# The Oscilloscope

What is an oscilloscope, what can you do with it, and how does it work? This section answers these fundamental questions.

The oscilloscope is basically a graph-displaying device - it draws a graph of an electrical signal. In most applications the graph shows how signals change over time: the vertical (Y) axis represents voltage and the horizontal (X) axis represents time. The intensity or brightness of the display is sometimes called the Z axis. (See Figure 1.) This simple graph can tell you many things about a signal. Here are a few:

- You can determine the time and voltage values of a signal.

- You can calculate the frequency of an oscillating signal.

- You can see the "moving parts" of a circuit represented by the signal.

- You can tell if a malfunctioning component is distorting the signal.

- You can find out how much of a signal is direct current (DC) or alternating current (AC).

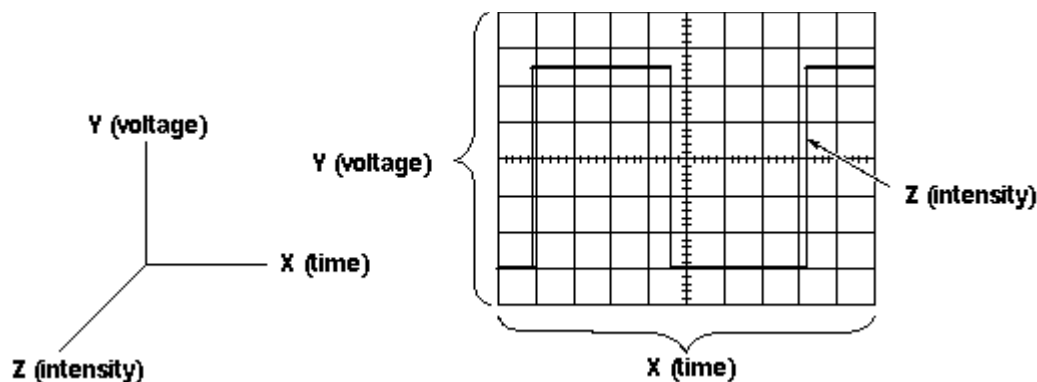- You can tell how much of the signal is noise and whether the noise is changing with time.



**Figure 1: X, Y, and Z Components of a Displayed Waveform**

An oscilloscope looks a lot like a small television set, except that it has a grid drawn on its screen and more controls than a television. The front panel of an oscilloscope normally has control sections divided into Vertical, Horizontal, and Trigger sections.

There are also display controls and input connectors. See if you can locate these front panel sections in Figures 2 and 3 and on your oscilloscope.
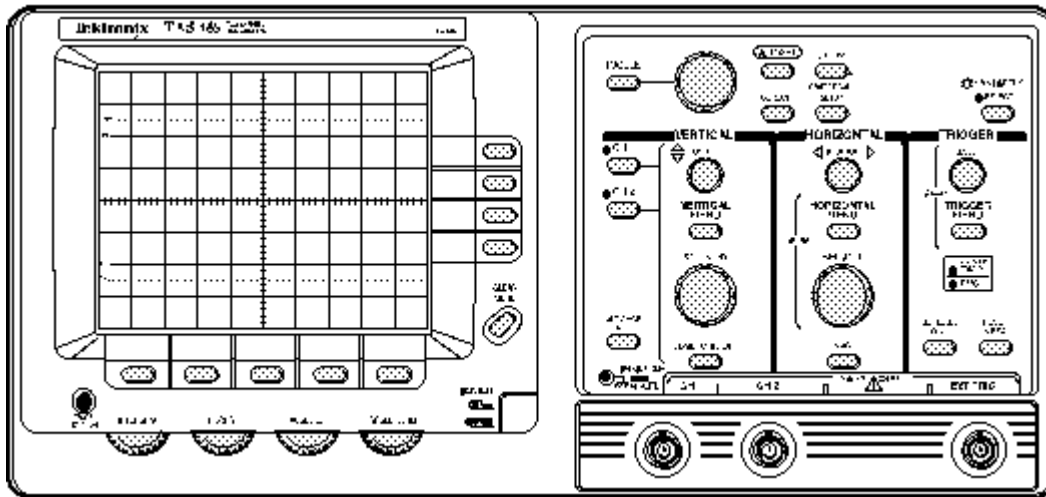


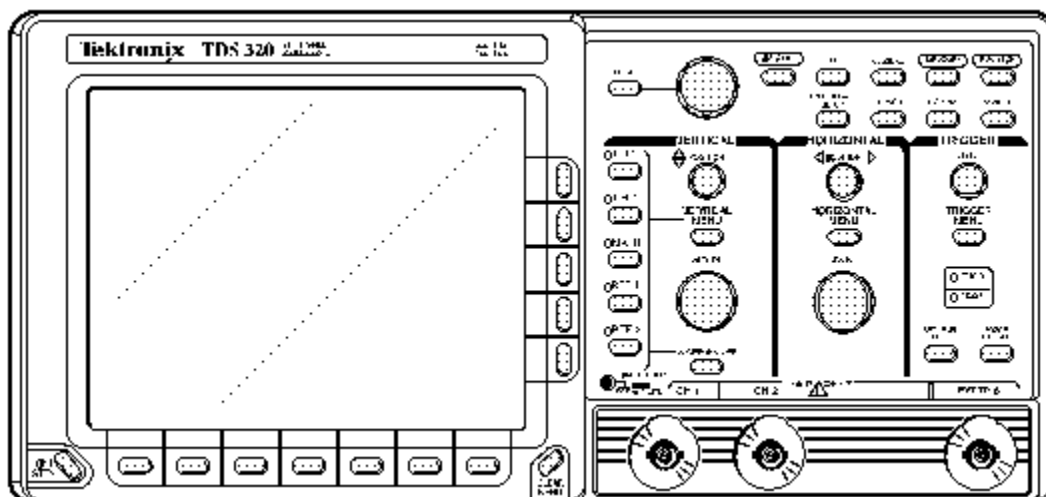**Figure 2: The TAS 465 Analog Oscilloscope Front Panel**



**Figure 3: The TDS 320 Digital Oscilloscope Front Panel**

**What Can You Do With It?**

Oscilloscopes are used by everyone from television repair technicians to physicists. They are indispensable for anyone designing or repairing electronic equipment.

