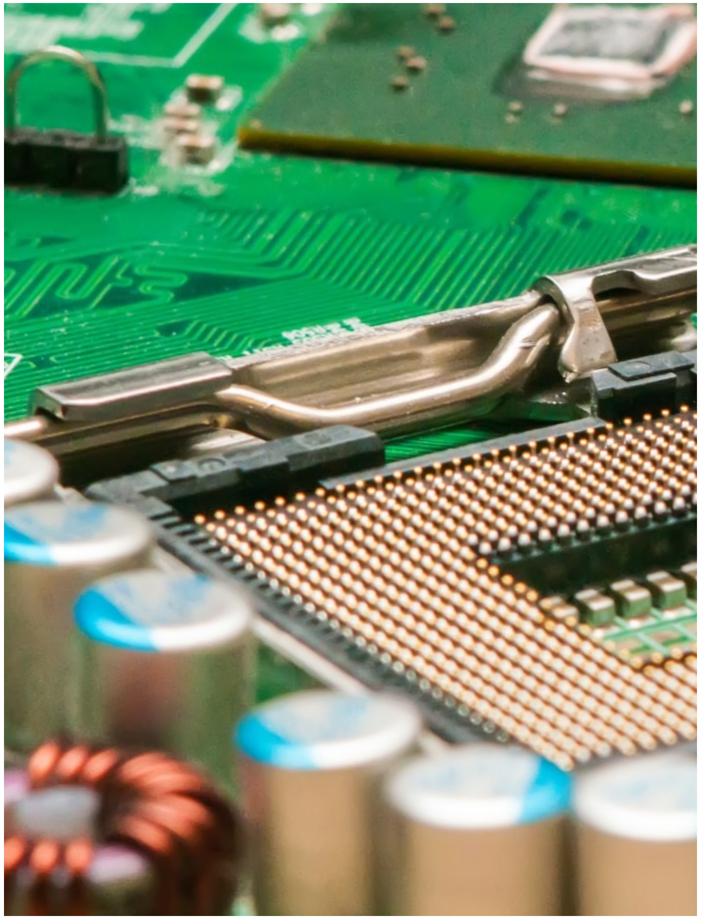
# Fundamentals of Electrical & Electronic Engineering

Prof. John G. Breslin, Electrical & Electronic Engineering



## Lecture 8

Introduction to Alternating Current and Voltage

Ollscoil na Gaillimhe
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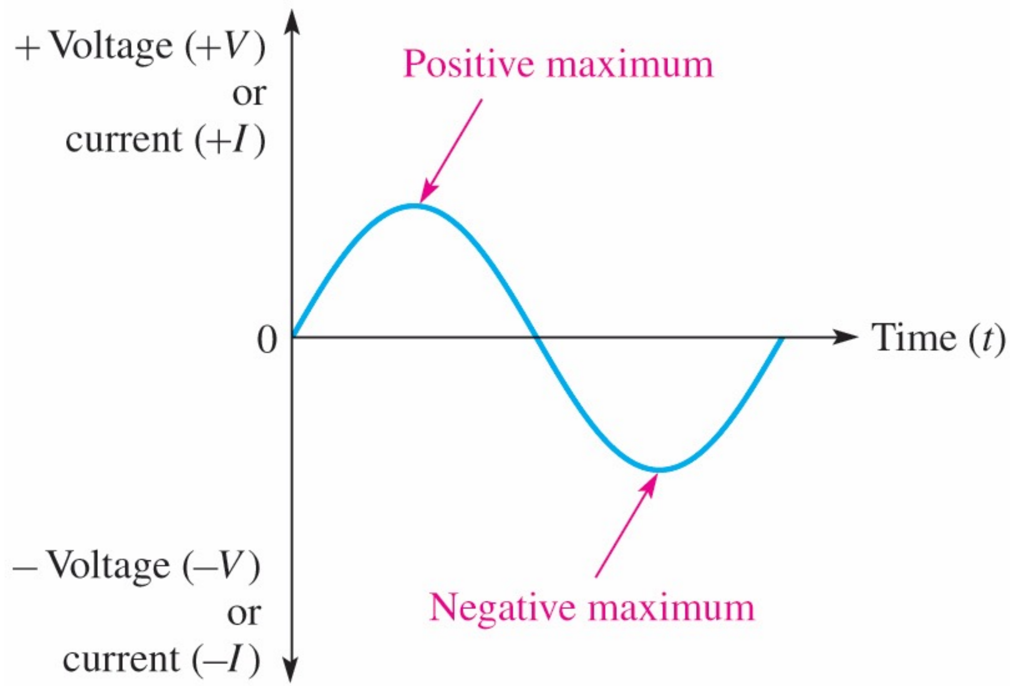
# Summary (1 of 41)

## Sine Waves

The sinusoidal waveform (sine wave) is the fundamental alternating current (ac) and alternating voltage waveform.

Electrical sine waves are named from the mathematical function with the same shape.



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A wave is a disturbance. Unlike water waves, electrical waves cannot be seen directly but they have similar characteristics. All periodic waves can be constructed from **sine waves**, which is why sine waves are fundamental.

# Summary (3 of 41)

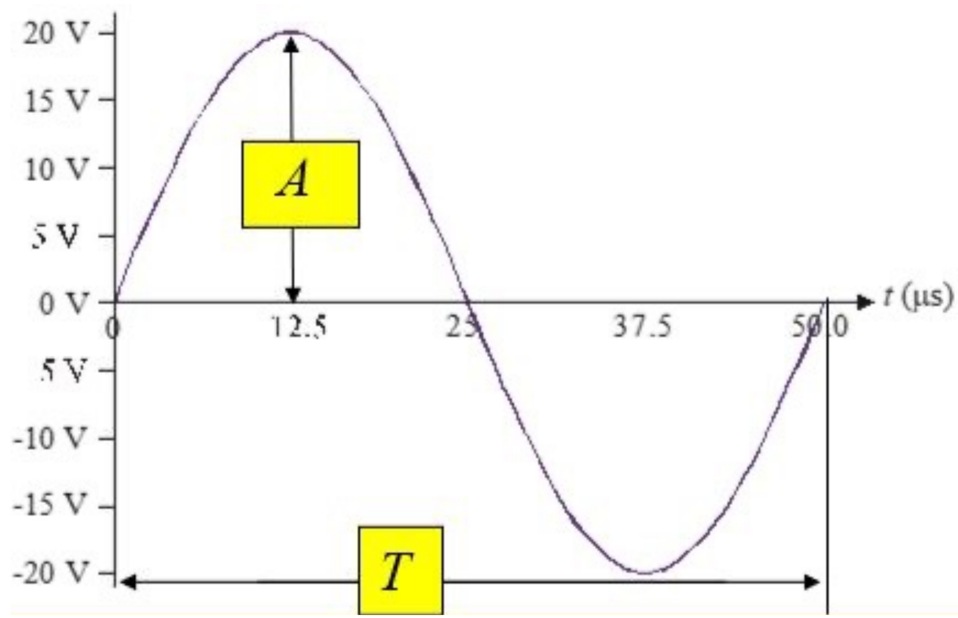
## Sine Waves

Sine waves are characterized by the amplitude and period. The **amplitude** is the maximum value of a voltage or current measured from the mean; the **period** is the time interval for one complete cycle.

**Example**

The amplitude ($A$) of this sine wave is 20 V.

The period is 50.0 μs.



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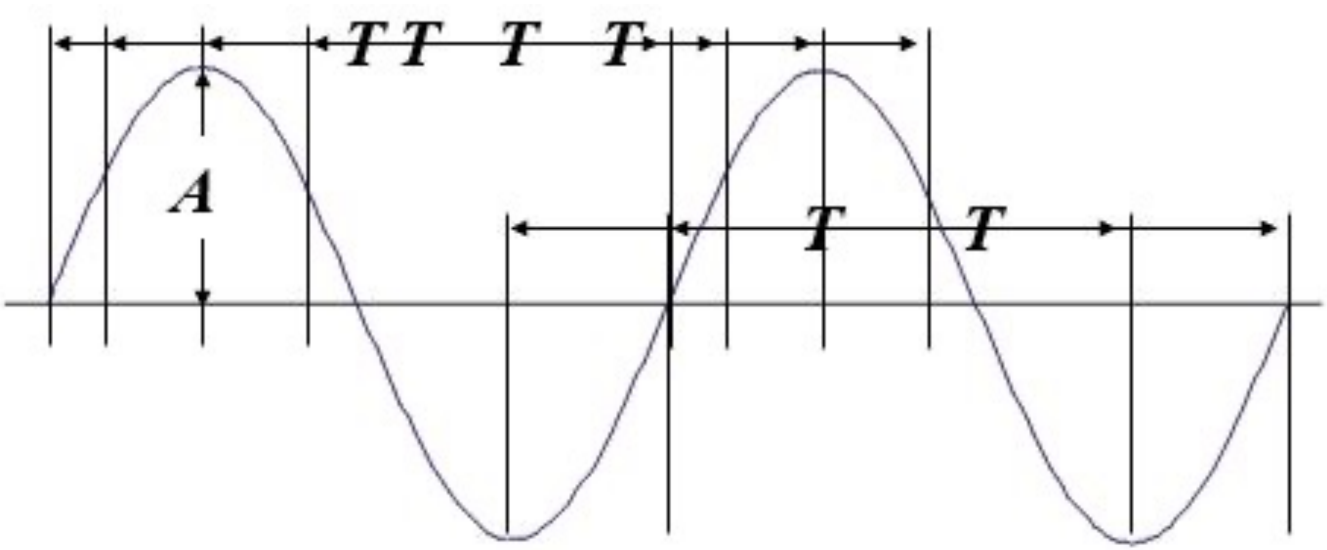
## Sine Waves

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




By contrast, the amplitude of a sine wave is only measured from the center to the maximum point.

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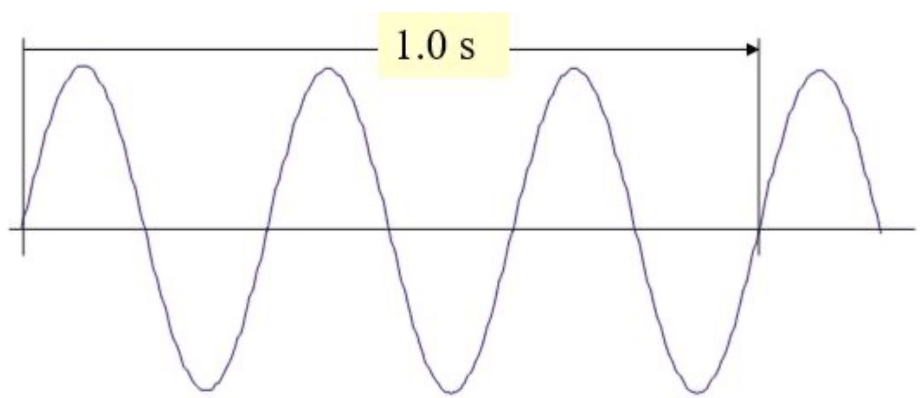
## Frequency

Frequency ( *f* ) is the number of cycles that a sine wave completes in one second. Frequency is measured in **hertz** (Hz)*.

