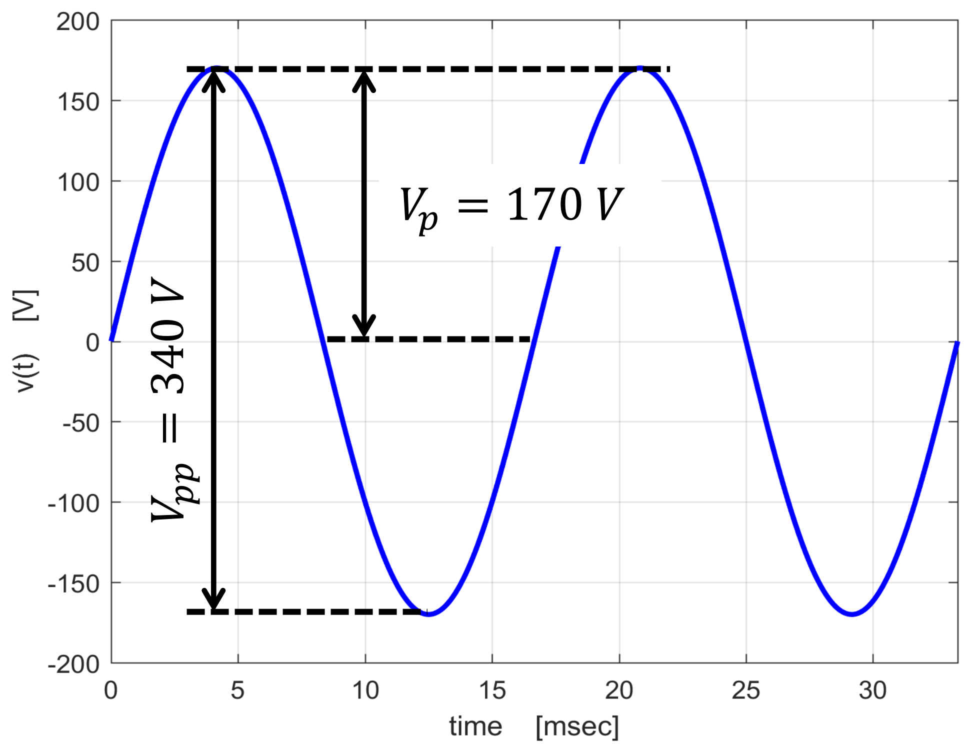
$$v(t) = V_p \cos(\omega t + \phi) = V_p \cos(2\pi \cdot f \cdot t + \phi)$$

- Sinusoidal signals defined by three parameters:
  - ***Amplitude***: V_p
  - ***Frequency***: ω or f
  - ***Phase***: ϕ

Amplitude

- ***Amplitude*** of a sinusoid is its ***peak*** voltage, V_p
- ***Peak-to-peak voltage***, V_{pp}, is twice the amplitude
  - $V_{pp} = 2V_p$
  - $V_{pp} = V_{max} - V_{min}$

