Chapter 8

Introduction to Alternating Current, Voltage and Power

Symbol for a sinusoidal voltage source

AC Voltage Source Symbol

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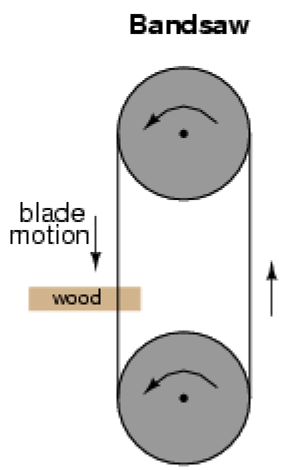
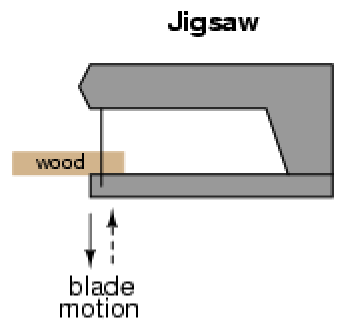
DC Vs AC Analogy



(analogous to DC)

Continuous Flow

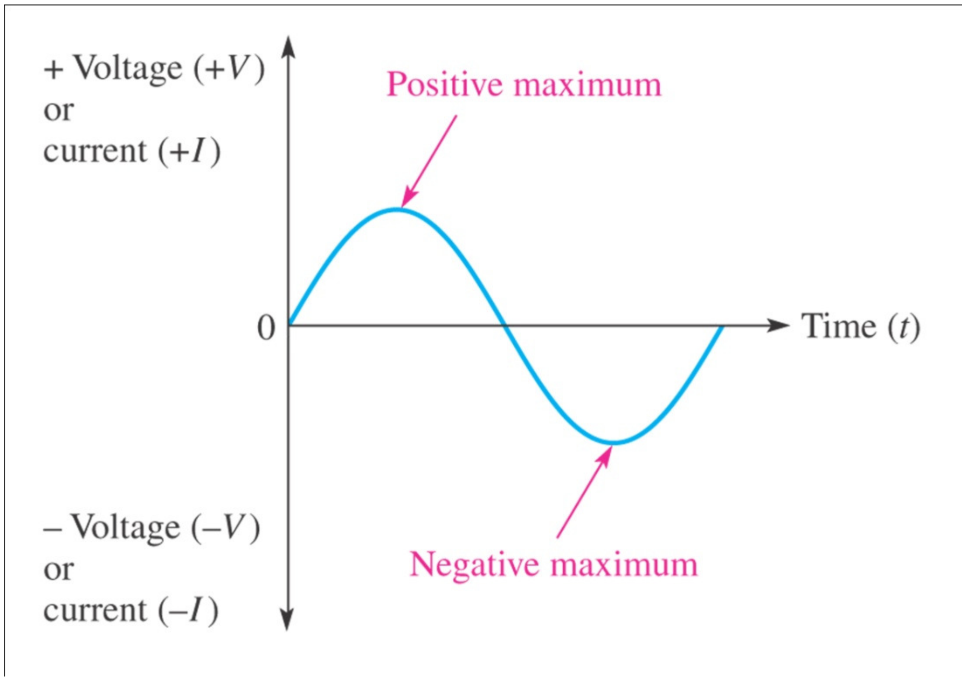


(analogous to AC)

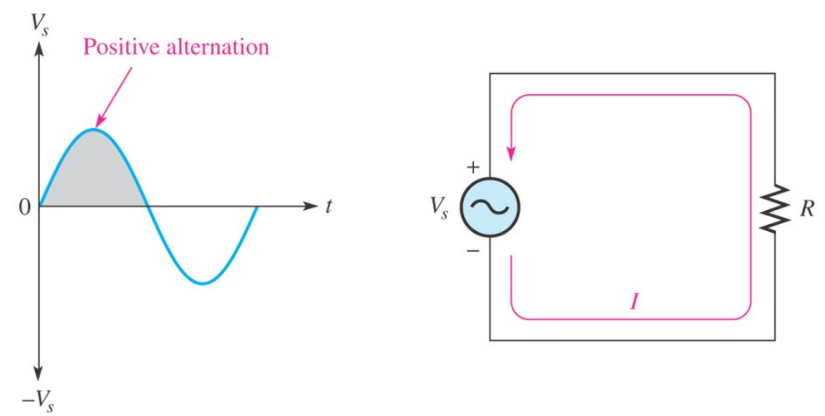
Alternating Flow

Sine Wave

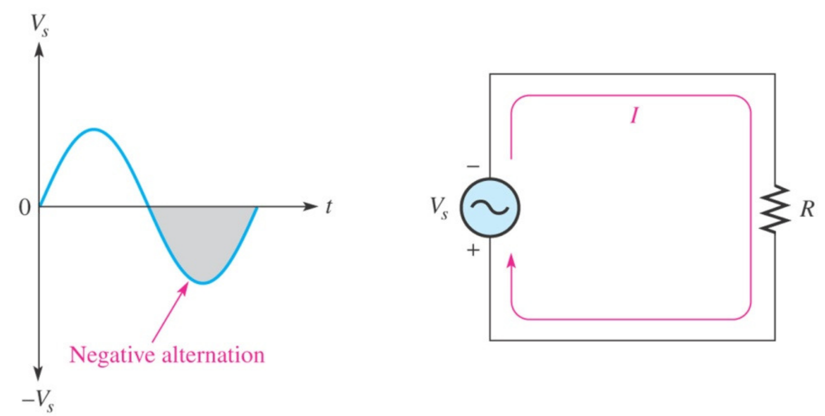
- The sine wave is a common type of alternating current (AC) and alternating voltage



Alternating current and voltage



(a) Positive voltage: current direction as shown



(b) Negative voltage: current reverses direction

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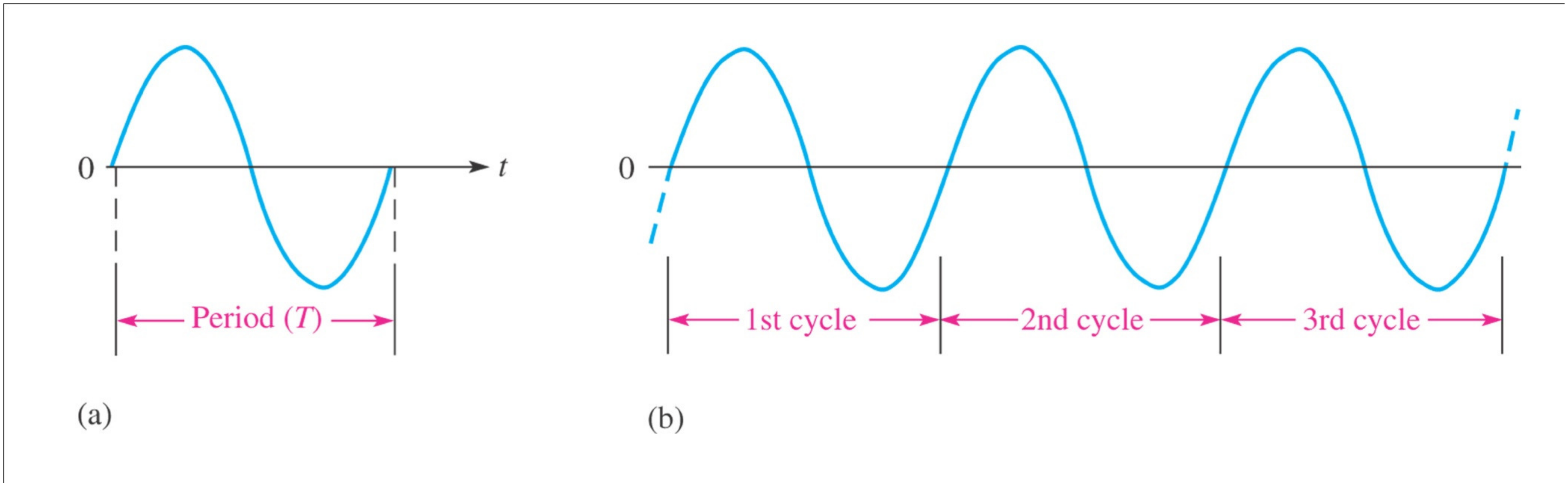
Period of a Sine Wave

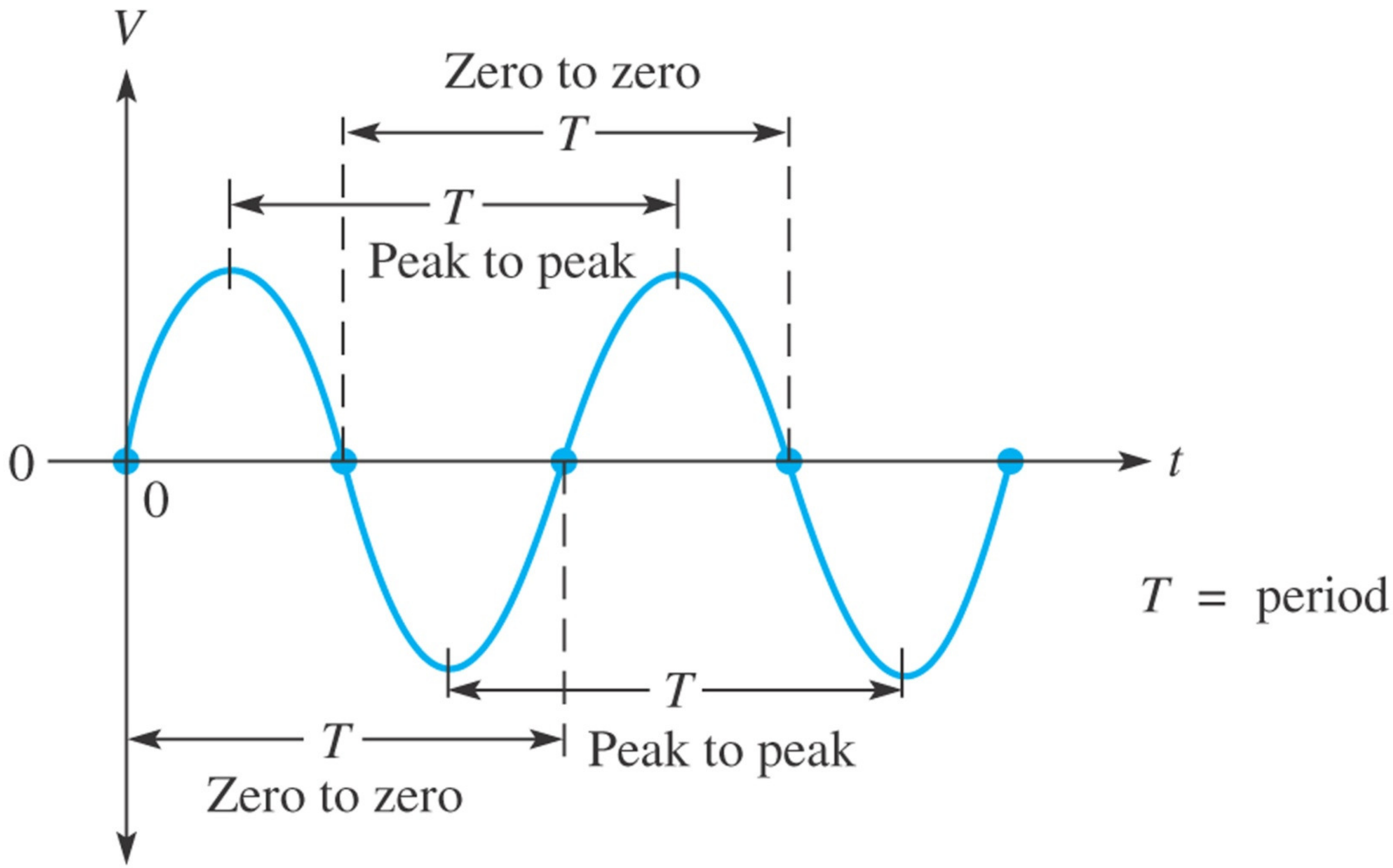
- The time required for a sine wave to complete one full cycle is called the period (T)
- A cycle consists of one complete positive, *and* one complete negative alternation

The period of a given sine wave is the same for each cycle



The period of a sine wave can be measured between any two corresponding points on the waveform

Measurement of the period of a sine wave



The period of a sine wave can be measured between any two corresponding points on the waveform

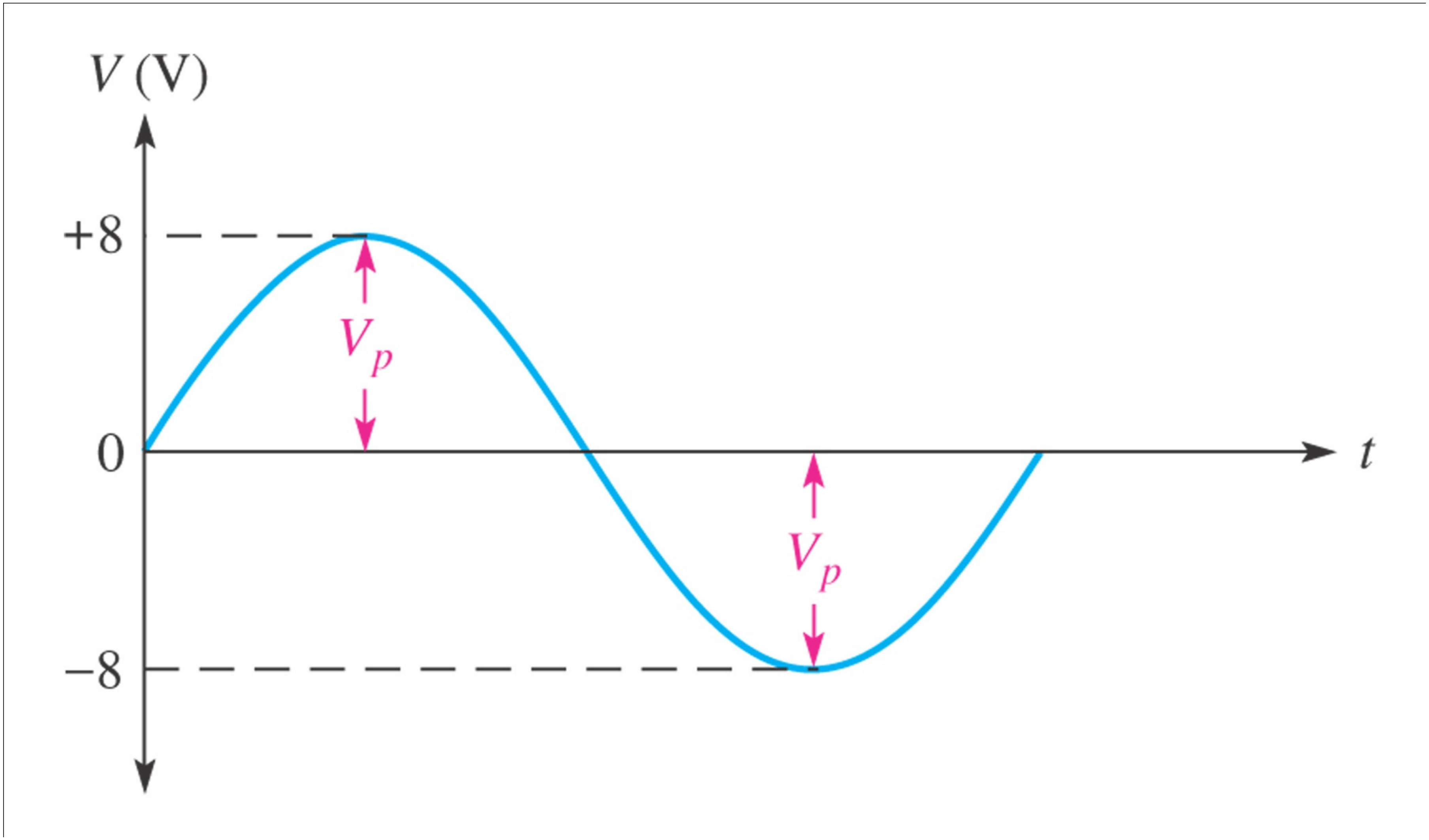
Peak Values of Sine Waves

- The **peak value** of a sine wave is the value of voltage or current at the positive or negative maximum with respect to zero

- Peak values are represented as:

$$V_p \text{ and } I_p$$

Peak values



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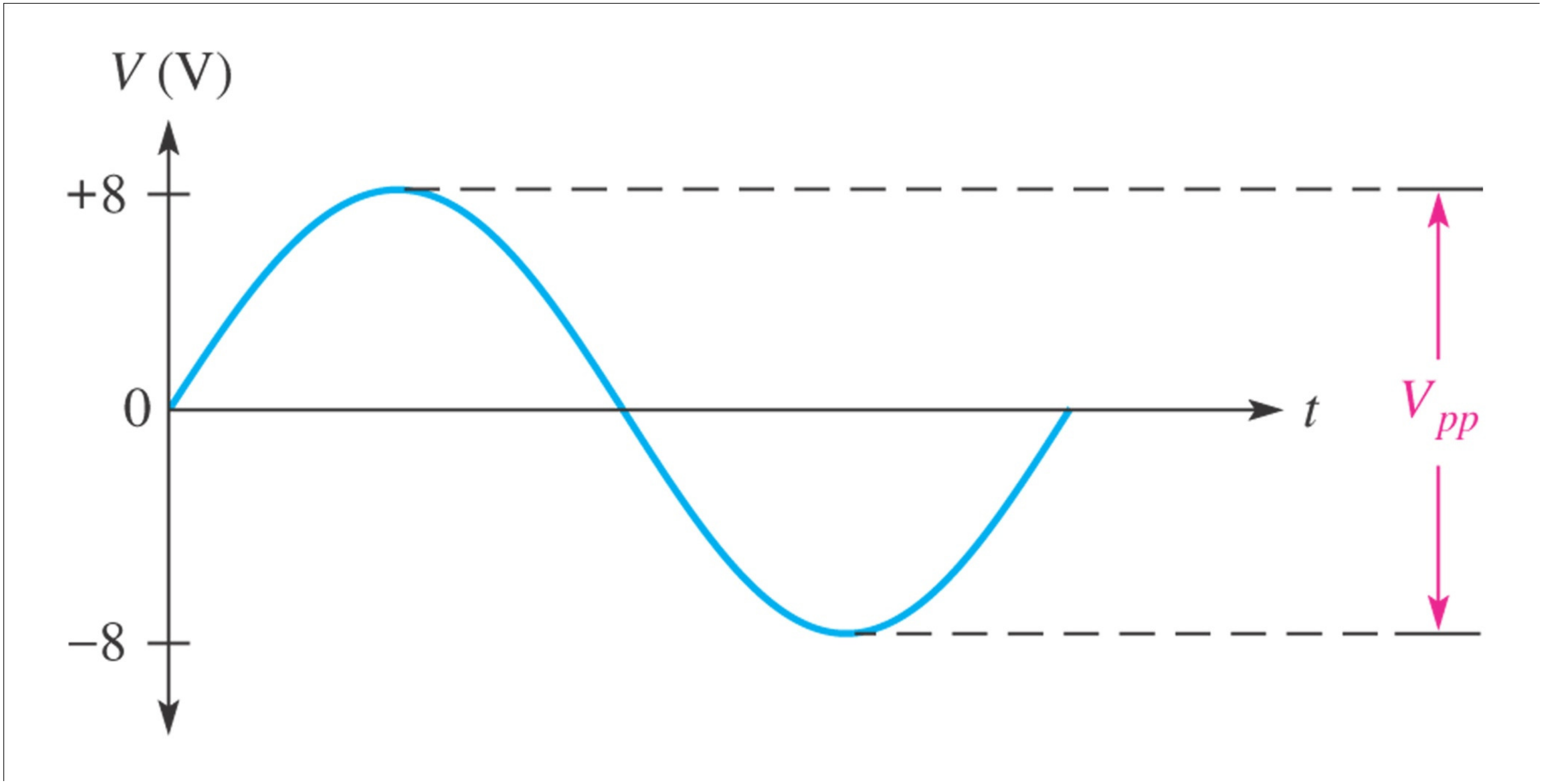
Peak-to-Peak Values

- The **peak-to-peak value** of a sine wave is the voltage or current from the positive peak to the negative peak
- The peak-to-peak value is twice the actual voltage value
- Not Often Used
- The peak-to-peak values are represented as:

$$V_{pp} \text{ and } I_{pp}$$

where: $V_{pp} = 2V_p$ and $I_{pp} = 2I_p$

Peak-to-peak values



8V Peak (Actual Value) = 16V Peak-To-Peak

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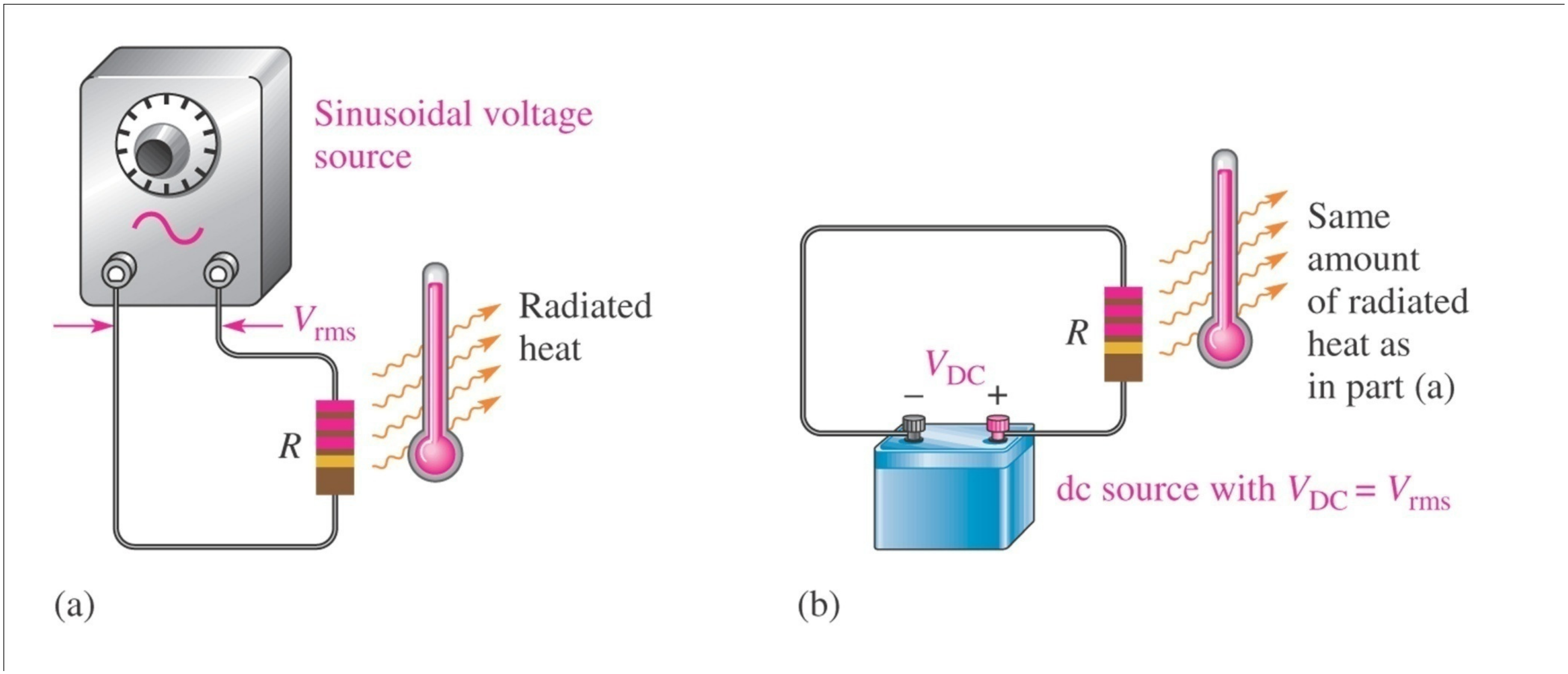
RMS Value of a Sine Wave

- The **rms** (root mean square) value, or **effective value**, of a sinusoidal voltage is equivalent to the dc voltage that would do the same amount of work (produce the same amount of heat in a resistive circuit)
- It is sometimes called the resistive *DC equivalent value*
- It takes into account that the AC source passes through zero twice in each cycle where it does no work at all

$$V_{rms} = 0.707V_p$$
$$I_{rms} = 0.707I_p$$
$$V_p = 1.414V_{rms}$$
$$I_p = 1.414I_{rms}$$

When the same amount of heat is being produced by the resistor in both setups, the sinusoidal voltage has an rms value equal to the dc voltage



- Most AC sources are specified with the RMS Value
    - **If a voltage source does not specify P or P-P, it is considered RMS**
- It reflects how much work the AC source can actually do