**Example**

If 3 cycles of a wave occur in one second, the frequency is 3.0 Hz.




*Frequency was originally measured in cycles per second (cps) but was changed to honor Heinrich Hertz.

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## Period and Frequency

The period and frequency are reciprocals of each other.

$$f = \frac{1}{T} \qquad \text{and} \qquad T = \frac{1}{f}$$

Thus, if you know one, you can easily find the other.

(The $1/x$ or $x^{-1}$ key on your calculator is handy for converting between $f$ and $T$.)

**Example** If the period is $50\ \mu s$, the frequency is

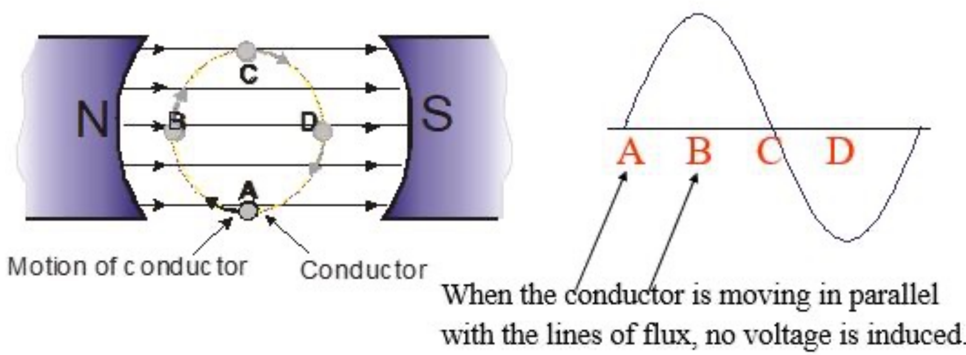
$$f = \frac{1}{T} = \frac{1}{50\ \mu s} = 20\ \text{kHz.}$$

# Summary (7 of 41)

## Generation of a Sine Wave

Sinusoidal voltages are produced by ac generators and electronic oscillators.

When a conductor rotates in a constant magnetic field, a sinusoidal wave is generated.




When the conductor is moving perpendicular to the lines of flux, the maximum voltage is induced.

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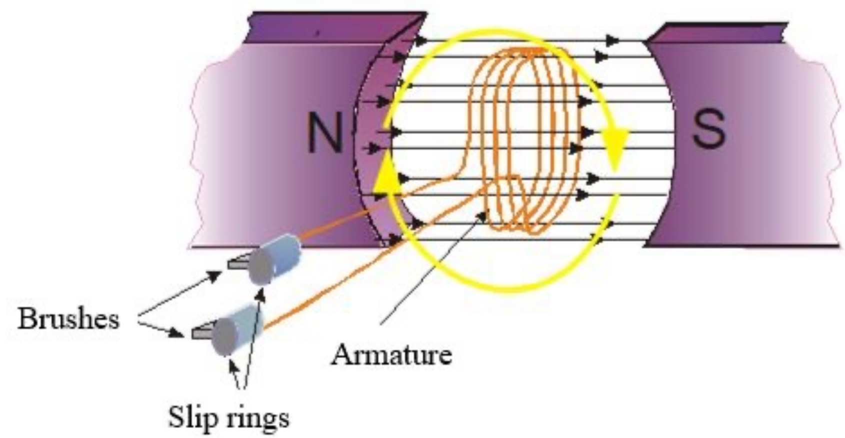
## AC Generator (Alternator)

Generators convert rotational energy to electrical energy. A stationary field alternator with a rotating armature is shown. The armature has an induced voltage, which is connected through slip rings and brushes to a load. The armature loops are wound on a magnetic core (not shown for simplicity).

Small alternators may use a permanent magnet as shown here; other use field coils to produce the magnetic flux.



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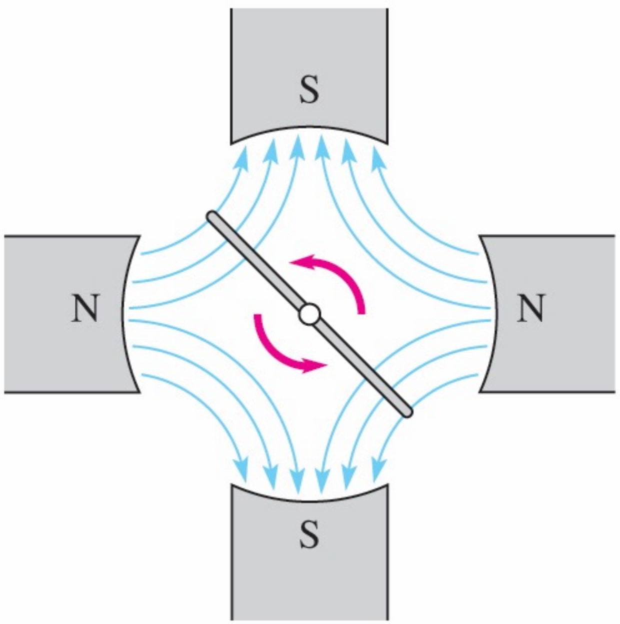
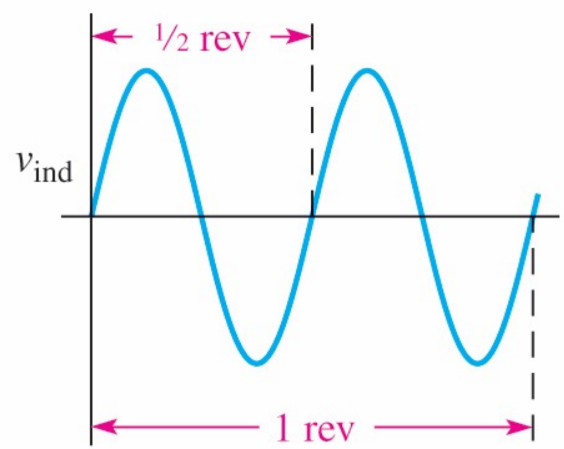
## AC Generator (Alternator)

By increasing the number of poles, the number of cycles per revolution is increased. A four-pole generator will produce two complete cycles in each revolution.



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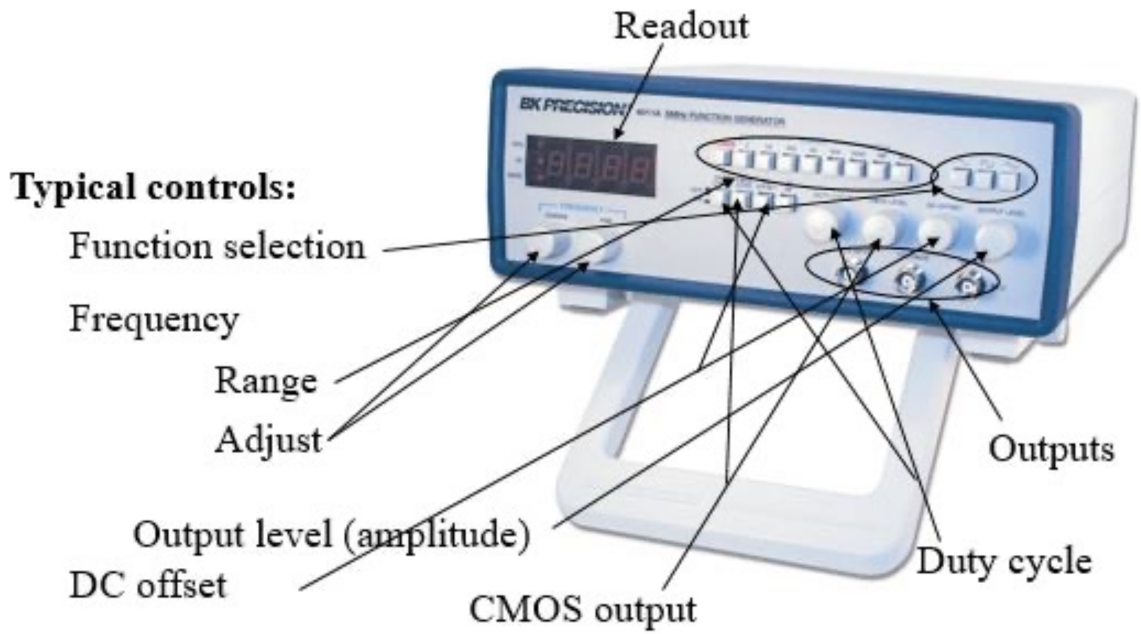
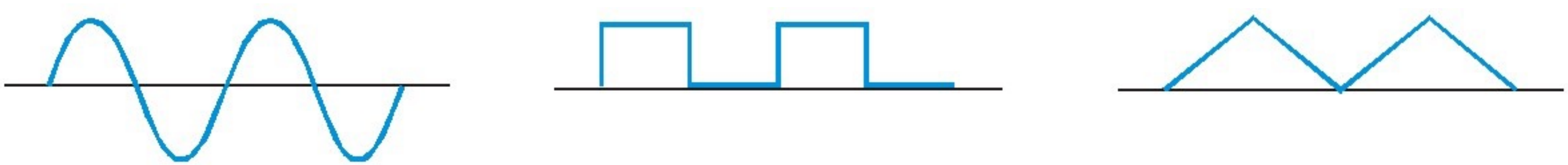
## Function Generators



Sine Square Triangle

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## Function Generators

An arbitrary function generator (AFG) has much more capability than a conventional function generator. The Tektronix AFG1022 (shown) has 50 built-in waveforms with various output modes (repetitive, burst, etc.) and multiple outputs.

A related instrument is the arbitrary waveform generator (AWG). An AWG has even more capability for generating complex waveforms.