$$v(t) = V_p \cdot \sin(\omega t + \phi) = V_p \cdot \sin(2\pi f t + \phi)$$



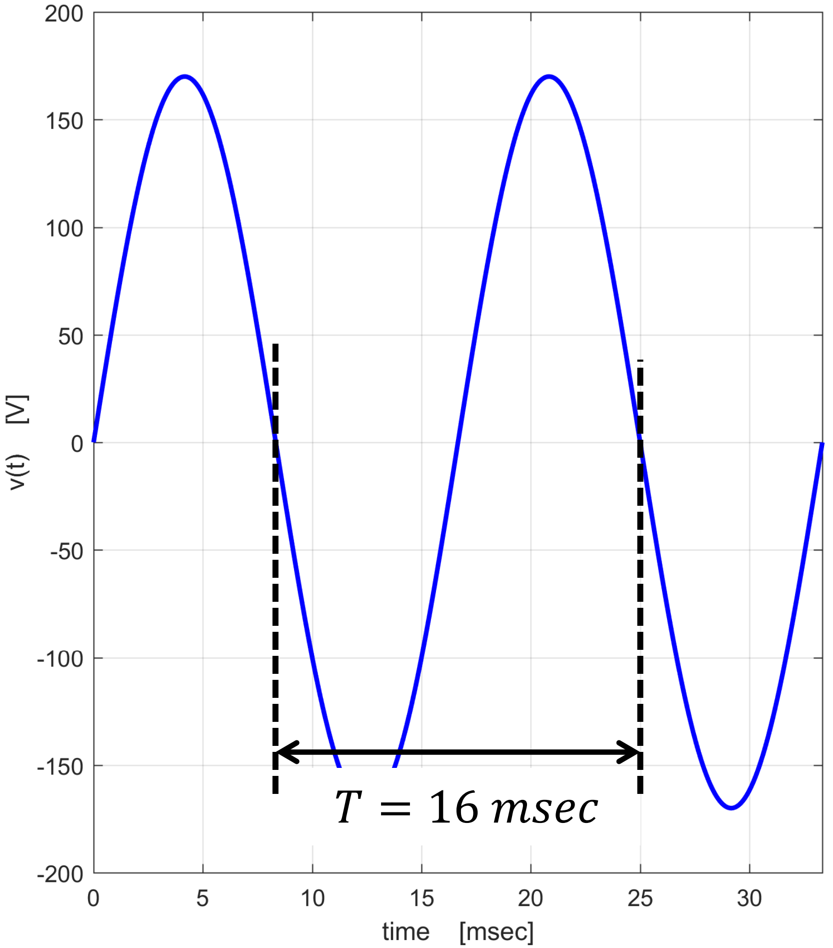
Frequency

- ***Period*** (T)
  - Duration of one cycle
- ***Frequency*** (f)
  - Number of periods per second

$$f = \frac{1}{T}$$

- ***Ordinary frequency***, f
  - Units: hertz (Hz), sec^{-1}, cycles/sec
- ***Angular frequency***, ω
  - Units: rad/sec

$$\omega = 2\pi f, \quad f = \frac{\omega}{2\pi}$$

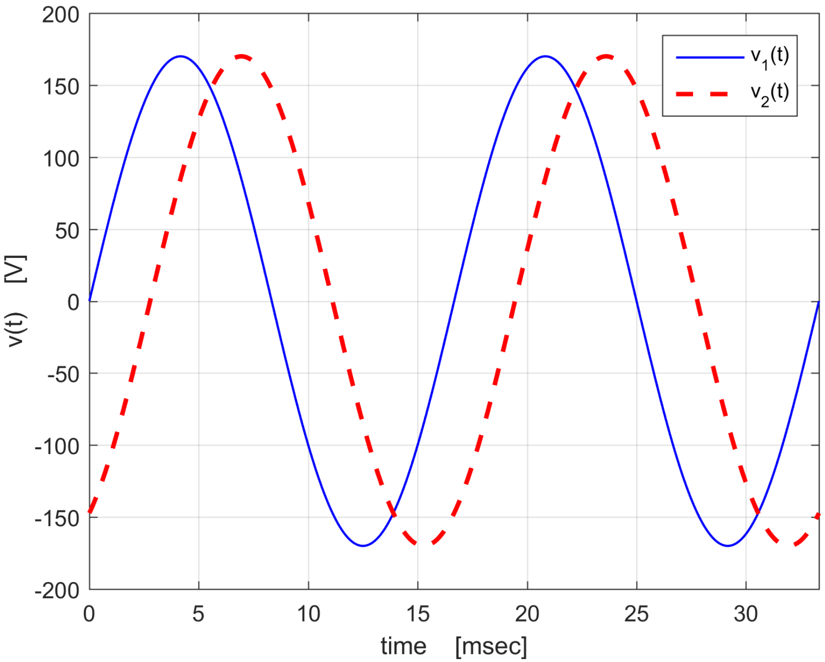


Phase

- ***Phase***
  - Angular constant in signal expression, ϕ

$$v(t) = V_p \sin(\omega t + \phi)$$

- Requires a time reference
  - Interested in relative, not absolute, phase
- Here,
  - $v_1(t)$ leads $v_2(t)$
  - $v_2(t)$ lags $v_1(t)$
- Units: radians
  - Not technically correct, but OK to express in degrees, e.g.:



