Electricity – The Meterman Basics

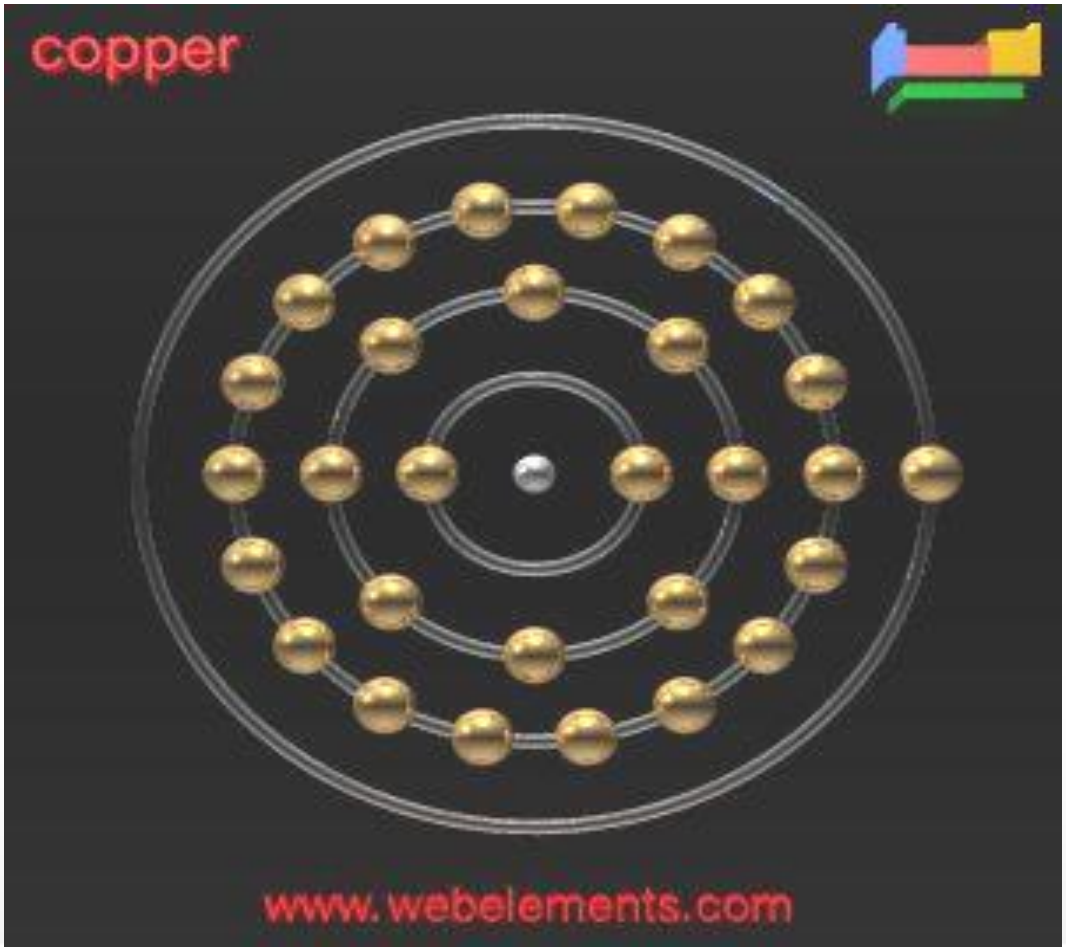
Basic Electricity

- **Voltage, current, power, energy**
- **Circuit components**
  - Resistors, Inductors, Capacitors, Transformers
  - Ohm's Law : Current is directly proportional to the voltage and inversely proportional to the resistance (impedance)
- **AC vs. DC**
  - AC Circuits → Two characteristics: Magnitude and frequency
    - Electrical Degrees" → measurement of time
  - Resistance, Reactance, Impedance
  - Active Power vs. Reactive Power
  - Power Triangle → Helps us understand AC circuit theory

Where does electricity come from?

- **Electricity is produced when electrons leave their atoms**
- **Normally the positive attraction of the nucleus counteracts the centrifugal force on the electron to keep the electron in orbit.**
- **However, an outside force can push or free the electron out of orbit which produces electricity**
- **There are a number of ways that an outside force can attempt to free the electron out of orbit:**
  - Friction
  - Chemicals
  - Heat
  - Pressure
  - Magnetism
  - Light

It starts at the elements…



- **Also the same reason why most good conductors are also NOT transparent…**
- **Or, why many insulators are transparent…**

VOLTAGE or Electromotive Force

- **Electrical charges are measured in Coulombs**
- **When two different objects have different charges then a difference of potential exists between those two objects**
- **This potential of difference causes a force to be exerted between those two objects and we call this resultant force "electromotive force" or "EMF"**
- **The unit used to measure EMF is the volt (V)**
- **1 volt = 1 EMF = 1 Coulomb (C) doing 1 joule of work**
- **Some typical voltages that you are probably familiar with are:**

1.5 volts for a flashlight battery	12 volts for a car battery
120/240 volts in your home	12,470v on a distribution power system

AMPERE (measure of current)

- The quantity current flowing in a wire is determined by the number of electrons that pass a given point in one second
- When 1 coulomb passes a point in 1 second that equals 1 ampere
- Thus, 1 ampere = 1C/s
- And, 1C = 6.24×10^{18} electrons
- Therefore, 6.24×10^{18} electrons must pass one point in one second to have one ampere of current

Resistance

- Resistance relates Voltage to Current
- A conductor is said to have a resistance of 1 OHM when an EMF of 1 volt causes a current of 1 ampere to flow through that conductor
- Resistance is a conductor's opposition to current flow. It is similar to friction.
- Furthermore, the higher the resistance the harder it is to make current flow and thus the current is dissipated and it's energy is turned into heat
- The Greek symbol upper-case omega, "Ω", is used to indicate resistance which is measured in ohms

Summary: Useful electrical terms

- **Voltage (V/U)**
  - The value of an electromotive force or potential difference, expressed in volts
  - It represents the potential to do work
  - Similar to pressure in a hydraulic or gas system (think garden hose)

- **Current (I)**
  - The rate of movement of charge, expressed in amperes or “amps”
  - Similar to water flow rate in the garden hose

- **Resistance (R, Ω)**
  - Opposition to the flow of electric current
  - Similar to how friction opposes mechanical (physical) movement → like pinching the garden hose

Example: V, I, R using the water analogy

- http://www.magnet.fsu.edu/education/tutorials/java/currentflow/index.html

Ohm's Law

- **Since Voltage causes current to flow in a closed circuit and resistance opposes the flow of current, a relationship exists between voltage, current and resistance**
- **This relationship was discovered by Georg Ohm so we call this formula "Ohm's Law"**
- **V= I × R**
  - Voltage equals Current times Resistance
- **Other algebraic manipulations :**
  - I = V / R
  - R = V / I
- **Remember that V is voltage and some people will use an E to represent EMF which is voltage in this equation**

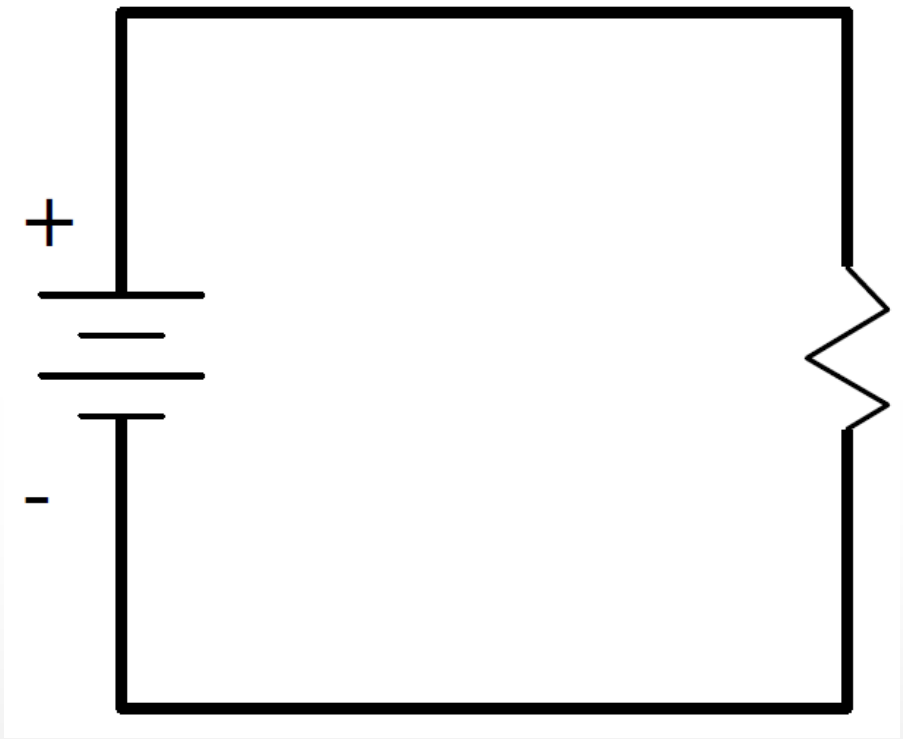
Georg Ohm
(1789-1854)

Ohm's Law (cont'd)

- **Ohm's Law: "The current, I, flowing in a conductor is directly proportional to the applied voltage and inversely proportional to its resistance, R"**
- **$I = V / R$ or $V = I \times R$ or $R = V / I$**
- **Ohm's Law means:**
  - In a circuit if you increase the voltage and resistance stays the same, the current or I will go up
  - If you lower the voltage, the current will go down
  - If you raise the R, the current will go down
  - If you lower the R, the current will go up

Quiz time!

I = 5 A?

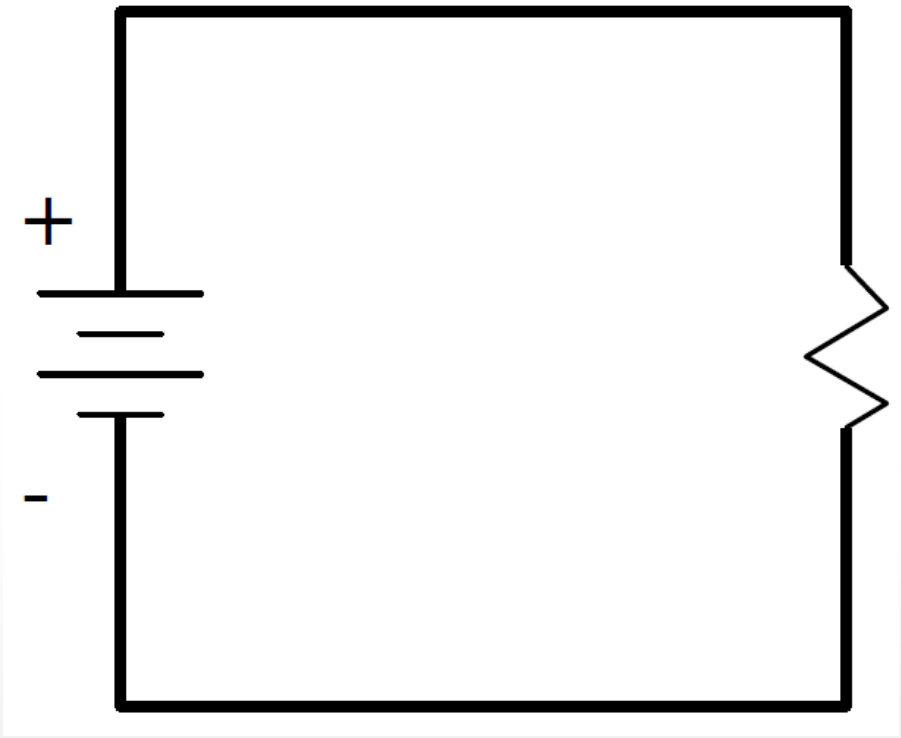


V = 15 VDC

R = 3Ω

Quiz time!