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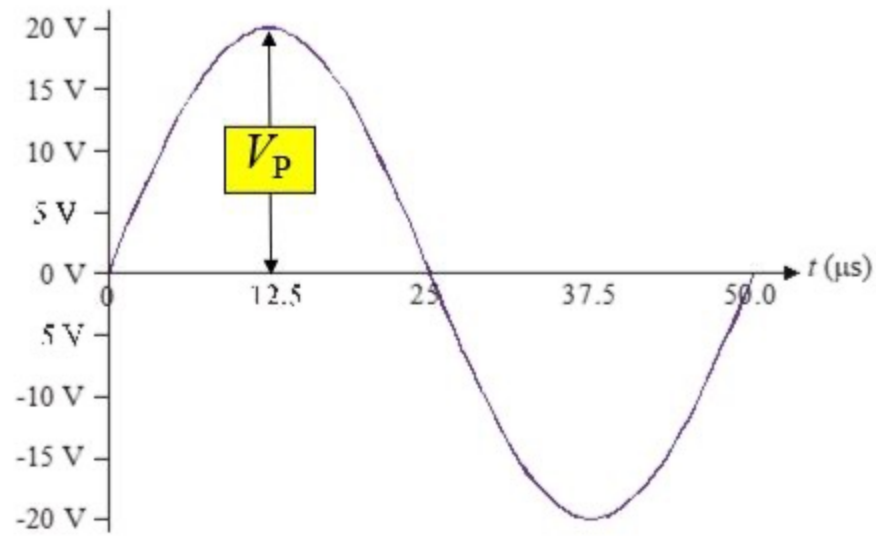
## Sine Wave Voltage and Current Values

There are several ways to specify the voltage of a sinusoidal voltage waveform. The amplitude of a sine wave is also called the peak value, abbreviated as $V_p$ for a voltage waveform.

**Example**

The peak voltage of this waveform is 20 V.



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## Sine Wave Voltage and Current Values

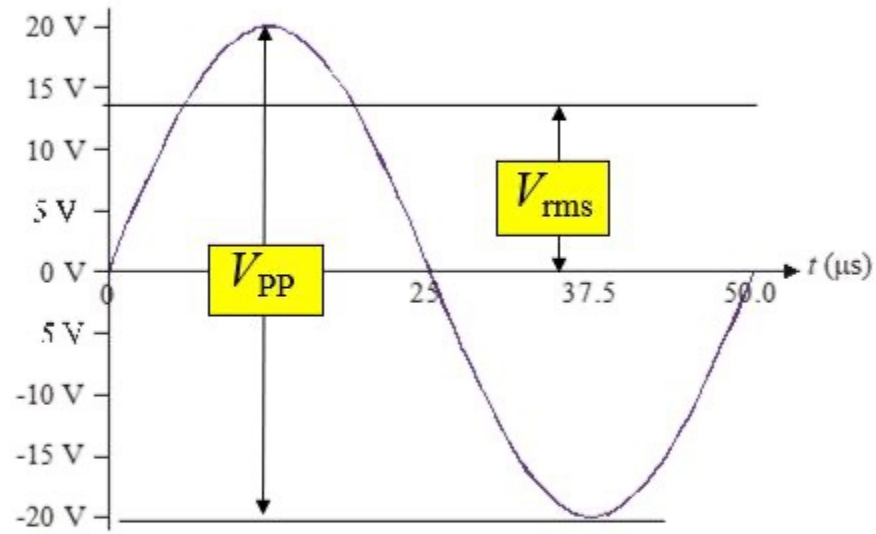
The voltage of a sine wave can also be specified as either the peak-to-peak or the rms value. The peak-to-peak is twice the peak value. The rms value is 0.707 times the peak value.

**Example**

The peak-to-peak voltage is

$40\ V_{PP}$.

The rms voltage is $14.1\ V_{rms}$.



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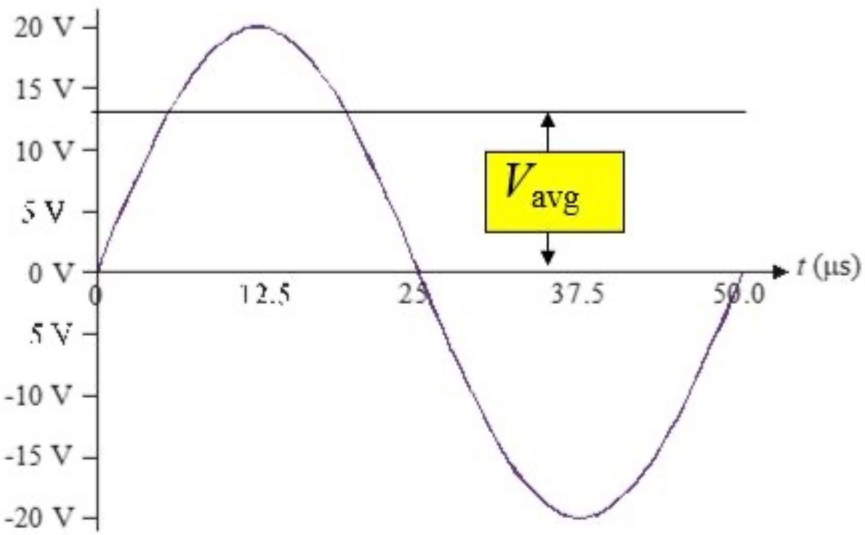
## Sine Wave Voltage and Current Values

For some purposes, the average value (actually the half-wave average) is used to specify the voltage or current. By definition, the average value is as 0.637 times the peak value.

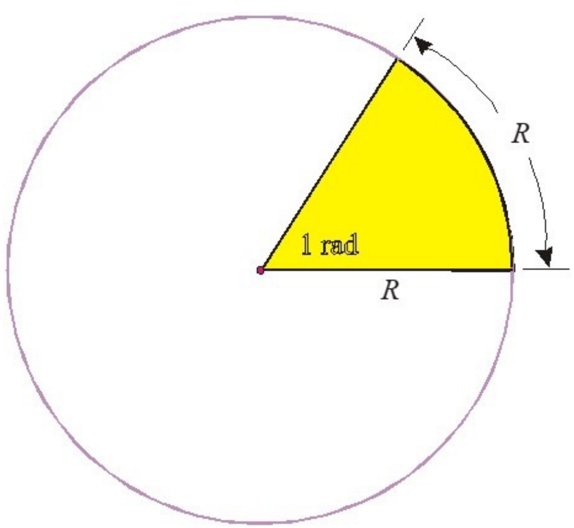
**Example**

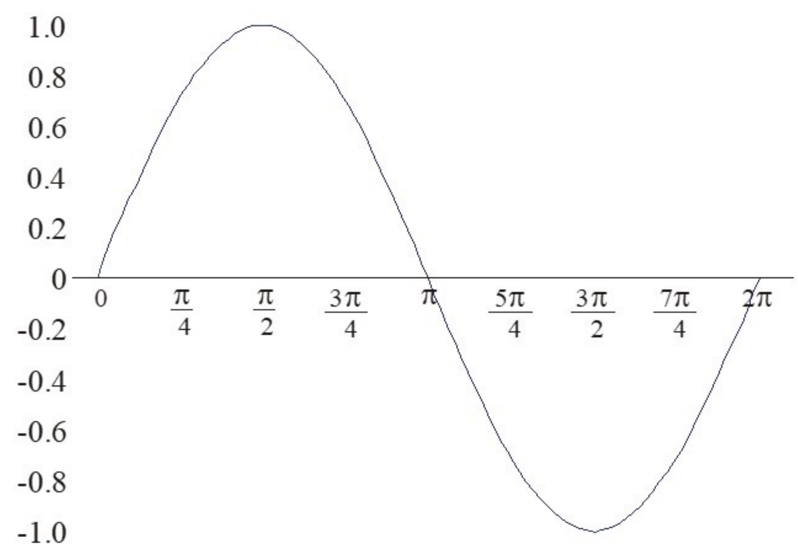
The average value for the sinusoidal voltage is 12.7 V.



## Angular Measurement

Angular measurements can be made in degrees (°) or radians. The radian (rad) is the angle that is formed when the arc is equal to the radius of a circle. There are 360° or $2\pi$ radians in one complete revolution.



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## Angular Measurement

There are $2\pi$ radians in one complete revolution and 360° in one revolution. To find the number of radians, given the number of degrees:

$$\text{rad} = \frac{2\pi\ \text{rad}}{360°} \times \text{degrees}$$

This can be simplified to: $\text{rad} = \dfrac{\pi\ \text{rad}}{180°} \times \text{degrees}$

To find the number of degrees, given the number of radians:

$$\text{deg} = \frac{180°}{\pi\ \text{rad}} \times \text{rad}$$

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## Angular Measurement

**Example** How many radians are in 45°?

## Sine Wave Equation

Instantaneous values of a wave are shown as $v$ or $i$. The equation for the instantaneous voltage ($v$) of a sine wave is

$$v = V_p \sin\theta$$

where

$V_p$ = peak voltage

$\theta$ = angle in rad or degrees

**Example**

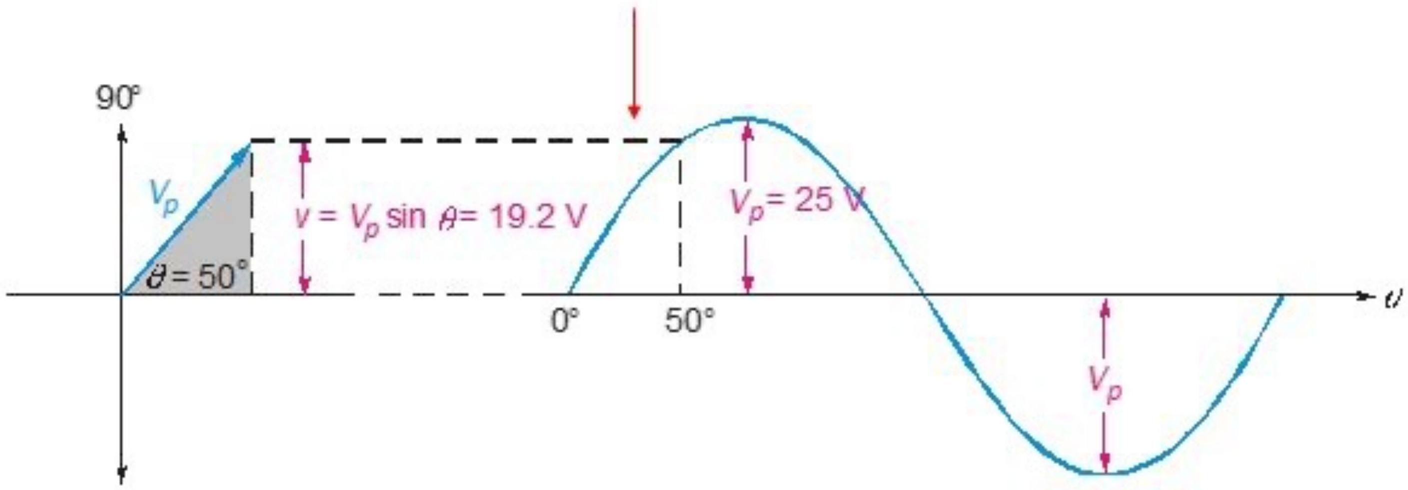
If the peak voltage is 25 V, the instantaneous voltage at 50 degrees is 19.2 V.