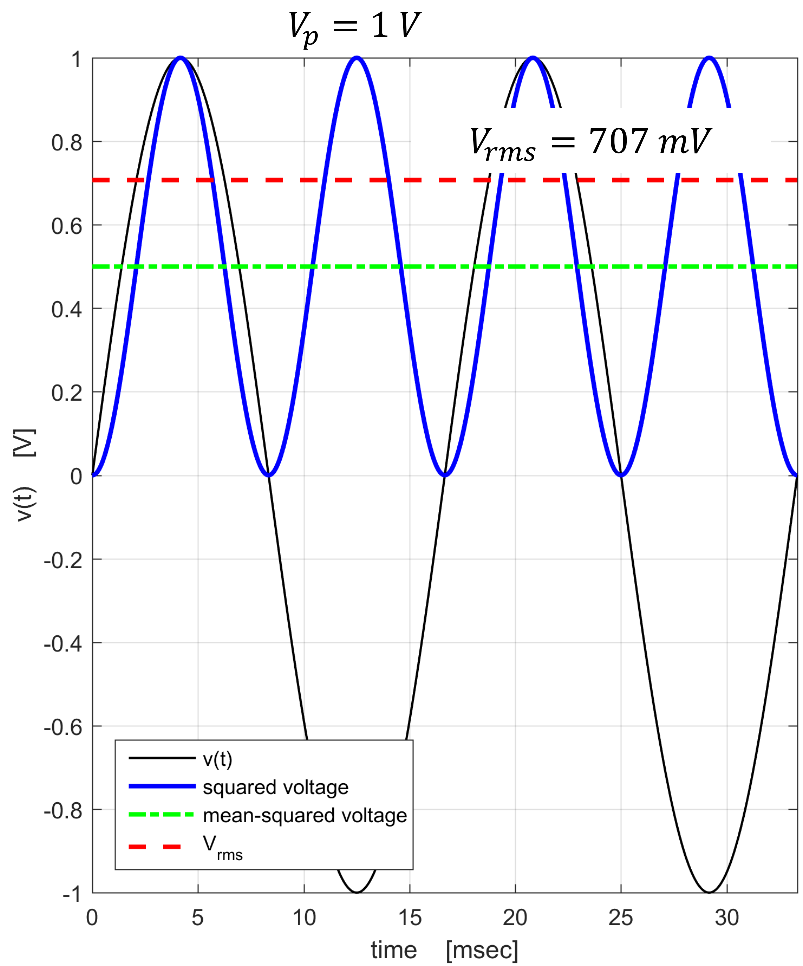
$$v(t) = 170\,V \sin(2\pi \cdot 60Hz \cdot t + 34°)$$

RMS Value

- ***Root mean square*** (rms) voltage/current
  - Square root of the time average of the voltage/current squared
  - AC voltage applied across a resistor results in same power dissipation as a DC voltage where $V_{DC} = V_{rms}$
- For ***sinusoids***:

$$V_{rms} = \frac{V_p}{\sqrt{2}}$$

$$v(t) = \sqrt{2}\, V_{rms} \sin(\omega t + \phi)$$



Electrical Energy & Power

Energy and Power

- True understanding of electrical systems comes from understanding how they behave in terms of ***energy***
  - True for dynamic systems in any domain – mechanical, electrical, etc.
- Electrical components can do one of four things:
  - Supply energy
  - Store energy
  - Dissipate energy
  - Transform/transmit/convert energy
- We're also concerned with the ***rate*** at which energy is supplied, stored, dissipated, or transformed
- ***Power*** is the ***rate of energy flow***
  - Unit of energy: joule (J)
  - Unit of power: watt (W), $1\ W = 1\frac{J}{s}$