I = 30A



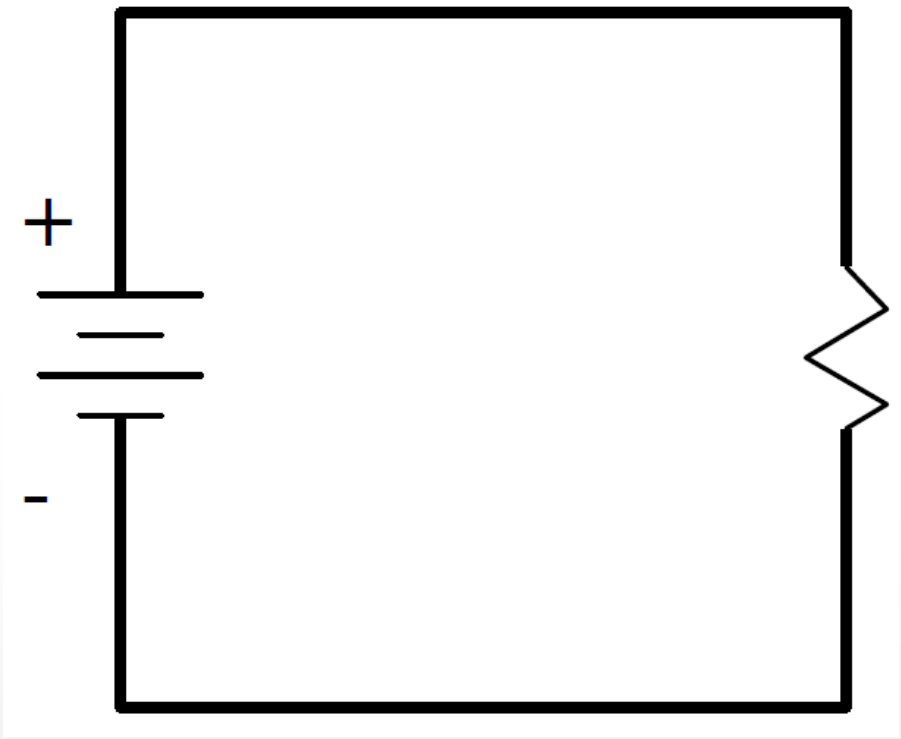
V = 240 VDC

R = 8 Ω?

Quiz time!

I = 3000A

V = 0 VDC?

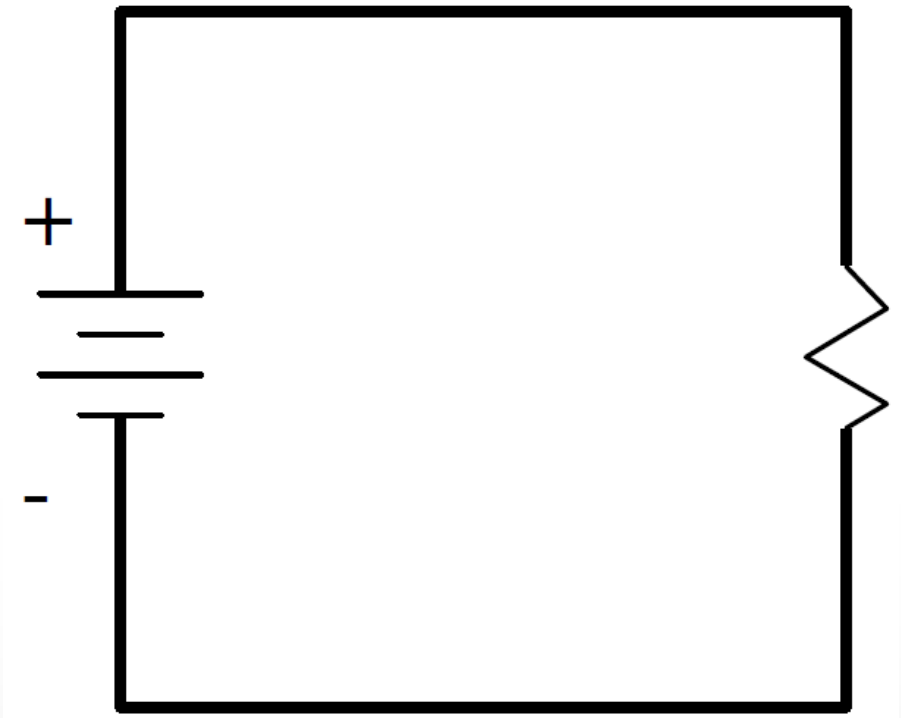


R = 0Ω

"short circuit"

Quiz time!

I = 3A



V = ∞ VDC?

R = ∞ Ω

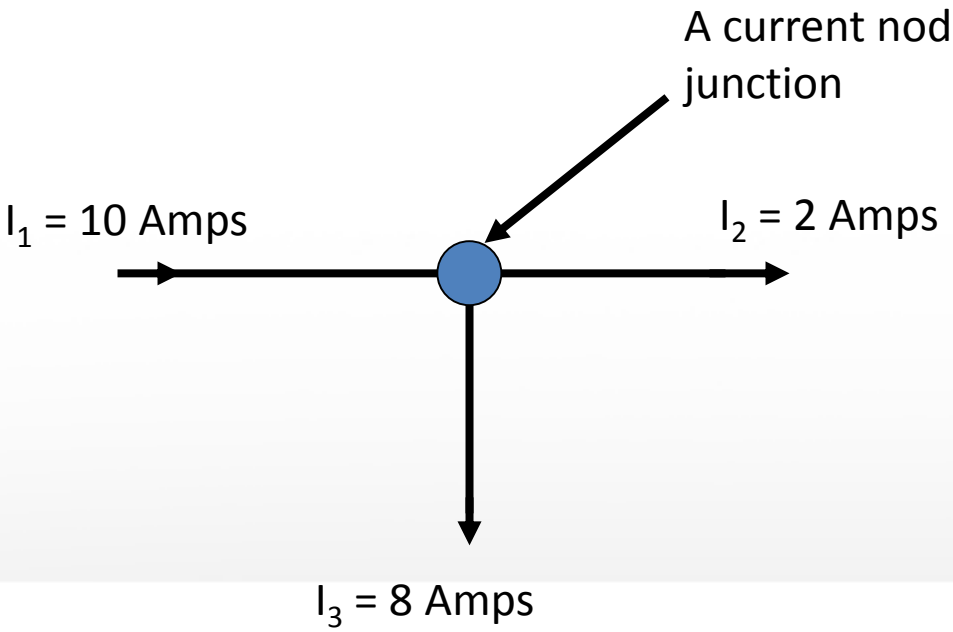
"open circuit"
"infinite R"

☞ Why you NEVER want to open the secondary of a CT loop

☞ Infinite V → arcing → injury → bad

Kirchhoff's Current and Voltage Laws

- **Kirchhoff's Current Law: The sum of the currents at a junction point equals zero**
- **Also another way to remember this law is: What goes in must come out when talking about a current node**



Two ways to look at it:

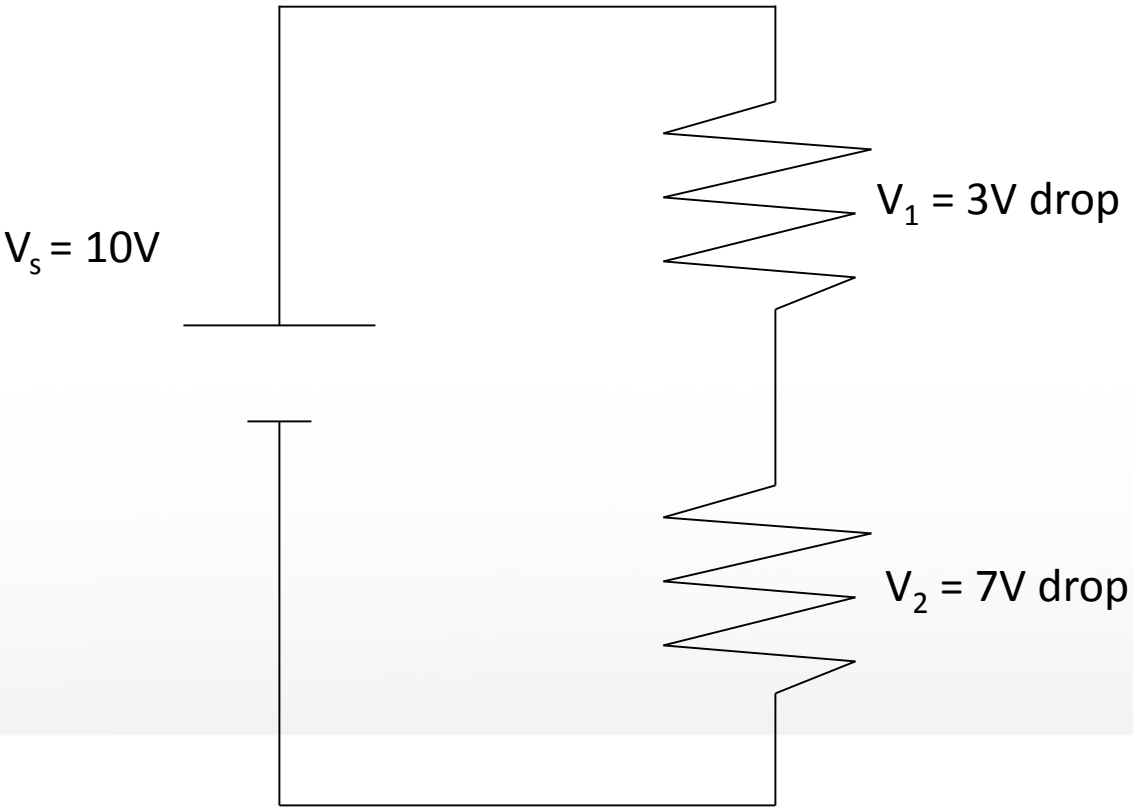
$I_1 + (-)I_2 + (-)I_3 = 0$

or,

$I_1 = I_2 + I_3$

Kirchhoff's Current and Voltage Laws

- **Kirchhoff's Voltage Law: The sum of all the voltage drops and voltage rises around a closed loop is equal to zero**



$V_s + V_1 + V_2 = 0$

10v + (-)3v + (-) 7v = 0

Quick quiz:
What's the current?

Power

- **Power = Work over a period of time**
  - Work (energy) per unit time
  - Work / Time or Energy / Time

- **Units of Power: WATTS!**
- **$P = I \times V$**

- **In case of resistive (Ohmic, or linear) loads, combine $P = I \times V$ with Ohm's Law $V = I \times R$:**

  $P = I \times I \times R = I^2 \times R$

  $P = V^2 / R$

- **Sometimes you need to convert watts to hp : 746 watts = 1hp**

Familiar example of Power and Resistance

An incandescent lamp is made by enclosing a resistance element called a filament, in a glass bulb. When a lamp is connected into a circuit, current flows through the filament, and I2R heating takes place. The heat is so severe that the filament becomes white-hot and gives off light. The more the filament is heated the more light the lamp gives off. When you buy a lamp according to its wattage rating you are really selecting it according to its light output. Looking at the power equation P = V x I you can see that either the voltage has to increase of the current has to increase to have more power or a brighter light. Since the power company normally doesn't vary the voltage much coming into your home that means that the current has to increase on a higher wattage bulb. Now thinking about both a 100w bulb versus a 40w bulb you can now see that the 100w bulb has to conduct more current. Also this means that the resistance of the filament of the 100w bulb is less than the resistance for the 40w bulb.