The usefulness of an oscilloscope is not limited to the world of electronics. With the proper *transducer*, an oscilloscope can measure all kinds of phenomena. A transducer is a device that creates an electrical signal in response to physical stimuli, such as sound, mechanical stress, pressure, light, or heat. For example, a microphone is a transducer. An automotive engineer uses an oscilloscope to measure engine vibrations. A medical researcher uses an oscilloscope to measure brain waves. The possibilities are endless.
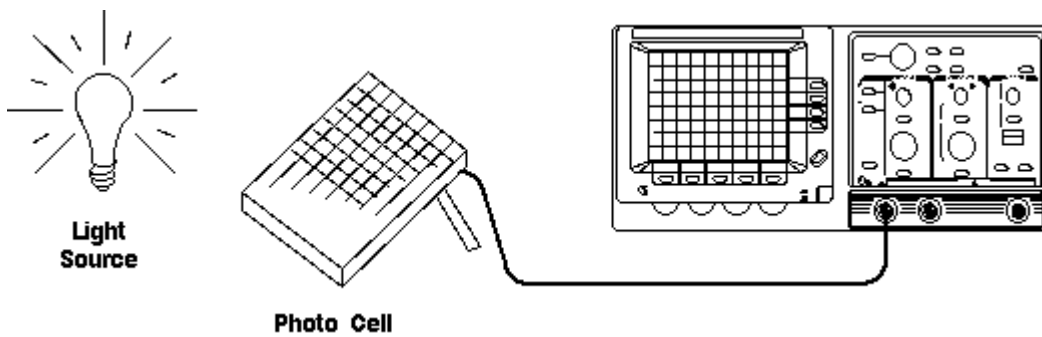
**Figure 4: Scientific Data Gathered by an Oscilloscope**

**Analog and Digital**

Electronic equipment can be divided into two types: analog and digital. *Analog* equipment works with continuously variable voltages, while *digital* equipment works with discrete binary numbers that may represent voltage samples. For example, a conventional phonograph turntable is an analog device; a compact disc player is a digital device.

Oscilloscopes also come in analog and digital types. An analog oscilloscope works by directly applying a voltage being measured to an electron beam moving across the oscilloscope screen. The voltage deflects the beam up and down proportionally, tracing the waveform on the screen. This gives an immediate picture of the waveform.

In contrast, a digital oscilloscope samples the waveform and uses an analog-to-digital converter (or ADC) to convert the voltage being measured into digital information. It then uses this digital information to reconstruct the waveform on the screen.
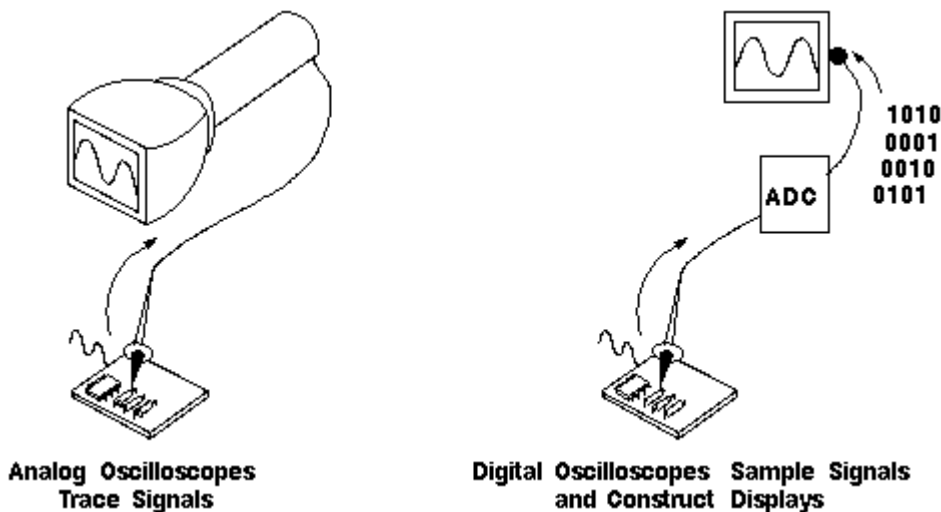


Analog Oscilloscopes
Trace Signals

Digital Oscilloscopes Sample Signals
and Construct Displays

**Figure 5: Digital and Analog Oscilloscopes Display Waveforms**

For many applications either an analog or digital oscilloscope will do. However, each type does possess some unique characteristics making it more or less suitable for specific tasks.

People often prefer analog oscilloscopes when it is important to display rapidly varying signals in "real time" (or as they occur).

Digital oscilloscopes allow you to capture and view events that may happen only once. They can process the digital waveform data or send the data to a computer for processing. Also, they can store the digital waveform data for later viewing and printing.

**How Does an Oscilloscope Work?**
To better understand the oscilloscope controls, you need to know a little more about how oscilloscopes display a signal. Analog oscilloscopes work somewhat differently than digital oscilloscopes. However, several of the internal systems are similar. Analog oscilloscopes are somewhat simpler in concept and are described first, followed by a description of digital oscilloscopes.