Energy and Power

- Power is the ***rate*** of energy flow
  - The ***time derivative*** of energy

$$P = \frac{dE}{dt}$$

$$[W] = \left[\frac{J}{s}\right]$$

- Similarly, energy is given by the ***integral*** of power

$$E = \int p(t)dt$$

- For constant power, this simplifies to the product of power and time

$$E = P \cdot t$$

$$[J] = \left[\frac{J}{s}\right] \cdot [s]$$

Electrical Energy

- The power utility company charges us for ***energy***, not power
  - Units: watt-hours (Wh or kWh)
  - For example: $0.12/kWh
- One watt-hour (1 Wh):
  - Quantity of energy equivalent to the consumption of 1 W for 1 hour

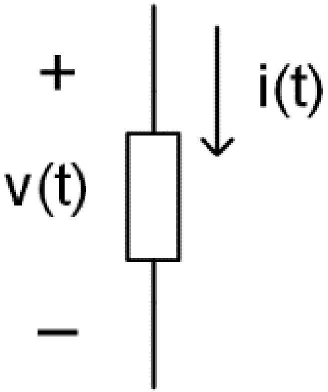
$$1\,Wh = 1\frac{J}{s}\cdot 1\,h = 1\frac{J}{s}\cdot 1\,h\cdot\frac{3600\,s}{1\,hr} = 3600\,J$$

$$1\,Wh = 3.6\times 10^3 J = 3.6\,kJ$$

$$1\,kWh = 3.6\times 10^6 J = 3.6\,MJ$$

Electrical Power

- A circuit component will have voltage across it and current flowing through it
  - In general, both are functions of time: $v(t)$ and $i(t)$
- Power flowing to/from that component is given by the ***product of voltage and current***



$$p(t) = v(t) \cdot i(t)$$

  - ***Instantaneous power***
  - A function of time
- If $i(t)$ and $v(t)$ are constant (DC) then $p(t)$ is constant as well

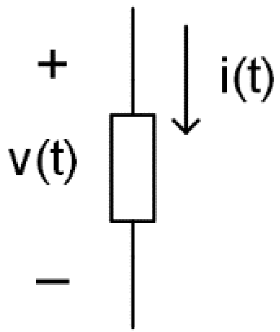
$$P = V \cdot I$$

Power – Passive Sign Convention

- ***Power*** can be ***supplied*** or ***absorbed*** by electrical components
- For any component, power is given by

$$p(t) = v(t) \cdot i(t)$$

- Use the ***passive sign convention*** to determine if power is supplied or absorbed:



- Positive current flows into the positive voltage terminal
- ***Positive*** power ($p > 0$) indicates power ***absorbed***
- ***Negative*** power ($p < 0$) indicates power ***supplied***

Electrical Energy - Batteries

- Batteries store electrochemical energy
  - Amount of energy stored is ***capacity***
    - Typically specified in units of ***ampere-hours*** (Ah)
- For example, a 90 Ah battery could supply the equivalent of 90 A for 1 hour

$$90\ Ah = 90\ A \cdot 1\ h = 90\frac{\mathrm{C}}{\mathrm{s}} \cdot 1\ h \cdot \frac{3600\ s}{1\ h} = 324 \times 10^3\ C$$

  - Or, 1 A for 90 hours (or any other equivalent combination)

$$90\ Ah = 1\ A \cdot 90\ h = 1\frac{\mathrm{C}}{\mathrm{s}} \cdot 90\ h \cdot \frac{3600\ s}{1\ h} = 324 \times 10^3\ C$$

- Clearly, this is a quantity of ***charge***, ***not energy***

Electrical Energy - Batteries

- To relate capacity in Ah to energy storage, we must know the battery's voltage
- For example, consider a 90 Ah, 12 V battery
  - If discharging at 1 A, for example, the power supplied is

$$P = V \cdot I = 12\,V \cdot 1\,A = 12\,W$$

  - At this rate the battery can discharge for 90 h, so the total stored energy is

$$E = P \cdot t = 12\,W \cdot 90\,h = 1080\,Wh = 1.08\,kWh$$

  - Energy capacity in Wh is given by the product of capacity in Ah and the battery voltage

$$E = (\text{capacity in Ah}) \cdot (\text{battery voltage})$$

Example Problems

How much charge is stored in an 80 Ah battery?