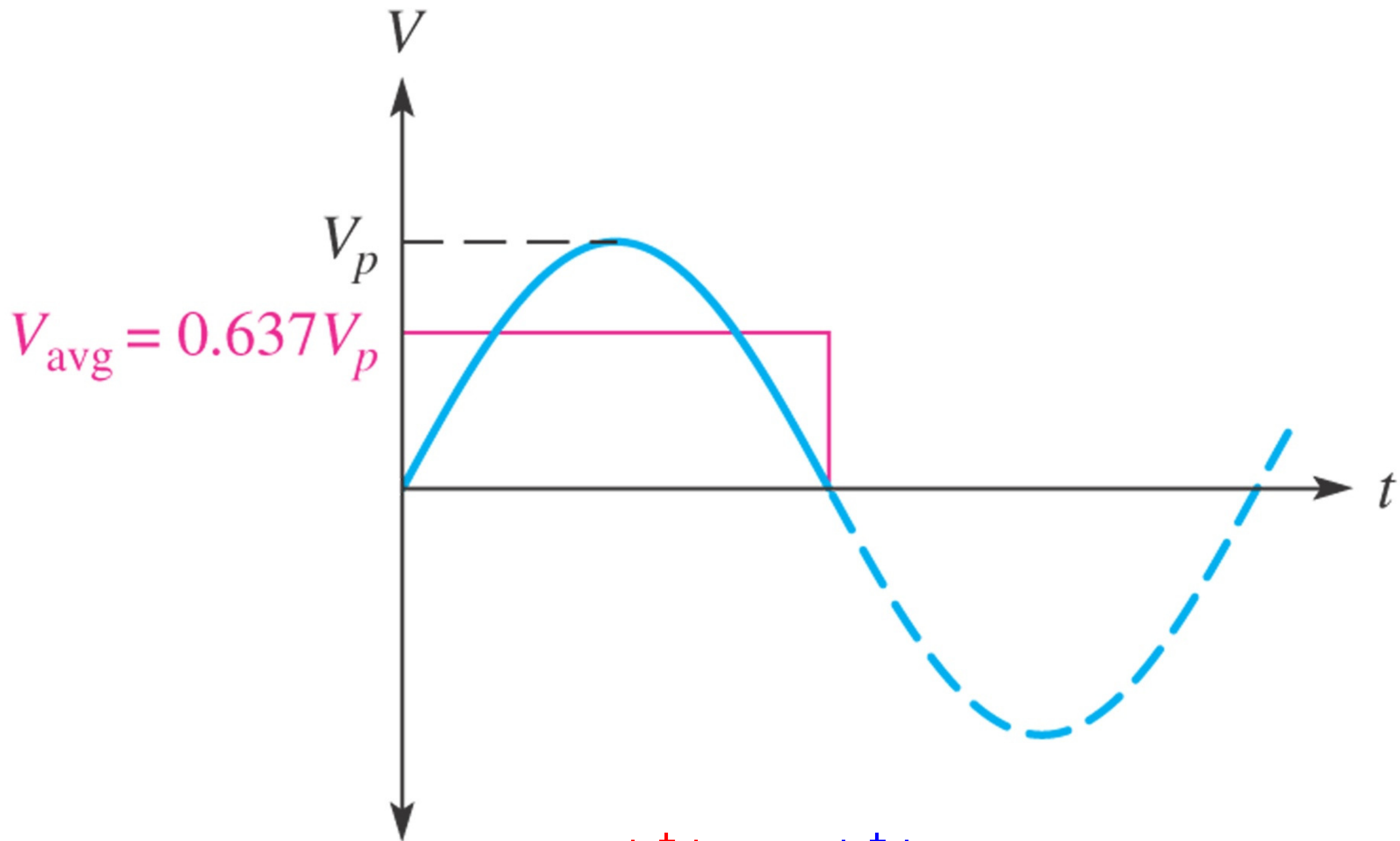
Average Value of a Sine Wave

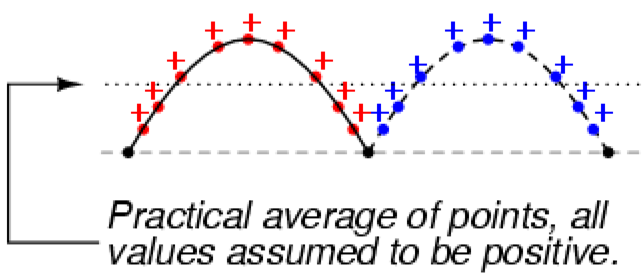
- The **average value** of a total sine wave voltage or current would be zero, therefore the **average value** is defined over a *half-cycle* and is expressed in terms of the peak value as follows:

$$V_{\text{avg (Half Cycle)}} = 0.637V_p$$

$$I_{\text{avg (Half Cycle)}} = 0.637I_p$$

Half-cycle average value





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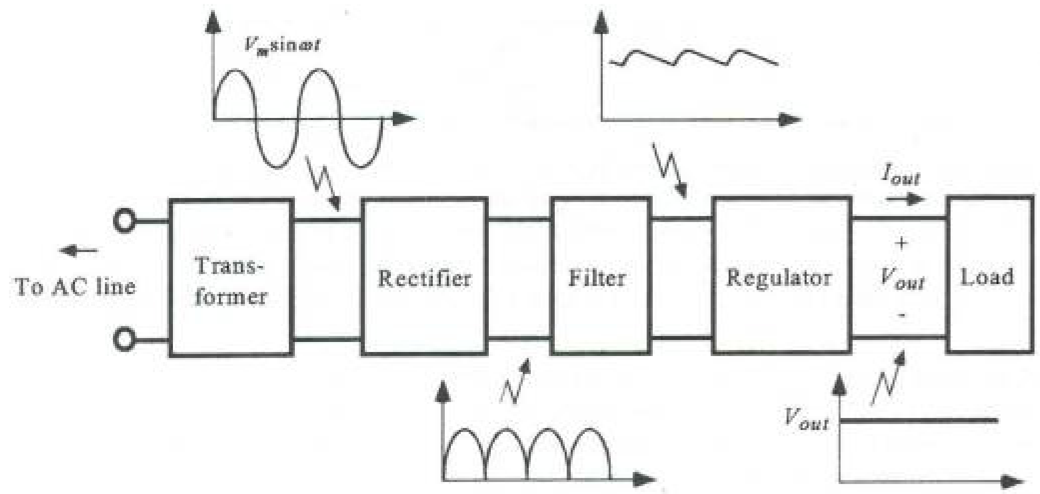
Half-cycle average value and Power Supplies

V_{in} 110VAC $_{RMS}$

V_{in} 156VAC $_{Peak}$



Components of a typical linear power supply

V_{out} 99VDC

The average value is the approximate output of a DC Power Supply

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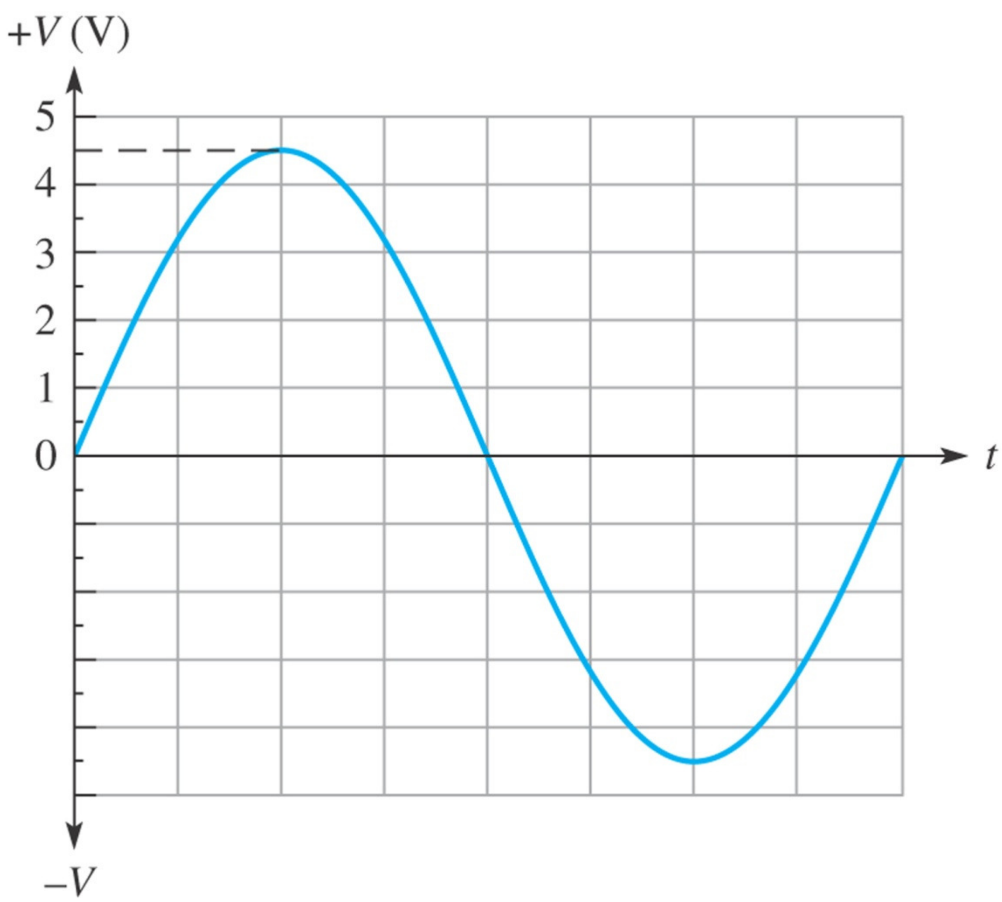

- $V_p = 4.5V$
- $V_{pp} = 2(4.5V) = 9V$
- $V_{rms} = 0.707(4.5V) = 3.18V$
- $V_{avg} = 0.637(4.5V) = 2.87V$

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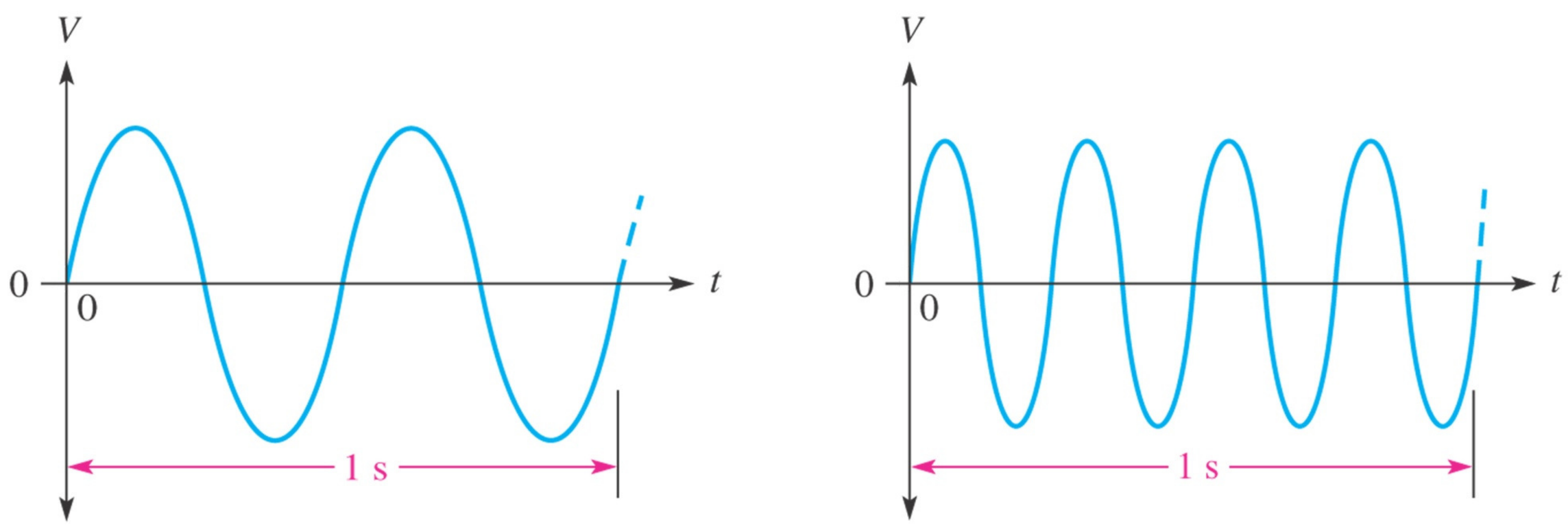
Frequency of a Sine Wave

- Frequency (f) is the number of cycles that a sine wave completes in one second
  - The more cycles completed in one second, the higher the frequency
  - Frequency is measured in **hertz** (Hz)
- Relationship between frequency (f) and period (T) is:

$$\boldsymbol{f = 1/T}$$

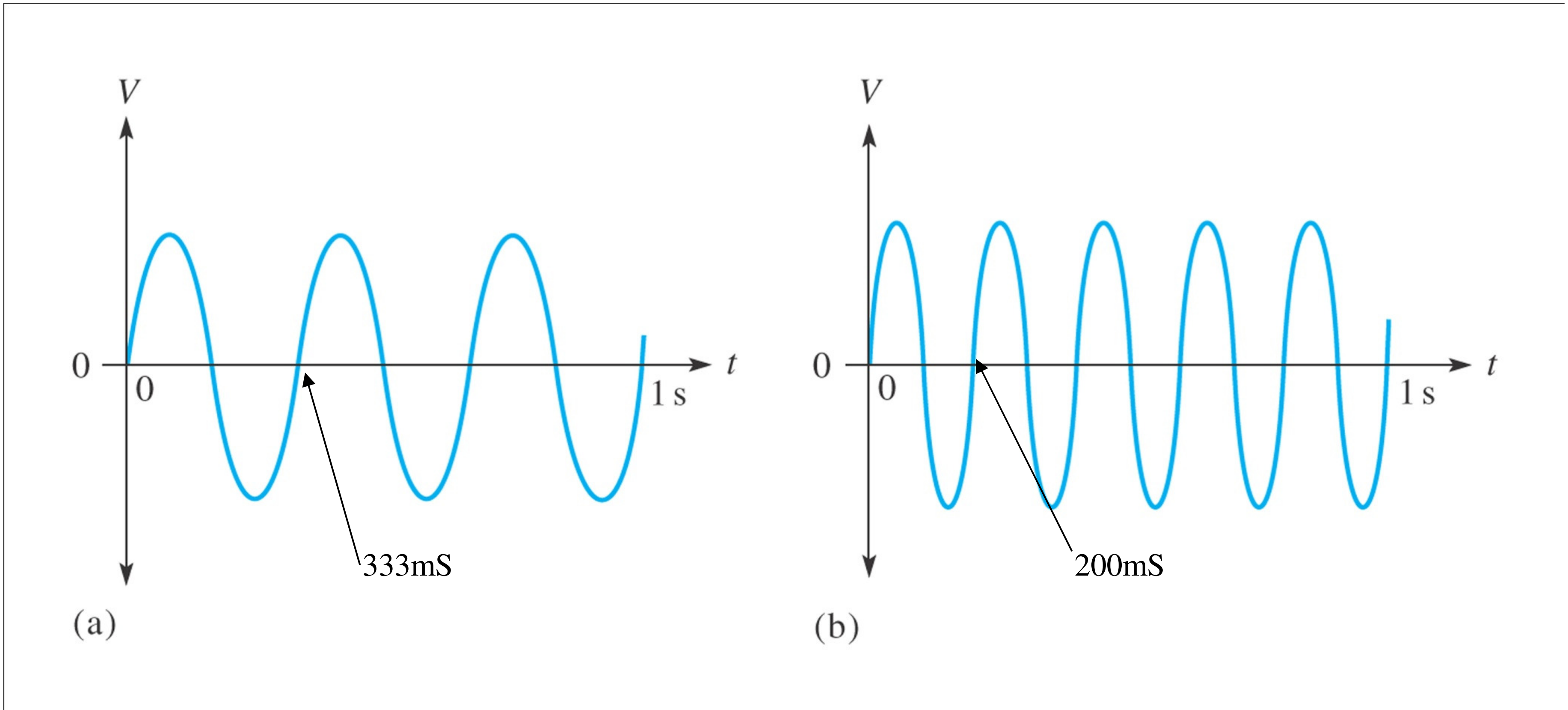
Illustration of frequency



(a) Lower frequency: fewer cycles per second

(b) Higher frequency: more cycles per second

Illustration of frequency



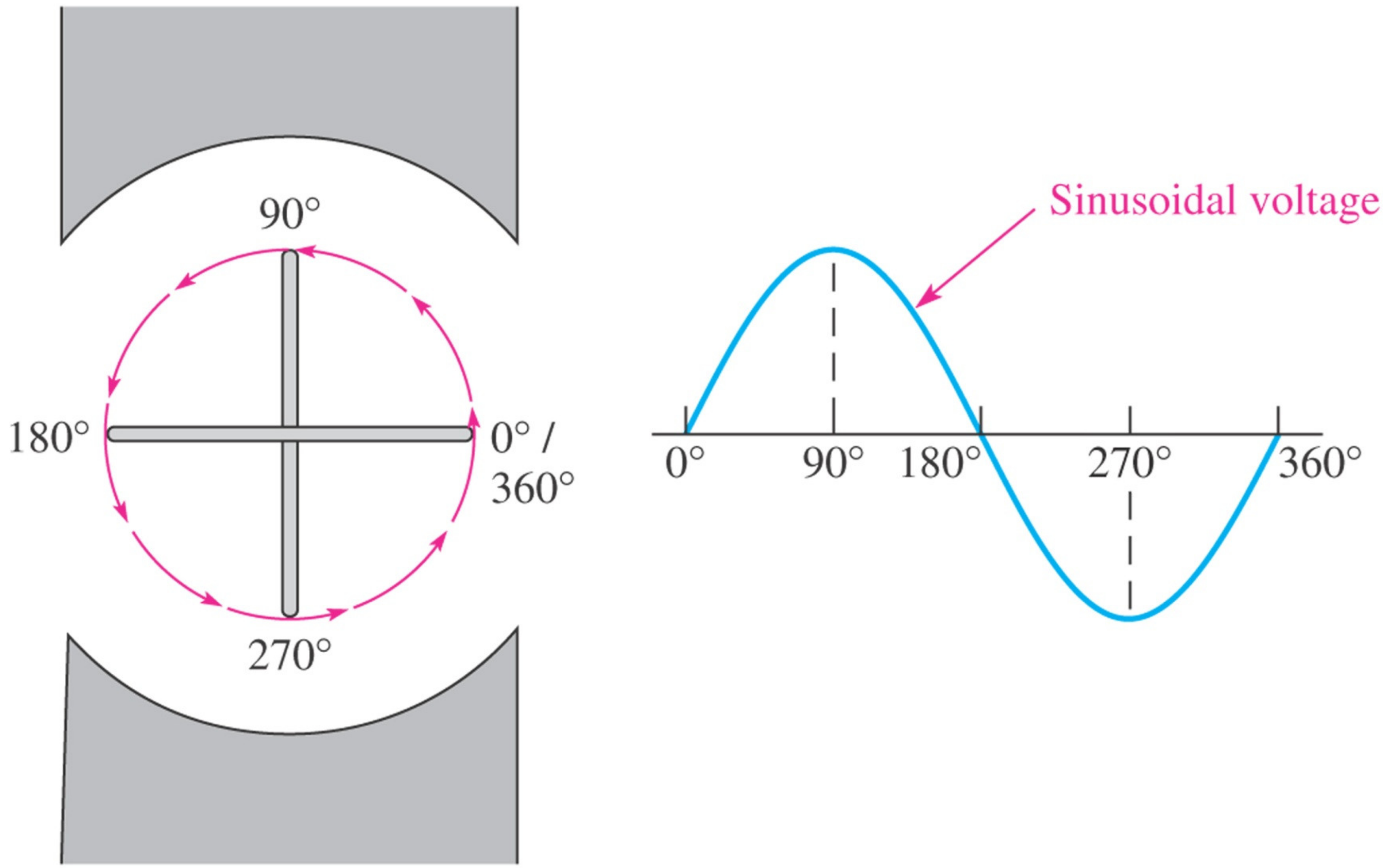
T = 333mS
F = 3Hz
(3 Cycles/Sec)

T = 200mS
F = 5Hz
(5 Cycles/Second)

Angular Measurement of a Sine Wave

- The angular measure measurement of Sine Waves can be done in Degrees or Radians
  - A **degree** is an angular measurement corresponding to 1/360 of a circle or a complete revolution

Relationship of a sine wave to the rotational motion in an ac generator



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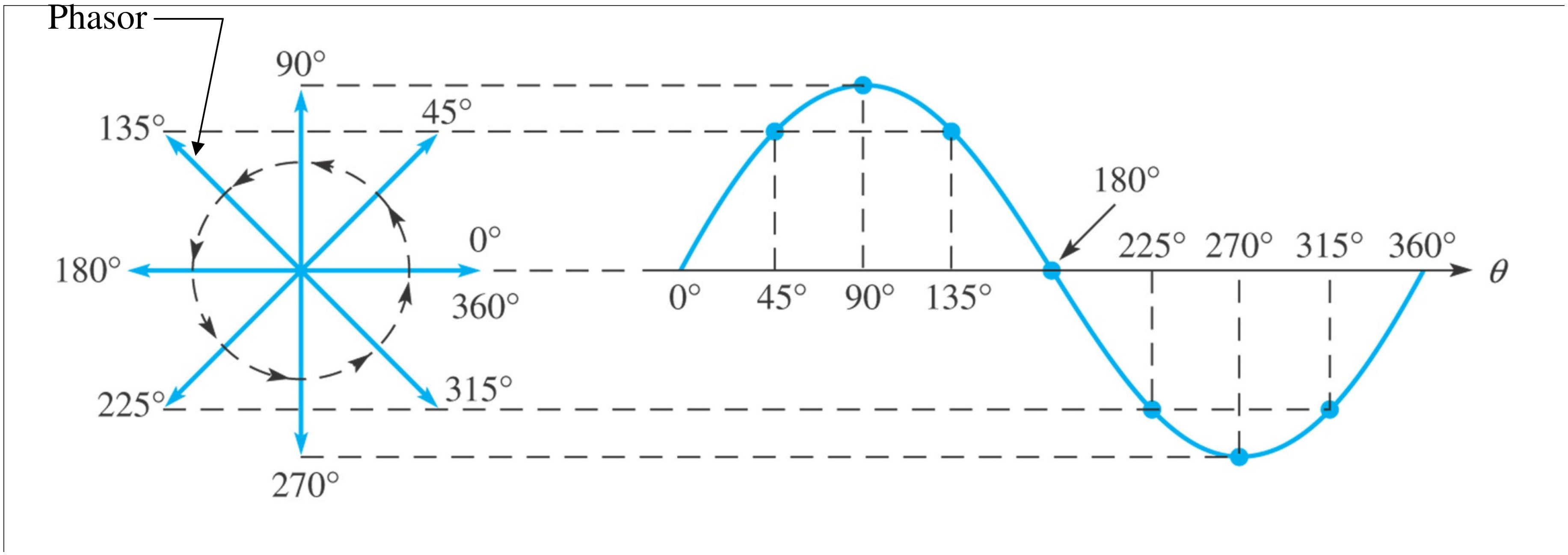
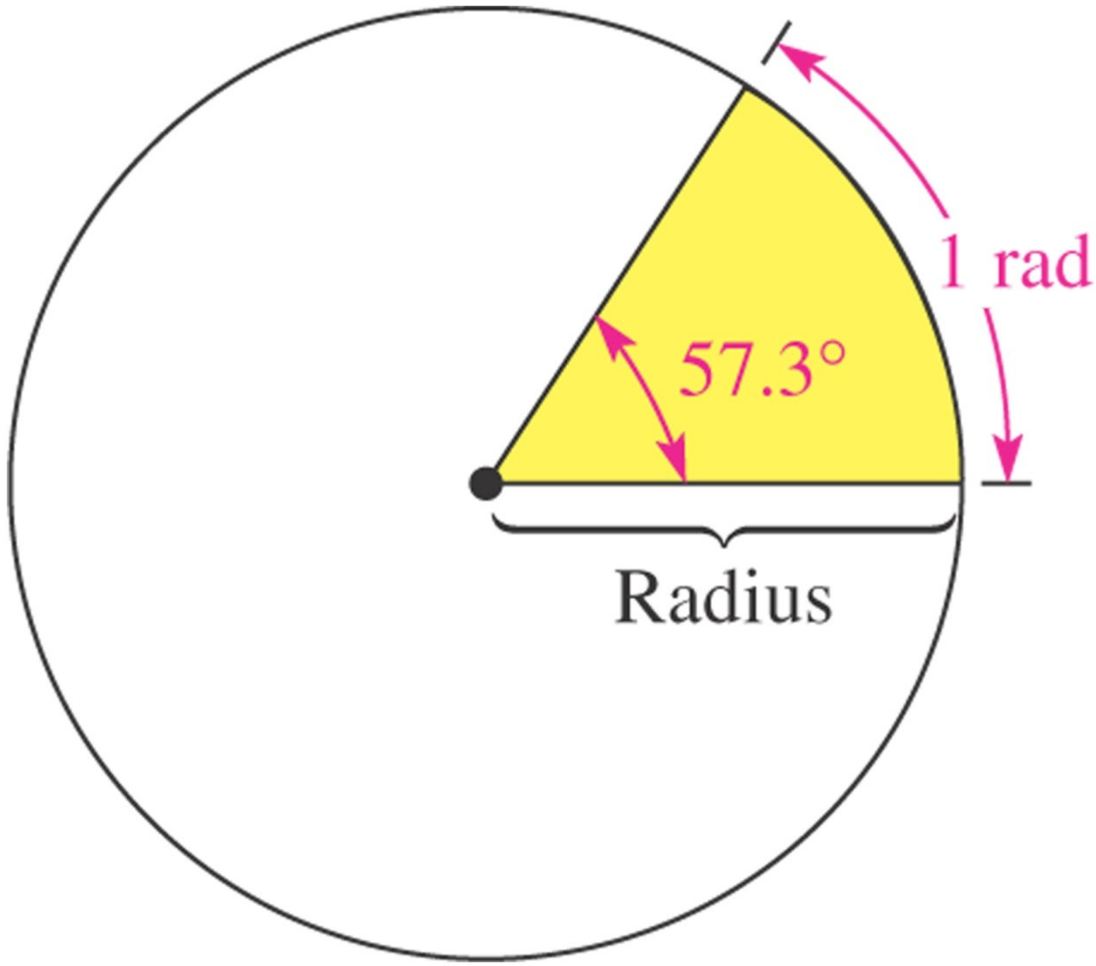
Sine wave values represented by a rotating phasor