# Analog Oscilloscopes

When you connect an oscilloscope probe to a circuit, the voltage signal travels through the probe to the vertical system of the oscilloscope. Figure 6 is a simple block diagram that shows how an analog oscilloscope displays a measured signal.
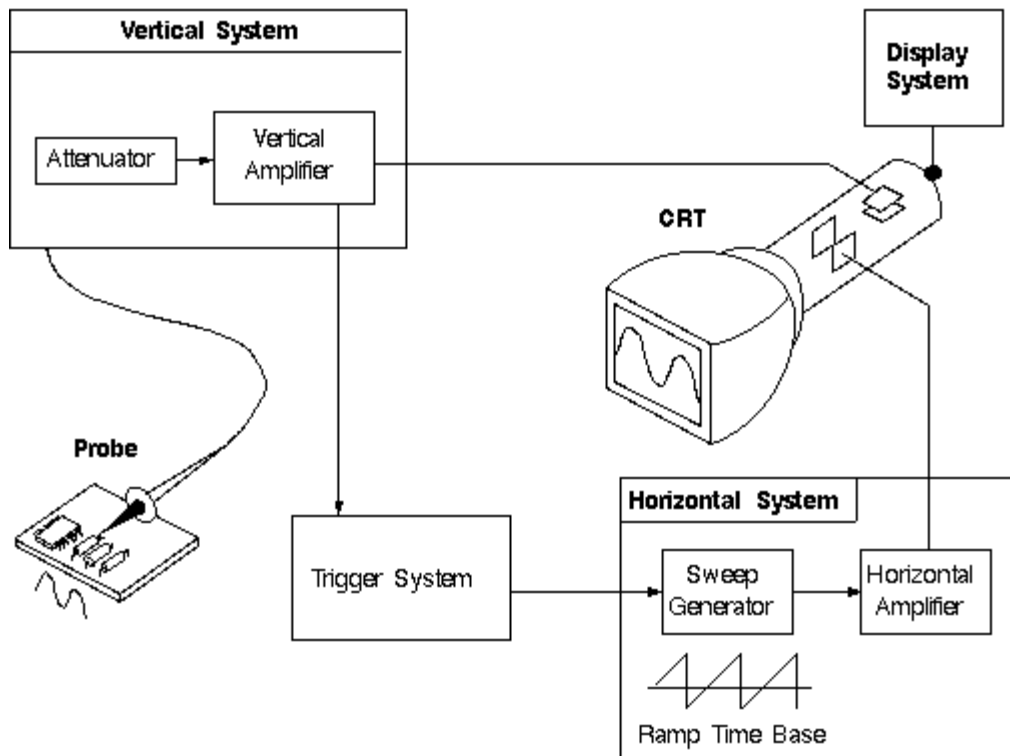


**Figure 6: Analog Oscilloscope Block Diagram**
Depending on how you set the vertical scale (volts/div control), an *attenuator* reduces the signal voltage or an *amplifier* increases the signal voltage.
Next, the signal travels directly to the vertical deflection plates of the cathode ray tube (CRT). Voltage applied to these deflection plates causes a glowing dot to move. (An electron beam hitting phosphor inside the CRT creates the glowing dot.) A positive voltage causes the dot to move up while a negative voltage causes the dot to move down.
The signal also travels to the trigger system to start or trigger a "horizontal sweep." Horizontal sweep is a term referring to the action of the horizontal system causing the glowing dot to move across the screen. Triggering the horizontal system causes the horizontal time base to move the glowing dot across the screen from left to right within a specific time interval. Many sweeps in rapid sequence cause the movement of the glowing dot to blend into a solid line. At higher speeds, the dot may sweep across the screen up to 500,000 times each second.
Together, the horizontal sweeping action and the vertical deflection action traces a graph of the signal on the screen. The trigger is necessary to stabilize a repeating signal. It

ensures that the sweep begins at the same point of a repeating signal, resulting in a clear picture as shown in Figure 7.
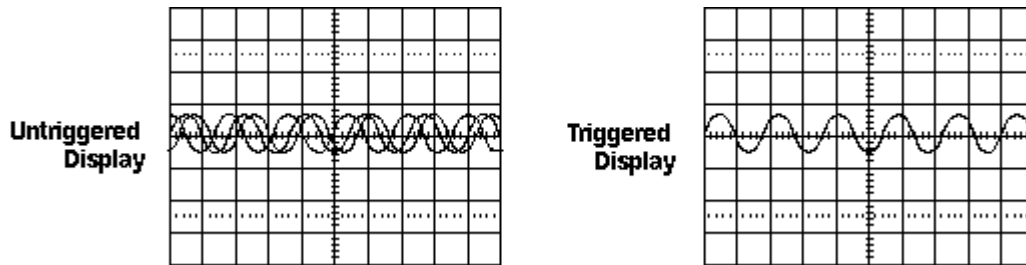


**Figure 7: Triggering Stabilizes a Repeating Waveform**

In conclusion, to use an analog oscilloscope, you need to adjust three basic settings to accommodate an incoming signal:

- The attenuation or amplification of the signal. Use the volts/div control to adjust the amplitude of the signal before it is applied to the vertical deflection plates.

- The time base. Use the sec/div control to set the amount of time per division represented horizontally across the screen.

- The triggering of the oscilloscope. Use the trigger level to stabilize a repeating signal, as well as triggering on a single event.

Also, adjusting the focus and intensity controls enables you to create a sharp, visible display.

# Digital Oscilloscopes

Some of the systems that make up digital oscilloscopes are the same as those in analog oscilloscopes; however, digital oscilloscopes contain additional data processing systems. (See Figure 8.) With the added systems, the digital oscilloscope collects data for the entire waveform and then displays it.

When you attach a digital oscilloscope probe to a circuit, the vertical system adjusts the amplitude of the signal, just as in the analog oscilloscope.

Next, the analog-to-digital converter (ADC) in the acquisition system samples the signal at discrete points in time and converts the signal's voltage at these points to digital values called *sample points*. The horizontal system's sample clock determines how often the ADC takes a sample. The rate at which the clock "ticks" is called the sample rate and is measured in samples per second.

The sample points from the ADC are stored in memory as *waveform points*. More than one sample point may make up one waveform point.

Together, the waveform points make up one waveform *record*. The number of waveform points used to make a waveform record is called the *record length*. The trigger system determines the start and stop points of the record. The display receives these record points after being stored in memory.