Using a 120V supply:

$I = P/V = 4/120 = 0.3333A$

40 watt bulb

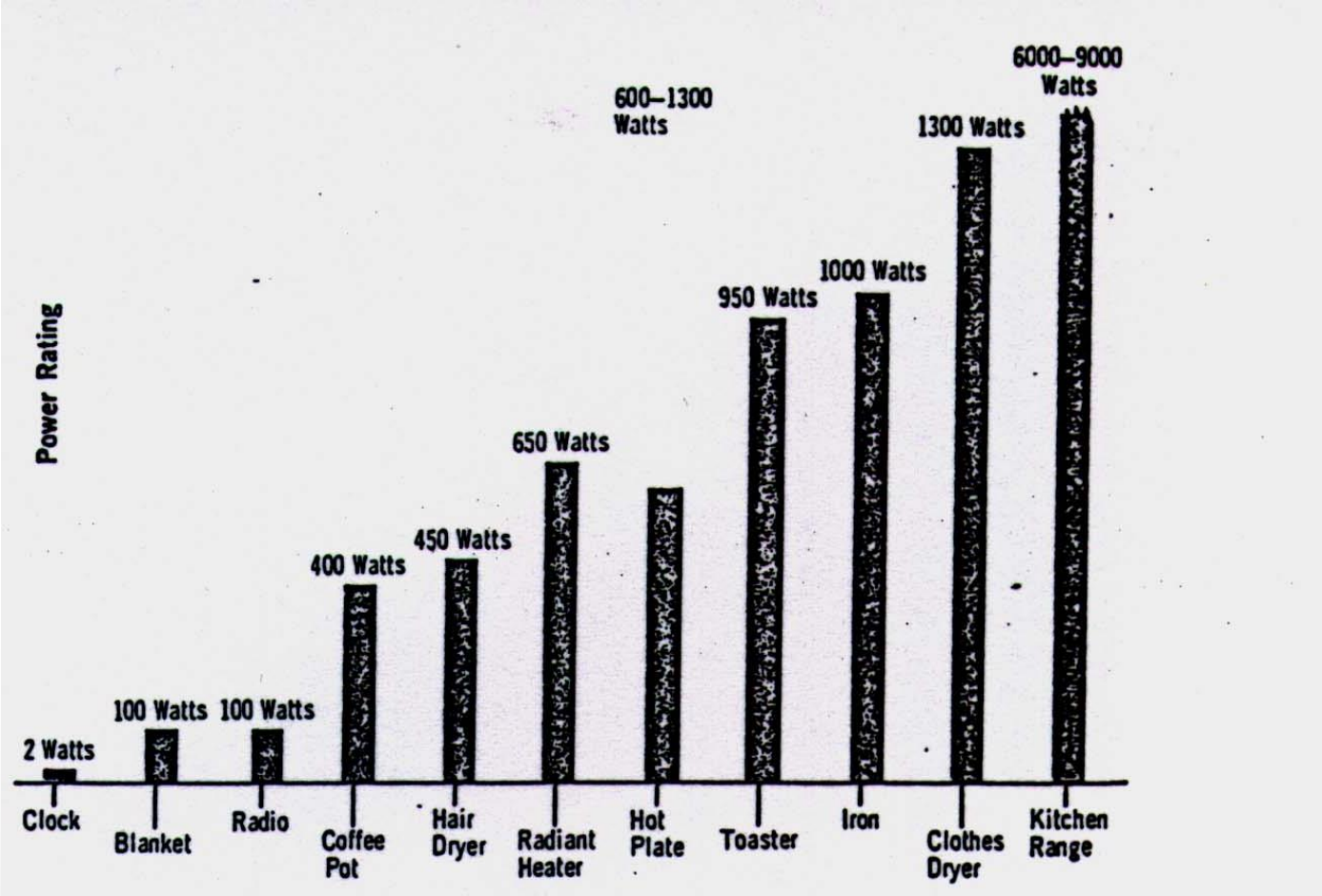
360 Ω filament

0.8333A

100 watt bulb

144Ω filament

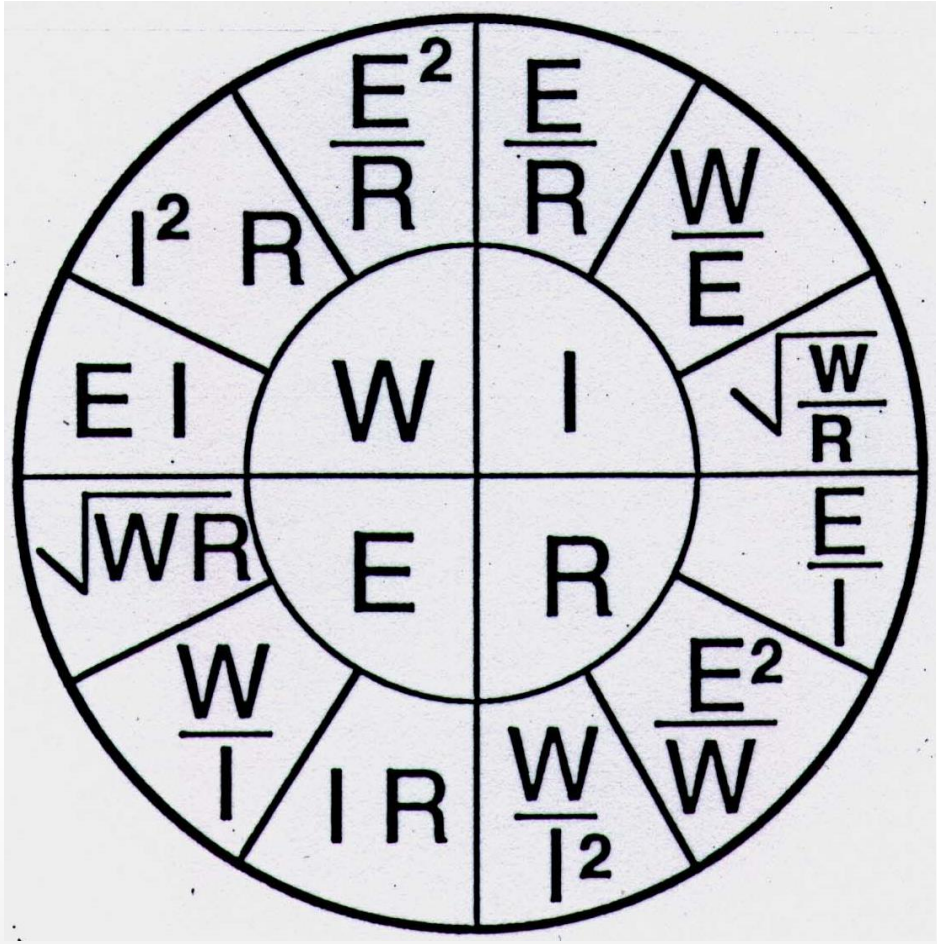
Typical power ratings of Electrical Appliances



Energy

- **If Power = Energy / Time**
- **Then Energy = Power × Time**
  - Units of Power: Watts
- **Units of Energy: Watt × Hours**
- **Or, simply: Wh**
- **Examples:**
  - 1W used for 1000 hour = 1 kWh
  - 1000W used for 1 hour = 1 kWh
  - 100W bulb burning for 1 hour = 100 Wh or 0.1 kWh

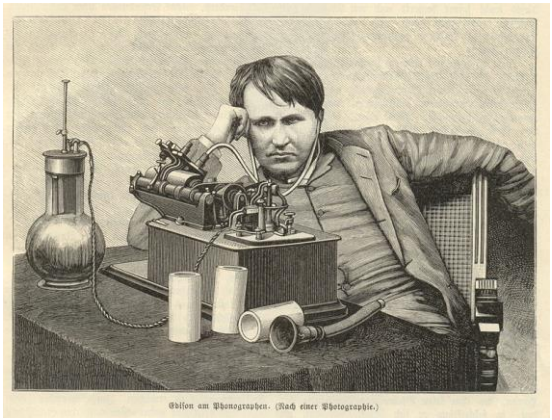
The Power Circle



DC and AC circuits

The War of Currents

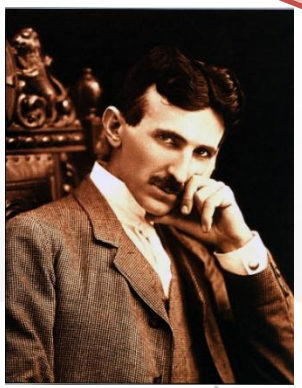
http://en.wikipedia.org/wiki/War_of_Currents

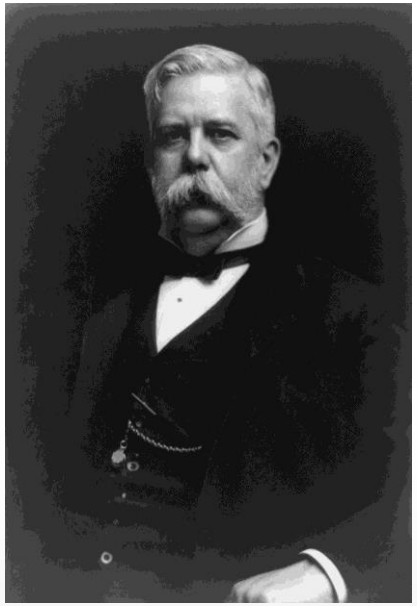


Thomas Edison
DC

VS.

Nikola Tesla
DC → AC





George Westinghouse
AC

Other factors:

- ***GE***
- ***Niagara Falls***

Direct vs. Alternating Current

- **Direct Current (DC) – and electric current whose magnitude and direction are constant in time**
- **Alternating Current (AC) – an electric current that moves first in one direction for a fixed period of time and then in the opposite direction for the same period in time**
  - If a “sine” wave, the current changes from zero to a maximum positive value to a maximum value and back to zero over a fixed period of time called a “cycle”
  - In the USA, basic AC has 60 complete cycles per second
    - Changes direction 120 times per second
  - “Cycles per second” ≡ “Hertz” ➔ 60 Hz frequency
  - 1 cycle = 1/60 = 0.01667 sec = 16.67 msec

Heinrich Rudolf Hertz
1857 - 1894

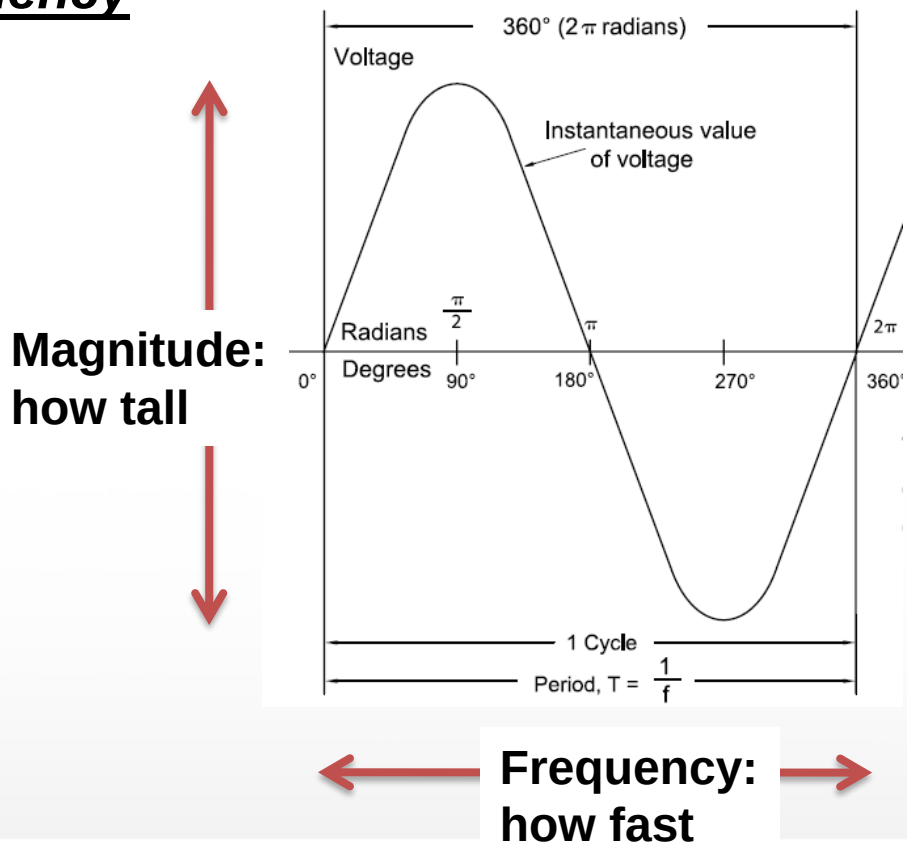
Examples
from Handbook for Electricity Metering