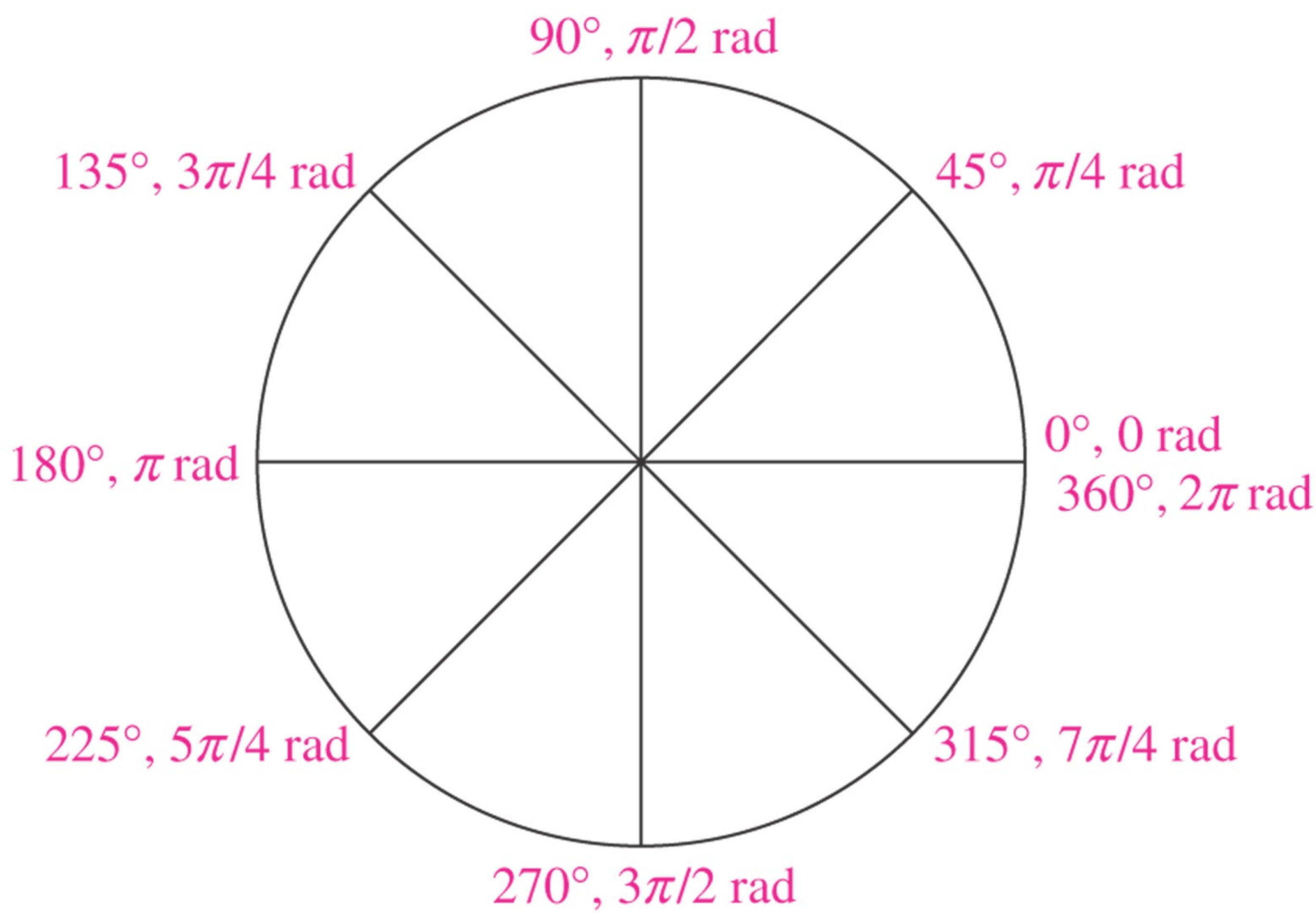
- Think of the arrow (phasor) rotating counter-clockwise around the center 360^0 each cycle of the sine wave
- θ is the rotation angle
- The instantaneous value at any angle can be determined by simple trigonometry

Angular measurement showing relationship of the radian to degrees



- A radian (rad) is the angular measure along the circumference of a circle that is equal to the radius of the circle
- There are 2π radians or 360° in one complete cycle of a sine wave

Angular measurements starting at 0º and going counterclockwise



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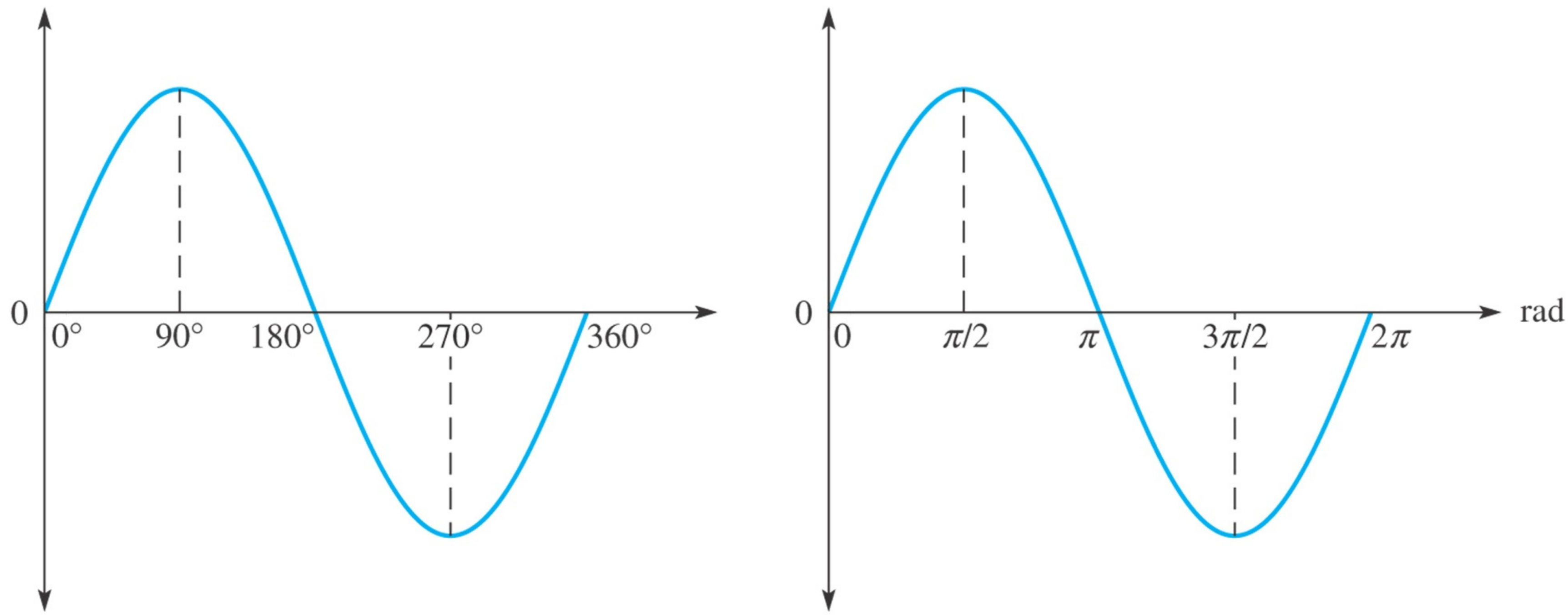
Sine wave angles



(a) Degrees (b) Radians

Comparison conversion of both systems

Radial Velocity is often used instead of Frequency (Radians/Second)

$$\omega = \frac{2\pi}{T} = 2\pi f \qquad f = \frac{\omega}{2\pi}$$

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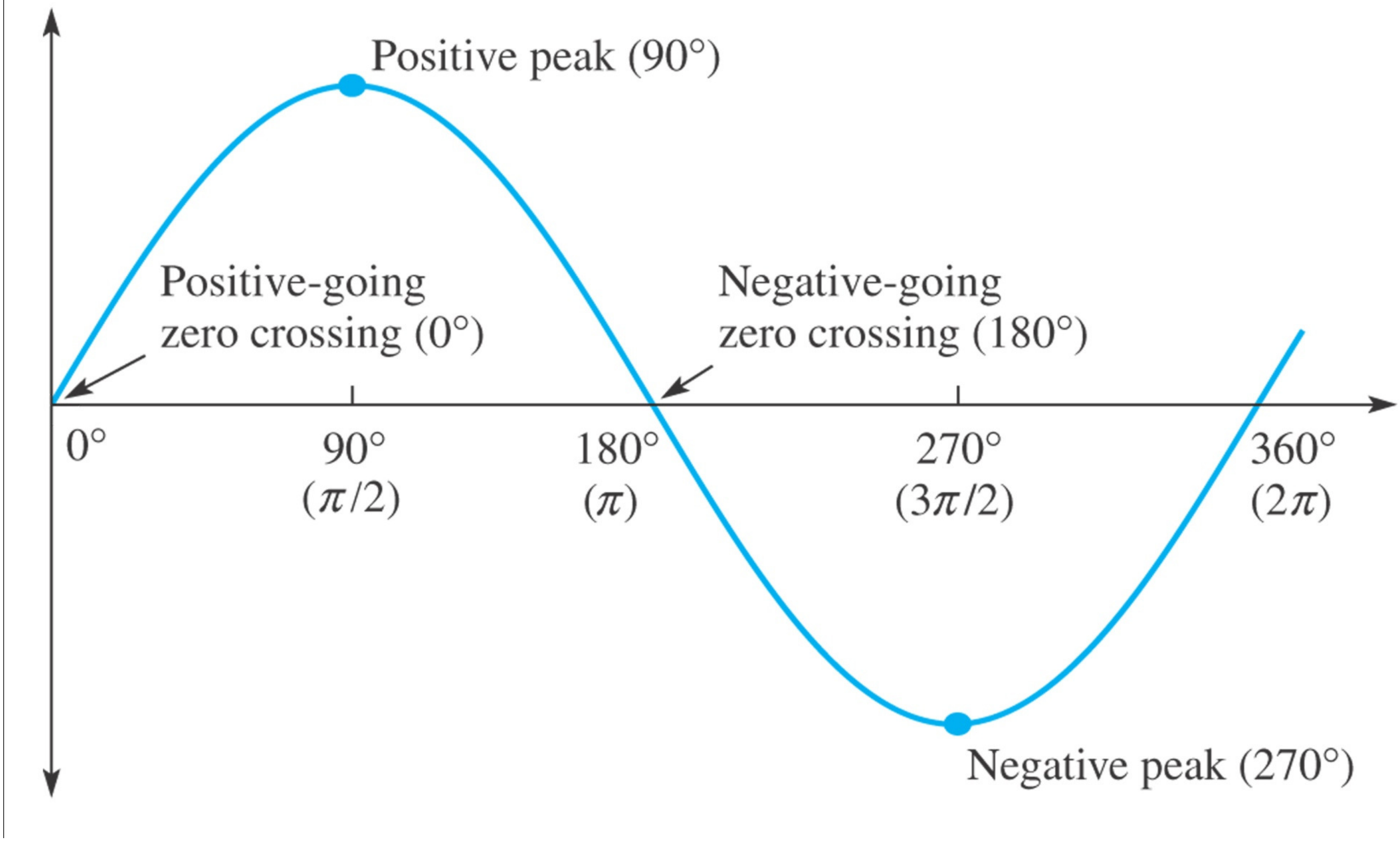
Major Phase References



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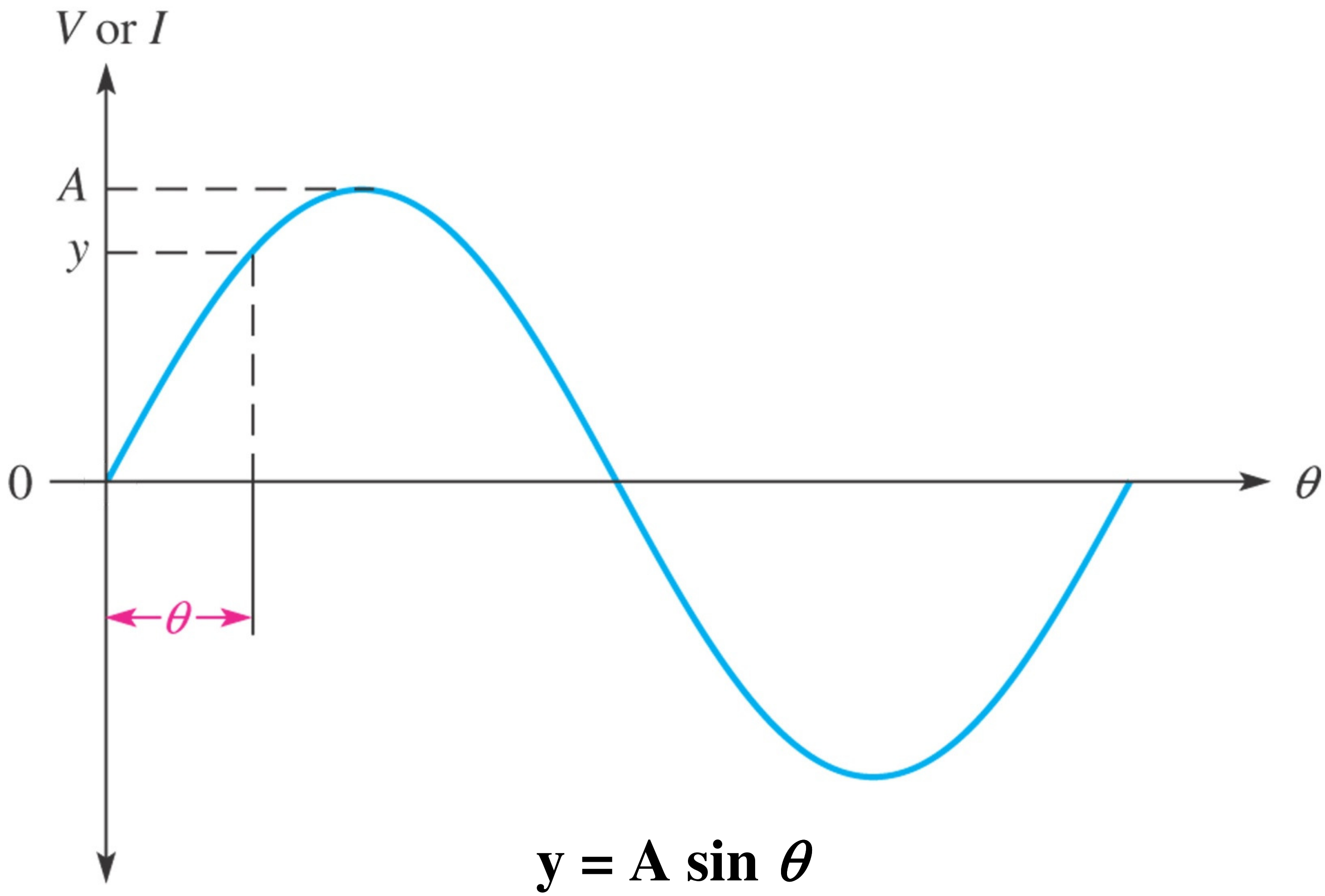
Instantaneous Values
Determined through a Formula



$$y = A \sin \theta$$

General Formula

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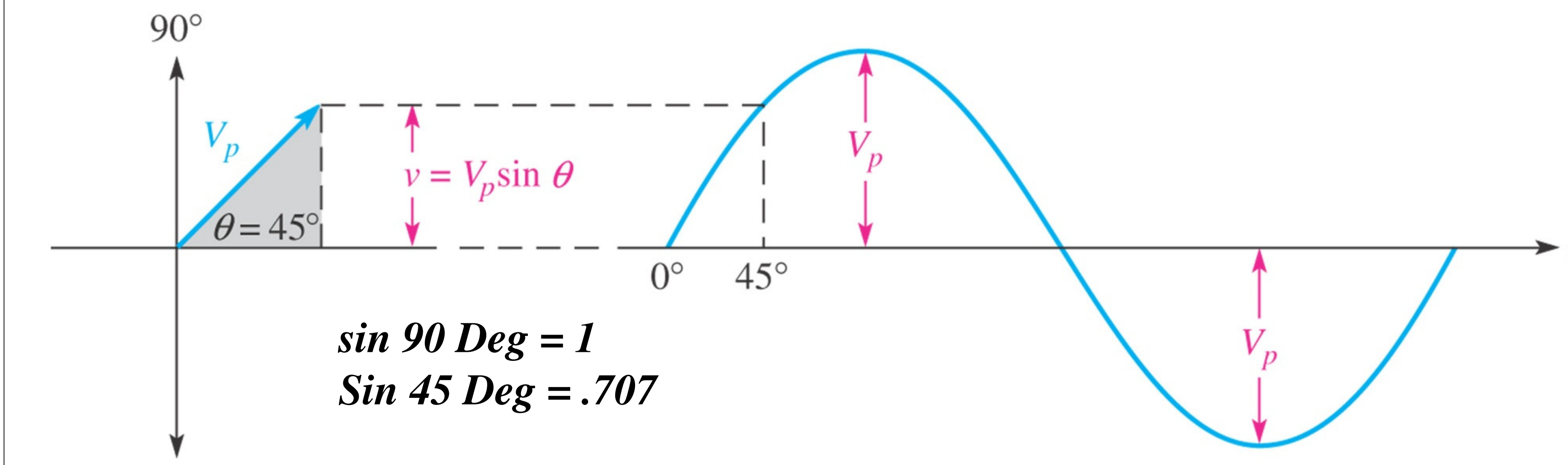
Instantaneous Voltage and Current derivation of the general sine wave formula

$$v = \mathbf{Vp} \sin \theta$$
$$i = \mathbf{Ip} \sin \theta$$



sin 90 Deg = 1
Sin 45 Deg = .707

•The instantaneous value can be found by dropping a vertical line from the tip of the arrow.
•Notice the Lower Case *v* and *i*

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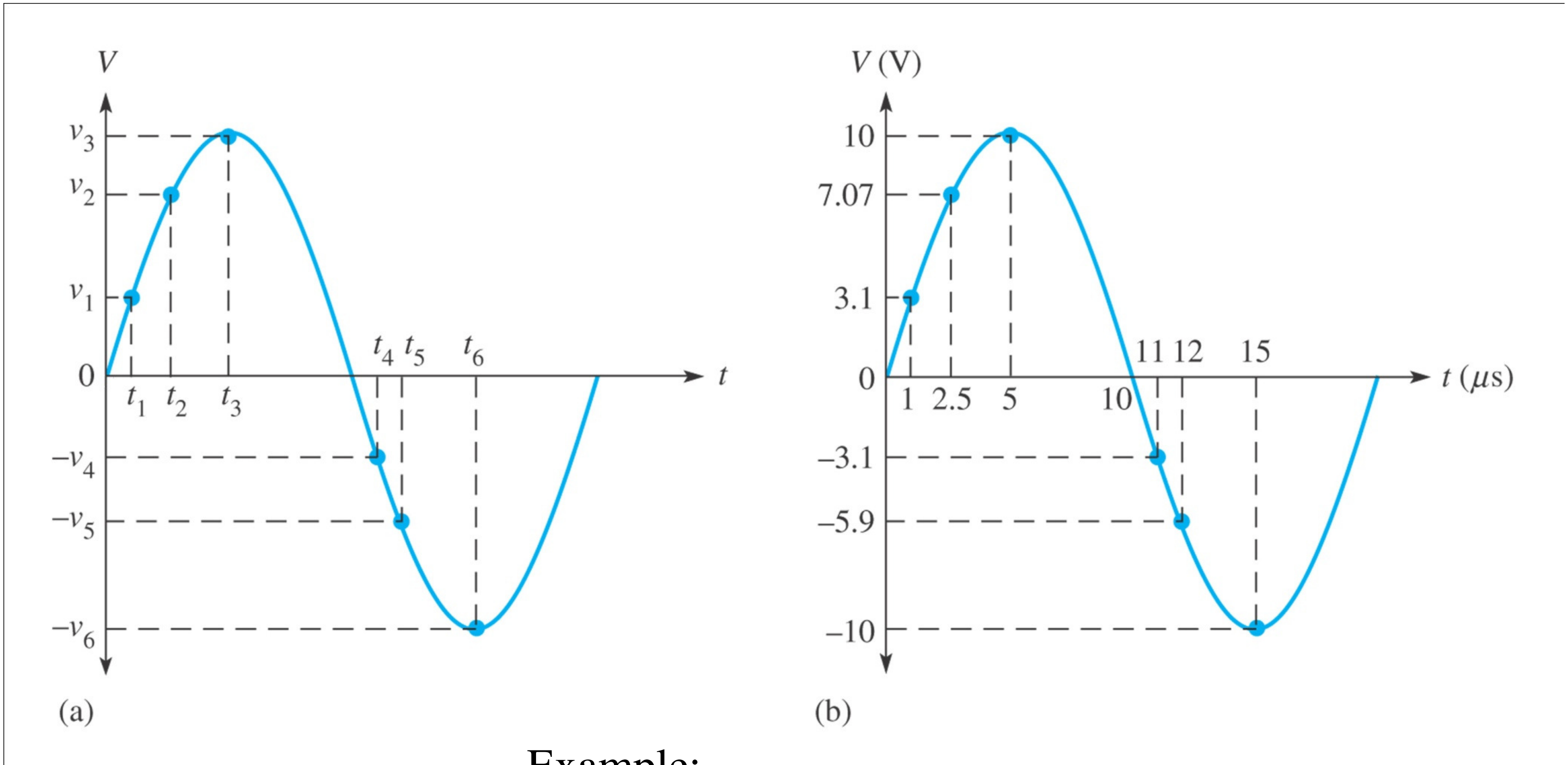
Instantaneous Voltage Values

Determined Graphically



Example:

t_1: 3.1V @ 1 uS

t_2:7.01V @ 2.5 uS

t_5: -5.9V @ 12 uS

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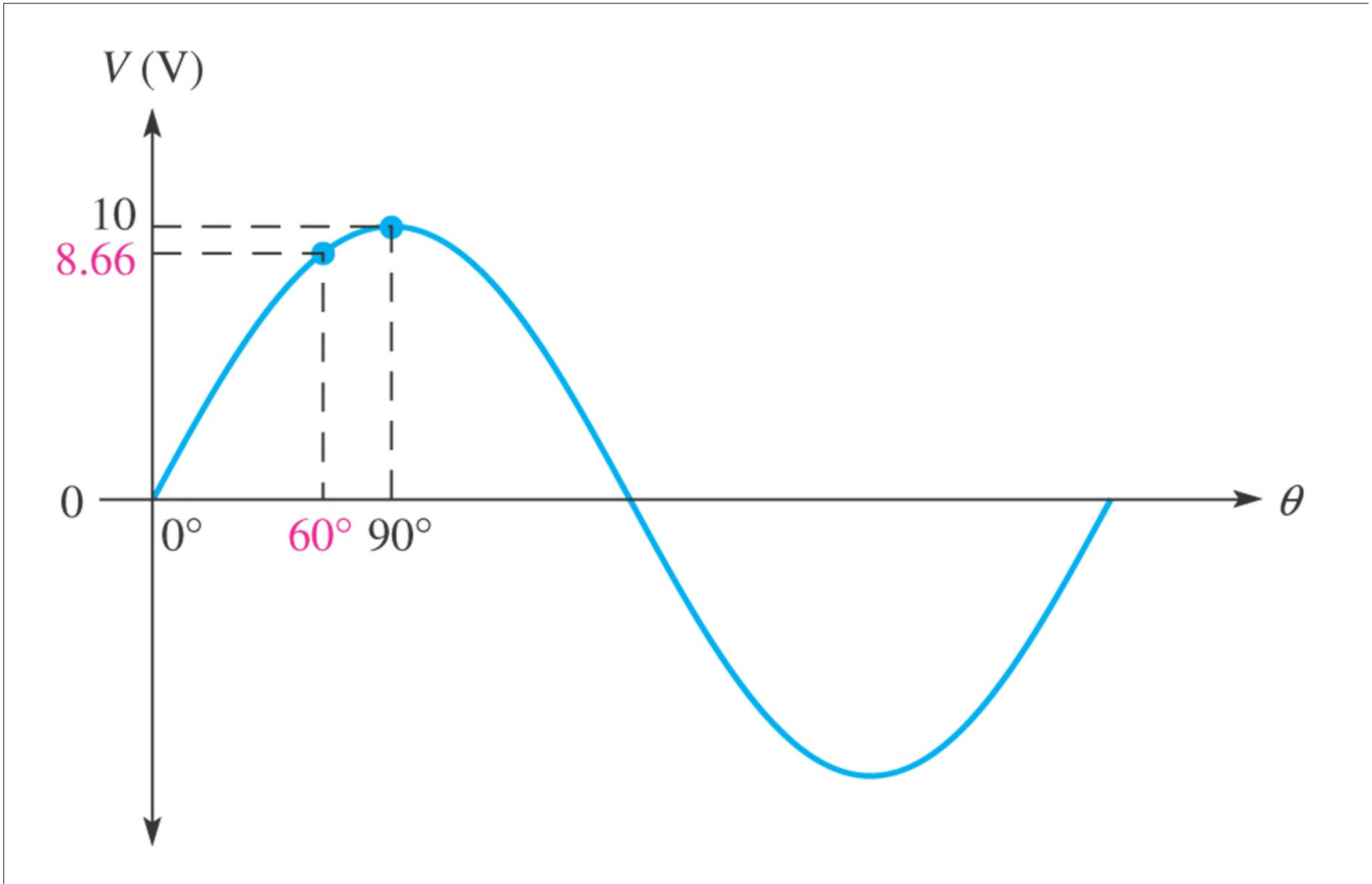
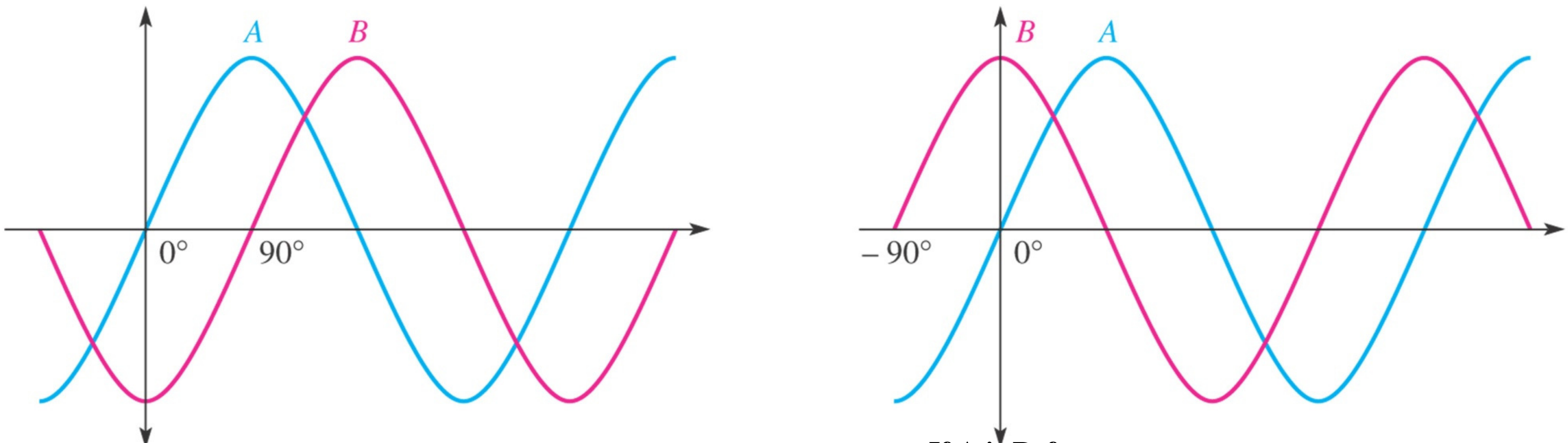
Illustration of the instantaneous value of a voltage sine wave at θ = 60º



$Y\ (V_{inst}) = 10V \sin 60^0$

y = 8.66V

Phase shift between two waveforms



If B is Reference **If A is Reference**

(a) A leads B by 90°, or B lags A by 90°.