What is this angle in radians? 0.873 rad.

# Summary (19 of 41)

## Sine Wave Equation

A plot of the example in the previous slide (peak at 25 V) is shown. The instantaneous voltage at 50° (or 0.873 rad) is 19.2 V as previously calculated.



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## Phase Shift

The phase of a sine wave is an angular measurement that specifies the position of a sine wave relative to a reference. To show that a sine wave is shifted to the left or right of this reference, a term, called the phase shift, is added to the equation given previously.

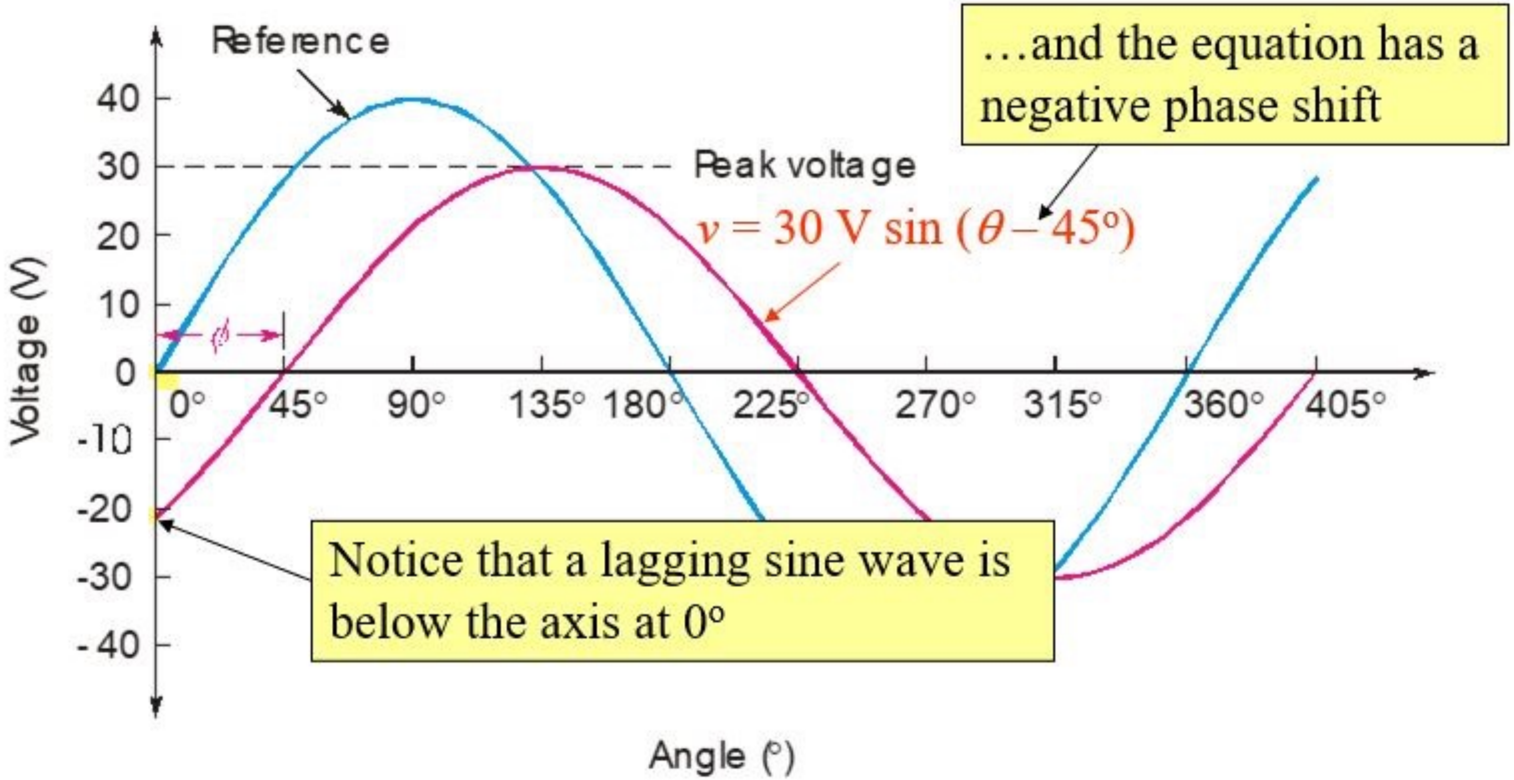
$$v = V_{P}\sin(\theta \pm \phi)$$

where

$$\phi = \text{phase shift}$$

## Phase Shift

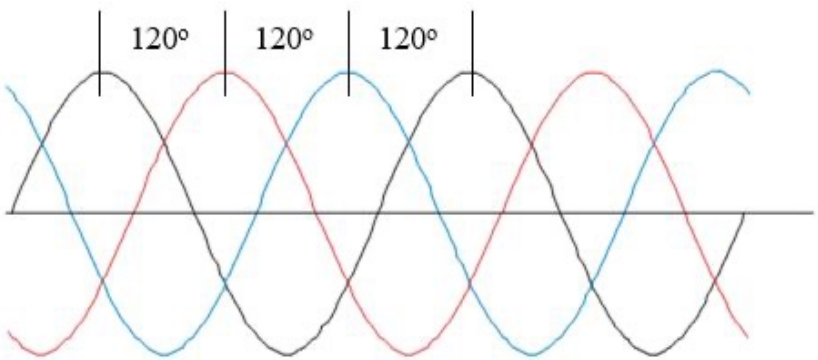
Example of a wave that lags the reference:



### Phase Shift

An important application of phase-shifted sine waves is in electrical power systems. Electrical utilities generate ac with three phases that are separated by 120° as illustrated.

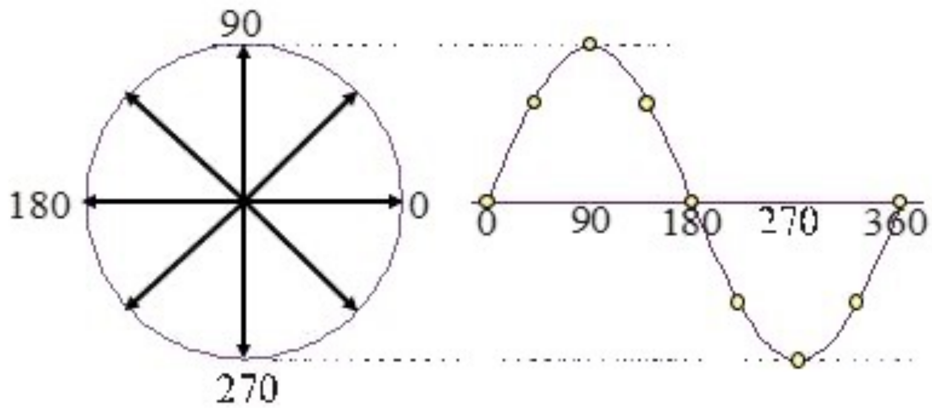
Normally, 3-phase power is delivered to the user with three hot lines plus neutral. The voltage of each phase, with respect to neutral is 120 V.



# Summary 

## Phasors

The sine wave can be represented as the projection of a vector rotating at a constant rate. This rotating vector is called a **phasor**.




One complete rotation represents one cycle, so the rate of rotation represents the frequency of the sine wave.

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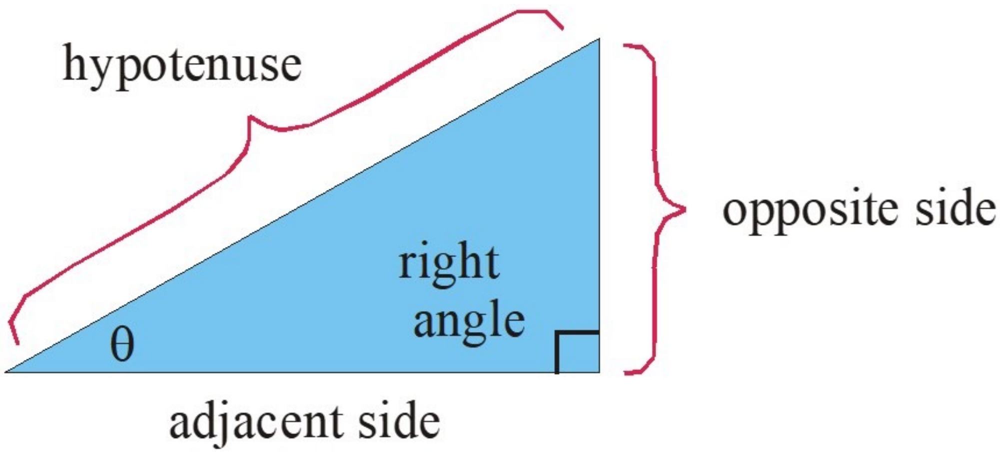
## Phasors

Phasors allow ac calculations to use basic trigonometry. The sine function in trigonometry is the ratio of the opposite side of a right triangle to the hypotenuse.




$$\sin\theta = \frac{\text{opposite side}}{\text{hypotenuse}}$$

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## Analysis of AC Circuits

Resistive ac circuits are analyzed with the same circuit laws and power formulas as for dc circuits including Ohm's law and Kirchhoff's laws. With ac circuits, voltage and current must be expressed consistently.

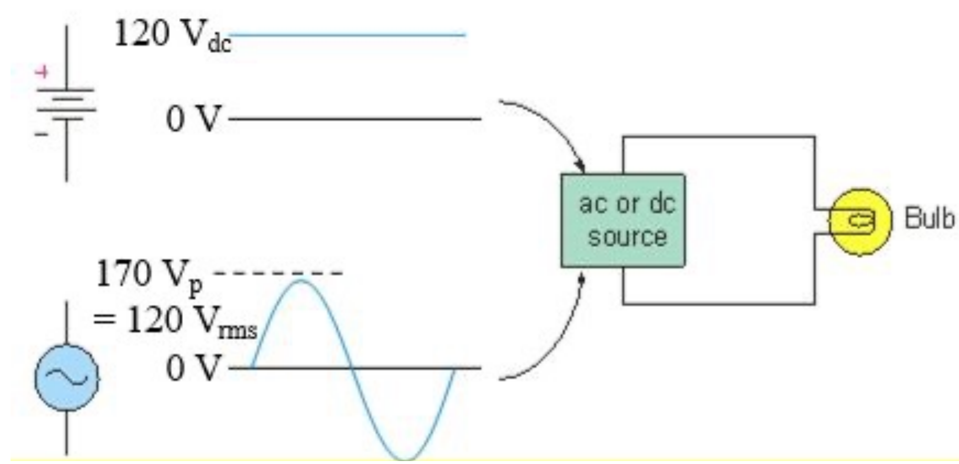
Watt's law must be applied using rms values. A review of Watt's law as written for ac circuit is shown in the box. When specifying ac as rms values, ac or dc sources will produce the same power to a given load.