Depending on the capabilities of your oscilloscope, additional processing of the sample points may take place, enhancing the display. Pretrigger may be available, allowing you to see events before the trigger point.
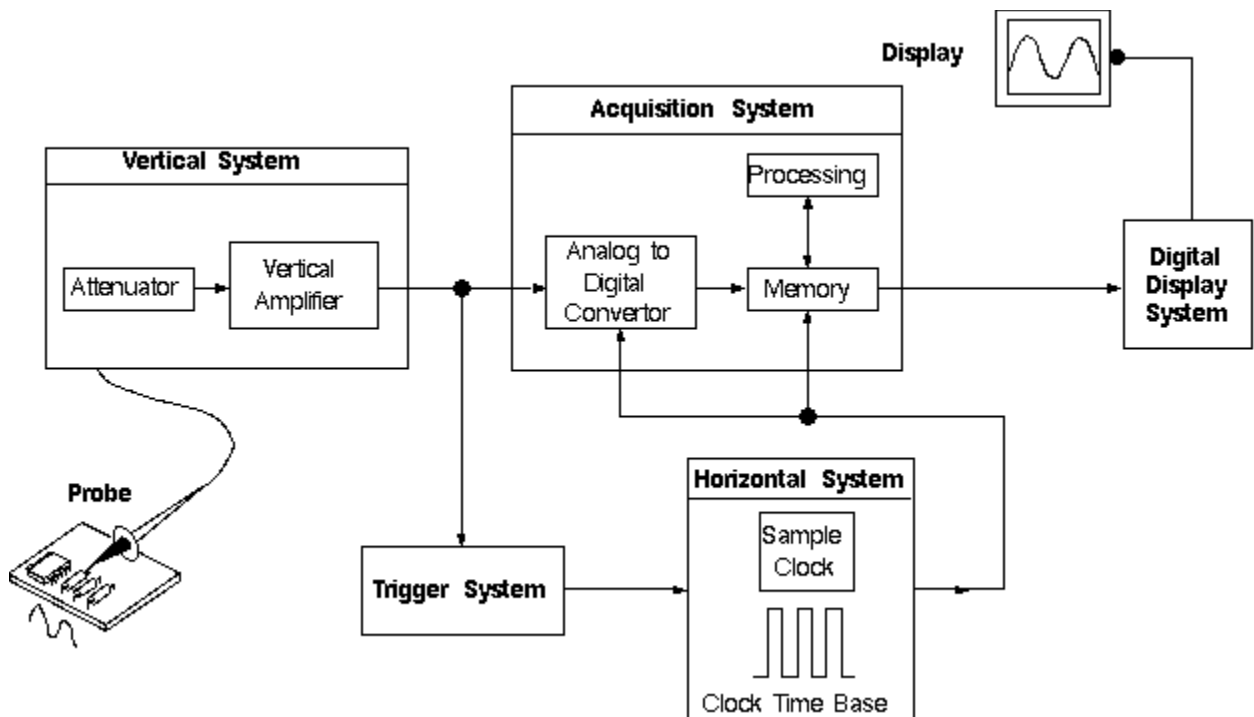
**Figure 8: Digital Oscilloscope Block Diagram**

Fundamentally, with a digital oscilloscope as with an analog oscilloscope, you need to adjust the vertical, horizontal, and trigger settings to take a measurement.

# Sampling Methods

The sampling method tells the digital oscilloscope how to collect sample points. For slowly changing signals, a digital oscilloscope easily collects more than enough sample points to construct an accurate picture. However, for faster signals, (how fast depends on the oscilloscope's maximum sample rate) the oscilloscope cannot collect enough samples. The digital oscilloscope can do two things:

- It can collect a few sample points of the signal in a single pass (in *real-time* sampling mode) and then use *interpolation*. Interpolation is a processing technique to estimate what the waveform looks like based on a few points.

- It can build a picture of the waveform over time, as long as the signal repeats itself (*equivalent-time* sampling mode).

# Real-Time Sampling with Interpolation

Digital oscilloscopes use real-time sampling as the standard sampling method. In real-time sampling, the oscilloscope collects as many samples as it can as the signal occurs. (See Figure 9.) For single-shot or transient signals you must use real time sampling.
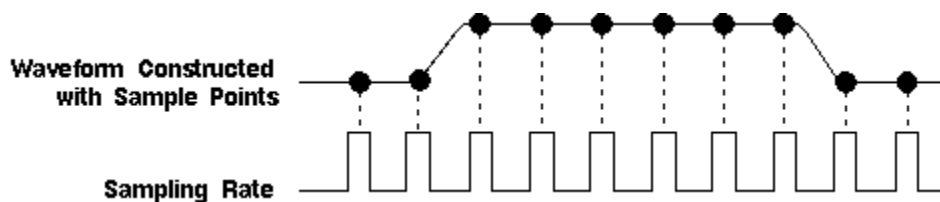


**Figure 9: Real-time Sampling**

Digital oscilloscopes use interpolation to display signals that are so fast that the oscilloscope can only collect a few sample points. Interpolation "connects the dots."

Linear interpolation simply connects sample points with straight lines. Sine interpolation (or *sin x over x* interpolation) connects sample points with curves. (See Figure 10.) *Sin x over x* interpolation is a mathematical process similar to the "oversampling" used in compact disc players. With sine interpolation, points are calculated to fill in the time between the real samples. Using this process, a signal that is sampled only a few times in each cycle can be accurately displayed or, in the case of the compact disc player, accurately played back.
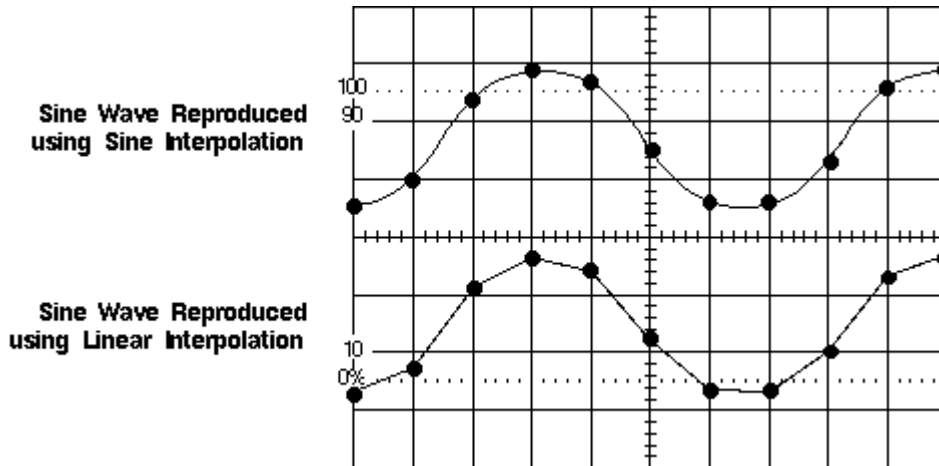