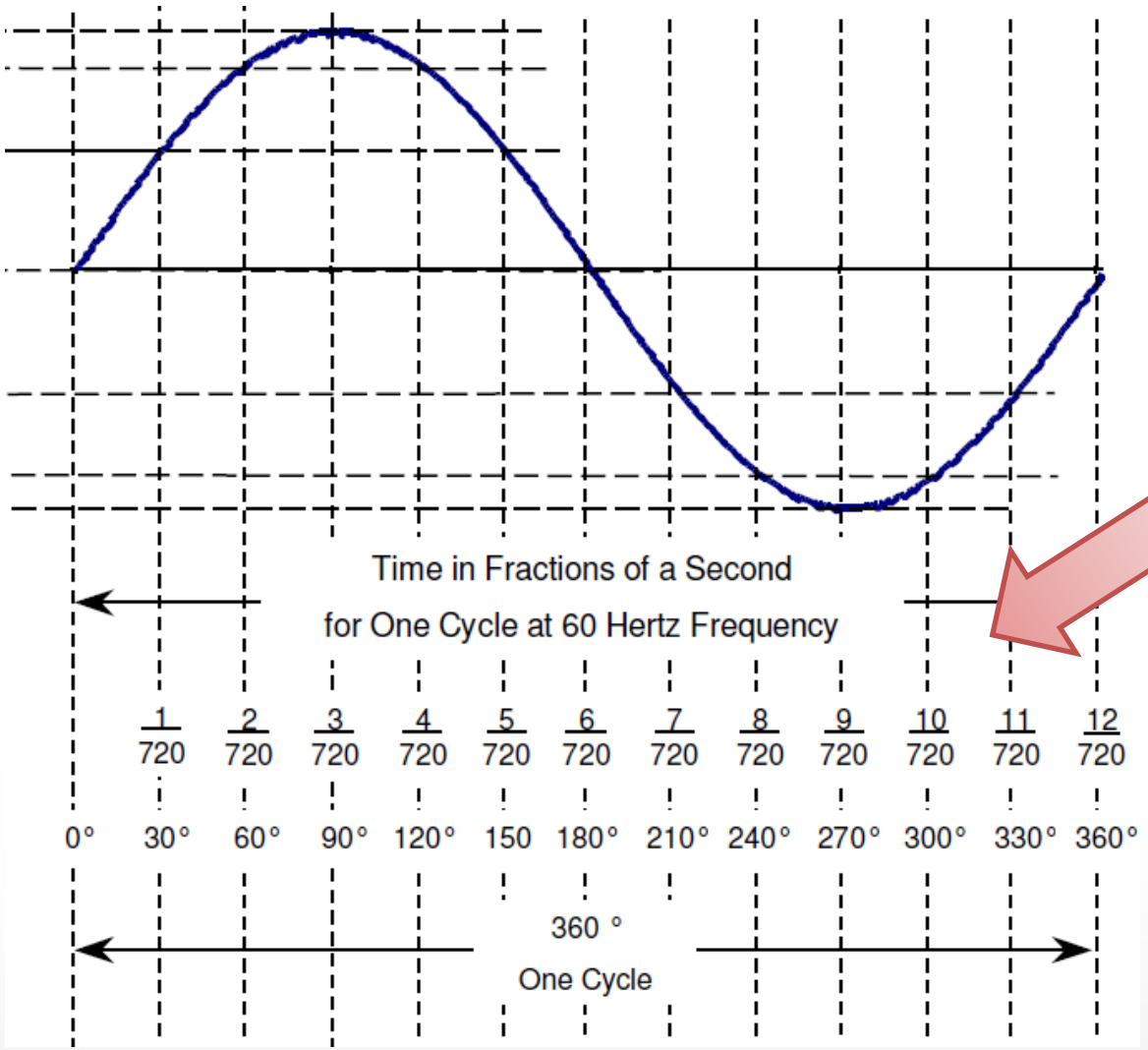
Application	Frequency
Direct current	0 Hz
Standard AC power (Europe influenced parts of the world)	50 Hz
Standard AC power (USA influenced parts of the world)	60 Hz
Audio sound	16 to 16,000 Hz
AM radio broadcasts	535 to 1,605 kHz
FM radio broadcasts	88 to 108 MHz
Television (Channels 2-13)	55 to 216 MHz
Communication satellites	5 GHz

AC signal

- ***An AC source has two general characteristics:***

  <u>Magnitude</u> and <u>Frequency</u>

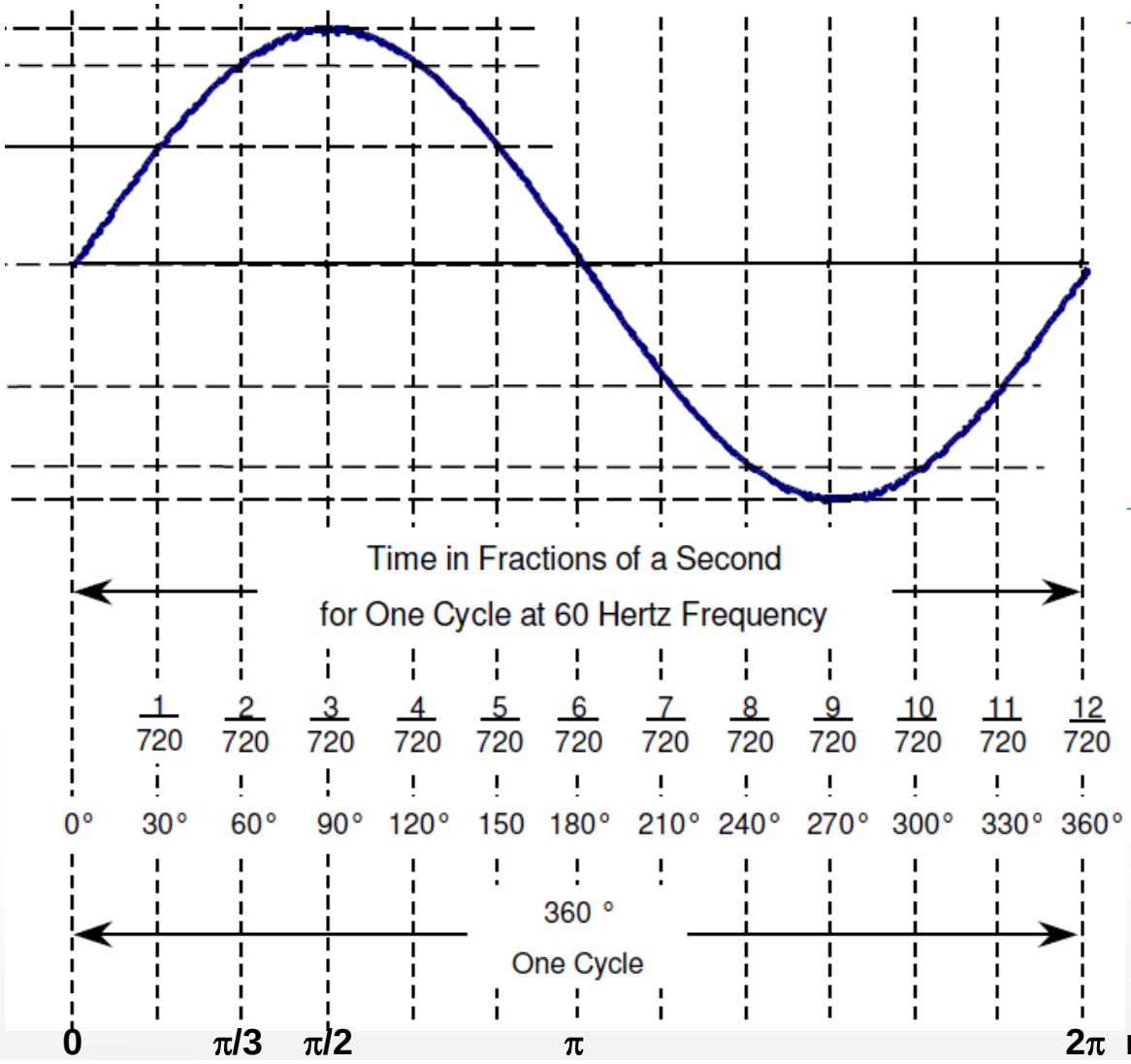




- Frequency
- Time
- Degrees
- Radians

…are just different ways to describe the horizontal X-axis

0 π/3 π/2 π 2π radians



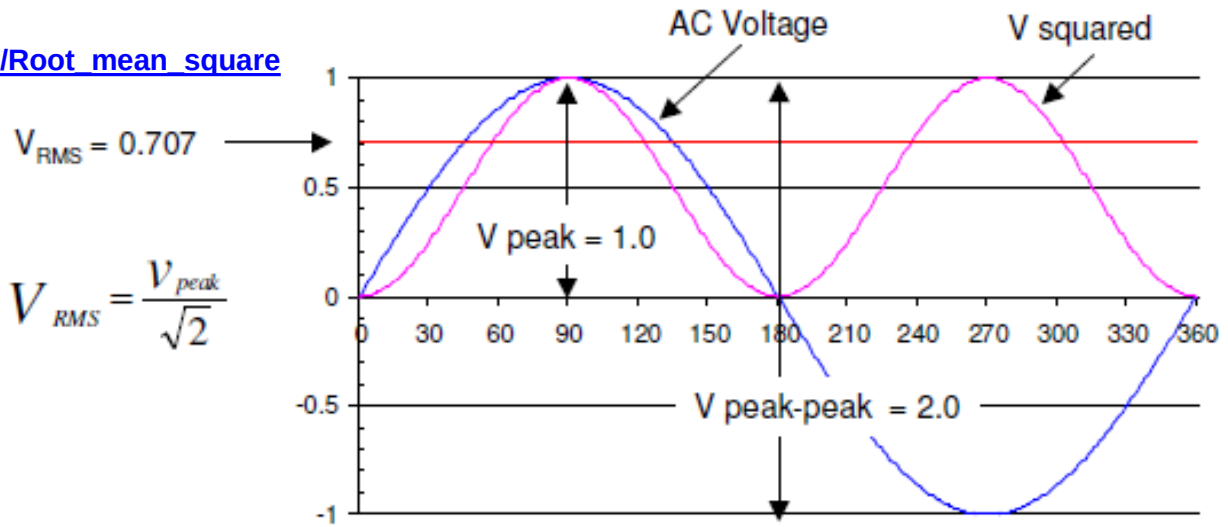
- **Peak-to-Peak**
- **RMS**

…are just different ways to describe the vertical Y-axis (magnitude)