If A is Reference **If B is Reference**

(b) B leads A by 90°, or A lags B by 90°.

- Generally, one waveform is considered the *reference* waveform and other waveform *leads* or *lags* that waveform
- Or:
    - Look for which waveform passes *positively* through 0V *first* to find the waveform that *leads*
    - Look for which waveform passes *positively* through 0V *last* to find the waveform that *lags*

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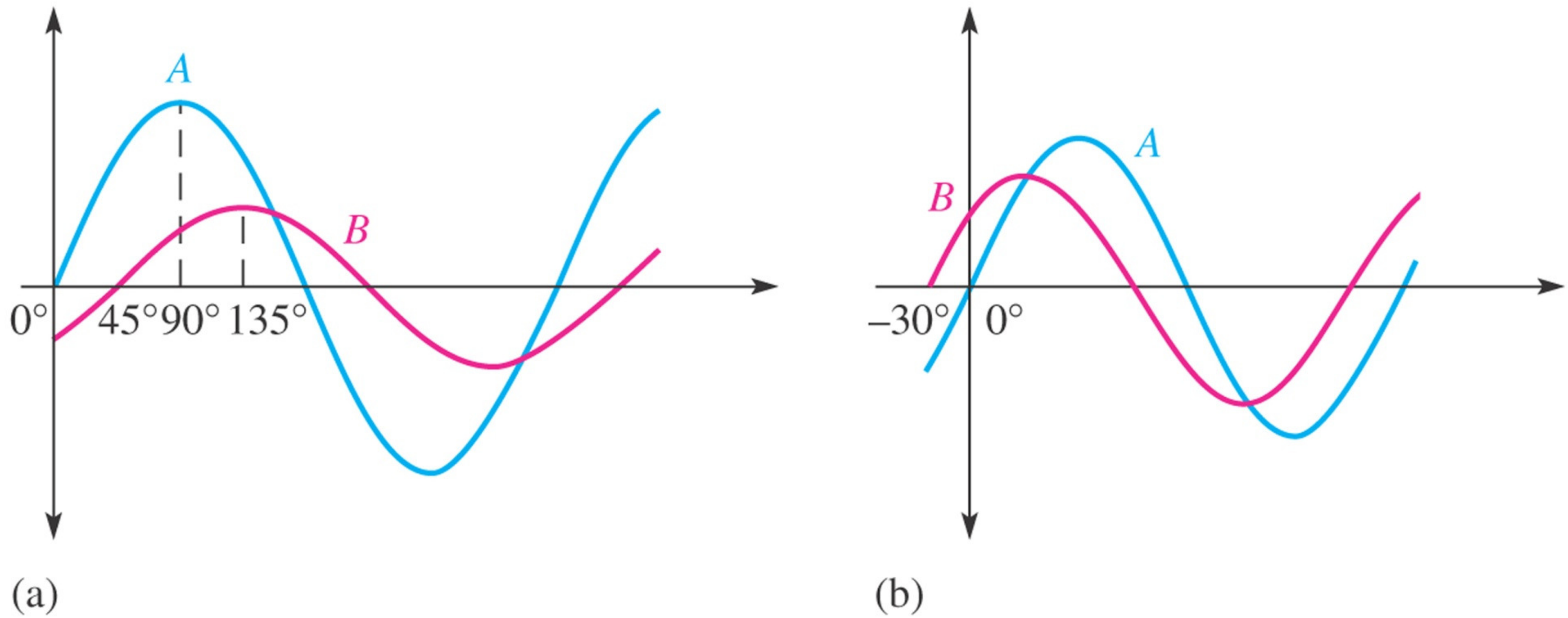
Phase shift between two waveforms



There is a 45^0 phase angle between A and B

- If A is reference, B is lagging
- If B is Reference, A is leading

There is a 30^0 phase angle between A and B

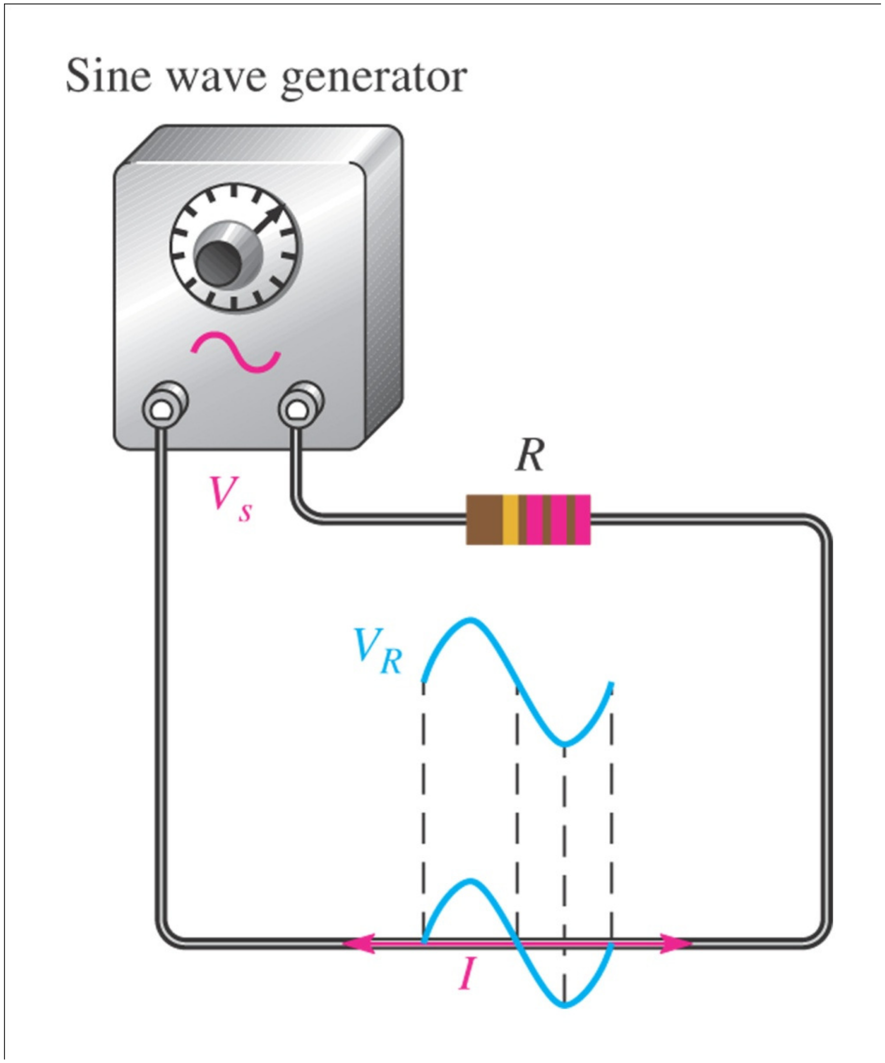
- If A is Reference, B is leading
- If B is the Reference, A is lagging

Ohms’s Law and Kirchhoff’s Laws in AC Circuits

- In purely resistive (or *passive)* circuits, Ohm’s law and Kirchhoff’s laws apply to AC circuits in the same way that they apply to DC circuits
- Always use the RMS value of the AC voltage

Ohms Law for AC Resistive Circuits

$I_{rms} = V_{rms}/R$
$V_s = I_{rms} * R$
$R = V_{rms} * I_{rm}s$



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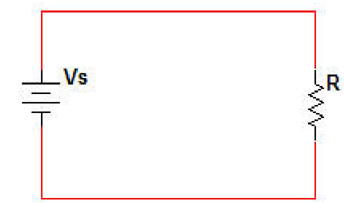
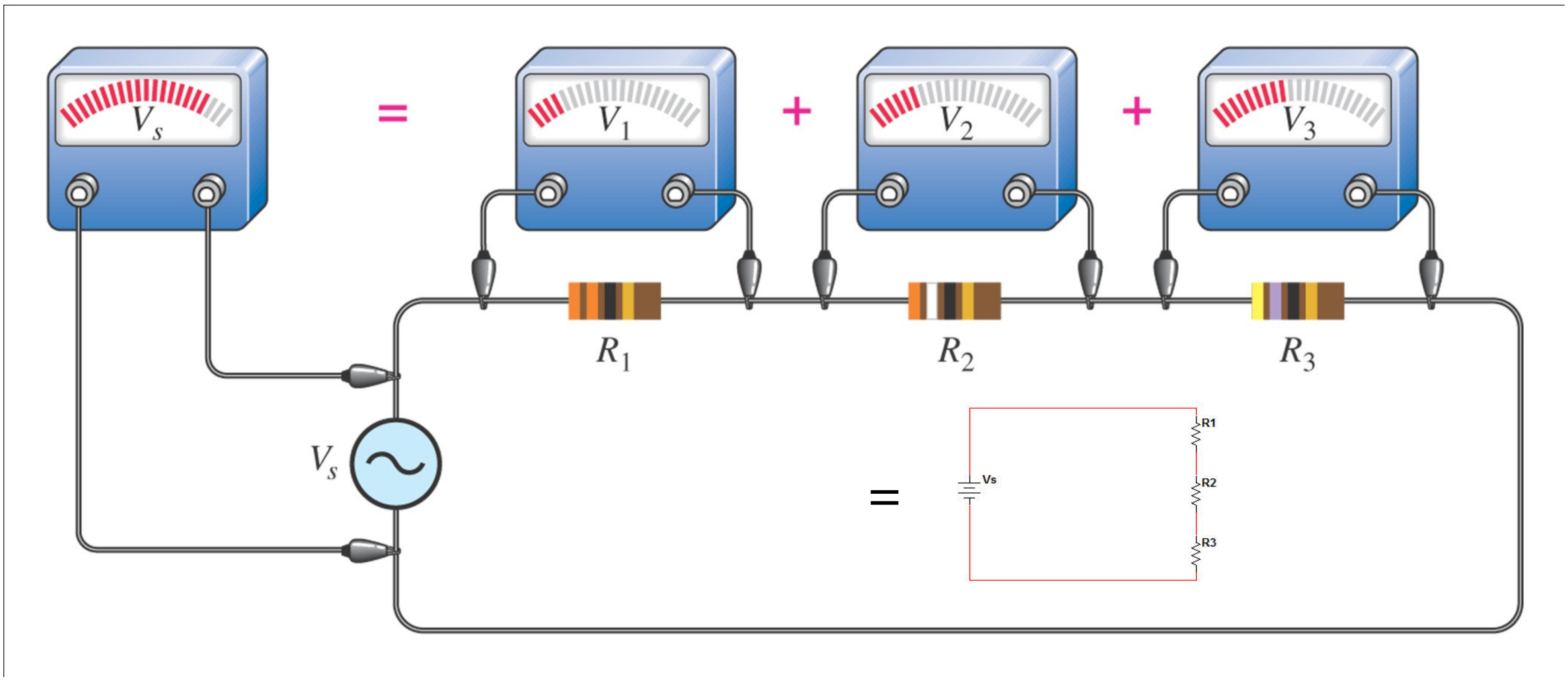


Illustration of Kirchhoff's voltage law in an ac circuit



$$Vs_{rms} = V1_{rms} + V2_{rm}s + V3_{rms} \ldots$$

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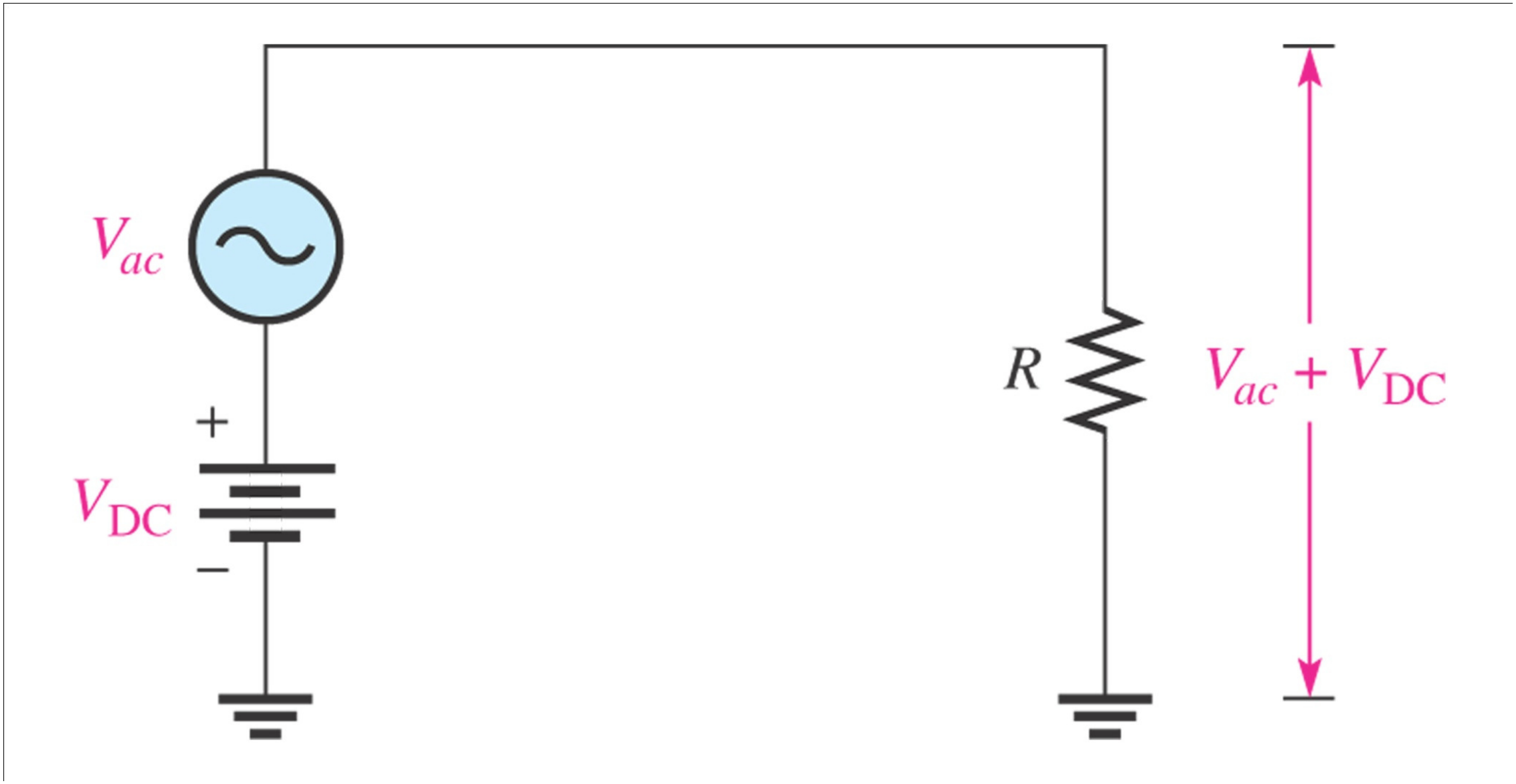
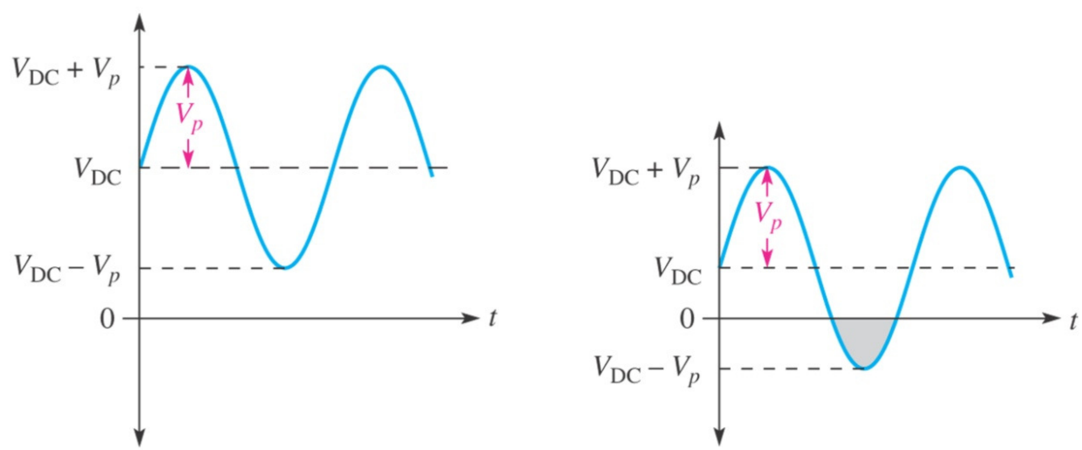
Superimposed (Biased) dc and ac voltages



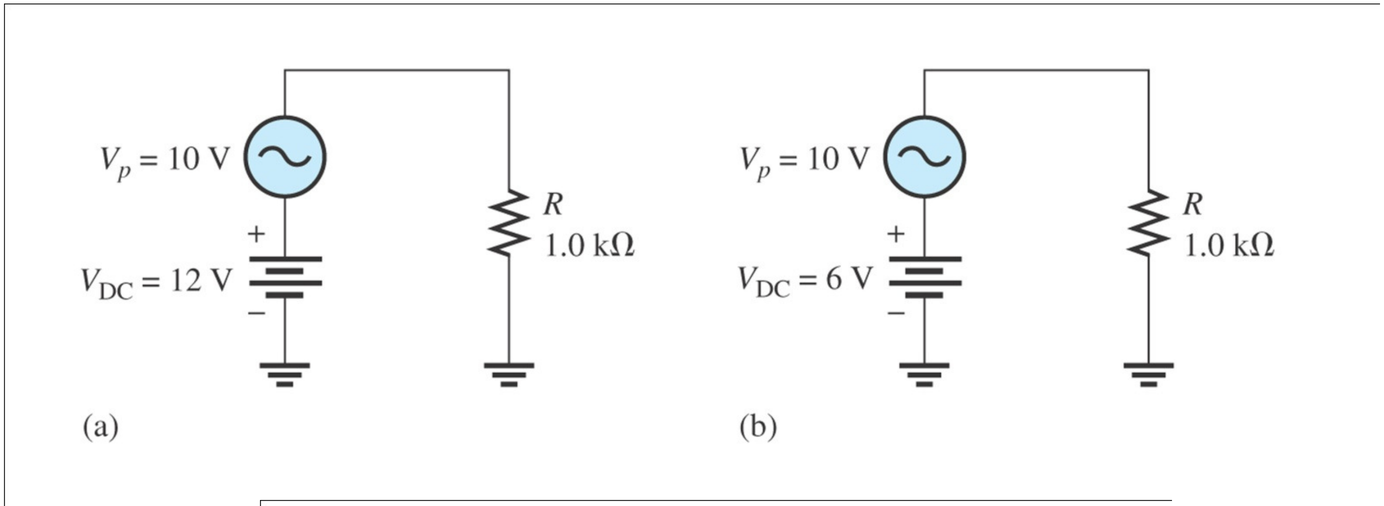
Superimposed (Biased) dc and ac voltages

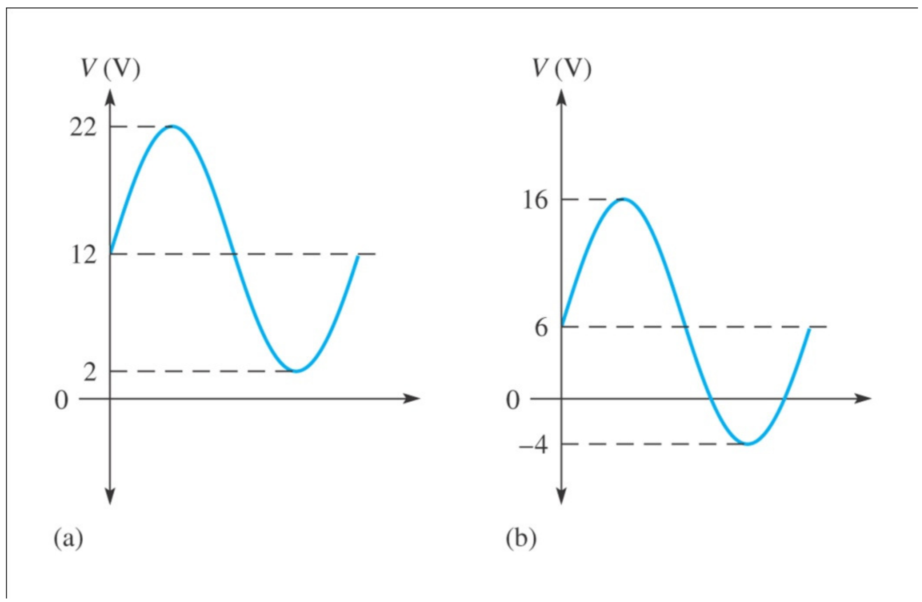
- DC and ac voltages will add algebraically, to produce an ac voltage "riding" on a dc level
- AKA - A *Biased* Signal



(a) $V_{DC} > V_p$. The sine wave never goes negative.

(b) $V_{DC} < V_p$. The sine wave reverses polarity during a portion of its cycle.