$$Q = 80\,Ah \cdot \frac{1\,C/s}{1\,A} \cdot \frac{3600\,s}{1\,hr} = 288\,kC$$

A 24 V battery pack will be used to power a 100 W load for 3 hours. What is the required battery capacity in Ah? In Wh? In J?

$$P = VI \longrightarrow I = \frac{P}{V}$$

$$I = \frac{100\ W}{24\ V} = 4.167\ A$$

$$\text{Capacity} = 3\text{hr} \cdot 4.167\ A = \underline{12.5\ Ah}$$

or

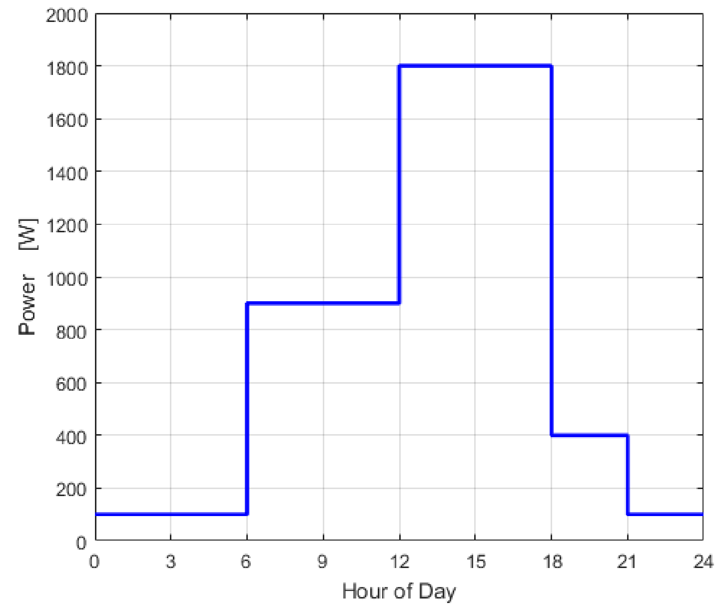
$$\text{Capacity} = 3\text{hr} \cdot 100\text{W} = \underline{300\ \text{Wh}}$$

or

$$\text{Capacity} = 300\ \text{Wh} \cdot \frac{3600\ s}{1\ \text{hr}} \ \frac{1\ J/s}{1\ W} = \underline{1.08\ MJ}$$

A daily load profile for a building is shown. How much energy is consumed each day?

If the cost of electricity is \$0.11/kWh, what is the daily cost of electricity? What is the yearly cost?



$$E = (100\,W \cdot 6\,hr) + (900\,W \cdot 6\,hr) + (1800\,W \cdot 6\,hr) + (400\,W \cdot 3\,hr) + (100\,W \cdot 3\,hr)$$

$$E = 600\,Wh + 5400\,Wh + 10{,}800\,Wh + 1200\,Wh + 300\,Wh$$

$$E = 18{,}300\,Wh = \underline{18.3\,kWh}$$

$$Cost/day = E/Day \cdot \$/kWh = 18.3\,kWh \cdot \$0.11/kWh$$

$$Cost/day = \underline{\$2.013}$$

$$Cost/year = Cost/day \cdot 365.25\ \frac{day}{year}$$

$$Cost/year = \$2.013/day \cdot 365.25\ \frac{day}{year}$$

$$Cost/year = \underline{\$735.25}$$

A typical 9 V battery has a capacity of 170 mAh. How many batteries would have to be connected in parallel to drive an 80 W load for 2 hours?