**Figure 10: Linear and Sine Interpolation**

# Equivalent-Time Sampling

Some digital oscilloscopes can use equivalent-time sampling to capture very fast repeating signals. Equivalent-time sampling constructs a picture of a repetitive signal by capturing a little bit of information from each repetition. (See Figure 11.) You see the waveform slowly build up like a string of lights going on one-by-one. With *sequential sampling* the points appear from left to right in sequence; with *random sampling* the points appear randomly along the waveform.
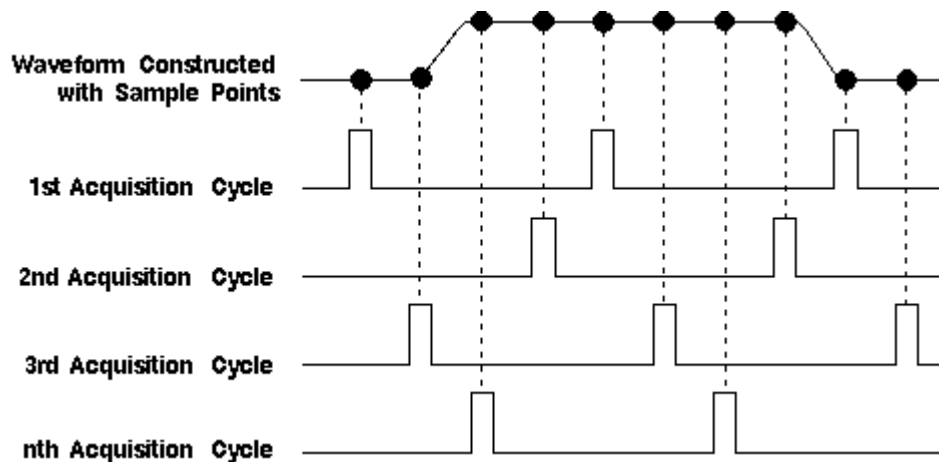


**Figure 11: Equivalent-time Sampling**

**Oscilloscope Terminology**
Learning a new skill often involves learning a new vocabulary. This idea holds true for learning how to use an oscilloscope. This section describes some useful measurement and oscilloscope performance terms.

**Measurement Terms**
The generic term for a pattern that repeats over time is a *wave* - sound waves, brain waves, ocean waves, and voltage waves are all repeating patterns. An oscilloscope measures voltage waves. One *cycle* of a wave is the portion of the wave that repeats. A *waveform* is a graphic representation of a wave. A voltage waveform shows time on the horizontal axis and voltage on the vertical axis.

Waveform shapes tell you a great deal about a signal. Any time you see a change in the height of the waveform, you know the voltage has changed. Any time there is a flat horizontal line, you know that there is no change for that length of time. Straight diagonal lines mean a linear change - rise or fall of voltage at a steady rate. Sharp angles on a waveform mean sudden change. Figure 1 shows common waveforms and Figure 2 shows some common sources of waveforms.
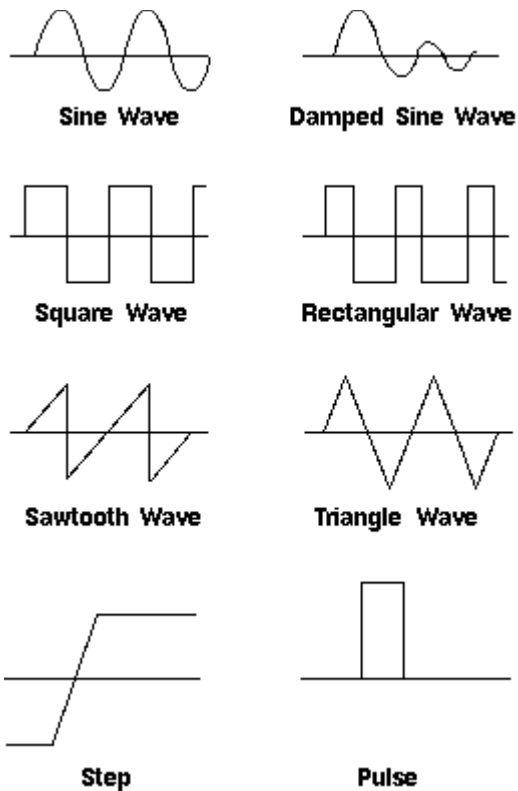
Sine Wave          Damped Sine Wave