Watts law:

$$P = V_{rms} I_{rms}$$

$$P = \frac{V_{rms}^2}{R}$$

$$P = I_{rms}^2 R$$



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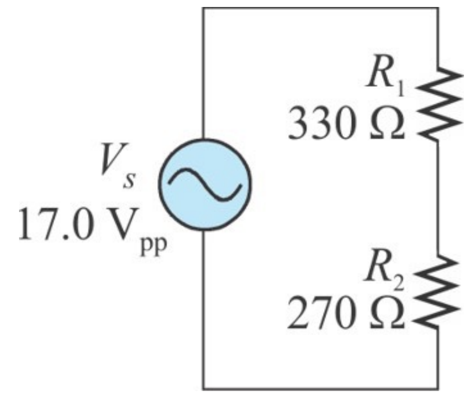
## Analysis of AC Circuits

**Example** Calculate the power in $R_2$.




To calculate power, you need to use rms values.

Converting $V_S$ :

$$V_S = \frac{(17.0\ \mathrm{V_{pp}})}{2.828} = 6.01\ \mathrm{V_{rms}}$$

Use the voltage-divider rule to find $V_2$ :

$$V_2 = V_S \frac{R_2}{(R_1 + R_2)} = 6.01\ \mathrm{V} \frac{270\ \Omega}{(330\ \Omega + 270\ \Omega)} = 2.71\ \mathrm{V}$$

Apply Watt's law to find $P_2$ : $P_2 = \frac{V_2^2}{R_2} = \frac{(2.71\ \mathrm{V})^2}{270\ \Omega} = 27.1\ \mathrm{mW}$



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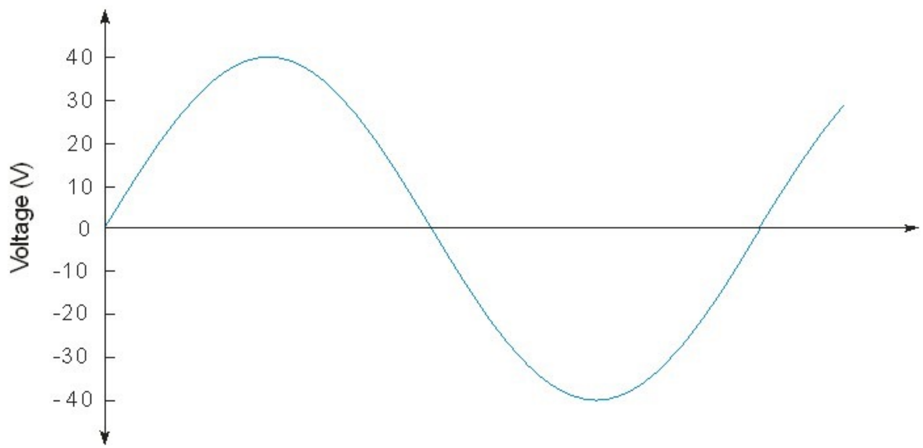
## Analysis of AC Circuits

**Example** Assume a sine wave with a peak value of 40 V is applied to a $100\,\Omega$ resistive load. What power is dissipated?




**Solution** $V_{rms} = 0.707 \times V_p = 0.707 \times 40\ \text{V} = 28.3\ \text{V}$

$$P = \frac{V_{rms}^2}{R} = \frac{28.3\ \text{V}^2}{100\,\Omega} = 8.0\ \text{W}$$



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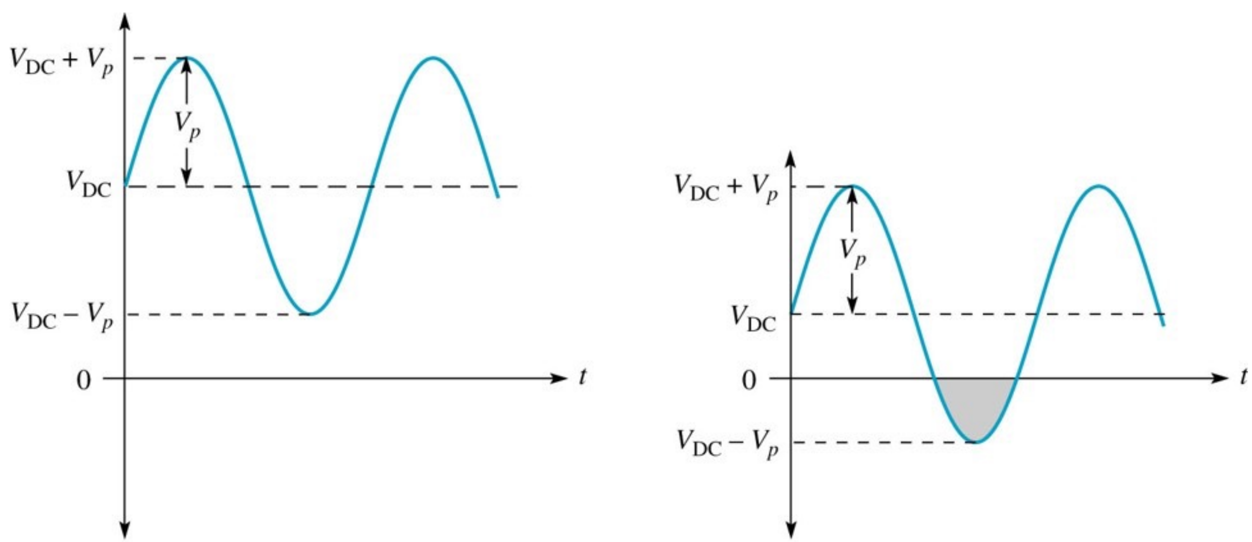
## Superimposed dc and ac voltages

Frequently dc and ac voltages are together in a waveform. They can be added algebraically, to produce a composite waveform of an ac voltage "riding" on a dc level.




(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, as indicated by the gray area.

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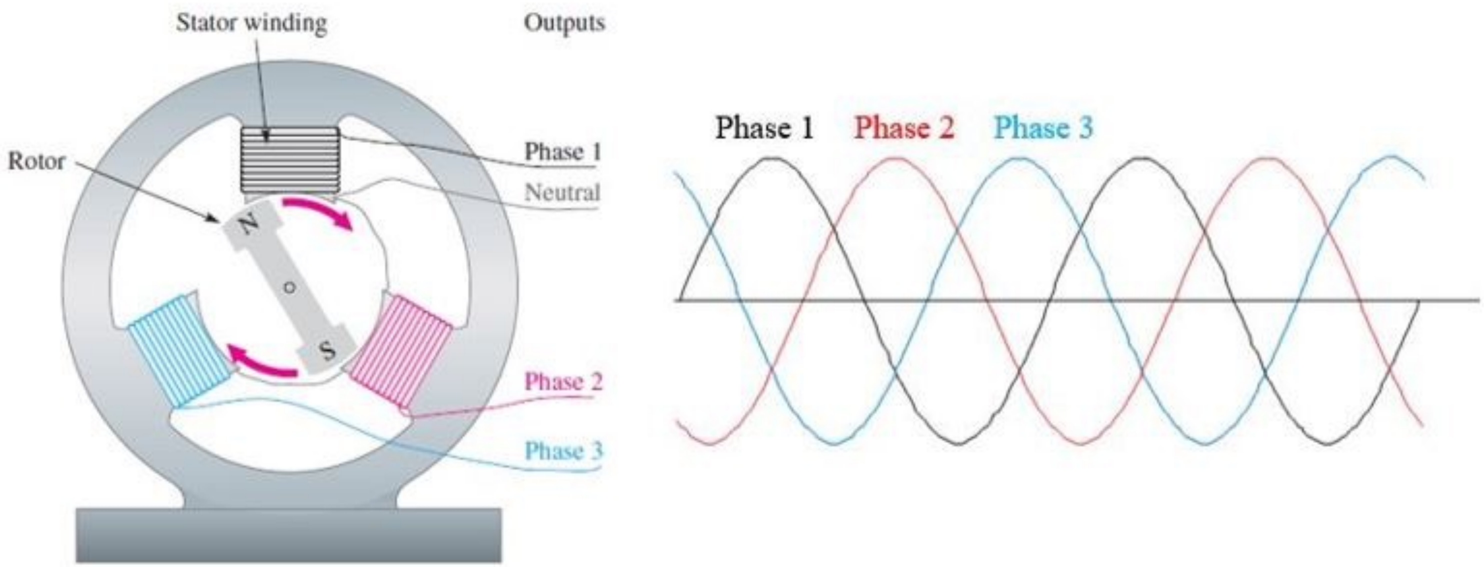
## Alternators

Alternators are ac generators. Utility companies use three-phase alternators and deliver all three phases to industrial customers. A simplified three-phase alternator is illustrated.



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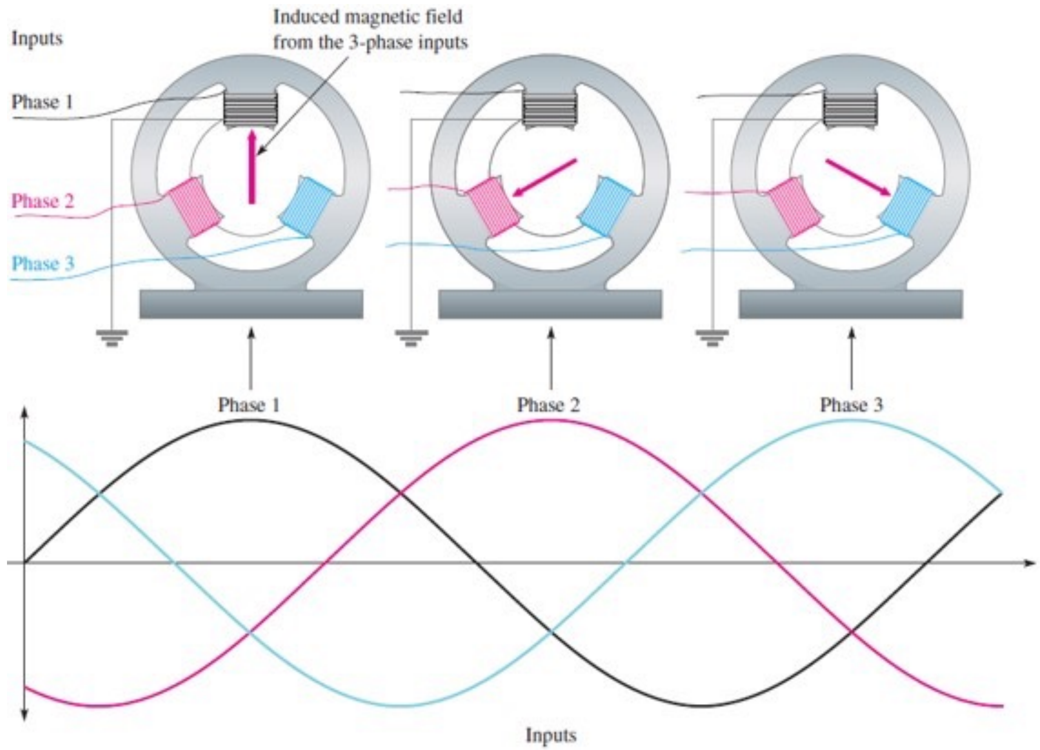
## Alternators

The magnetic field of a three-phase alternator rotates as illustrated here.