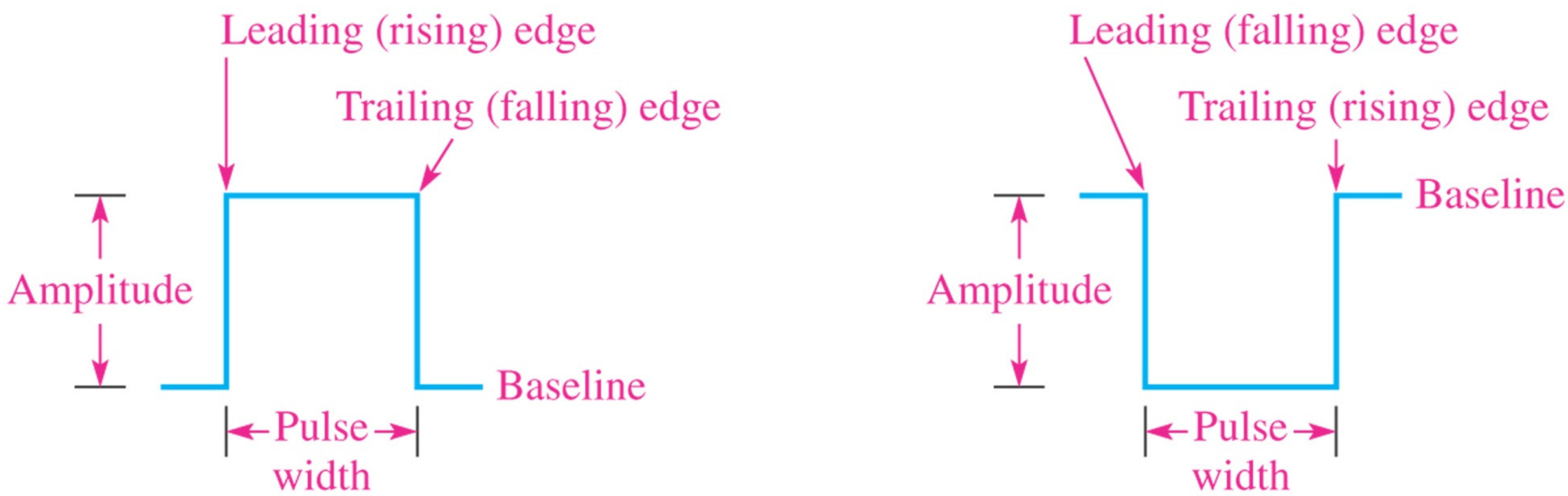
- Signal biased at 12V
- Signal Varies between 22V and 2V
- Does not alternate

- Signal biased at 6V
- Signal Varies between 16V and -4V
- Does alternate

Pulse Waveforms

- A pulse has a *rapid vertical transition* (**leading** or **rising edge**) from a baseline to an amplitude level, then, after a period of time, a *rapid vertical transition* (**trailing** or **falling edge**) back to the baseline level
- Pulses can be positive-going, or negative-going, depending upon where the baseline is
- The distance between *rising* and *falling* edge is termed the **pulse width**
- Pulse waveforms are used in applications such as *stepper* and *servo* motors and *digital* electronics

Ideal pulses



(a) Positive-going pulse

(b) Negative-going pulse

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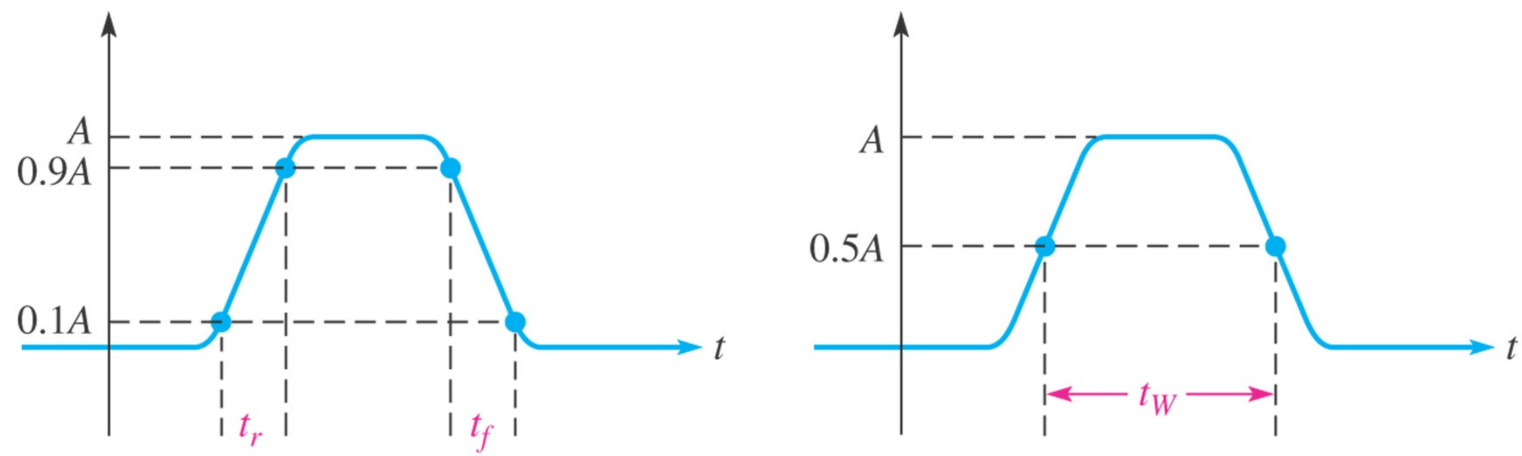
Non-ideal Pulse

- A non-ideal pulse has a *rising and falling time interval*, measured between 10% and 90% of its Amplitude
- *Pulse width* is taken at the half-way point



(a) Rise and fall times (b) Pulse width

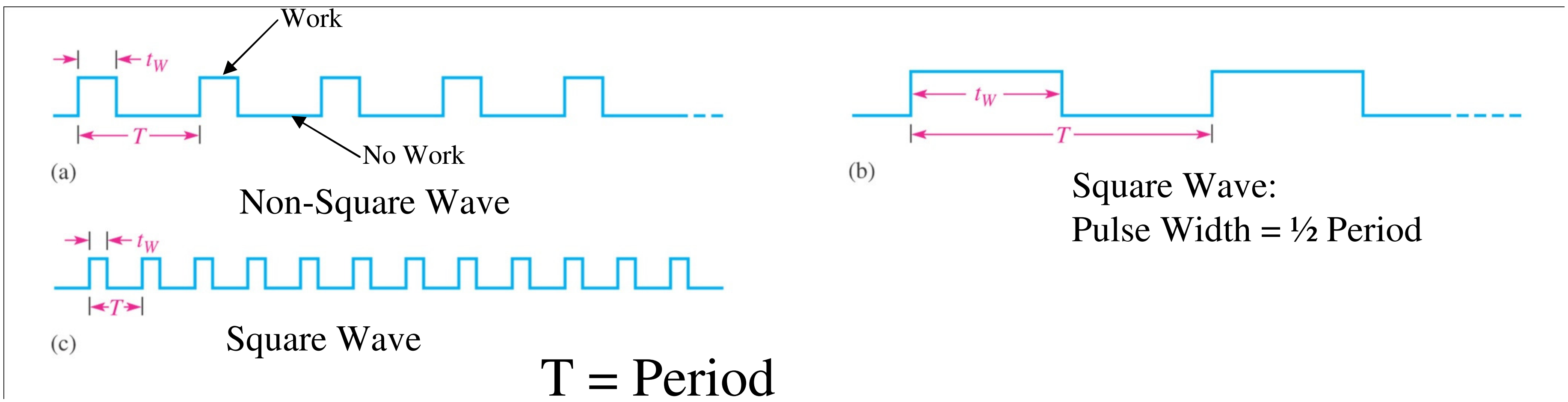
Repetitive/Periodic Pulses

•Any waveform that *repeats* itself at *fixed intervals* is **periodic.**

•The time from one pulse to the corresponding point on the next pulse is the *period*, T (f =1/T)

•The pulse width does not always equal one half the period

- ➢ As it does a *square wave*



T = Period

Tw = Pulse Width (Work)

Frequency = 1/Period

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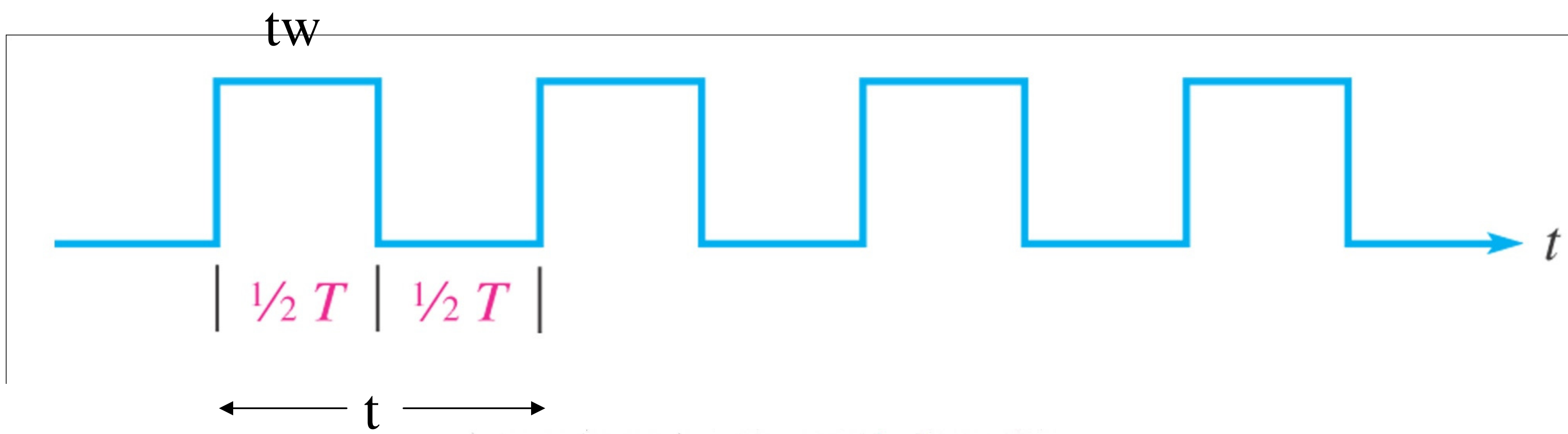
Square Wave has 50% a Duty Cycle

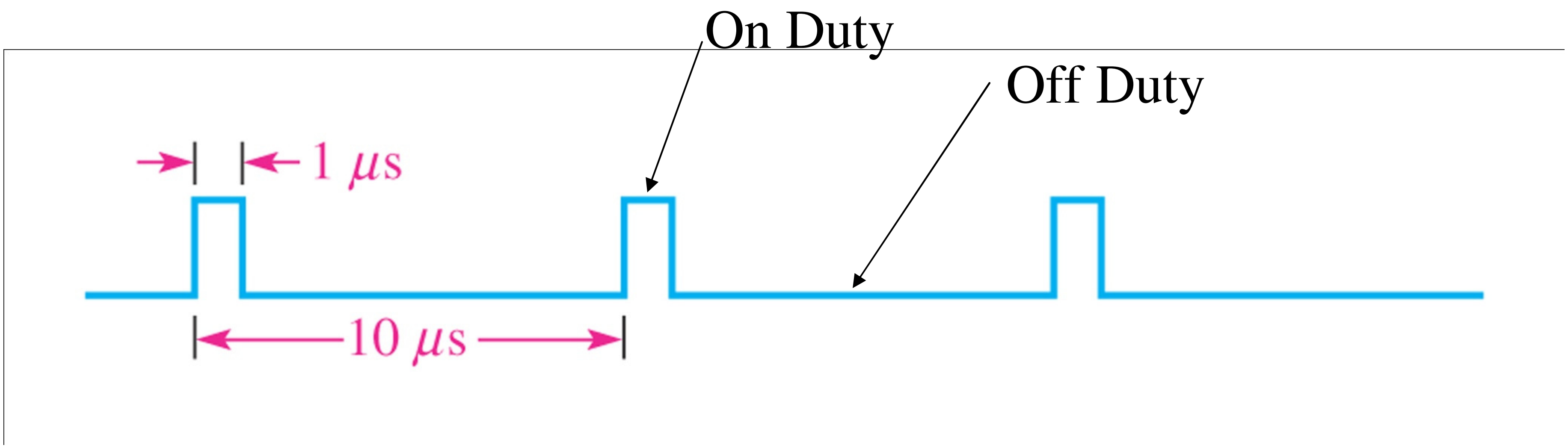
The **duty cycle** is the ratio of the pulse width (tw) to the period (T), and can be expressed as %



$$\text{Percent duty cycle} = \left(\frac{t_W}{T}\right)100\,\%$$

Square Waves have a 50% duty cycle

Non-50% Duty Cycle Periodic Pulses



Frequency = 1/Time => 1/10uS = 100kHz

Percent Duty cycle = $(t_w/T)100\%$ => (1us/10us)100% = 10%

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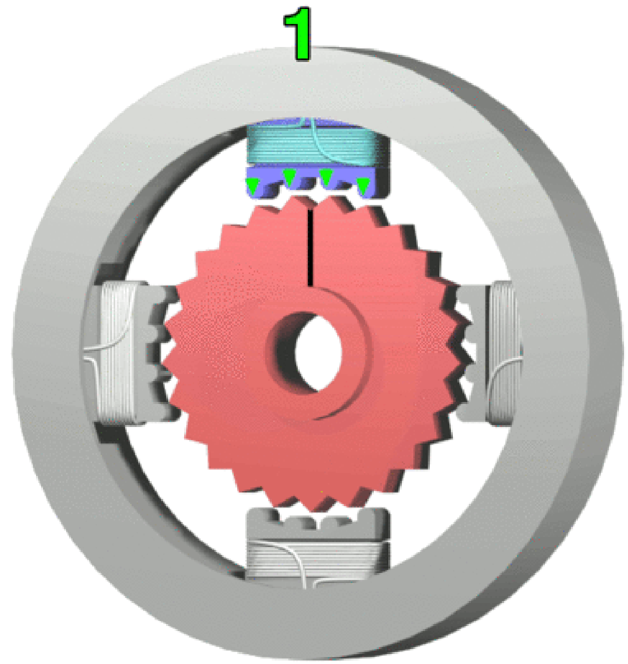
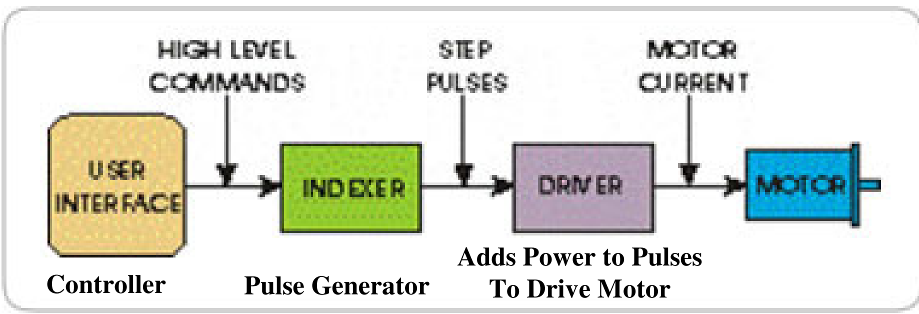
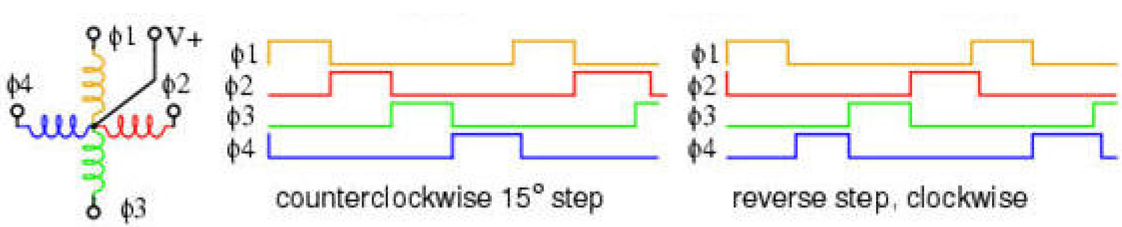
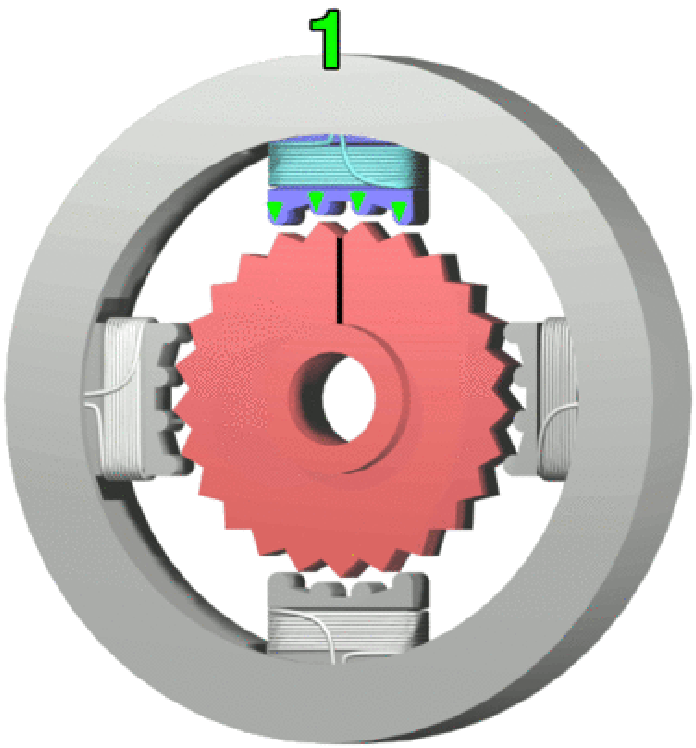
Stepper Motors

- •The stepper motor converts digital pulses into mechanical rotation
- •Each pulse turns the shaft a certain number of degrees
- •They control movement very accurately
- •Can be configured for full or half steps





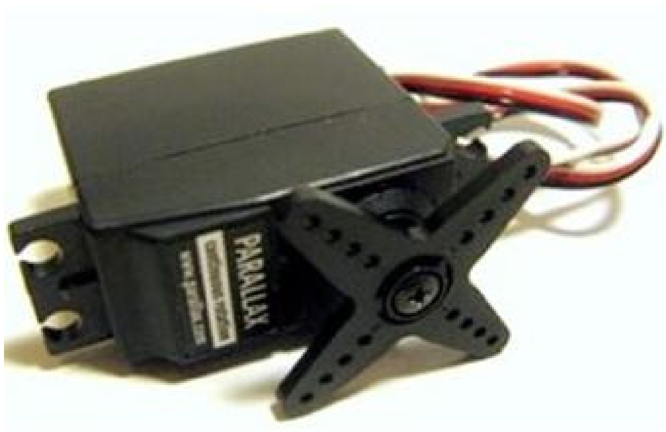


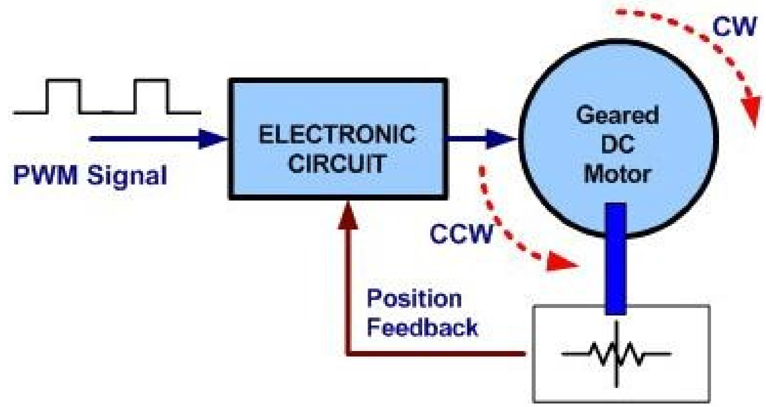


Frame 1: The top electromagnet (1) is turned on, attracting the nearest tooth of a gear-shaped iron rotor. With the teeth aligned to electromagnet 1, they will be slightly offset from electromagnet 2.
Frame 2: The top electromagnet (1) is turned off, and the right electromagnet (2) is energized, pulling the nearest teeth slightly to the right. This results in a rotation of 3.6° in this example.
Frame 3: The bottom electromagnet (3) is energized; another 3.6° rotation occurs.
Frame 4: The left electromagnet (4) is enabled, rotating again by 3.6°. When the top electromagnet (1) is again enabled, the teeth in the sprocket will have rotated by one tooth position; since there are 25 teeth, it will take 100 steps to make a full rotation in this example.

Servo Motors

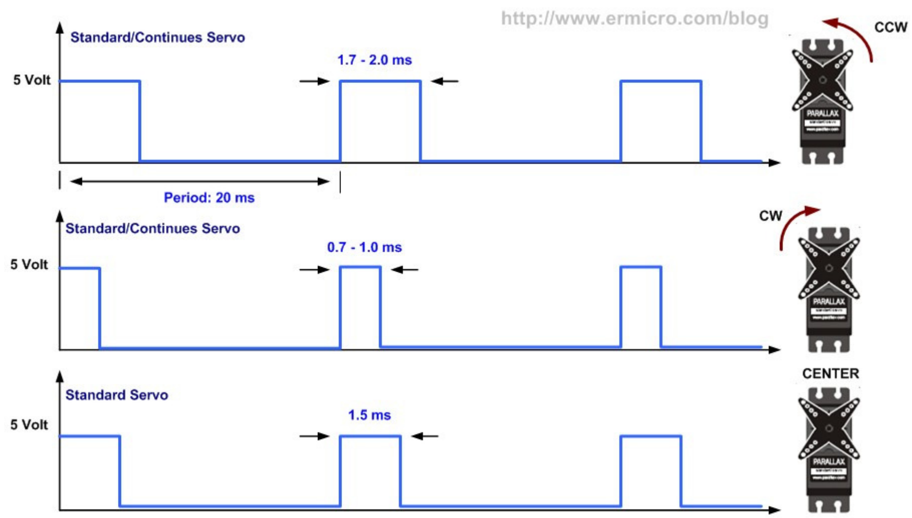
Many servo motors are controlled with Pulse-Width Modulation (PWM) where the percent duty cycle determines what the motor does.





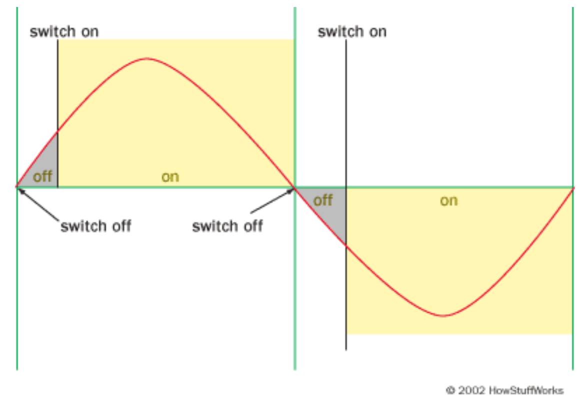
Typical Servo Motor (RC "Hobby" Servo Motor)

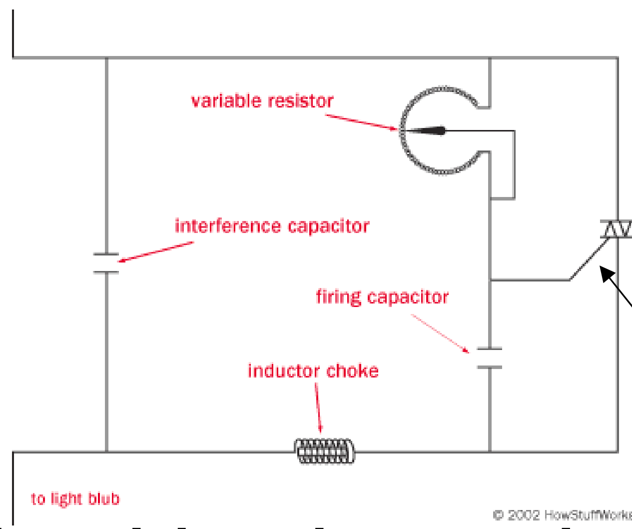
Servo Motor Block Diagram



Servo Motor PWM Timing Diagram

- **Lamp Dimmers use a form of PWM to control the brightness of the light**
- **The Active device is called a *triac* which "Chops Up" the incoming sine wave where it crosses 0V.**
- **The amount of chopping is determined the voltage at the gate of the triac which is *controlled by a variable resistor* along with charge capacitor**
- **The more chopped up the waveform is the less light and more the sine wave begins to resemble a *square wave***





Triac

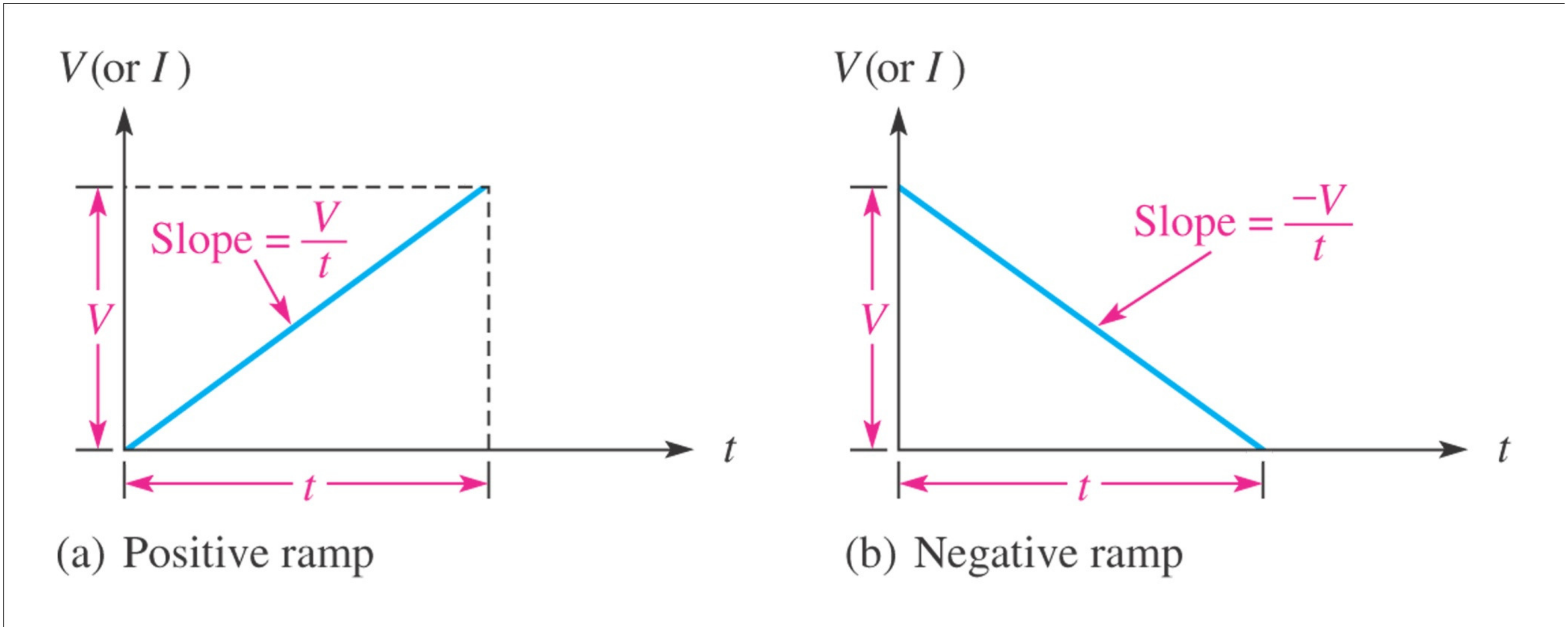
Gate or "Trigger"
- **0V = Off**
- **More Voltage = More Output (Less Chopping)**

The interference capacitor and inductor choke are there to smooth out the square waveform at low-light to eliminate the "Buzzing" sound