Square Wave        Rectangular Wave

Sawtooth Wave      Triangle Wave

Step               Pulse
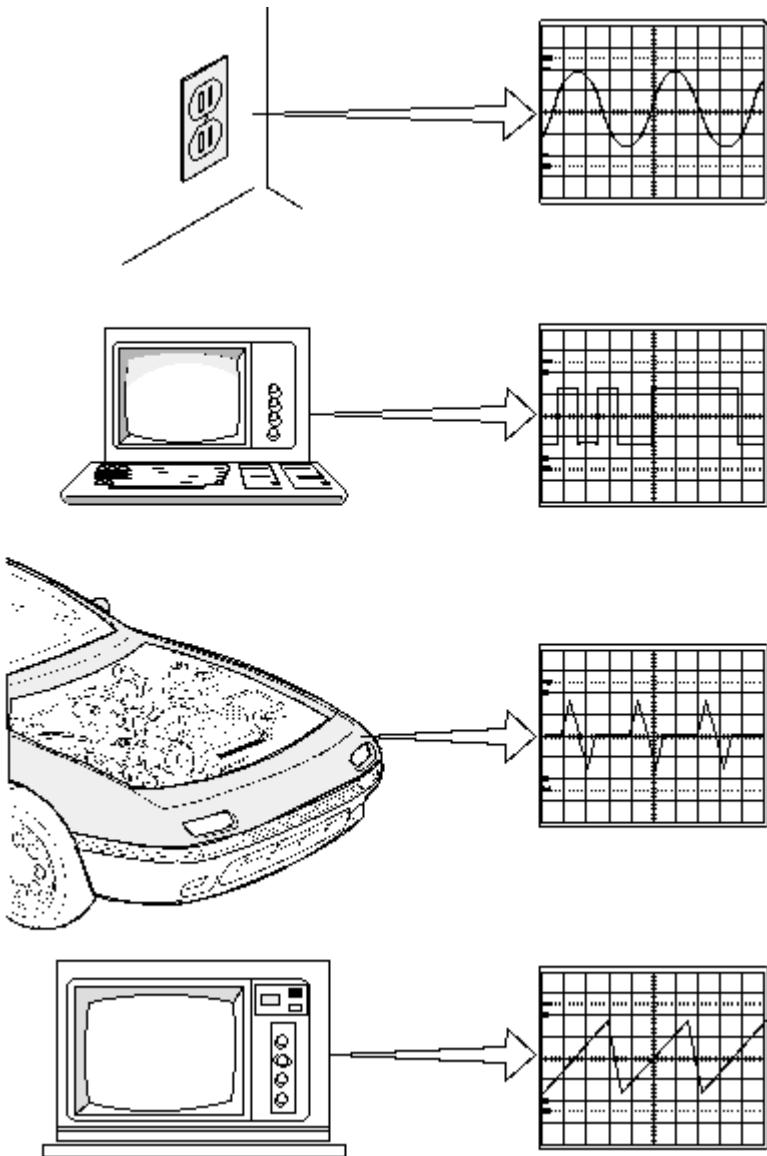
**Figure 1: Common Waveforms**

**Figure 2: Sources of Common Waveforms**
**Types of Waves**
You can classify most waves into these types:

- Sine waves

- Square and rectangular waves

- Triangle and sawtooth waves

- Step and pulse shapes

# Sine Waves

The *sine wave* is the fundamental wave shape for several reasons. It has harmonious mathematical properties - it is the same sine shape you may have studied in high school trigonometry class. The voltage in your wall outlet varies as a sine wave. Test signals produced by the oscillator circuit of a signal generator are often sine waves. Most AC power sources produce sine waves. (*AC* stands for alternating current,

although the voltage alternates too. *DC* stands for direct current, which means a steady current and voltage, such as a battery produces.)

The *damped sine wave* is a special case you may see in a circuit that oscillates but winds down over time.

Figure 3 shows examples of sine and damped sine waves.



**Figure 3: Sine and Damped Sine Waves**

# Square and Rectangular Waves

The *square wave* is another common wave shape. Basically, a square wave is a voltage that turns on and off (or goes high and low) at regular intervals. It is a standard wave for testing amplifiers - good amplifiers increase the amplitude of a square wave with minimum distortion. Television, radio, and computer circuitry often use square waves for timing signals.

The *rectangular wave* is like the square wave except that the high and low time intervals are not of equal length. It is particularly important when analyzing digital circuitry.

Figure 4 shows examples of square and rectangular waves.



**Figure 4: Square and Rectangular Waves**

# Sawtooth and Triangle Waves

Sawtooth and *Triangle waves* result from circuits designed to control voltages linearly, such as the horizontal sweep of an analog oscilloscope or the raster scan of a television. The transitions between voltage levels of these waves change at a constant rate. These transitions are called *ramps*.

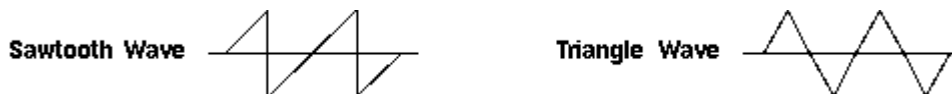Figure 5 shows examples of sawtooth and triangle waves.



**Figure 5: Sawtooth and Triangle Waves**

# Step and Pulse Shapes

Signals such as *steps* and *pulses* that only occur once are called *single-shot* or *transient* signals. The step indicates a sudden change in voltage, like what you would see if you turned on a power switch. The pulse indicates what you would see if you turned a power switch on and then off again. It might represent one bit of information traveling through a computer circuit or it might be a *glitch* (a defect) in a circuit.

A collection of pulses travelling together creates a *pulse train.* Digital components in a computer communicate with each other using pulses. Pulses are also common in x-ray and communications equipment.

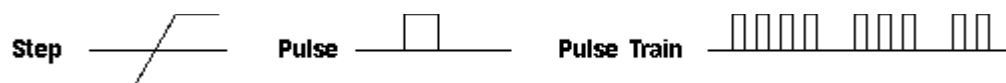Figure 6 shows examples of step and pulse shapes and a pulse train.



**Figure 6: Step, Pulse, and Pulse Train Shapes**

**Waveform Measurements**

You use many terms to describe the types of measurements that you take with your oscilloscope. This section describes some of the most common measurements and terms.