Peak vs. RMS

- **For AC current or voltage, its average value over time is zero.**
- **A more practical measure is its equivalent DC (direct current) heating effect on a resistor**
  - $P = V^2 / R$
- **It is calculated as the square Root of the Mean (average) of the Squared values of the current or voltage over one (or more) cycles**
- http://en.wikipedia.org/wiki/Root_mean_square

$$V_{RMS} = \frac{V_{peak}}{\sqrt{2}}$$



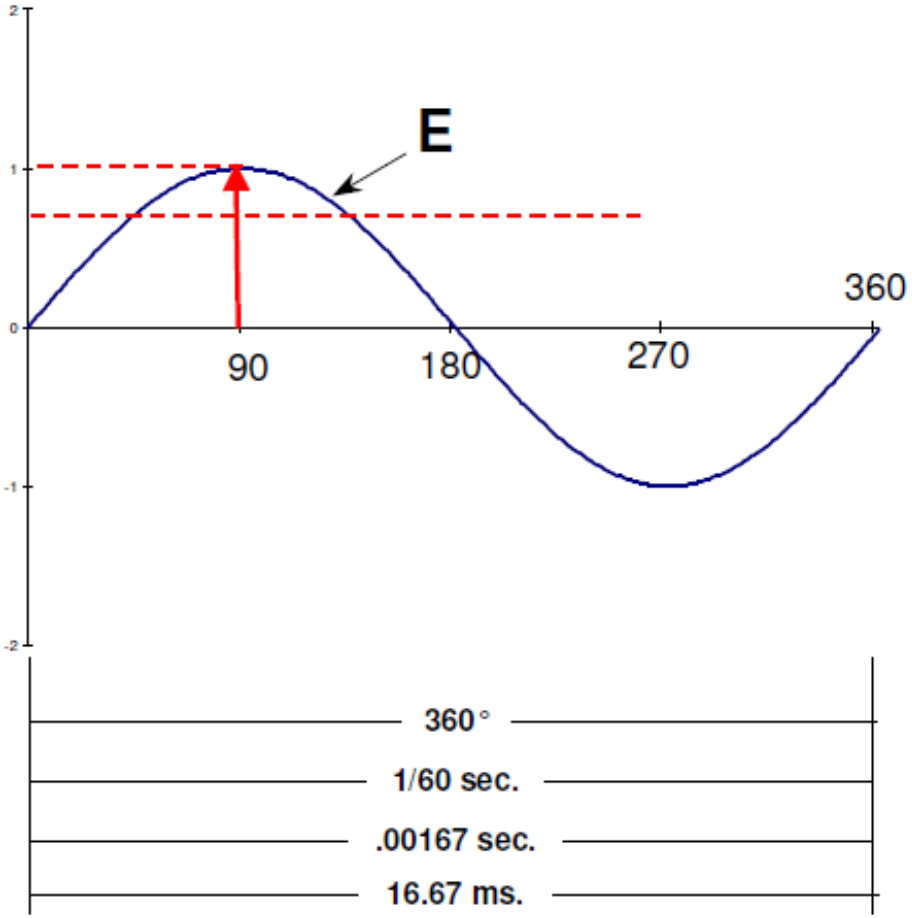
Peak vs. RMS for Household 120 VAC

E_{peak}

$E_{RMS} = 120$

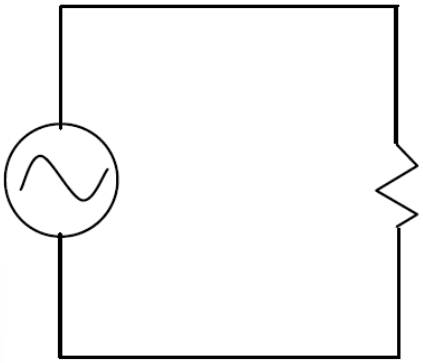
$E_{peak} = 120\sqrt{2}$

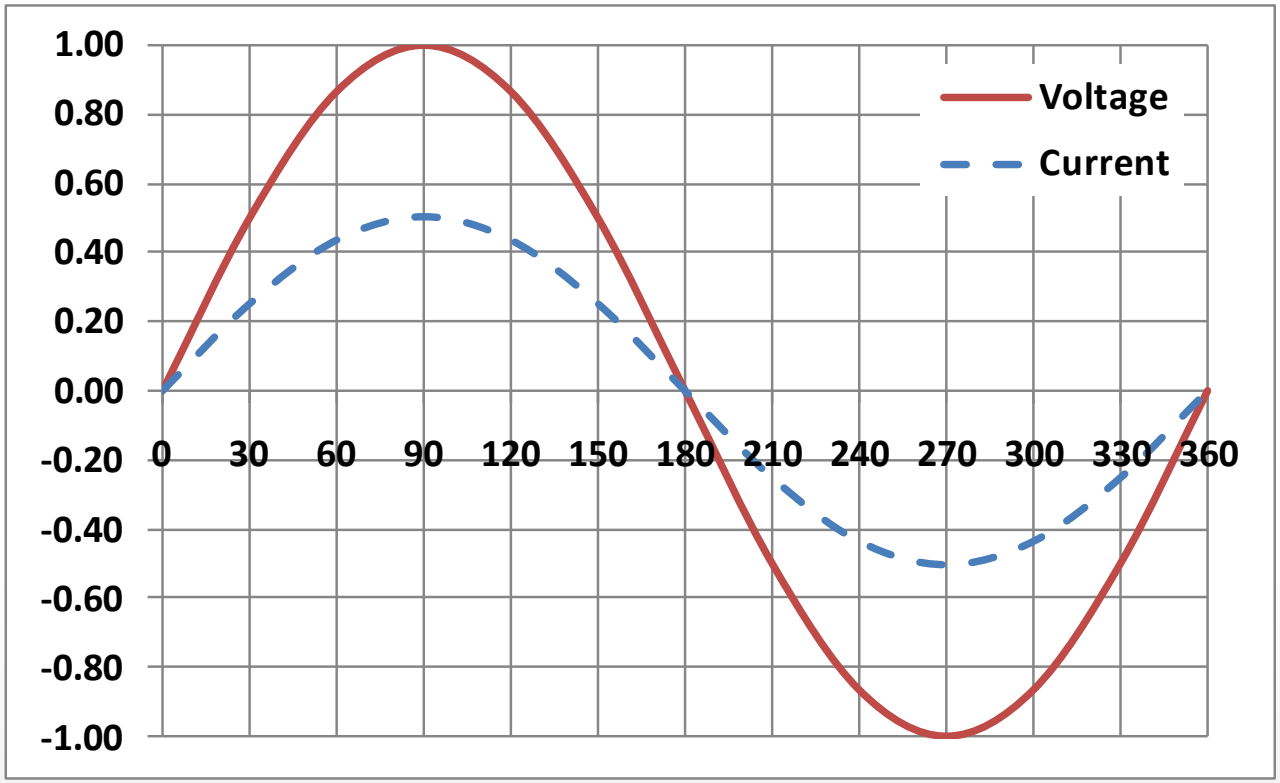
$E_{peak} = 169$



Resistors in AC

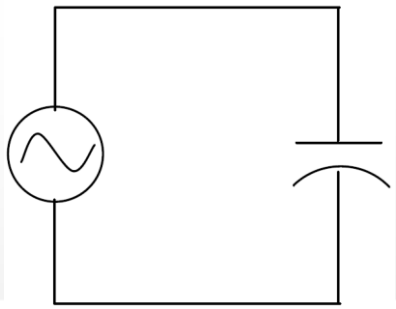
- **Quick quiz: What's R?**

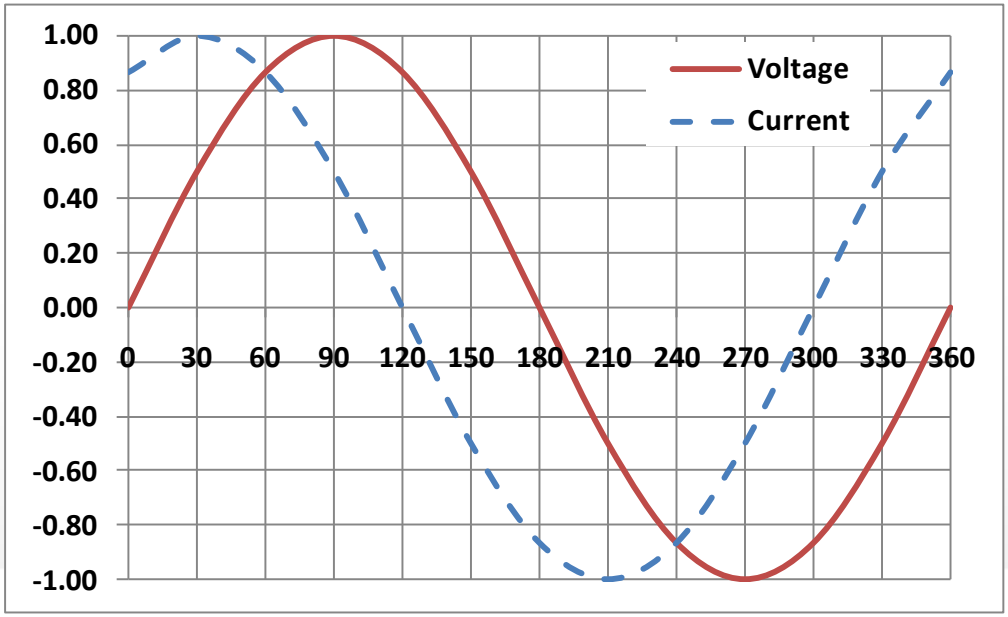




Capacitors (C)

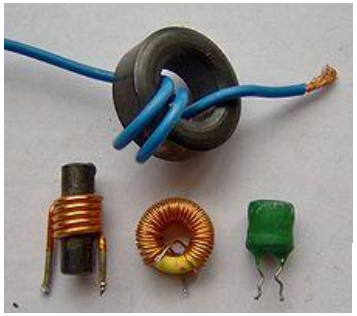
- A device that stores charge on conducting plates through the action of an electrostatic field between the plates
- In an AC circuit, the current leads the applied voltage on a capacitor
- Capacitance is measured in Farads (F)

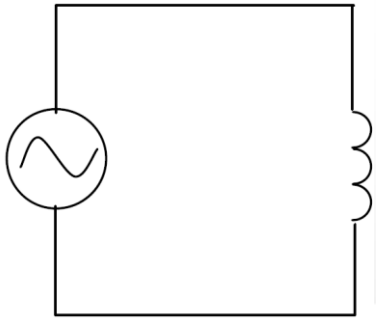


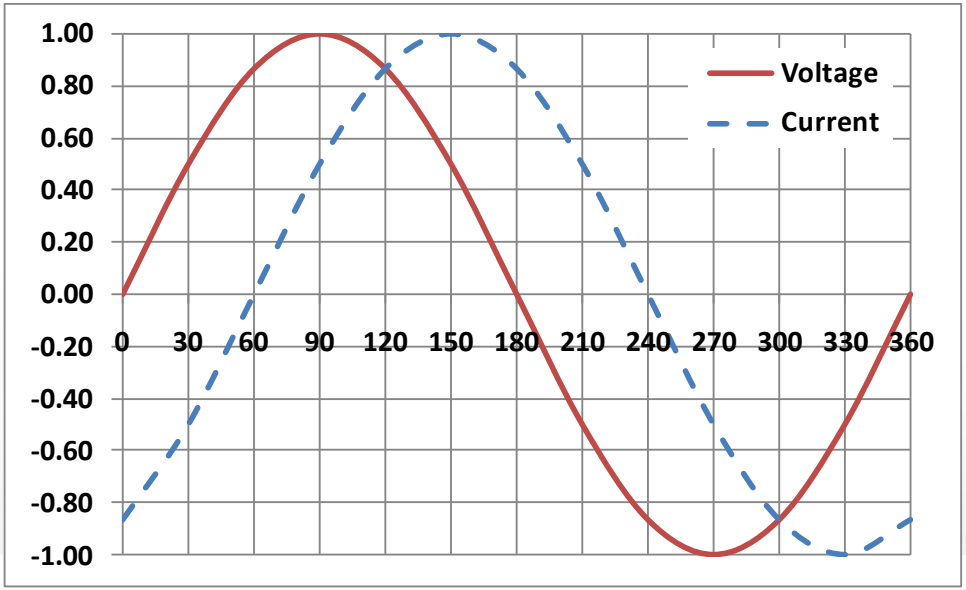


Inductor (L)