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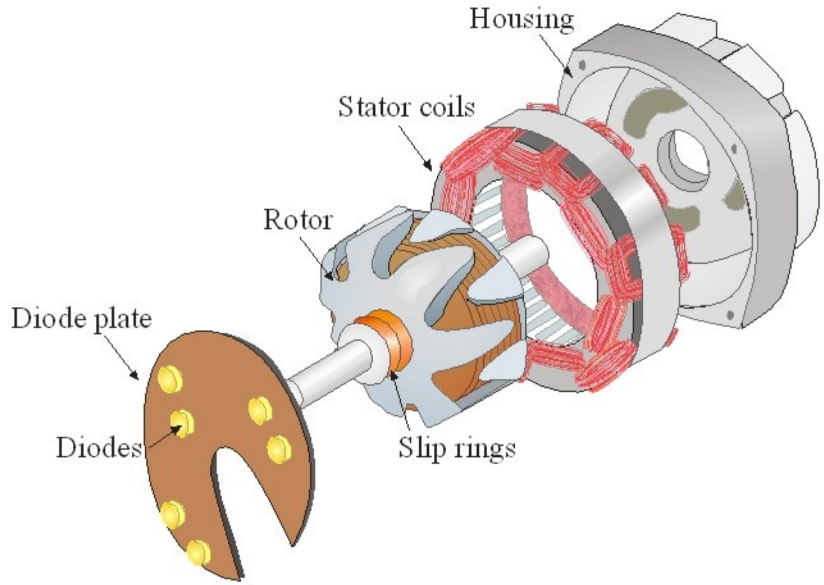
## Alternators

In vehicles, alternators generate ac, which is converted to dc for operating electrical devices and charging the battery. A basic vehicle alternator is illustrated. AC is more efficient to produce and can be easily regulated, hence it is generated and converted to dc by diodes.

The output is taken from the rotor through the slip rings.



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## AC Motors

There are two major classifications of ac motors. These are the **induction motor** and the **synchronous motor**. Both types use a rotating field in the stator windings.

Induction motors work because current is induced in the rotor by the changing current in the stator. This current creates a magnetic field that reacts with the moving field of the stator, which develops a torque and causes the rotor to turn.

Synchronous motors have a magnet for the rotor. In small motors, this can be a permanent magnet, which keeps up with the rotating field of the stator. Large motors use an electromagnet in the rotor, with external dc supplied to generate the magnetic field.

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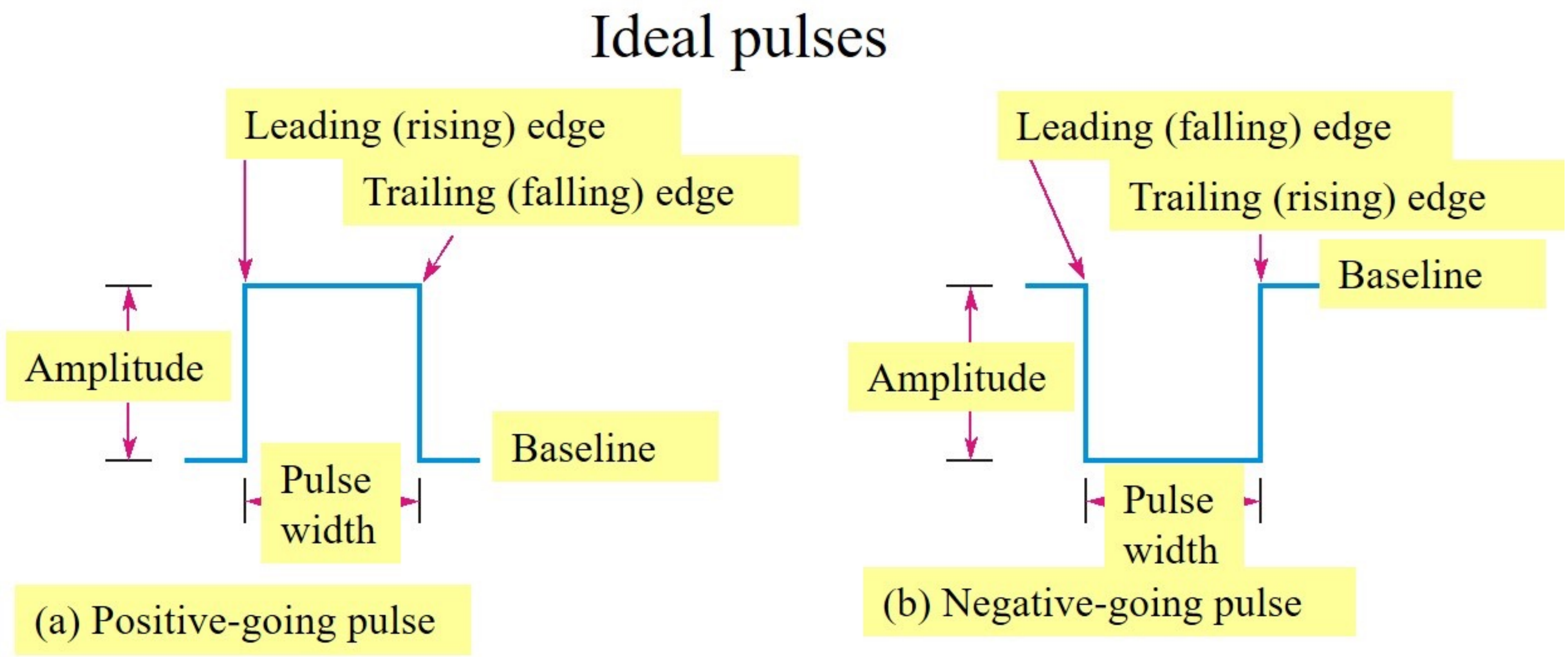
## Pulse Definitions



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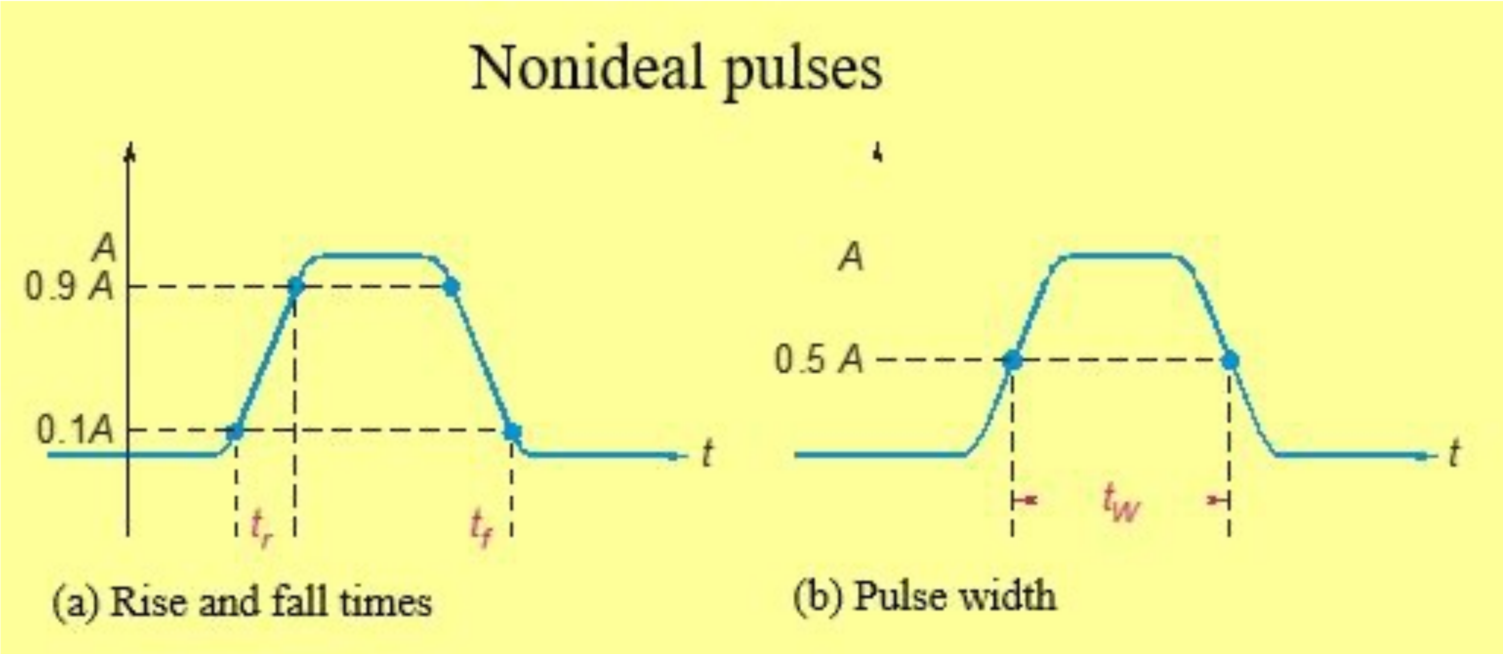
## Pulse Definitions




Notice that rise and fall times are measured between the 10% and 90% levels whereas pulse width is measured at the 50% level.

## Triangular and Sawtooth Waves

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 duration.

The sawtooth waveform consists of two ramps, one of much longer duration than the other.

## Harmonics

All repetitive nonsinusoidal waveforms are composed of a **fundamental frequency** (repetition rate of the waveform) and **harmonic frequencies**.