# Frequency and Period

If a signal repeats, it has a *frequency*. The frequency is measured in Hertz (Hz) and equals the number of times the signal repeats itself in one second (the cycles per second). A repeating signal also has a *period* - this is the amount of time it takes the signal to complete one cycle. Period and frequency are reciprocals of each other, so that 1/period equals the frequency and 1/frequency equals the period. So, for example, the sine wave in Figure 7 has a frequency of 3 Hz and a period of 1/3 second.
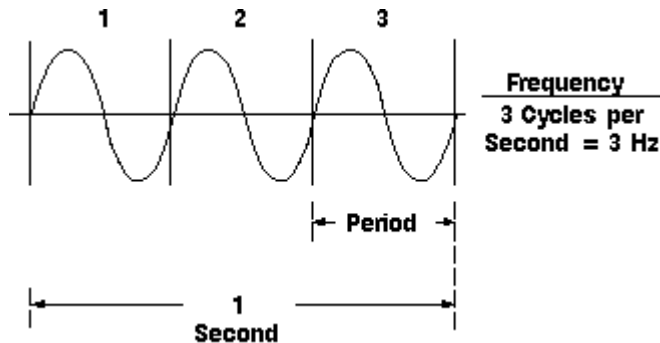


**Figure 7: Frequency and Period**

# Voltage

Voltage is the amount of electric potential (a kind of signal strength) between two points in a circuit. Usually one of these points is ground (zero volts) but not always - you may want to measure the voltage from the maximum peak to the minimum peak of a waveform, referred to at the peak-to-peak voltage. The word amplitude commonly refers to the maximum voltage of a signal measured from ground or zero volts. The waveform shown in Figure 8 has an amplitude of one volt and a peak-to-peak voltage of two volts.

# Phase

*Phase* is best explained by looking at a sine wave. Sine waves are based on circular motion and a circle has 360 degrees. One cycle of a sine wave has 360 degrees, as shown in Figure 8. Using degrees, you can refer to the phase angle of a sine wave when you want to describe how much of the period has elapsed.
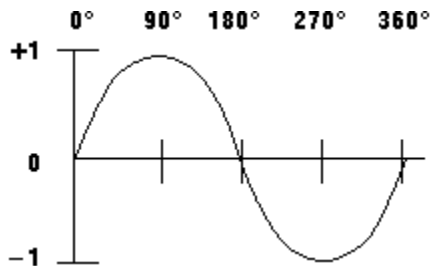


**Figure 8: Sine Wave Degrees**

Phase shift describes the difference in timing between two otherwise similar signals. In Figure 9, the waveform labeled "current" is said to be 905 out of phase with the waveform labeled "voltage," since the waves reach similar points in their cycles exactly 1/4 of a cycle apart (360 degrees/4 = 90 degrees). Phase shifts are common in electronics.
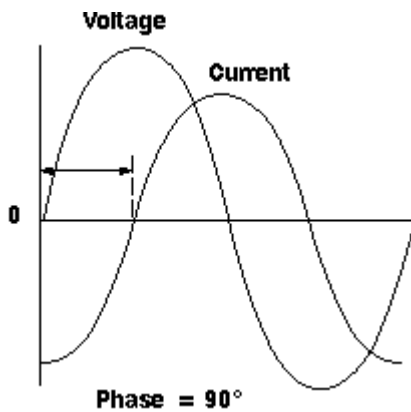
**Figure 9: Phase Shift**

**Performance Terms**

The terms described in this section may come up in your discussions about oscilloscope performance. Understanding these terms will help you evaluate and compare your oscilloscope with other models.

# Bandwidth

The bandwidth specification tells you the frequency range the oscilloscope accurately measures.

As signal frequency increases, the capability of the oscilloscope to accurately respond decreases. By convention, the bandwidth tells you the frequency at which the displayed signal reduces to 70.7% of the applied sine wave signal. (This 70.7% point is referred to as the "-3 dB point," a term based on a logarithmic scale.)

# Rise Time

Rise time is another way of describing the useful frequency range of an oscilloscope. Rise time may be a more appropriate performance consideration when you expect to measure pulses and steps. An oscilloscope cannot accurately display pulses with rise times faster than the specified rise time of the oscilloscope.

# Vertical Sensitivity

The vertical sensitivity indicates how much the vertical amplifier can amplify a weak signal. Vertical sensitivity is usually given in millivolts (mV) per division. The smallest voltage a general purpose oscilloscope can detect is typically about 2 mV per vertical screen division.

# Sweep Speed

For analog oscilloscopes, this specification indicates how fast the trace can sweep across the screen, allowing you to see fine details. The fastest sweep speed of an oscilloscope is usually given in nanoseconds/div.

# Gain Accuracy

The gain accuracy indicates how accurately the vertical system attenuates or amplifies a signal. This is usually listed as a percentage error.

# Time Base or Horizontal Accuracy

The time base or horizontal accuracy indicates how accurately the horizontal system displays the timing of a signal. This is usually listed as a percentage error.

# Sample Rate

On digital oscilloscopes, the sampling rate indicates how many samples per second the ADC (and therefore the oscilloscope) can acquire. Maximum sample rates are usually given in megasamples per second (MS/s). The faster the oscilloscope can sample, the more accurately it can represent fine details in a fast signal. The minimum sample rate may also be important if you need to look at slowly changing signals over long periods of time. Typically, the sample rate changes with changes made to the sec/div control to maintain a constant number of waveform points in the waveform record.

# ADC Resolution (Or Vertical Resolution)

The resolution, in bits, of the ADC (and therefore the digital oscilloscope) indicates how precisely it can turn input voltages into digital values. Calculation techniques can improve the effective resolution.

# Record Length

The record length of a digital oscilloscope indicates how many waveform points the oscilloscope is able to acquire for one waveform record. Some digital oscilloscopes let you adjust the record length. The maximum record length depends on the amount of memory in your oscilloscope. Since the oscilloscope can only store a finite number of waveform points, there is a trade-off between record detail and record length. You can acquire either a detailed picture of a signal for a short period of time (the oscilloscope "fills up" on waveform points quickly) or a less detailed picture for a longer period of time. Some oscilloscopes let you add more memory to increase the record length for special applications.

**Setting Up**

This section briefly describes how to set up and start using an oscilloscope - specifically, how to ground the oscilloscope, set the controls in standard positions, and compensate the probe.

**Grounding**

Proper grounding is an important step when setting up to take measurements or work on a circuit. Properly grounding the oscilloscope protects you from a hazardous shock and grounding yourself protects your circuits from damage.

# Ground the Oscilloscope

Grounding the oscilloscope is necessary for safety. If a high voltage contacts the case of an ungrounded oscilloscope, any part of the case, including knobs that appear insulated, it can give you a shock. However, with a properly grounded oscilloscope, the current travels through the grounding path to earth ground rather than through *you* to earth ground.