Triangular and Sawtooth Waveforms

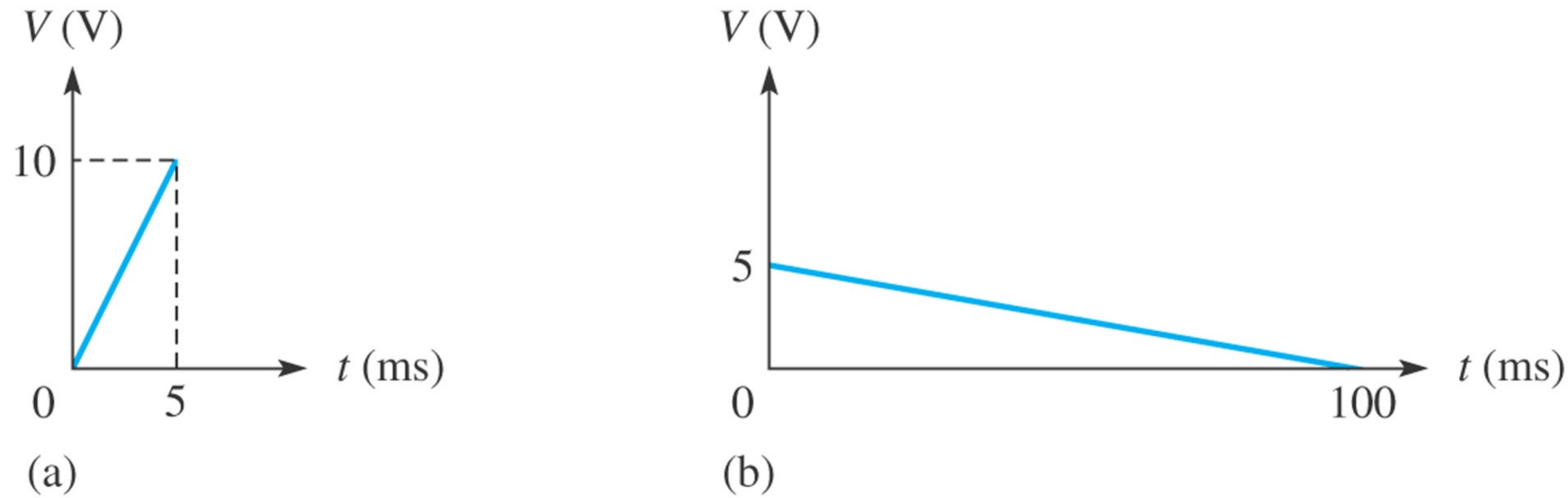
- **Triangular** and **Sawtooth** waveforms are formed by voltage or current *ramps* (linear increase/decrease)
- **Triangular waveforms** have positive-going and negative-going ramps of *equal slope*
- The **sawtooth waveform** is a special case of the triangular wave consisting of *two ramps*, one of much longer duration than the other. A sawtooth voltage is sometimes called a *sweep voltage*

Ramp Slopes



Ramp is usually expressed in Volts per Second (V/s)

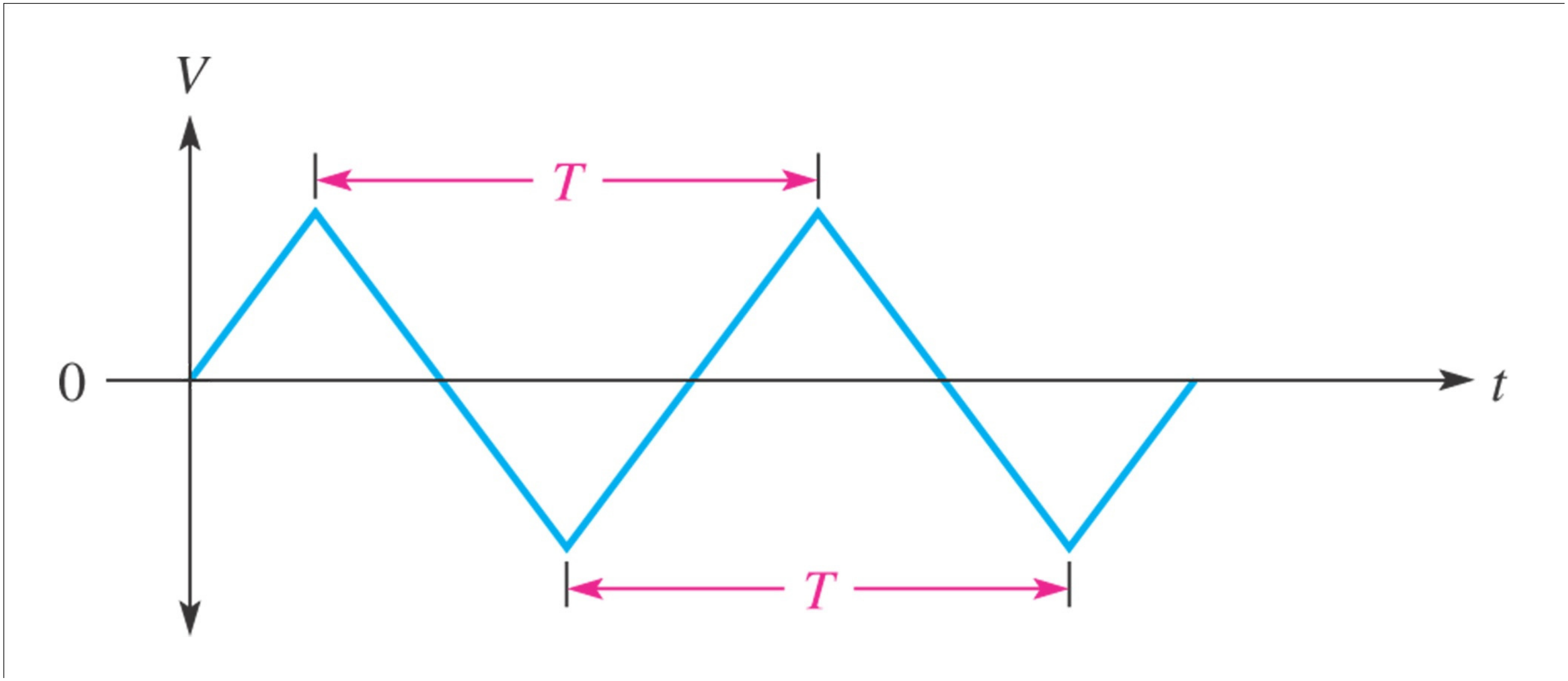
Ramp (V/s) => V/t



Ramp => V/t => 10V/5 ms => 2V/ms => 2000 V/s

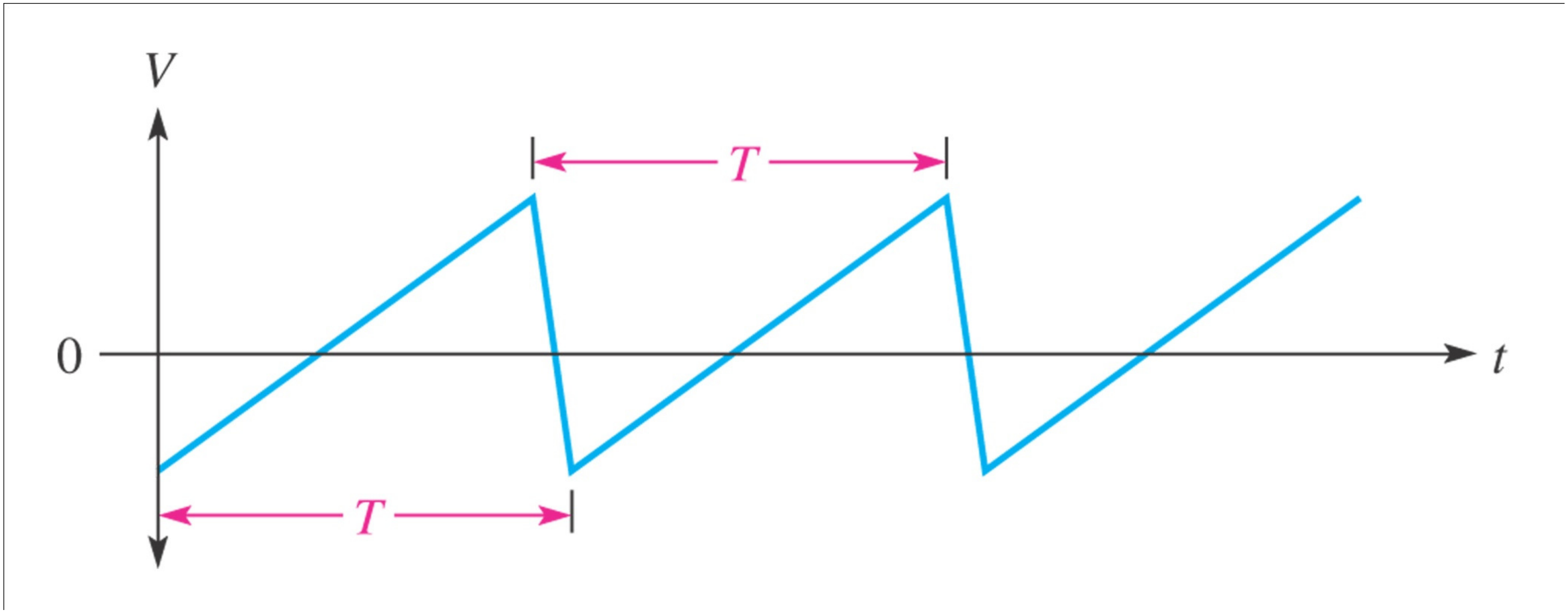
Ramp => V/t => -5V/100 ms => -0.05V/ms => -50 V/s

Alternating triangular waveform



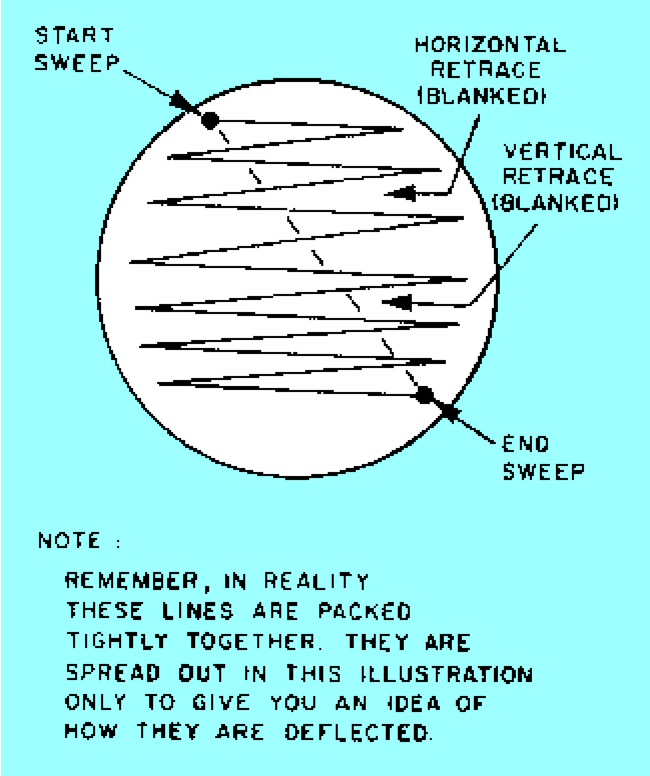
Alternating triangular waveforms
- Have equal slopes
- A 50% Duty Cycle

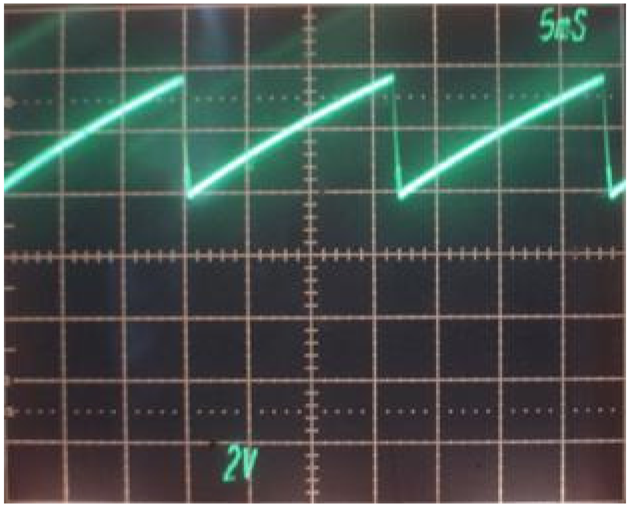
Sawtooth Waveforms



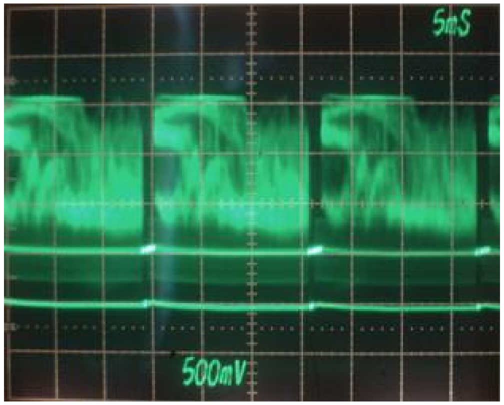
•Alternating sawtooth waveforms have unequal slopes
•Their Duty Cycle is not 50%
•They are commonly used in TV vertical and horizontal sweep voltages

Sawtooth Waveforms in Action

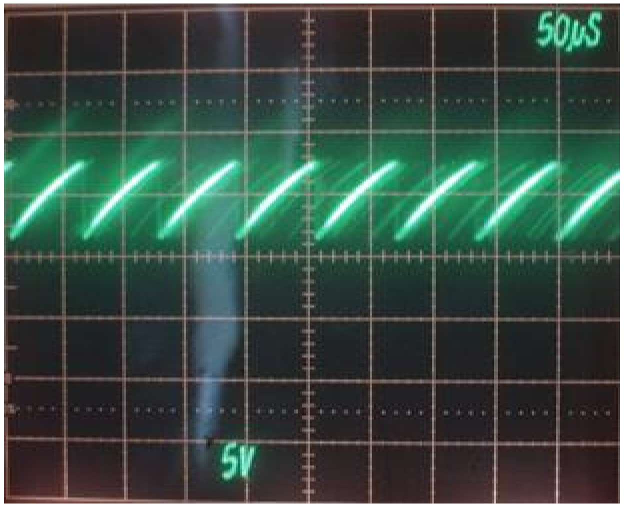




Vertical Trace Sweep (60Hz)



Full Video Signal

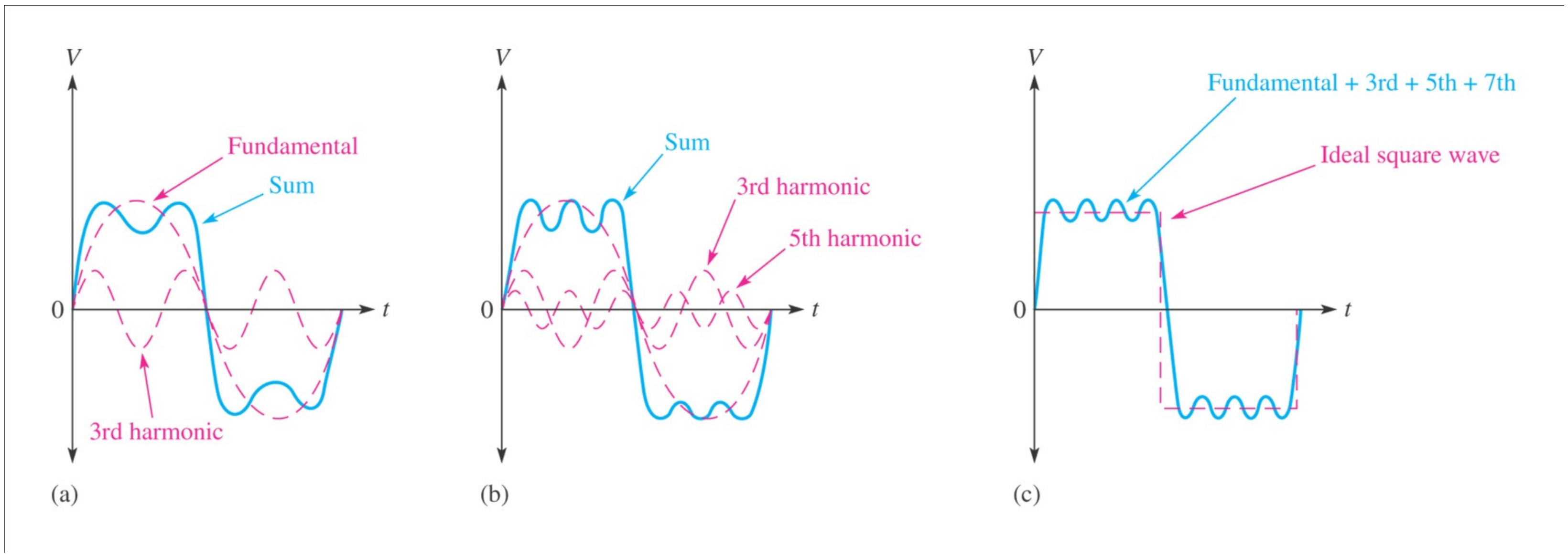


Horizontal Trace Sweep (15.75Khz)

Harmonics

- A repetitive non-sinusoidal waveform is composed of a **fundamental frequency** or **first harmonic** and **harmonic frequencies**
- This is primarily why two instruments playing the same note sound different
- **Odd harmonics** are frequencies that are odd multiples of the fundamental frequency (1Khz Fund – 3Khz, 5Khz, 7Khz, . . .)
- **Even harmonics** are frequencies that are even multiples of the fundamental frequency (200Hz Fund – 400Hz, 800Hz, 1200Hz, . . .)
- **Non-Sine Waves** are composites of a fundamental frequency and harmonics.
- A **square wave** is made up from a fundamental frequency sine wave and an *infinite* number of *odd* harmonics.
- A **sawtooth** wave form consists of a fundamental plus an *infinite* number of *even* harmonics.

Odd Harmonics Produce a Square Wave

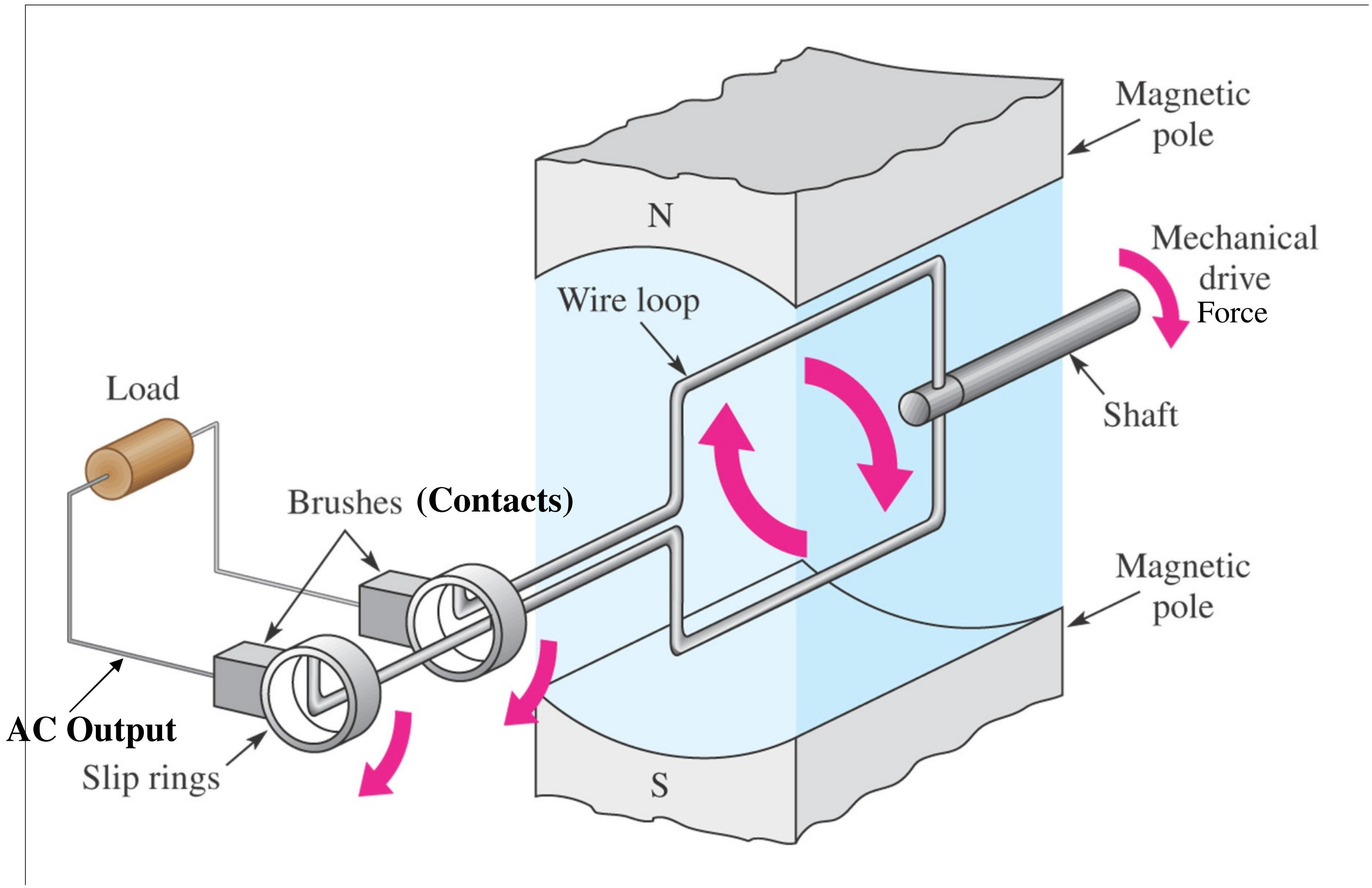


Square Waves are made up of odd harmonics (Instantaneous Algebraic Sum)
The period of the Square wave is the same as the fundamental harmonic

Basic AC Generator (Alternator)

- The ac generator has *slip rings* (one on each end of the wire loop) that pick up the induced voltage through a complete rotation cycle
- The induced voltage is related to the number of lines of flux being cut and cutting rate.
- Just like a DC Generator W/O a Split Commutator:
  - When the loop is moving parallel with the lines of flux, no voltage is induced.
  - When the loop is moving perpendicular to the lines of flux, the maximum voltage is induced

Basic ac generator operation



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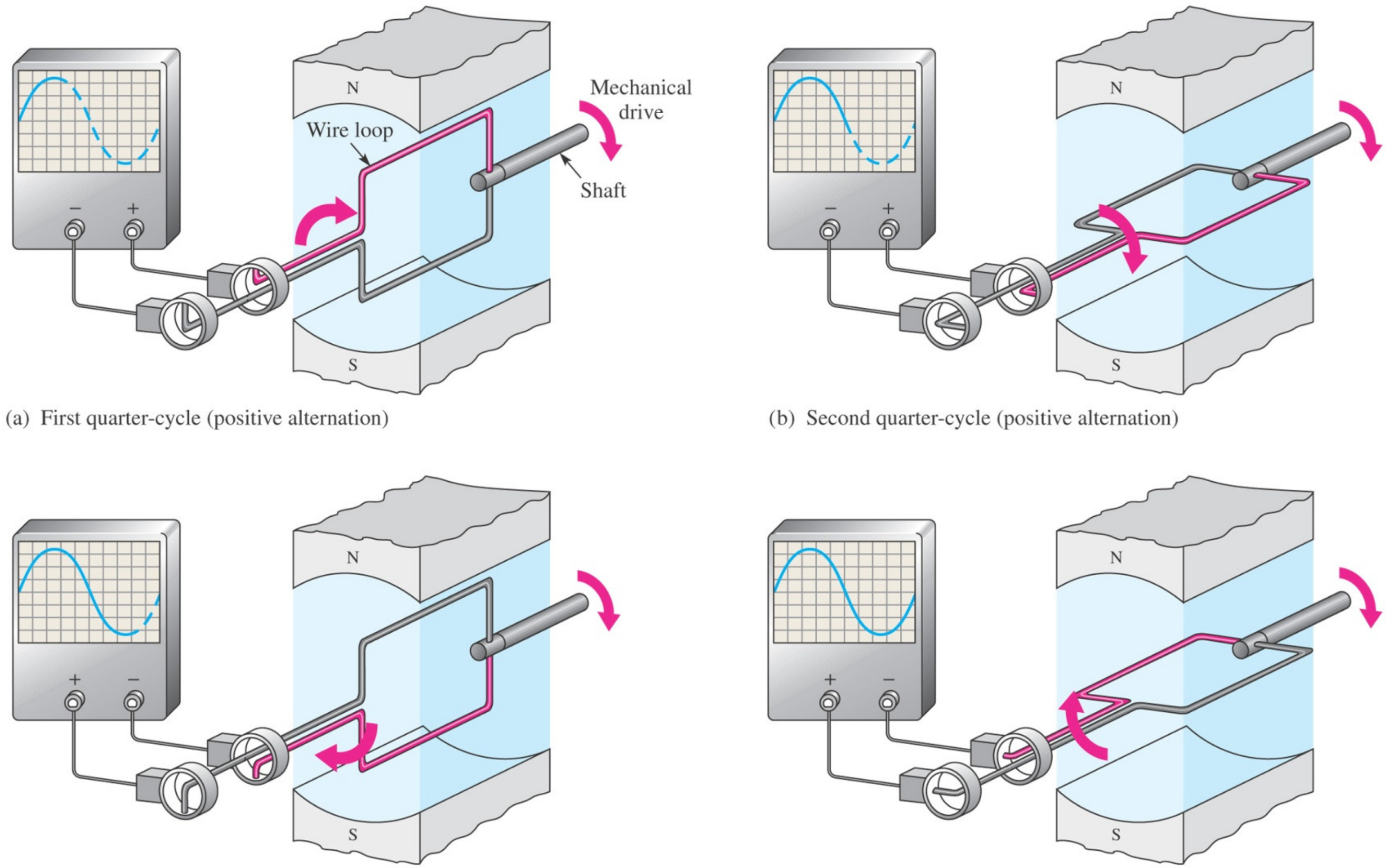
Electric Circuit Fundamentals, 6e

One revolution of the wire loop generates one cycle of the sinusoidal voltage



(a) First quarter-cycle (positive alternation)

(b) Second quarter-cycle (positive alternation)

(c) Third quarter-cycle (negative alternation)

(d) Fourth quarter-cycle (negative alternation)

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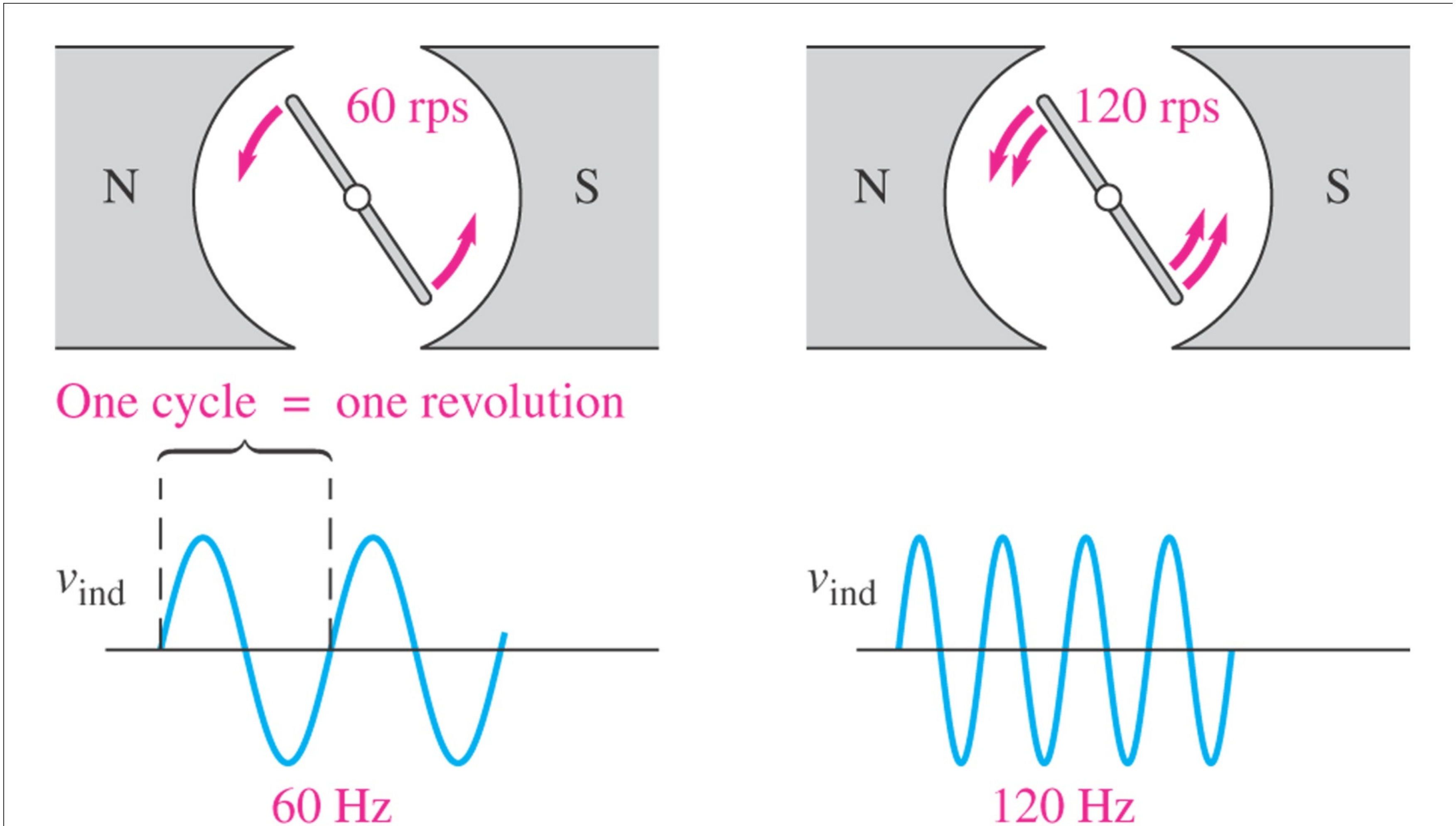
Frequency is directly proportional to the rate of rotation of the wire loop in an ac generator



Frequency is directly proportional to the rate of rotation of the wire loop in an ac generator.