- **A conductor whose property is to <u>oppose any change</u> in the existing current**
  - Is present only when the current is changing
  - A coil of wire in an AC circuit would be one example of an inductor
- **In an AC circuit, the <u>current lags</u> the applied voltage on an inductor**
- **Inductance is measured in Henrys (H)**







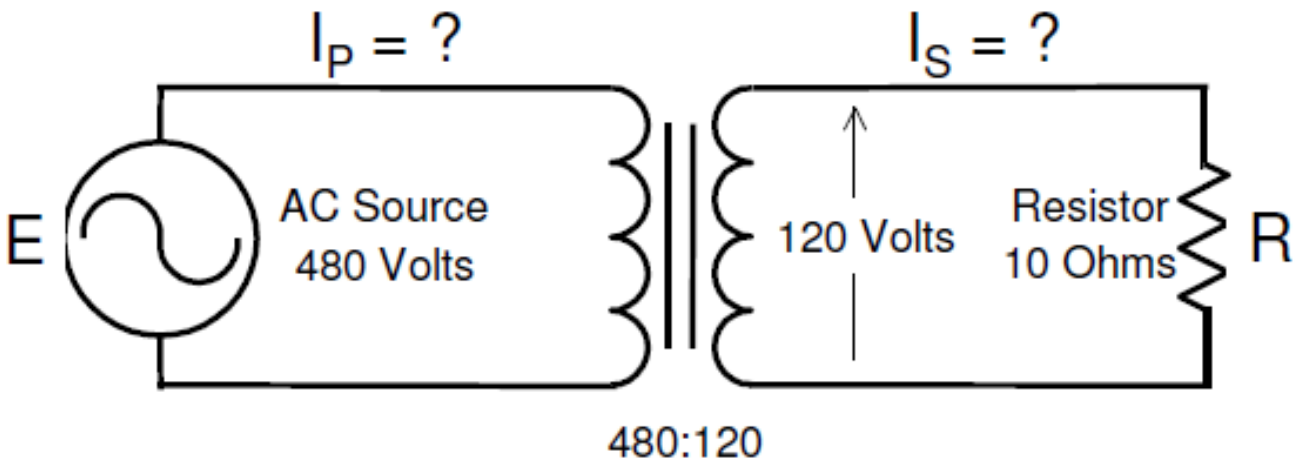
Lead, lag, whatever → how do I remember? ELI the ICE man

- **Looking at ELI:**
  - E = Voltage, I = Current, and L = Inductive Circuit
  - The Current LAGS the Voltage in an Inductive circuit because I comes after E in the word ELI
    - This can also be said that the Voltage leads the Current
- **Look at ICE:**
  - I = current, E = voltage, and C = Capacitive circuit
  - The Current LEADS the Voltage in a Capacitive Circuit because the I comes before the E in the word ICE
    - This can also be said that the Voltage lags the Current

Demonstration of R, C, L

- http://www.magnet.fsu.edu/education/tutorials/java/ac/index.html

The Transformer



$I_s = V / R = 120V / 10\Omega = 12A$

$V_s \times I_s = V_p \times I_p$

$\therefore I_p = 120V \times 12A / 480V = 3A$

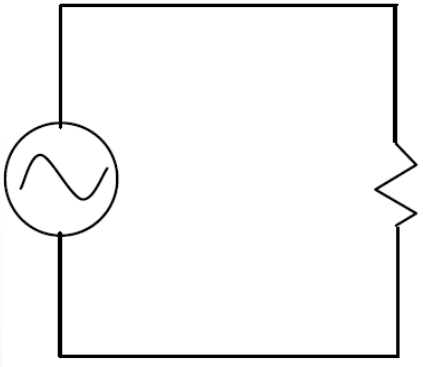
Another way:

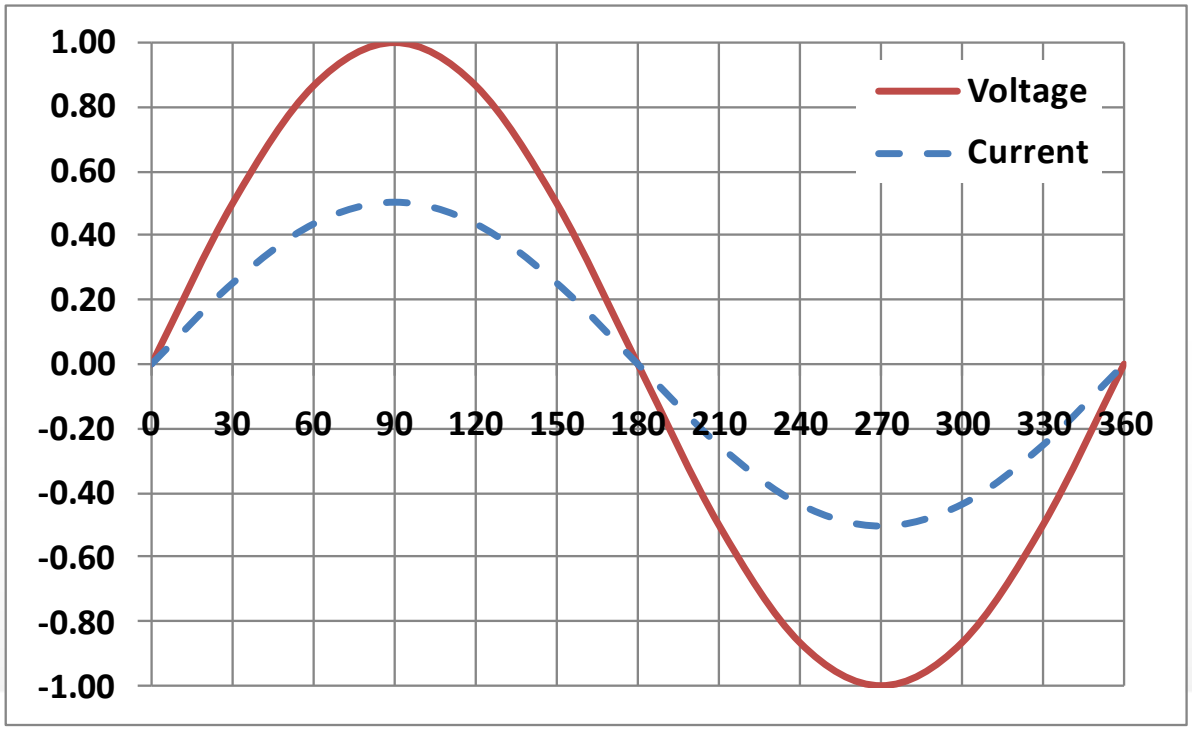
$V_p:V_s = 4:1$

$\therefore I_p:I_s = 1:4$

Ohm's Law for AC

- **V= I × R becomes V = I × Z** (Z = Impedance)
- **Quick quiz: What's R in the graph below?**





Resistance, Reactance, Impedance: Related, but not the same

- ***Z = R + jX***

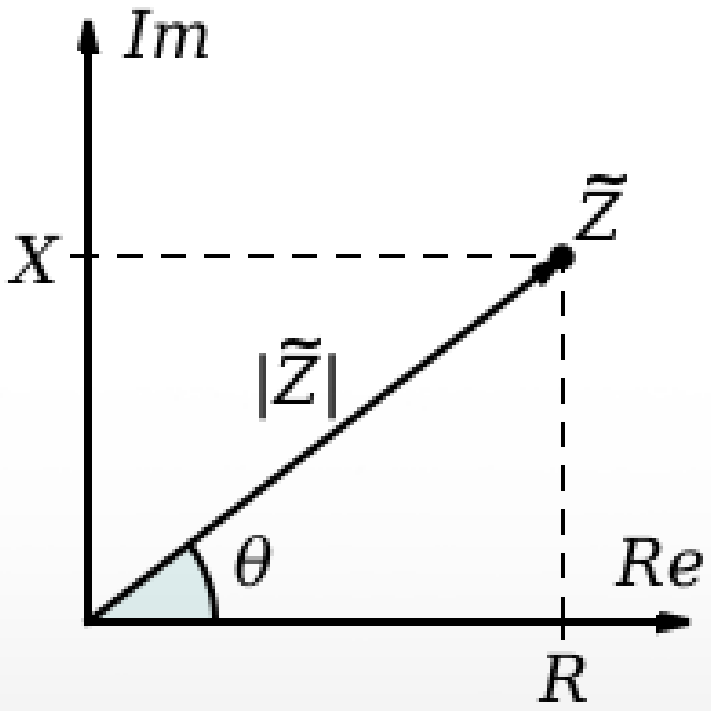
  Z = Impedance

  R = Resistance

  X = Reactance

- Reactance of an inductor:
  - $X_L = 2\pi fL$

- Reactance of a capacitor:
  - $X_C = -1/2\pi fC$



Resistance, Reactance, Impedance

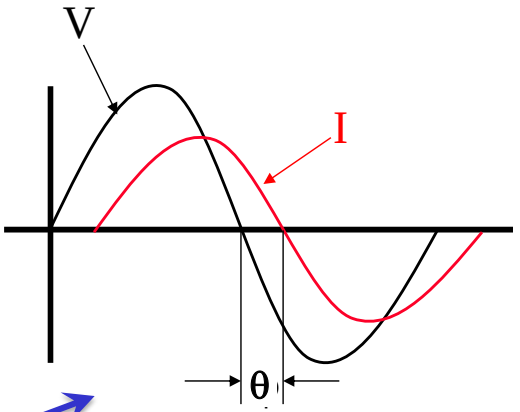
- **Resistance (R, Ω)**
  - Opposition to the flow of electric current
  - Similar to how friction opposes mechanical (physical) movement

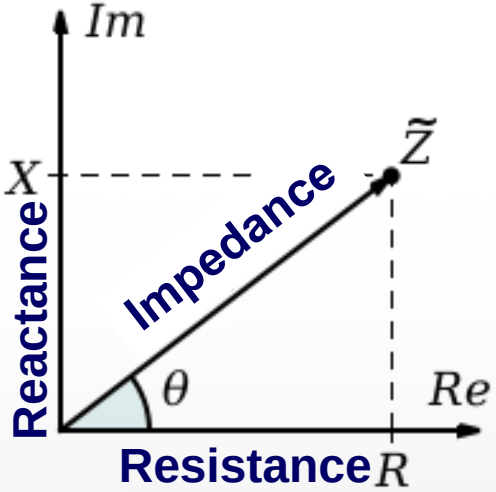
- **Reactance (X, Ω)**
  - Opposition to the flow of alternating current (associated with capacitors and inductors)