Total energy required is

$$E = 80W \cdot 2h = 160\,Wh$$

Capacity of each 9V cell in Wh:

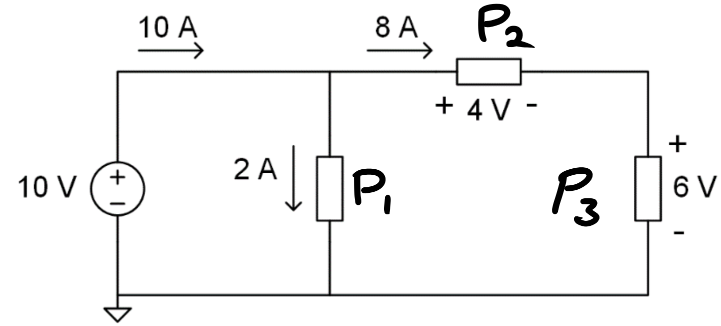
$$E_{cell} = 170\,mAh \cdot 9V = 1.53\,Wh$$

Required # of cells:

$$\#cells = \frac{E}{E_{cell}} = \frac{160\,Wh}{1.53\,Wh} = 104.6 \text{ cells}$$

$$\underline{\#cells = 105}$$

Determine the power for the source and for each branch element in the following circuit. Show that power is conserved.



$P_s = 10V(-10A) = \underline{-100W}$ (supplied)

$P_1 = 10V(2A) = \underline{20W}$

$P_2 = 4V(8A) = \underline{32W}$

$P_3 = 6V(8A) = \underline{48W}$

$P = P_s + P_1 + P_2 + P_3$

$P = -100W + 20W + 32W + 48W$

$P = -100W + 100W = 0W$ $\therefore$ power is conserved

How much energy is delivered by a 20 hp motor in 15 minutes?

If the motor is 92% efficient, how much energy is consumed by the motor during that time? (1 hp = 746 W)

$$E_{out} = P_{out} \cdot t = 20\ hp\ \frac{746\ W}{1\ hp} \cdot 15\ min \cdot \frac{60\ s}{1\ min} \cdot \frac{1\ J/s}{1\ W}$$

$$E_{out} = 14.92\ kW \cdot 900\ s \cdot \frac{1\ J/s}{1\ W}$$

$$\underline{E_{out} = 13.43\ MJ}$$

$$E_{in} = \frac{E_{out}}{\eta} = \frac{13.43\ MJ}{0.92}$$

$$\underline{E_{in} = 14.96\ MJ}$$

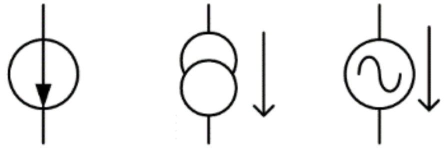
Electrical Circuit Components

Circuit Components

- ***Independent voltage source***
  - **Schematic symbol:**

  - **Description:**
    - Generates a fixed voltage between its terminals
    - DC or AC
  - **Units**: volts (V)

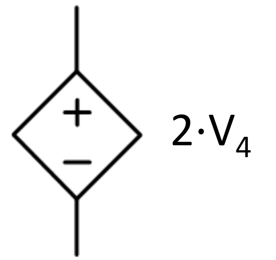
- ***Independent current source***
  - **Schematic symbol:**



  - **Description:**
    - Generates a fixed current
    - DC or AC
    - Current flows in one terminal and out the other
  - **Units**: amperes (A)

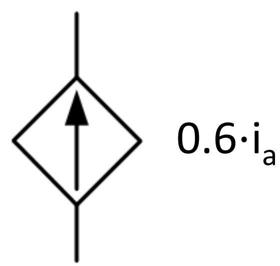
Circuit Components

- ***Dependent voltage source***
  - **Schematic symbol:**



  - **Description:**
    - Generates a voltage that is a function of another voltage or current in the circuit
    - Voltage-controlled voltage source (VCVS) or current-controlled voltage source (CCVS)
  - **Units**: volts (V)

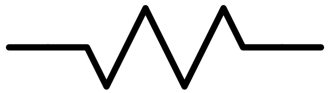
- ***Dependent current source***
  - **Schematic symbol:**



  - **Description:**
    - Generates a current that is a function of another current or voltage in the circuit
    - Current-controlled current source (CCCS) or voltage-controlled current source (VCCS)
  - **Units**: amperes (A)

Circuit Components

- ***Resistor***
  - **Schematic symbol:**



  - **Description:**
    - Circuit element that resists the flow of electrical current
    - Intentional or parasitic resistance (even wires are resistive)
  - **Units**: ohms (Ω)