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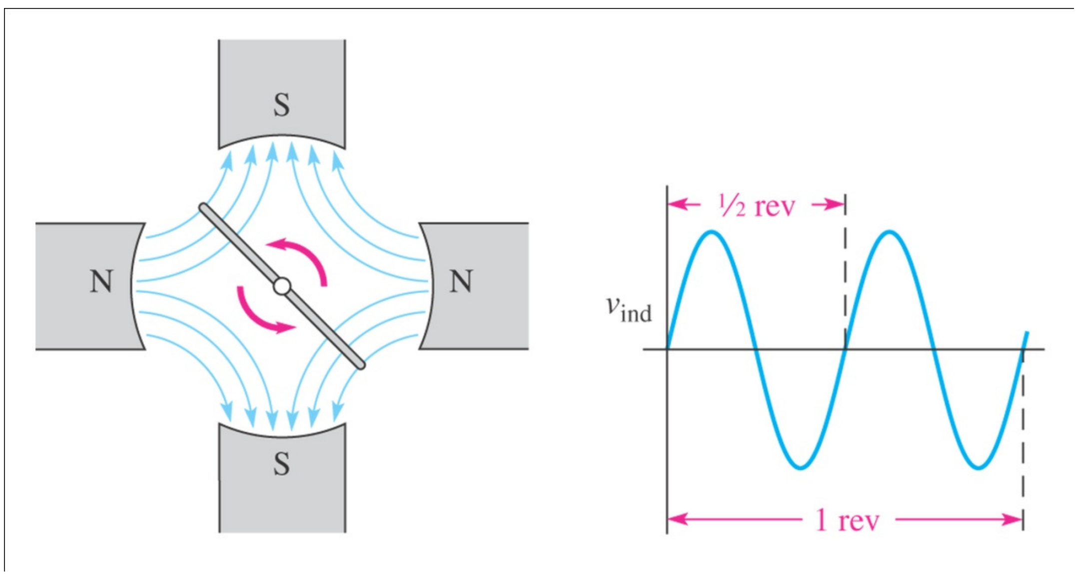
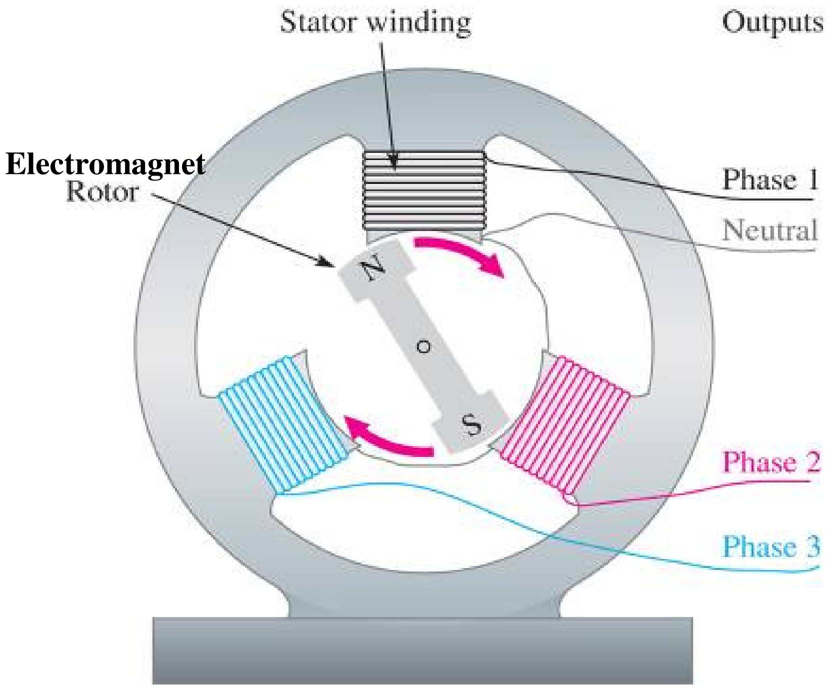
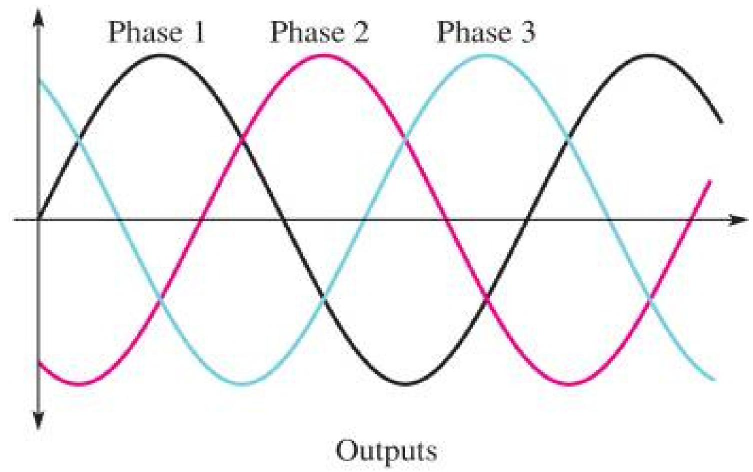
Multi-pole ac Generator

- By increasing the number of magnetic poles, the number of cycles per revolution can be increased
  - For example, doubling the number of poles doubles the output frequency
- As with DC Generators, multiple-loop rotors are used and the magnetic field is created by electromagnet coils (field windings)

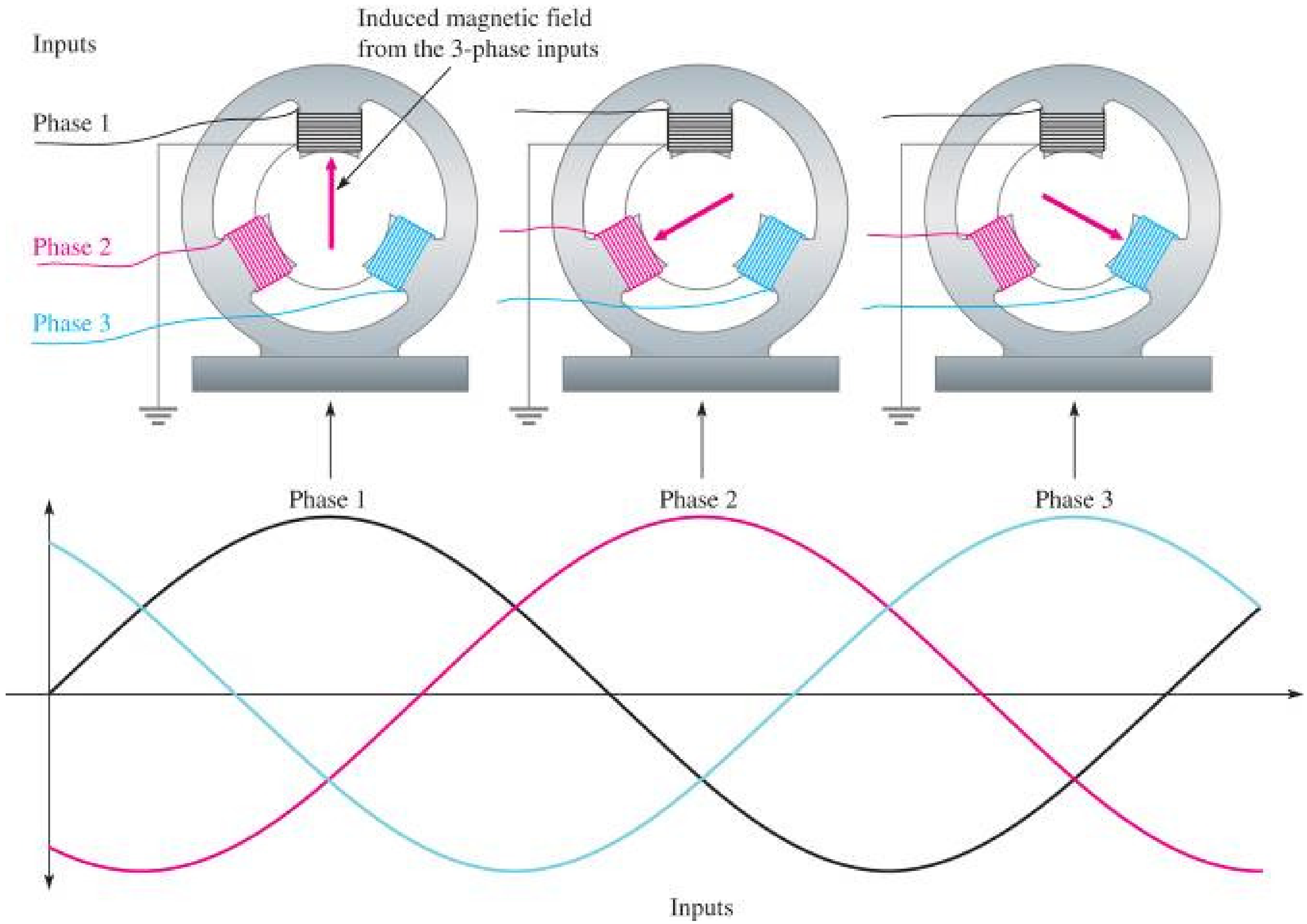


Rotating Field Alternator (Most Common)



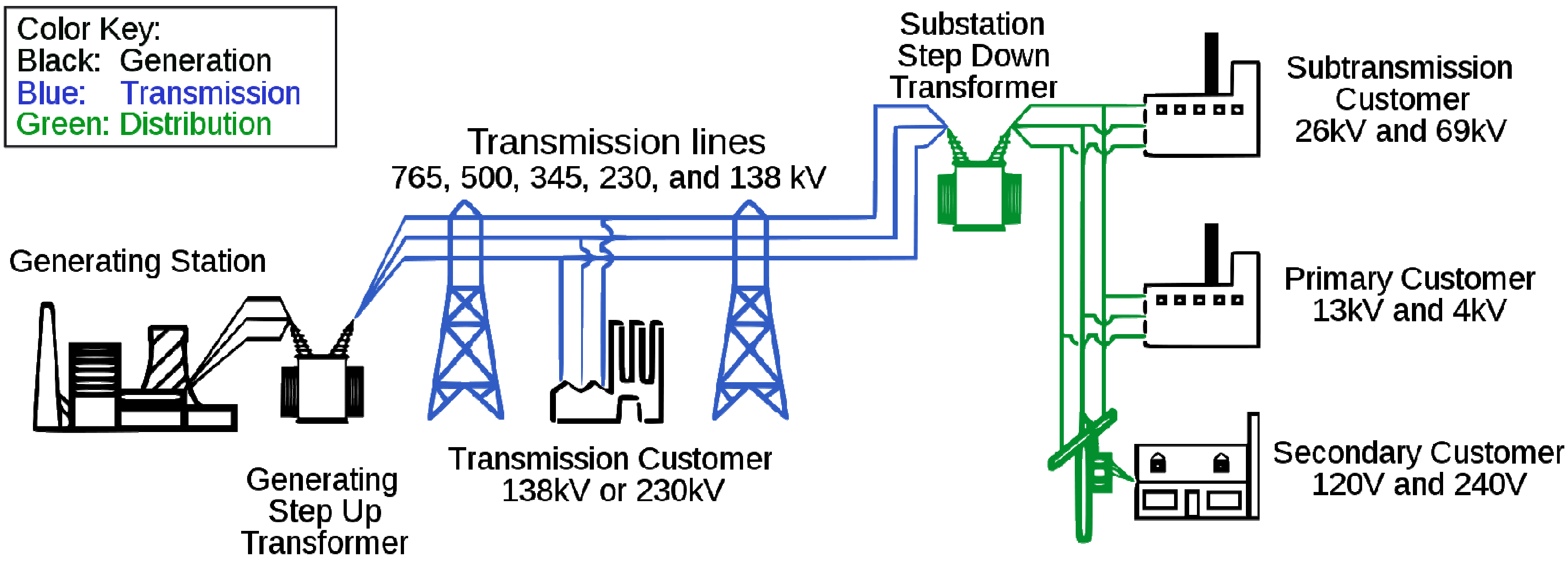


•In this alternator, the rotor is a strong electromagnet which rotates and the output induced voltage is taken from the stator windings (Reverse of previous example)
•This eliminates the need for the slip rings/contacts/brushes for the main output
•As the rotor sweeps past each stator windings, a sine wave is produced across that winding. The neutral is the reference
•This alternator is producing 3-phase power

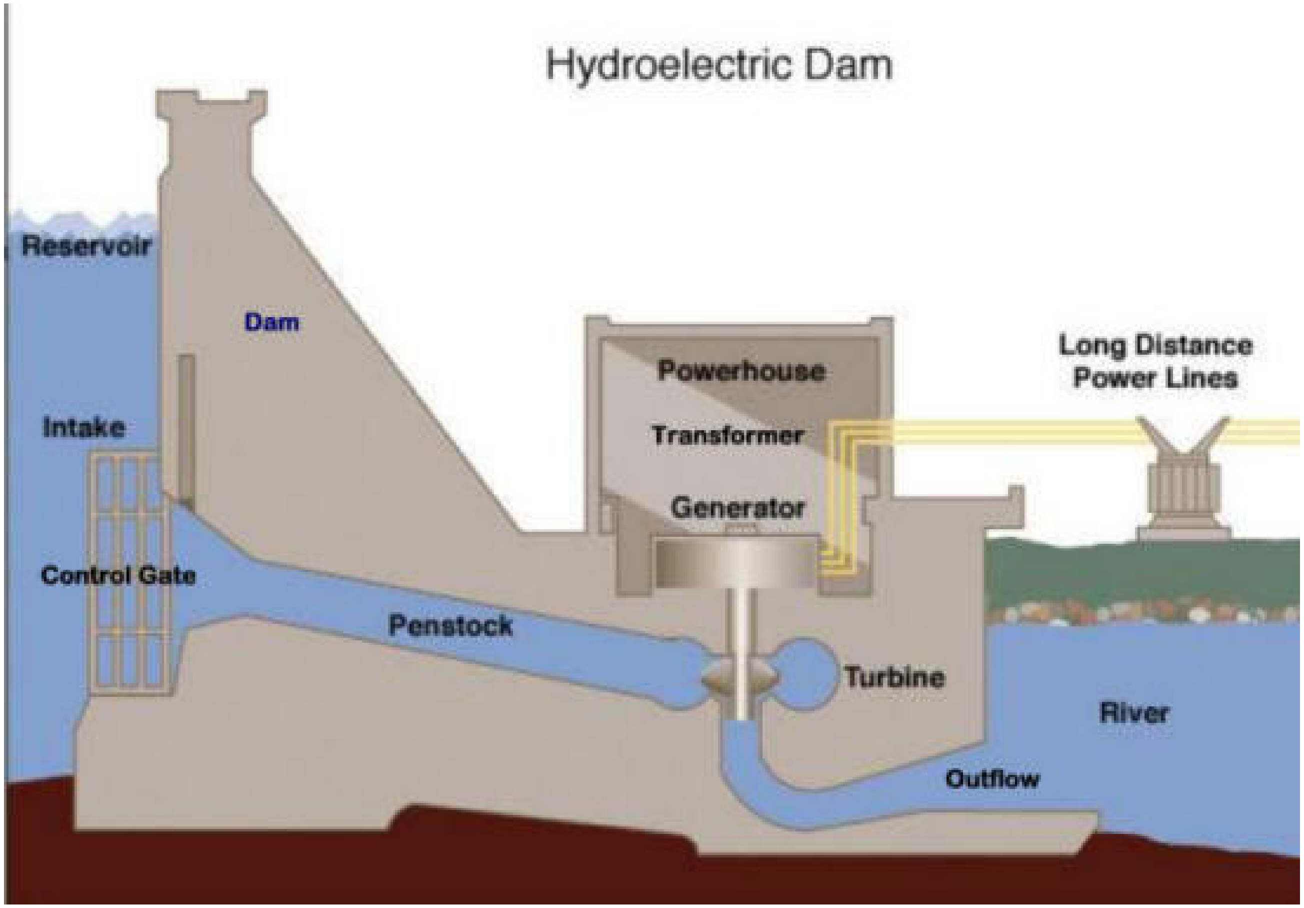


- 3-Phase power is widely used in power distribution grids
- Is needed for heavy industrial machinery
    - Provides for less fluctuation and higher amperage (Power) capability
    - At any given moment one of the phases is nearing or at peak

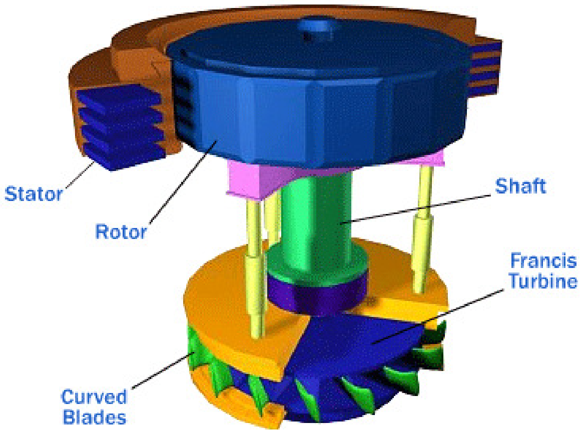
Power Generation, Transmission and Distribution



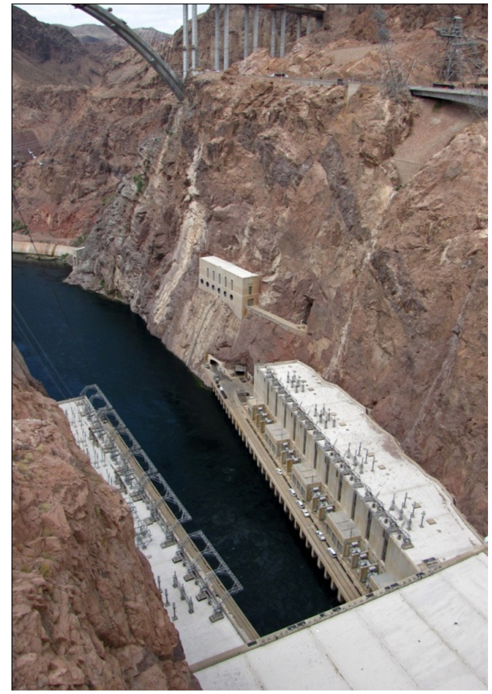
Power Generation



Boulder Dam Generators



Penstock



Power Plants

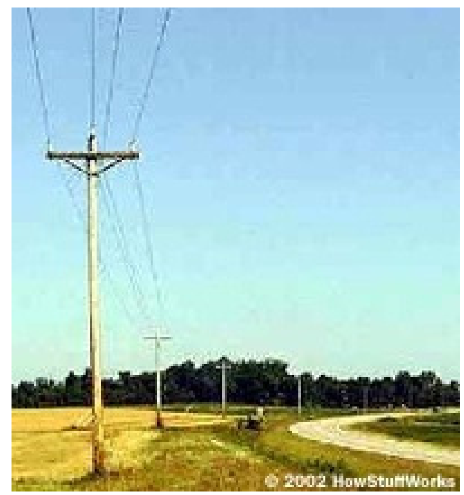
3-Phase Power being Pulled off of Power Plant

Step Up Transformer

Leaking Tunnels in Rock

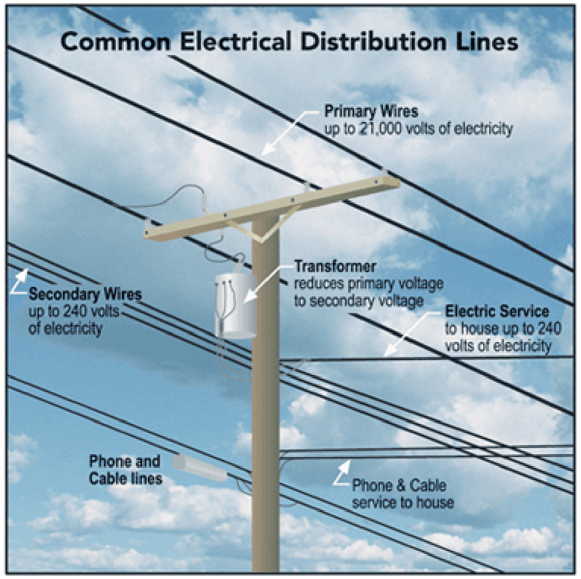
High Voltage Transmission Lines have three wires for the 3-Phase Power

Approx 500KV 3 Phase



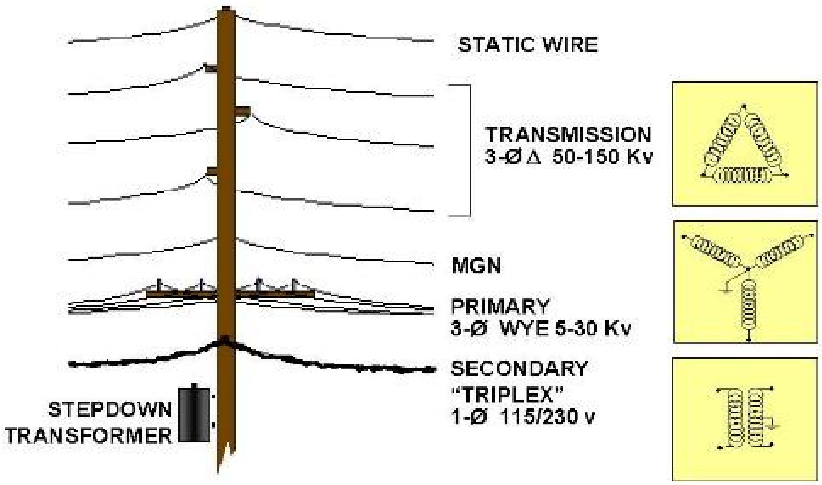
10KV – 27KV 3 Phase

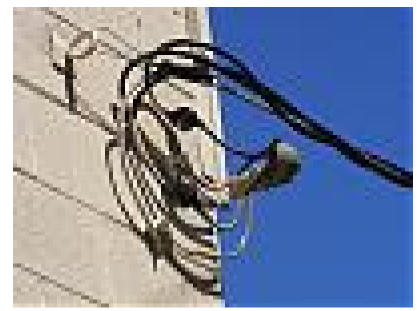
Step Down Substations and Distribution Lines - 3 and Single Phase Power



3-Phase distribution wiring is largely determined by which transformer systems are used and the requirements of the customers

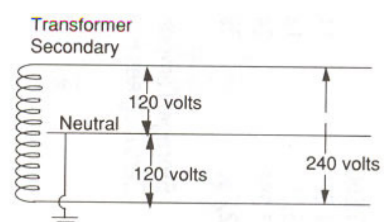
Do Power Transformers Ever Explode?