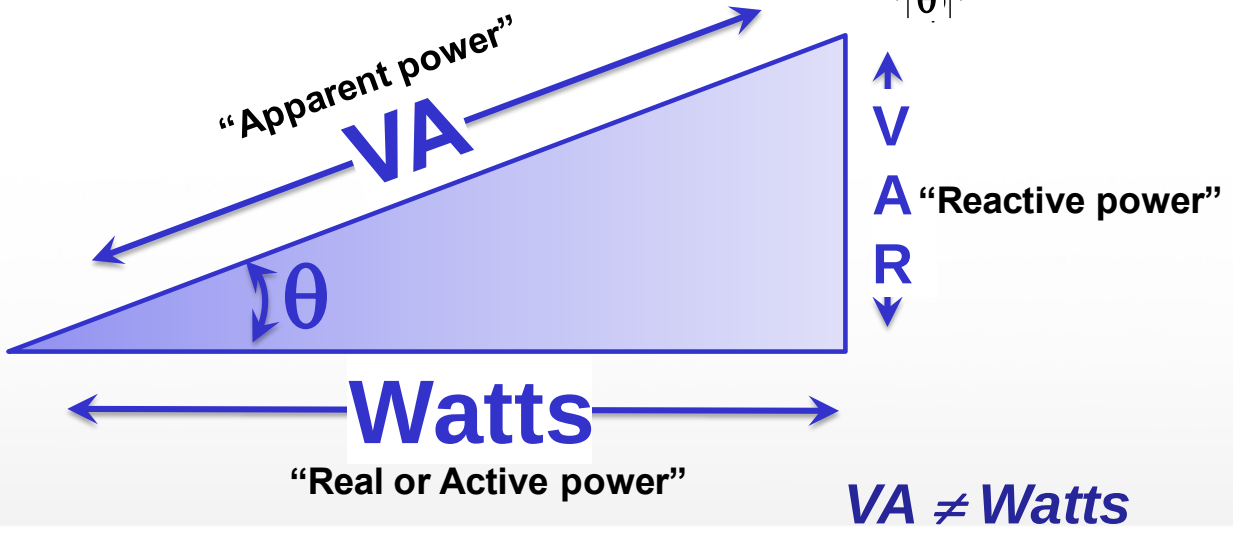
- **Impedance (Z, Ω)**
  - Similar to resistance, but used in AC circuits
  - It is the vector sum of resistance and the capacitive and inductive reactance

Okay, okay, I get the Resistance, Reactance, Impedance thing. Now what about Power?

- DC: P = I × V (Watts)
- AC: It's all about θ (phase angle)

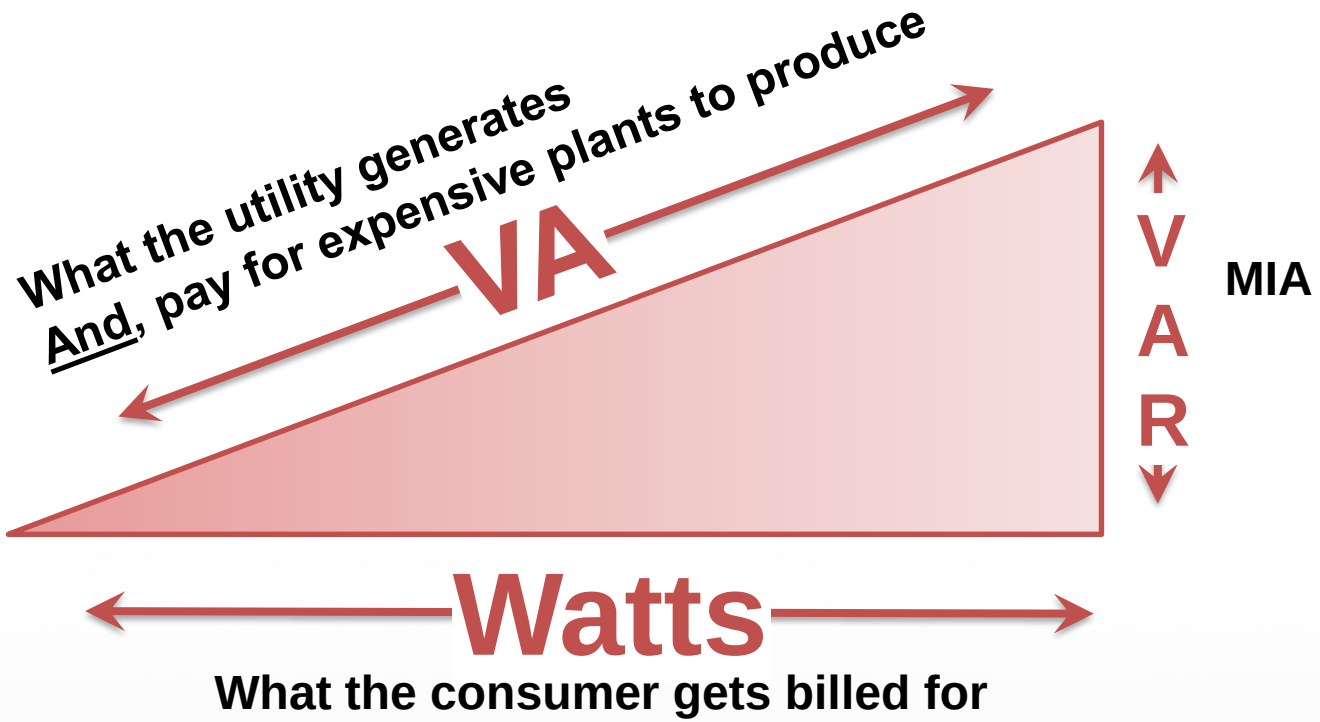






VA ≠ Watts

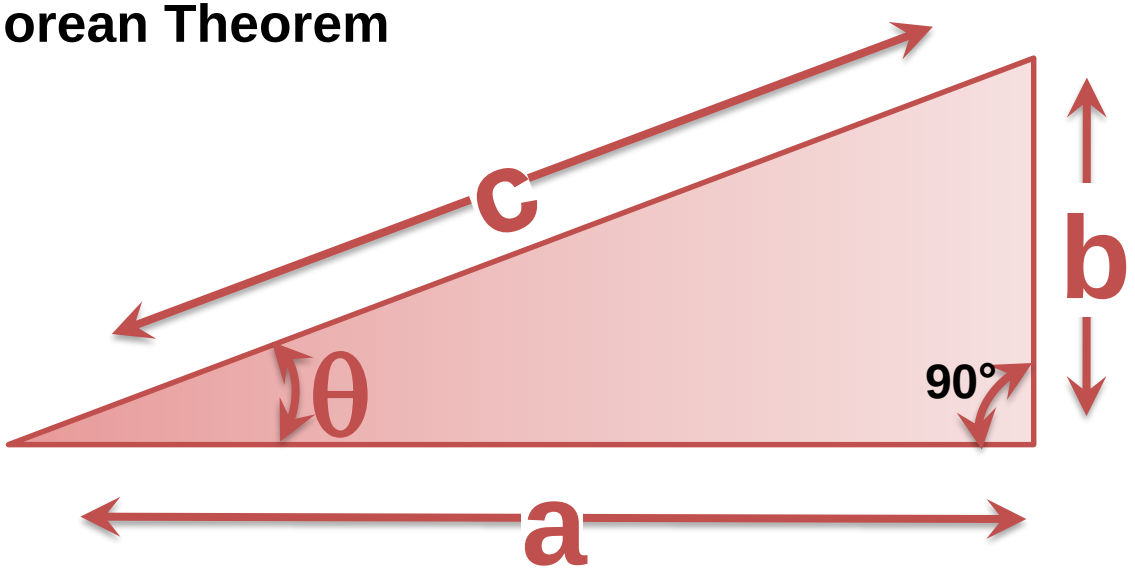
VA, Watts, VARs



☞I.e., utilities pay to generate VARs but no energy is transferred!

AC circuits

- **Right triangle → Pythagorean Theorem**
  - a = “run” or “adjacent”
  - b = “rise” or “opposite”
  - c = “hypotenuse”



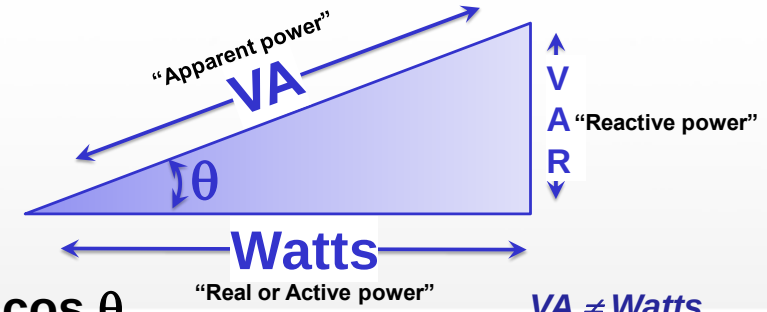
$$c^2 = a^2 + b^2$$

$$c = \sqrt{a^2 + b^2}$$

$$\sin\theta = \frac{\text{opposite}}{\text{hypotenuse}} = \frac{b}{c} = \frac{VAR}{VA}$$

$$\cos\theta = \frac{\text{adjacent}}{\text{hypotenuse}} = \frac{a}{c} = \frac{Watt}{VA}$$

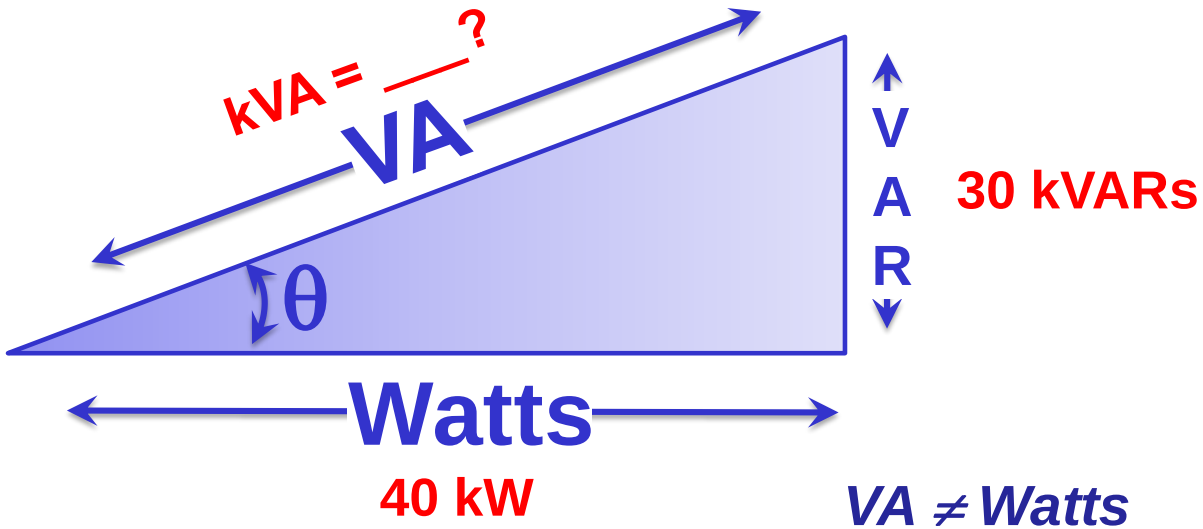
$$\tan\theta = \frac{\text{opposite}}{\text{adjacent}} = \frac{b}{a} = \frac{VAR}{Watt}$$