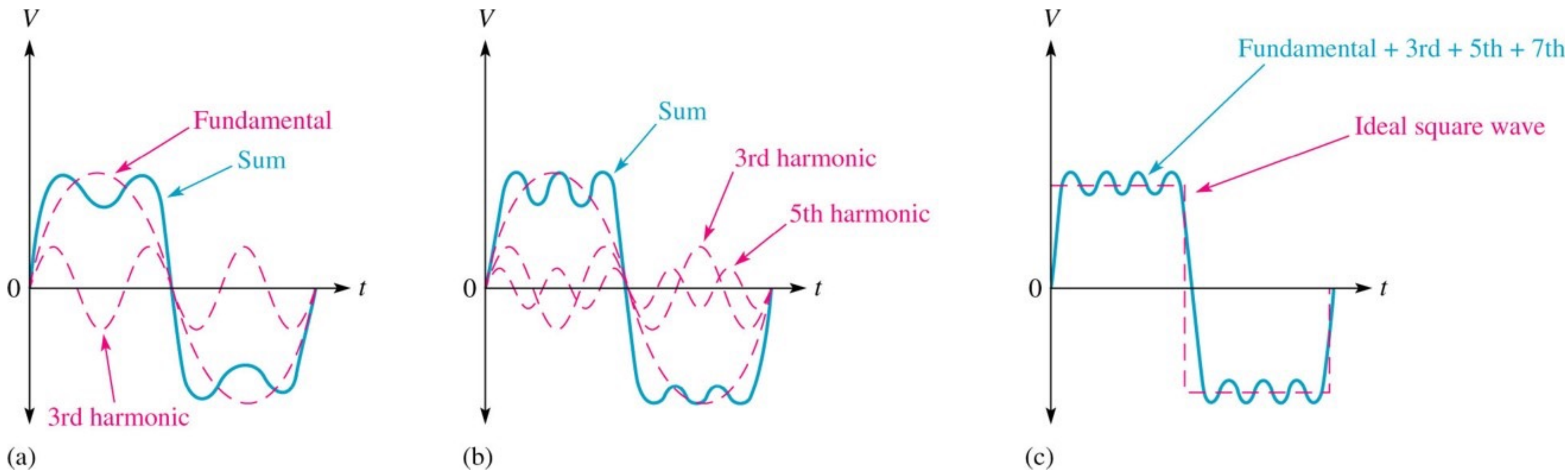
**Odd harmonics** are frequencies that are odd multiples of the fundamental frequency.

**Even harmonics** are frequencies that are even multiples of the fundamental frequency.

# Summary (37 of 41)

## Harmonics

A square wave is composed only of the fundamental frequency and odd harmonics (of the proper amplitude).



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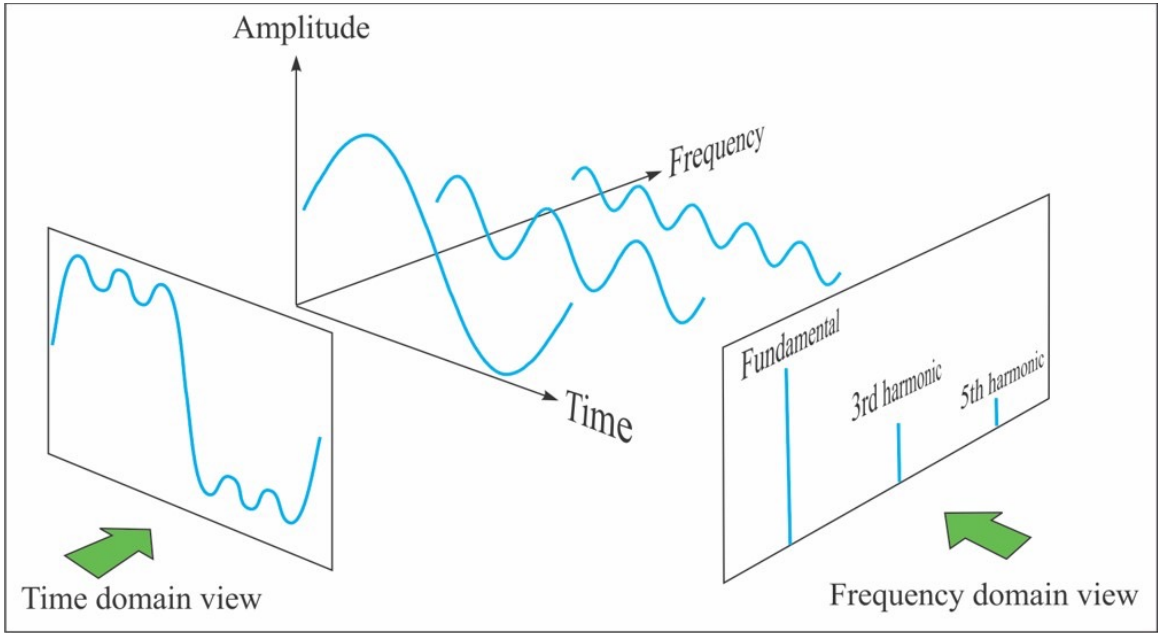
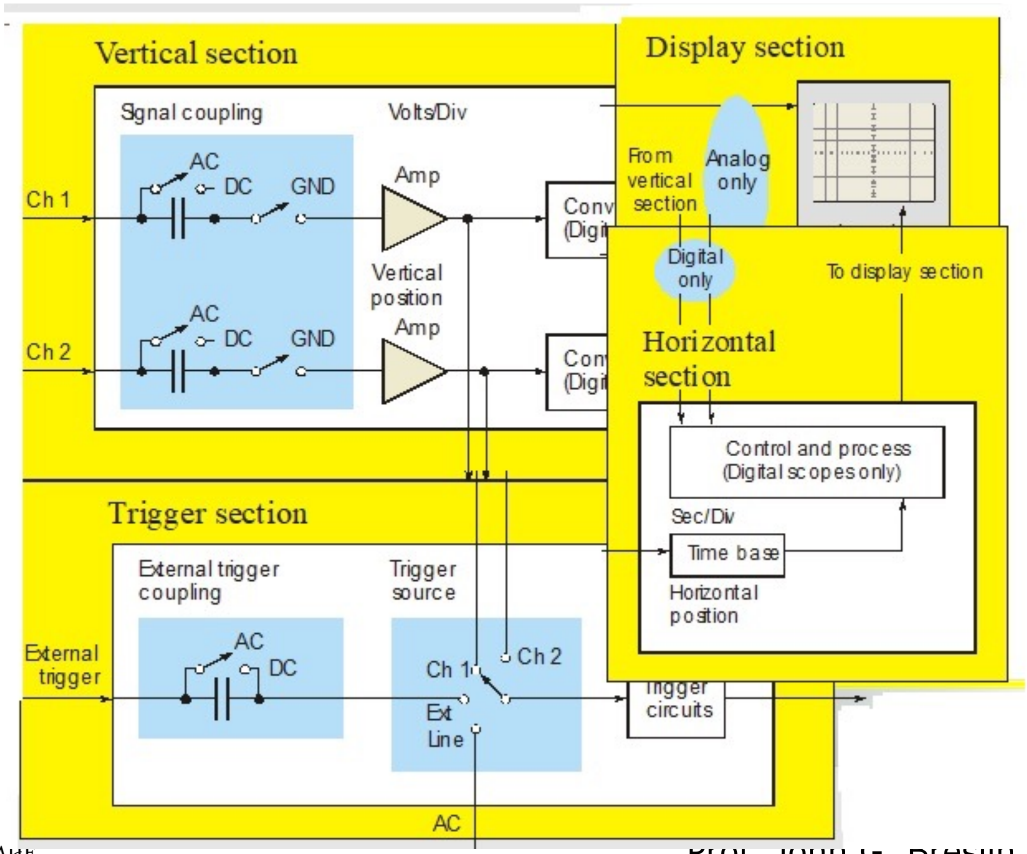
## Harmonics

Another way of looking at the frequency composition of a square wave is to view a three-dimensional view that shows time and frequency as variables plotted against amplitude:



## Oscilloscopes

The oscilloscope is divided into four main sections.



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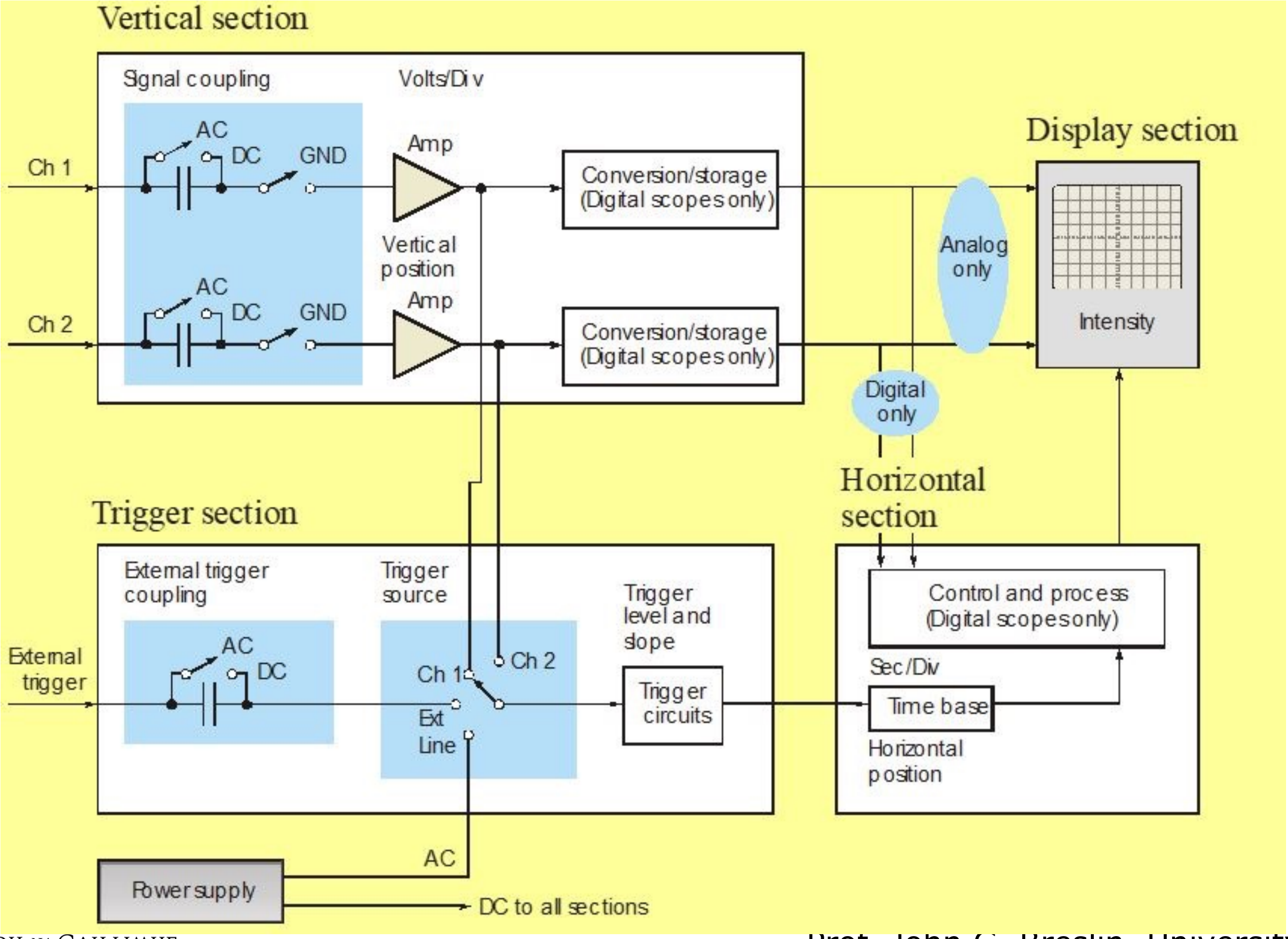
## Oscilloscopes