3-Phase 480V Service Entrance
(4 wires going into "Gooseneck")

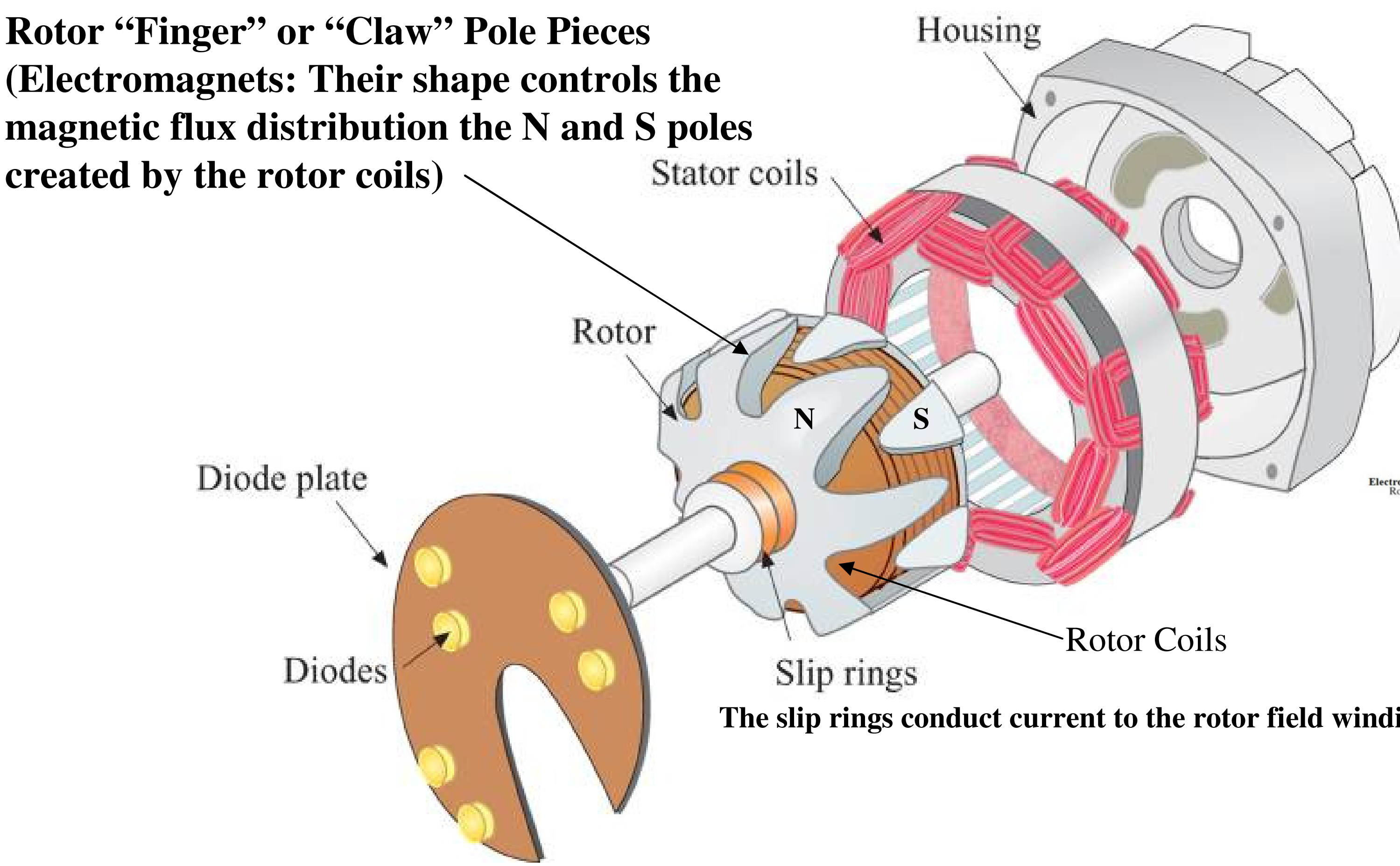
Typical Pole Transformer
12KV ⟶ 240V



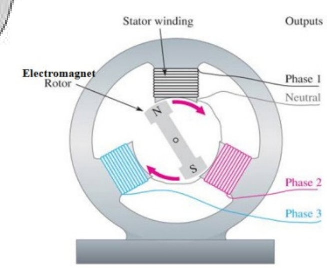
Single Phase, lower voltages can be "tapped" off of the three phases for single-phase house wiring

Single-phase house wiring

Simplified view of a an alternator that ultimately produces DC (Automotive)

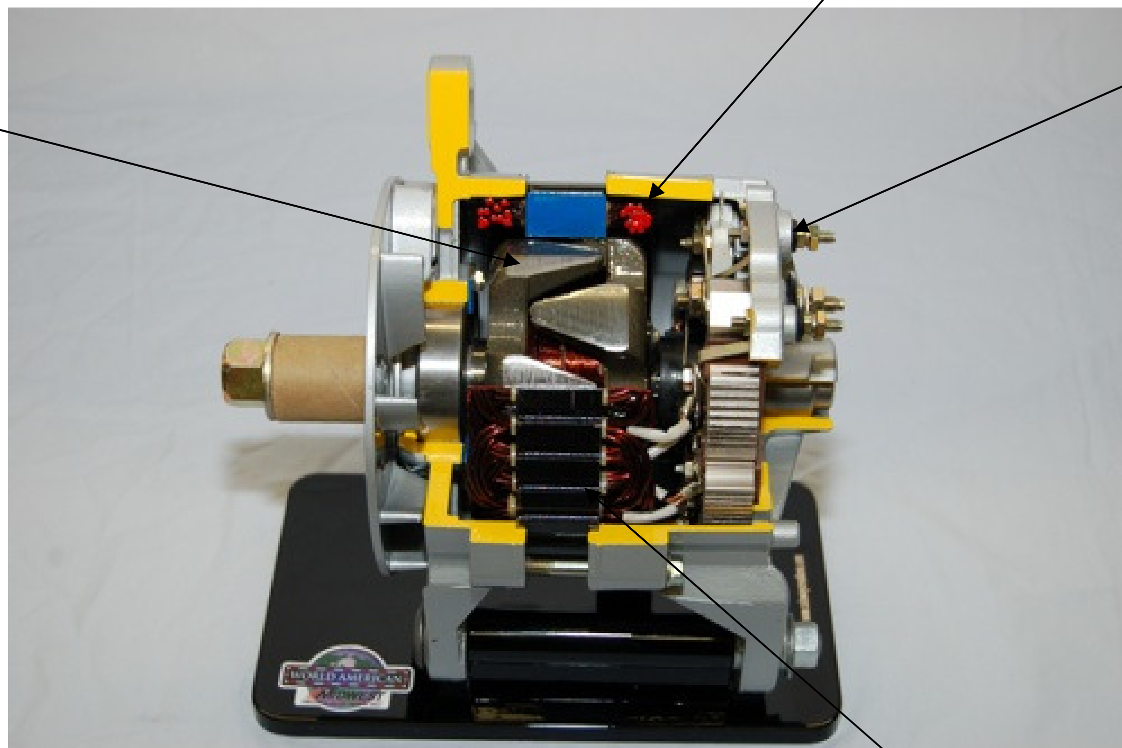


The slip rings conduct current to the rotor field winding



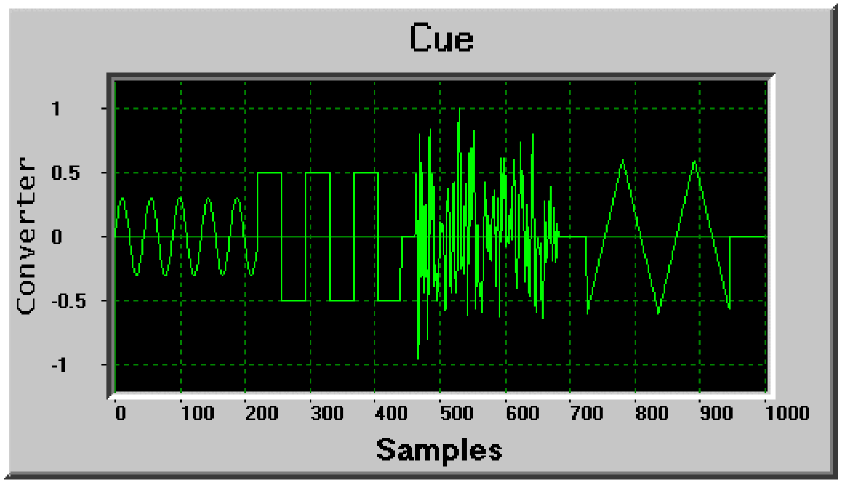
•The alternator produces 3-phase AC voltage but the output voltage is converted to pulsating DC through the diodes (A Diode is a one-way valve for current)

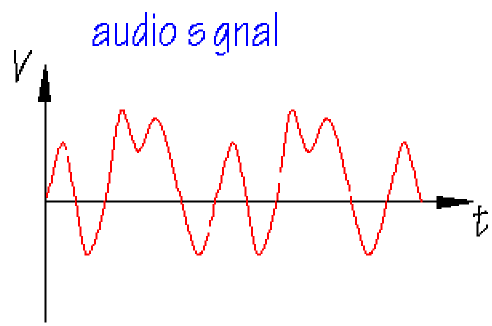
Automotive Alternator

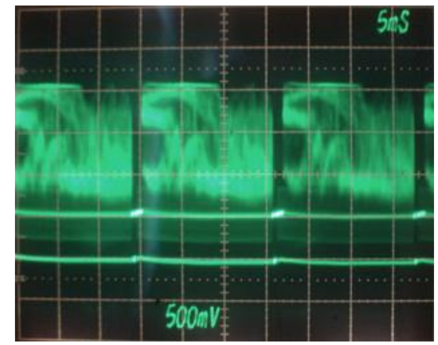


http://auto.howstuffworks.com/alternator.htm

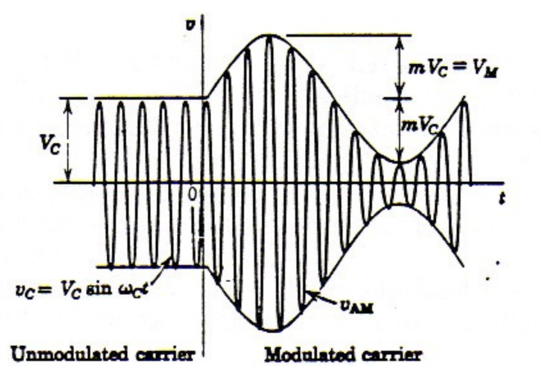
Different Types of Signals

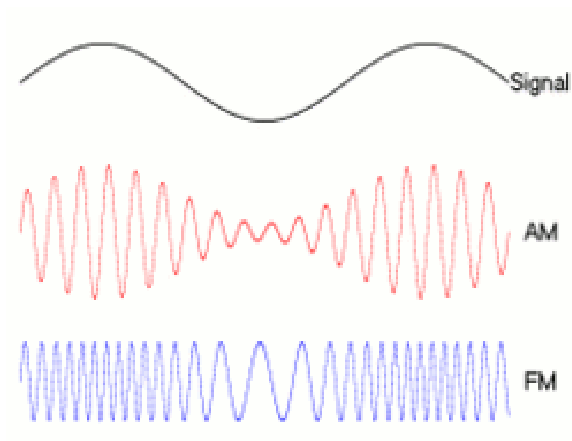






Video Signal





Modulated Signals

Electronic Signal Generators

- In the lab, we usually use a signal generator to produce a variety of waveforms at a wide range of frequencies
  - An oscillator in the signal generator produces the repetitive wave
  - We are able to set the frequency and amplitude of the signal from the signal generator

FIGURE 8-15 Typical signal generators. (Copyright Tektronix, Inc. Reproduced by permission.)

Oscilloscopes are Used to Read Waveform Signals
(Copyright Tektronix, Inc. Reproduced with permission.)

(a)

(b)

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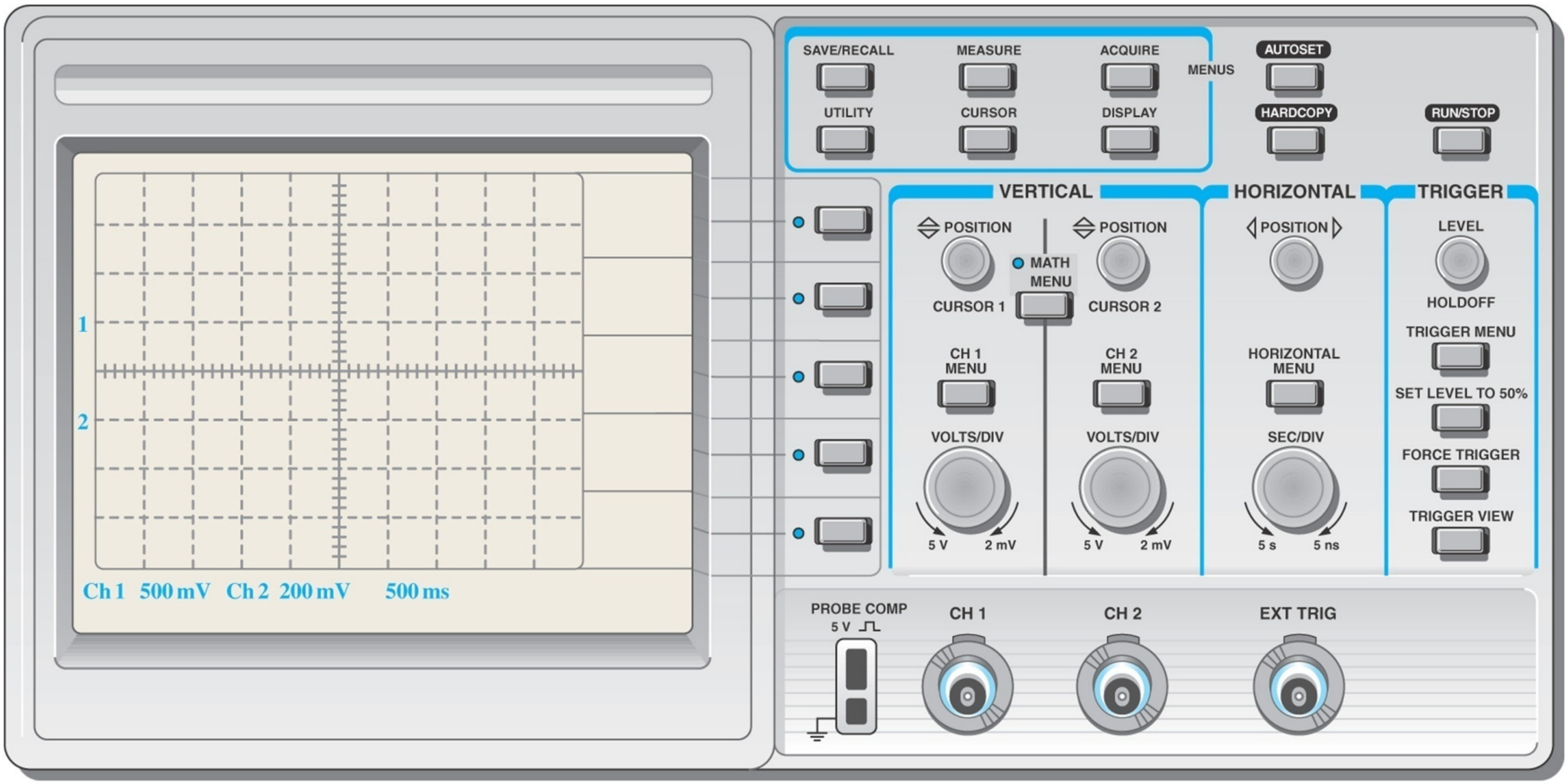
A typical dual-channel Digital oscilloscope
Digital "O'Scopes" allow you to save waveforms and often display the RMS and Frequency values



Waveforms are displayed:

Y-Axis: Voltage Amplitude (Volts/Division)

X-Axis: Time base (Seconds/Division)

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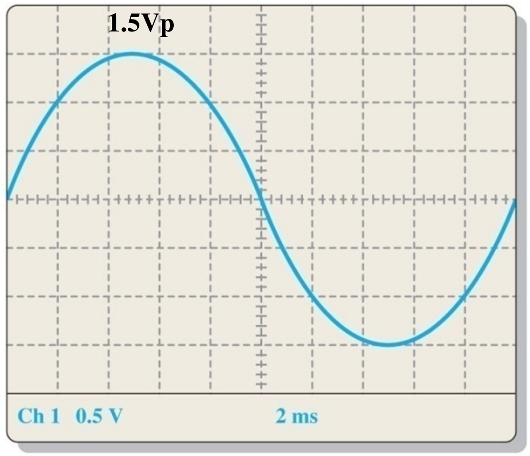
Examples of Different Waveform Readings

The larger the Volts/Division,
The more peak Voltage

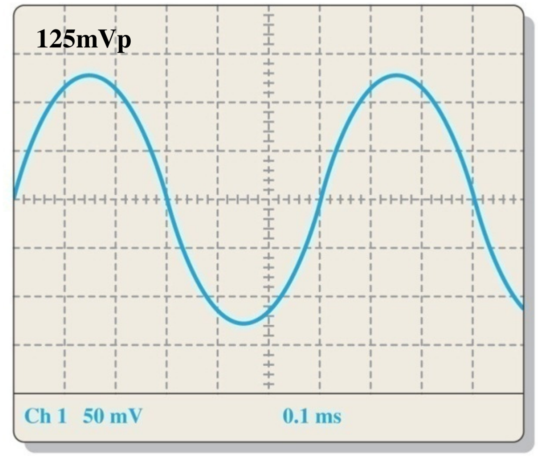
The smaller the Seconds/Division,
The higher the Frequency

3 X 500mV/Div = 1.5Vp
=>1.06Vrms



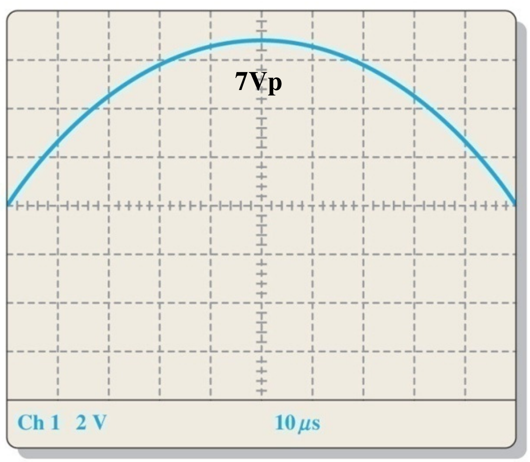
(a) **10 X 2mS/Div = 20mS Period => 50Hz**

2.5 X 50mV/Div = 125mVp
=>70.7mVrms



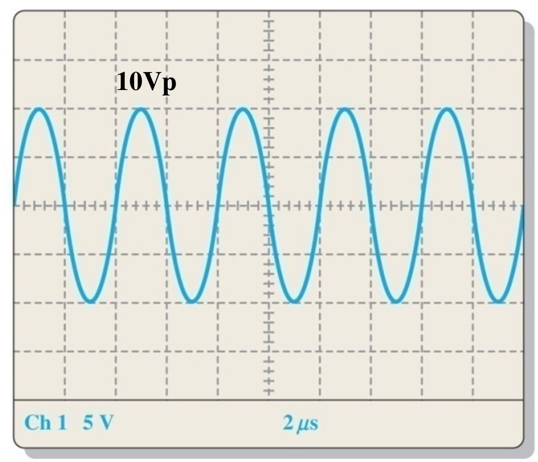
(b) **6 X 100uS/Div = 600uS Period => 1.67kHz**

3.5 X 2V/Div = 7Vp
=>4.95Vrms



(c) **20 X 10uS/Div = 200uS Period => 5kHz**

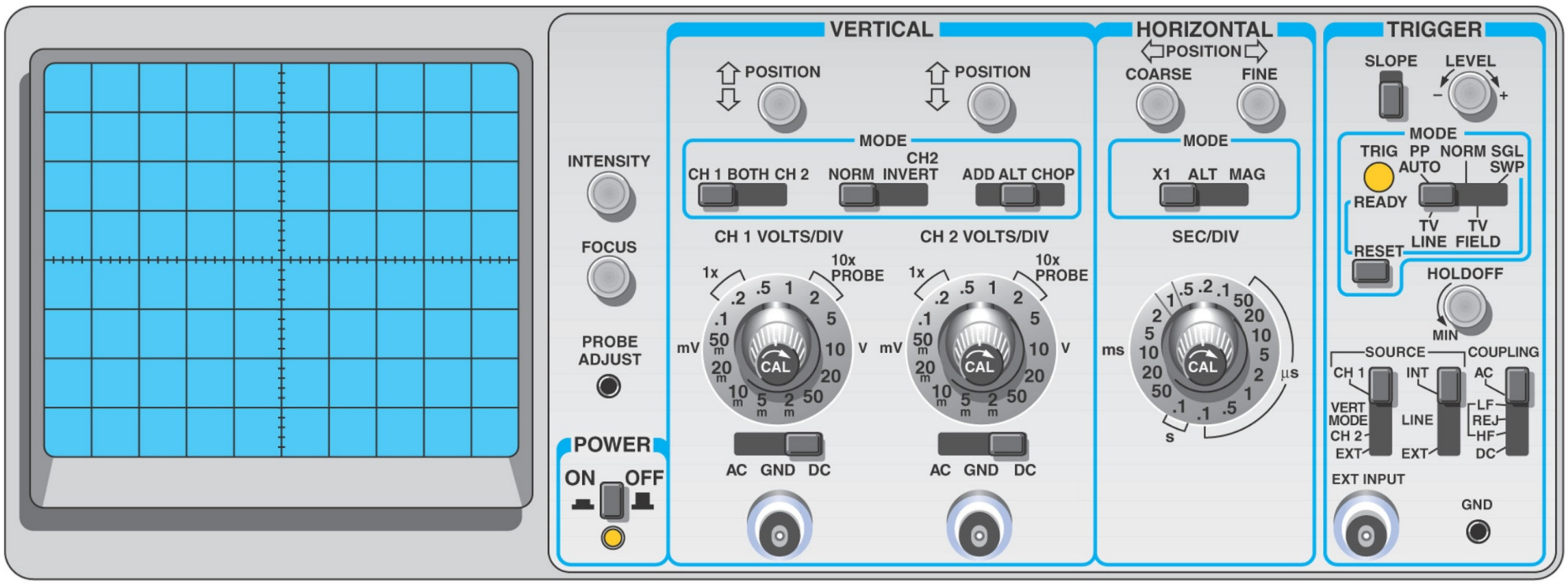
2 X 5V/Div = 10Vp
=>7.07Vrms



(d) **2 X 2uS/Div = 4uS Period => 250kHz**

Sine waves are centered vertically on the screen.

A typical dual-channel *Analog* oscilloscope.



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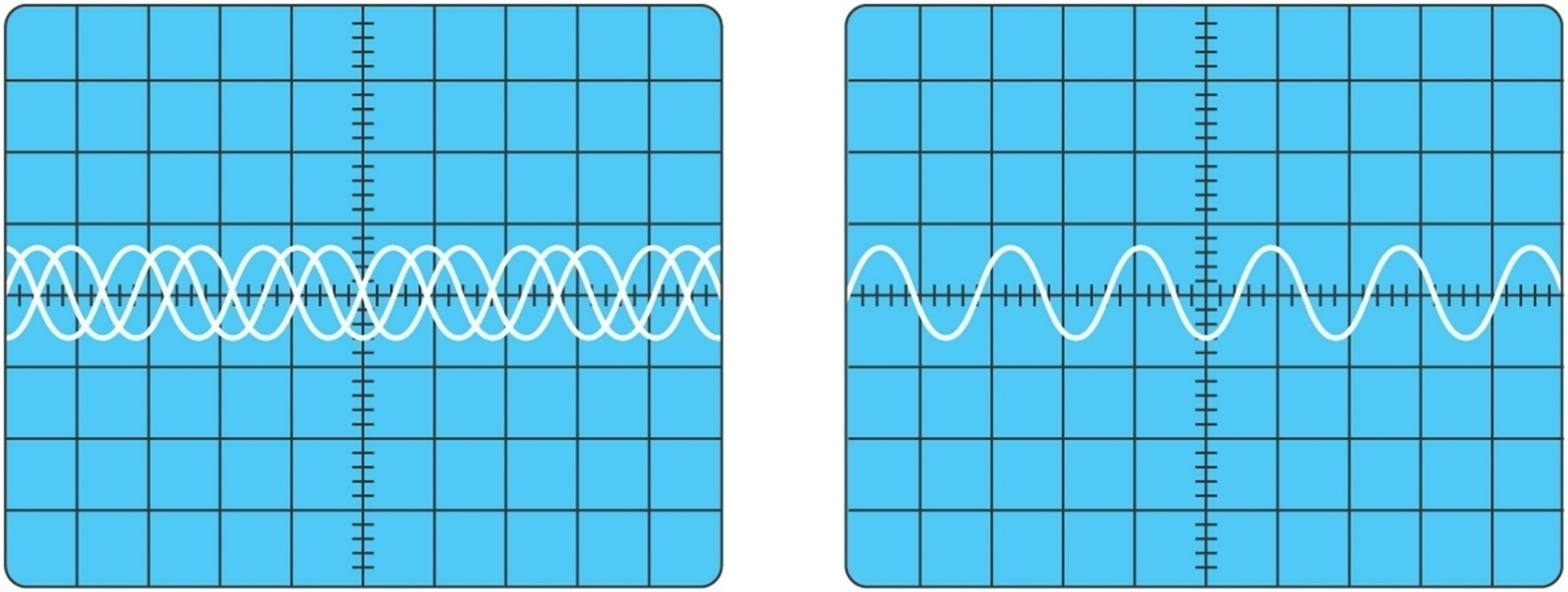
Proper triggering stabilizes a repeating waveform.



(a) Untriggered display (b) Triggered display

- A Trigger is a Reference used to *stabilize* (synchronize) a waveform on the display
- It is commonly where the waveform passes positively through 0V
- An external trigger can also be used to stabilize the waveform at any point