- ***Ground***
  - **Schematic symbol:**

  - **Description:**
    - Voltage reference for a circuit
    - Ground node
    - Potential of 0 V

Circuit Components

- ***Capacitor***
  - **Schematic symbol:**

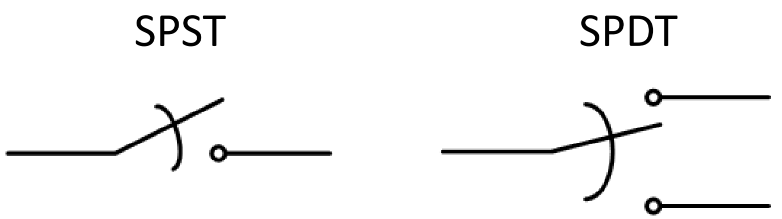
  - **Description:**
    - Stores energy in an electric field
    - Two electrodes separated by a dielectric
    - Stores a charge differential between the two electrodes
  - **Units**: farads (F)

- ***Inductor***
  - **Schematic symbol:**

  - **Description:**
    - Stores energy in a magnetic field
    - A coil of wire
  - **Units**: henries (H)

Circuit Components

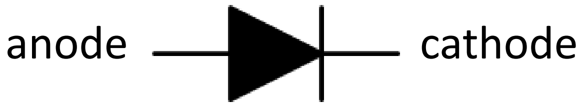
- ***Switch***
  - **Schematic symbol:**



  - **Description:**
    - Controls connections between multiple nodes in a circuit
    - Single-pole single-throw (SPST) switch makes/breaks connection between two nodes
    - Single-pole double-throw (SPDT) switch connects one node to one of two other nodes
    - Many other configurations, e.g. DPDT, 3PDT, 6P3T, etc.

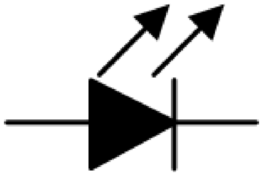
Circuit Components

- ***Diode***
  - **Schematic symbol:**



  - **Description:**
    - Two-terminal semiconductor device
    - Junction of p-type and n-type semiconductor – a p-n junction
    - Allows current to flow in one direction only (anode to cathode)
    - Analogous to a check valve

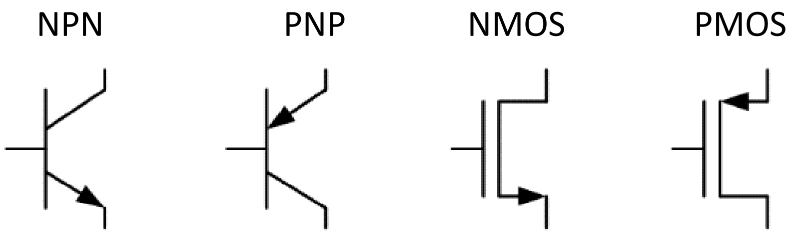
- ***Light-emitting diode (LED)***
  - **Schematic symbol:**



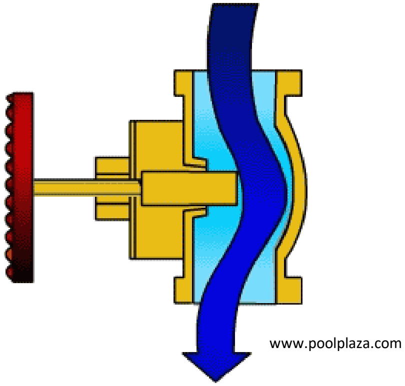
  - **Description:**
    - Diode that emits photons in response to current flowing through it