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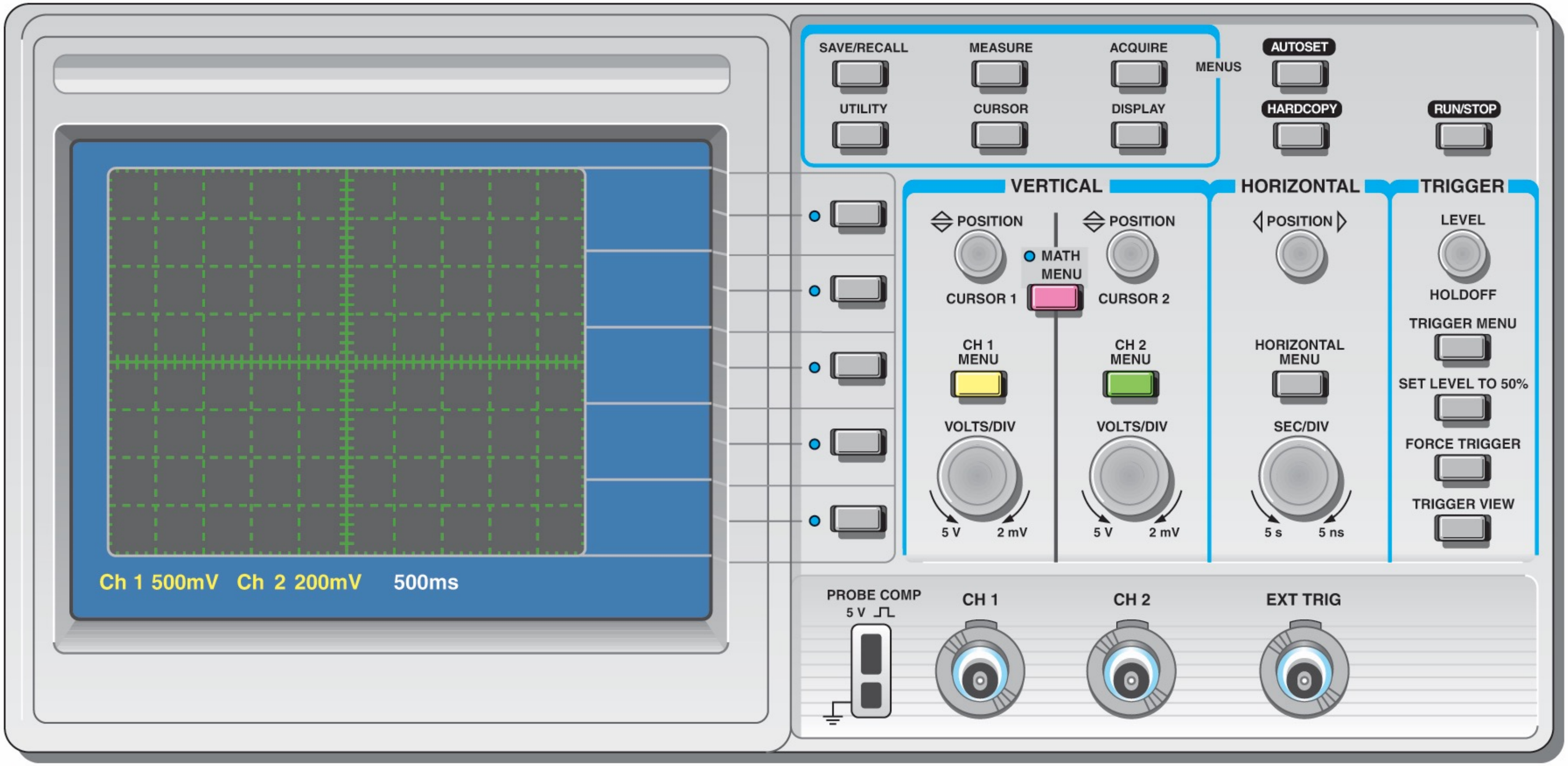
## Oscilloscopes



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# Selected Key Terms (1 of 3)

| | |
|---|---|
| ***Sine wave*** | A type of waveform that follows a cyclic sinusoidal pattern defined by the formula $y = A \sin \theta$. |
| ***Alternating current*** | Current that reverses direction in response to a change in source voltage polarity. |
| ***Period (T)*** | The time interval for one complete cycle of a periodic waveform. |
| ***Frequency (f)*** | A measure of the rate of change of a periodic function; the number of cycles completed in 1 s. |
| ***Hertz*** | The unit of frequency. One hertz equals one cycle per second. |

# Selected Key Terms (2 of 3)

| | |
|---|---|
| ***Instantaneous value*** | The voltage or current value of a waveform at a given instant in time. |
| ***Peak value*** | The voltage or current value of a waveform at its maximum positive or negative points relative to its median value. |
| ***Peak-to-peak value*** | The voltage or current value of a waveform measured from its minimum to its maximum points. |
| ***rms value*** | The value of a sinusoidal voltage that indicates its heating effect, also known as effective value. It is equal to 0.707 times the peak value. *rms* stands for root mean square. |

# Selected Key Terms (3 of 3)

| | |
|---|---|
| ***Radian*** | A unit of angular measurement. There are $2\pi$ radians in one complete 360° revolution. |
| ***Phase*** | The relative angular displacement of a time-varying waveform in terms of its occurrence with respect to a reference. |
| ***Amplitude*** | The maximum value of a voltage or current. |
| ***Pulse*** | A type of waveform that consists of two equal and opposite steps in voltage or current separated by a time interval. |
| ***Harmonics*** | The frequencies contained in a composite waveform, which are integer multiples of the pulse repetition frequency. |

# Quiz (1 of 11)

1. In North America, the frequency of ac utility voltage is 60 Hz. The period is

   a. 8.3 ms.

   b. 16.7 ms.

   c. 60 ms.

   d. 60 s.



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# Quiz (2 of 11)

2. The amplitude of a sine wave is measured

   a. at the maximum point.

   b. between the minimum and maximum points.

   c. at the midpoint.

   d. anywhere on the wave.

# Quiz (3 of 11)

3. An example of an equation for a waveform that lags the reference is

   a. $v = -40 \text{ V} \sin(\theta)$

   b. $v = 100 \text{ V} \sin(\theta + 35°)$

   c. $v = 5.0 \text{ V} \sin(\theta - 27°)$

   d. $v = 27 \text{ V}$



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# Quiz (4 of 11)

4. In the equation $v = V_p \sin\theta$, the letter $v$ stands for the

   a. peak value.

   b. average value.

   c. rms value.

   d. instantaneous value.

# Quiz (5 of 11)

5. The time base of an oscilloscope is determined by the setting of the

   a. vertical controls.

   b. horizontal controls.

   c. trigger controls.

   d. none of the above.

# Quiz (6 of 11)

6. A sawtooth waveform has

   a. equal positive and negative going ramps.

   b. two ramps – one much longer than the other.

   c. two equal pulses.

   d. two unequal pulses.

# Quiz (7 of 11)

7. The number of radians in 90° are

   a. $\pi/2$.

   b. $\pi$.

   c. $2\pi/3$.

   d. $2\pi$.

# Quiz (8 of 11)

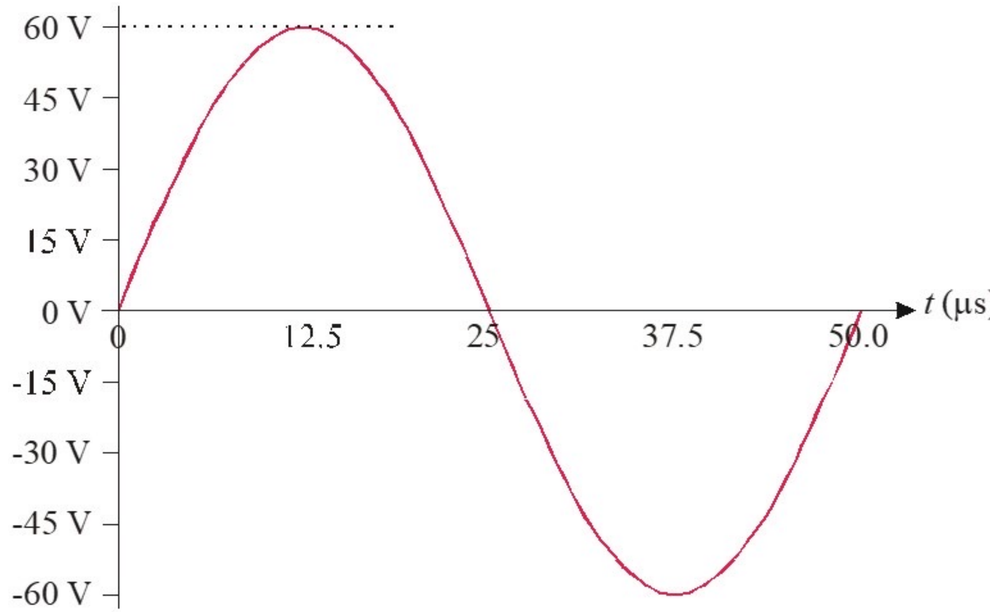
8. For the waveform shown, the same power would be delivered to a load with a dc voltage of

   a. 21.2 V.

   b. 37.8 V.

   c. 42.4 V.

   d. 60.0 V.



# Quiz (9 of 11)

9. A square wave consists of

   a. the fundamental and odd harmonics.

   b. the fundamental and even harmonics.

   c. the fundamental and all harmonics.

   d. only the fundamental.

# Quiz (10 of 11)

10. A control on the oscilloscope that is used to set the desired number of cycles of a wave on the display is

    a. volts per division control.

    b. time per division control.

    c. trigger level control.

    d. horizontal position control.



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# Quiz (11 of 11)

Answers:

1. b
2. a
3. c
4. d
5. b
6. b
7. a
8. c
9. a
10. b



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