By definition Power Factor PF = $\frac{Watt}{VA}$ = cos θ

VA ≠ Watts

Power triangle: Example



VA ≠ Watts

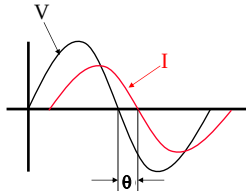
$$kVA = \sqrt{40^2 + 30^2} = \sqrt{1600 + 900} = \sqrt{2500}$$

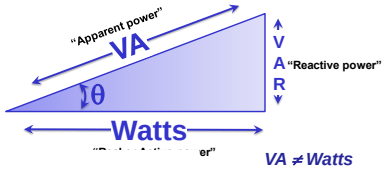
$$PF = \frac{Watt}{VA} = \frac{40}{50} = 0.8 = 80\%$$

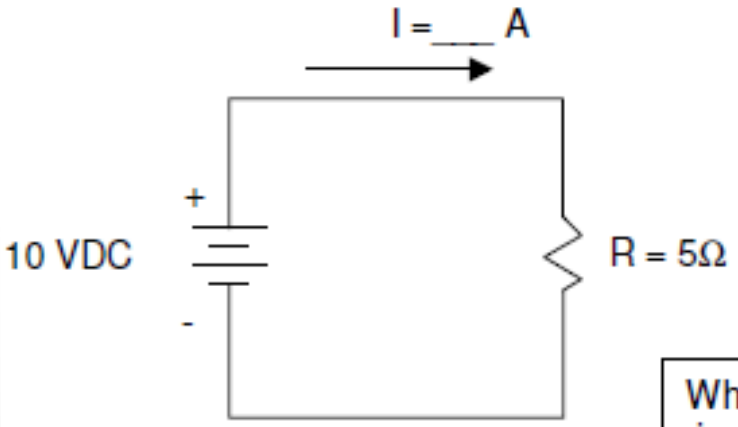
θ = arccos(0.8) = cos^{-1}(0.8) = 0.643 radians = 36.87°

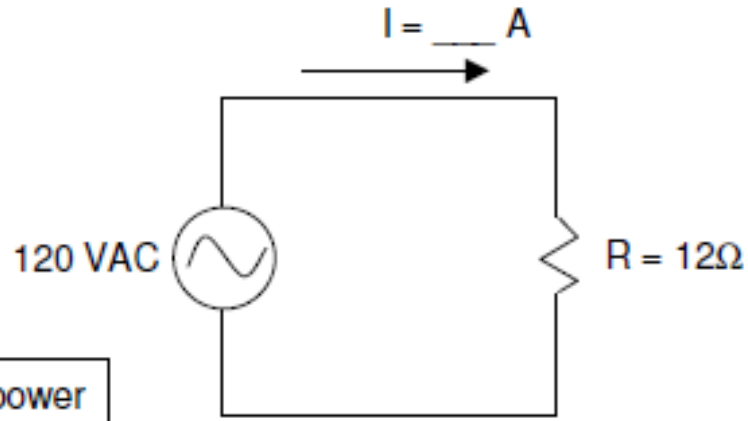
AC Active power (Watts)

- **For DC: Active power (P) = V × I (watts)**
- **For AC: Active power (P) = V × I × cos θ (watts)**
  - For resistive load, still have $P = I^2R$







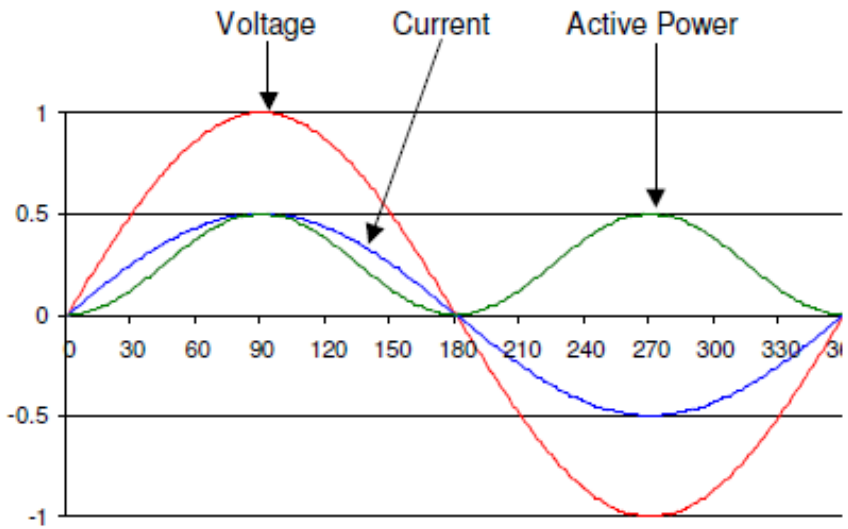


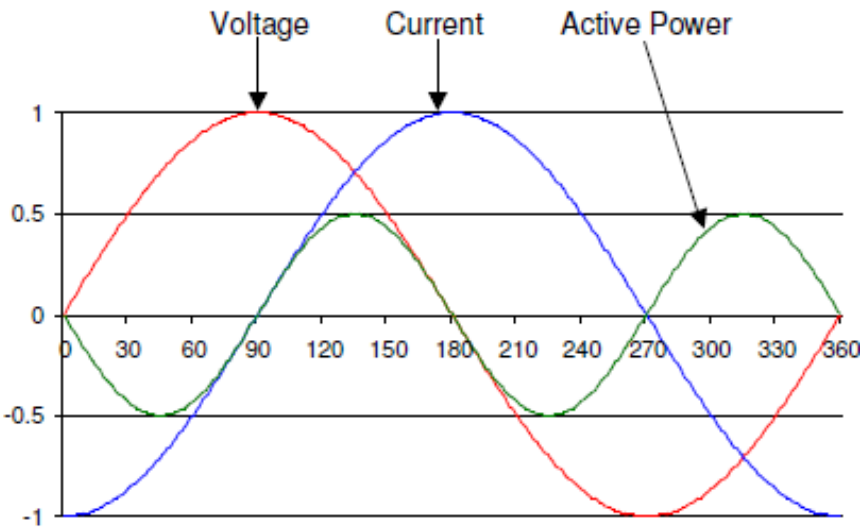
What is the power in each circuit?

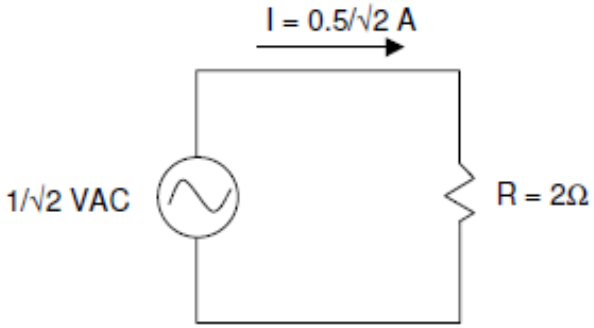
Active Power = _____ Watts?

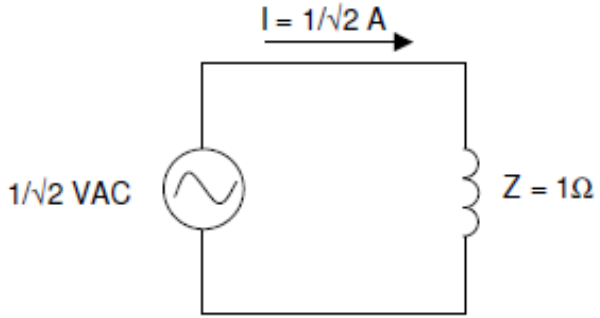
Active Power = _____ Watts?

Active power vs. Reactive power

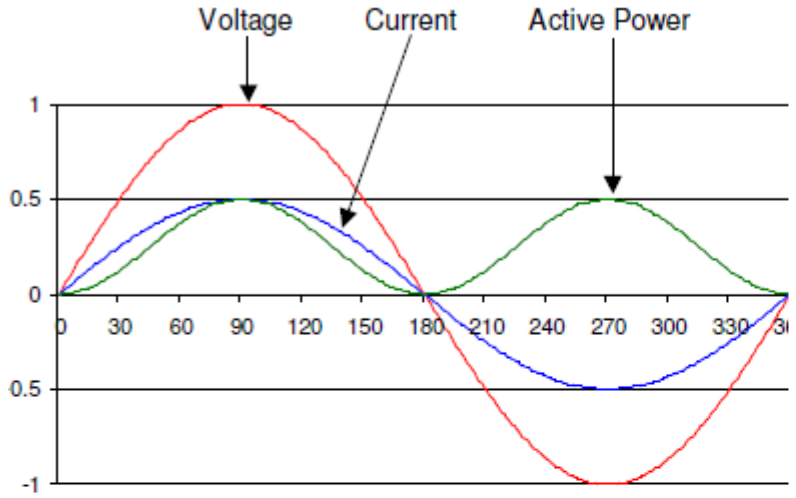


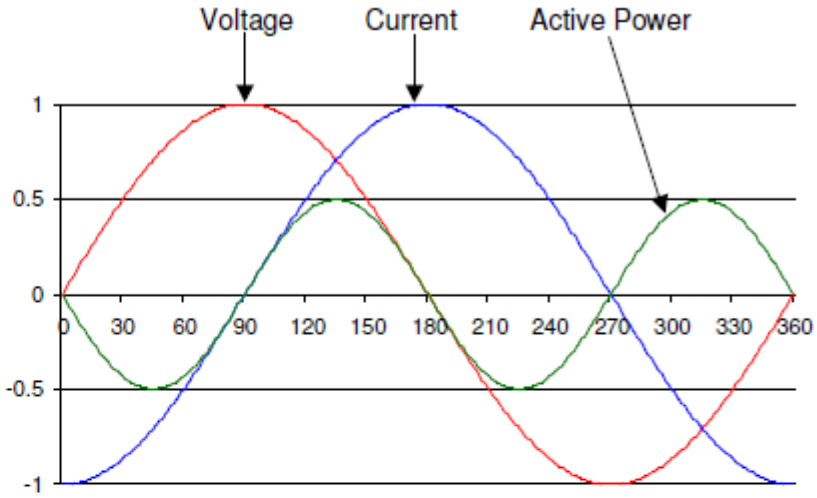






Active power vs. Reactive power: Another way to look at it





Active Power, $P = VI\cos\theta = \frac{1}{\sqrt{2}}\frac{0.5}{\sqrt{2}}\cos(0) = 0.25$ watts

Apparent Power, $U = VI = \frac{1}{\sqrt{2}}\frac{0.5}{\sqrt{2}} = 0.25$ VA

Reactive Power, $Q = VI\sin\theta = \frac{1}{\sqrt{2}}\frac{0.5}{\sqrt{2}}\sin(0) = 0$ vars

Active Power, $P = VI\cos\theta = \frac{1}{\sqrt{2}}\frac{1}{\sqrt{2}}\cos(90) = 0$ watts

Apparent Power, $U = VI = \frac{1}{\sqrt{2}}\frac{1}{\sqrt{2}} = 0.5$ VA

Reactive Power, $Q = VI\sin\theta = \frac{1}{\sqrt{2}}\frac{1}{\sqrt{2}}\sin(90) = 0.5$ vars

Phasor Power, $S = \sqrt{\text{watts}^2 + \text{vars}^2}$

Basic Electricity summary

- **Voltage, current, power, energy**
- **Circuit components**
  - Resistors, Inductors, Capacitors, Transformers
  - Ohm's Law : Current is directly proportional to the voltage and inversely proportional to the resistance (impedance)
- **AC vs. DC**
  - AC Circuits → Two characteristics: Magnitude and frequency
    - Electrical Degrees" → measurement of time
  - Resistance, Reactance, Impedance
  - Active Power vs. Reactive Power
  - Power Triangle → Helps us understand AC circuit theory