Circuit Components

- ***Transistor***
  - **Schematic symbol:**

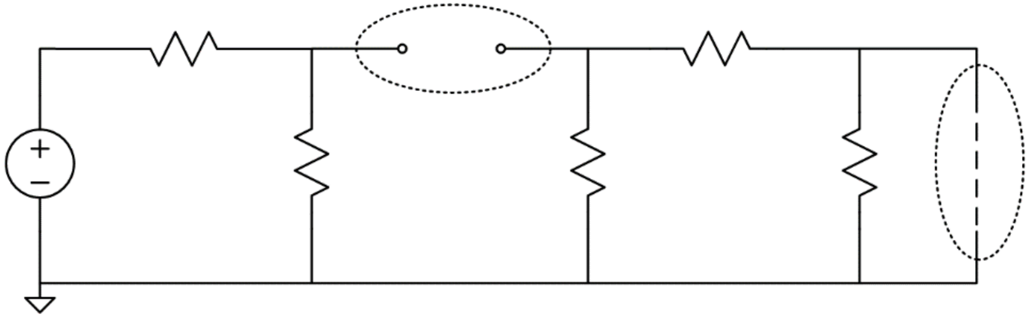


  - **Description:**
    - Three-terminal semiconductor device
    - Small voltage on/current into one terminal controls current flow between the other two terminals
    - Primary building block of integrated circuits
    - Can be used as ***switches*** or ***amplifiers***
    - Analogous to ***valves***:



Short Circuits & Open Circuits

- ***Short circuit***
  - Direct connection between multiple nodes in a circuit
  - A direct path for current to flow
  - Often refers to an unintentional connection
- ***Open circuit***
  - Lack of any electrical connection between two nodes in a circuit
  - No path for current to flow
  - Again, often used to refer to an unintended condition



Complete Circuits

- Electrical current always flows in a ***complete circuit***
  - A return current path must always exist for current to flow
  - Consider a simple lamp:
    - Two-conductor cord – line and neutral
    - Current flows from socket, down one conductor – line
    - Current flows through the bulb
    - Current returns back along the neutral conductor to the wall, and, ultimately, to the power plant
  - Ladder on a power line vs. bird on power line

Miscellany

Problem Solving

- Engineering is all about solving problems, e.g.:
  - Designing complex systems to solve problems
  - Troubleshooting malfunctioning prototypes
  - Solving homework/exam problems as a student

- All engineering problems are different, but we can apply a similar general process to all problem solving:
  1. Carefully define the problem
  2. Present everything you know about the problem
  3. Establish a list of alternative approaches to solving the problem and select the "*best*" approach
  4. Attempt to solve the problem
  5. Evaluate the solution and check for accuracy
  6. If the problem is solved, you're done, if not, go to step 3

Problem Solving

- In ***flowchart*** form:

1. Carefully define the problem
2. Present everything you know about the problem
3. Establish a list of alternative approaches to solving the problem and select the "*best*" approach
4. Attempt to solve the problem
5. Evaluate the solution and check for accuracy
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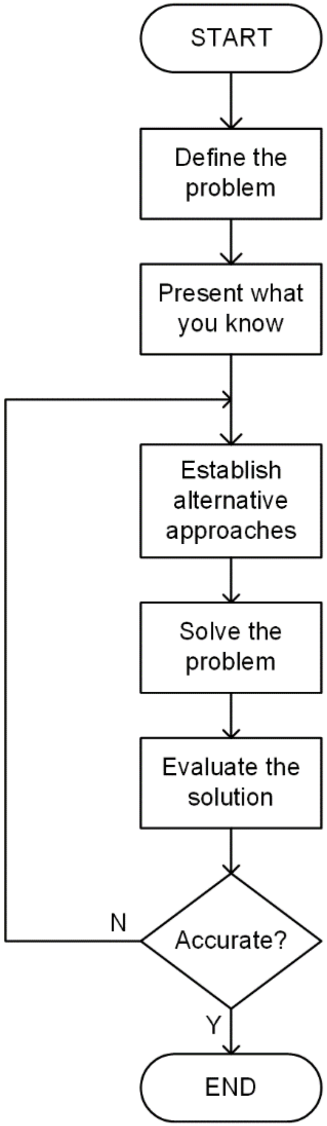

SI Prefixes

- Use ***SI prefixes*** for unit scaling whenever possible
  - Simplifies notation
  - Makes quantities easier to read and prevents errors
  - For example: 18 psec vs. 0.000000000018 sec

Multiplier	Prefix	Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	K
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a