To ground the oscilloscope means to connect it to an electrically neutral reference point (such as earth ground). Ground your oscilloscope by plugging its three-pronged power cord into an outlet grounded to earth ground.

Grounding is also necessary for taking accurate measurements with your oscilloscope. The oscilloscope needs to share the same ground as any circuits you are testing.

Some oscilloscopes do not require the separate connection to earth ground. These oscilloscopes have insulated cases and controls, which keeps any possible shock hazard away from the user.

# Ground Yourself

If you are working with integrated circuits (ICs), you also need to ground yourself. Integrated circuits have tiny conduction paths that can be damaged by static electricity that builds up on your body. You can ruin an expensive IC simply by walking across a carpet or taking off a sweater and then touching the leads of the IC. To solve this problem, wear a grounding strap (see Figure 1). This strap safely sends static charges on your body to earth ground.
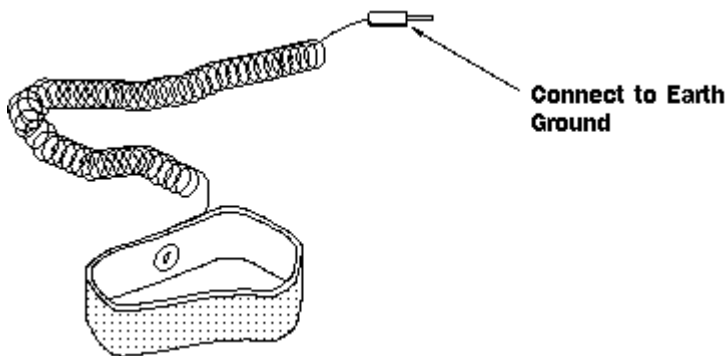
**Figure 1: Typical Wrist Type Grounding Strap**

**Setting the Controls**

After plugging in the oscilloscope, take a look at the front panel. It is divided into three main sections labeled *Vertical*, *Horizontal*, and *Trigger*. Your oscilloscope may have other sections, depending on the model and type (analog or digital).

Notice the input connectors on your oscilloscope. This is where you attach probes. Most oscilloscopes have at least two input channels and each channel can display a waveform on the screen. Multiple channels are handy for comparing waveforms.
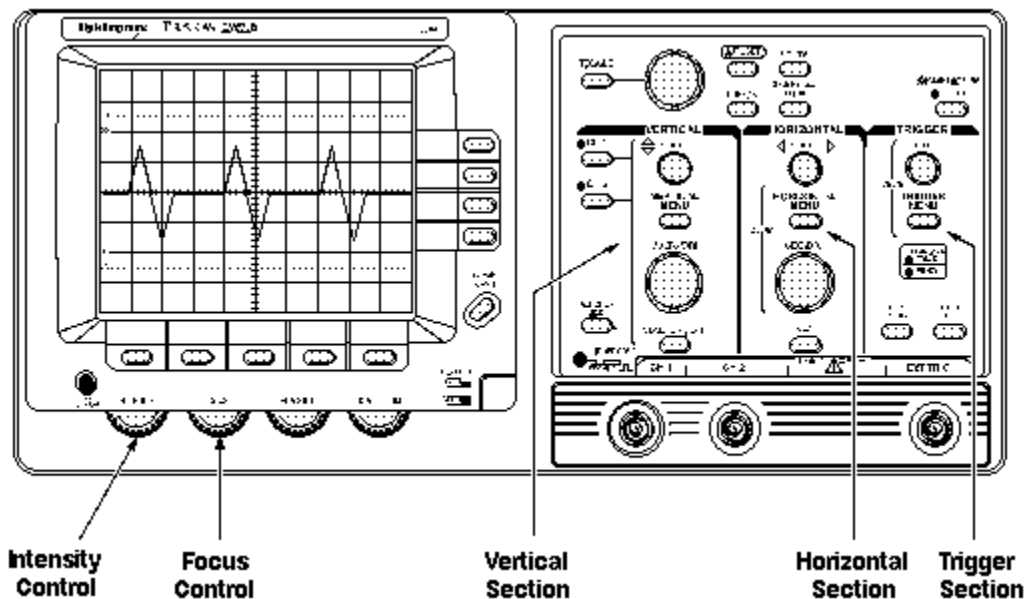


**Figure 2: Front Panel Control Sections of an Oscilloscope**

Some oscilloscopes have an AUTOSET or PRESET button that sets up the controls in one step to accommodate a signal. If your oscilloscope does not have this feature, it is helpful to set the controls to standard positions before taking measurements.

Standard positions include the following:

- Set the oscilloscope to display channel 1

- Set the volts/division scale to a mid-range position

- Turn off the variable volts/division

- Turn off all magnification settings

- Set the channel 1 input coupling to DC

- Set the trigger mode to auto

- Set the trigger source to channel 1

- Turn trigger holdoff to minimum or off

- Set the intensity control to a nominal viewing level

- Adjust the focus control for a sharp display

These are general instructions for setting up your oscilloscope. If you are not sure how to do any of these steps, refer to the manual that came with your oscilloscope. The *Controls* section describes the controls in more detail.

**Probes**

Now you are ready to connect a probe to your oscilloscope. It is important to use a probe designed to work with your oscilloscope. A probe is more than a cable with a clip-on tip. It is a high-quality connector, carefully designed not to pick up stray radio and power line noise.

Probes are designed not to influence the behavior of the circuit you are testing. However, no measurement device can act as a perfectly invisible observer. The unintentional interaction of the probe and oscilloscope with the circuit being tested is called *circuit loading*. To minimize circuit loading, you will probably use a 10X attenuator (passive) probe.

Your oscilloscope probably arrived with a passive probe as a standard accessory. Passive probes provide you with an excellent tool for general-purpose testing and troubleshooting. For more specific measurements or tests, many other types of probes exist. Two examples are active and current probes.

Descriptions of these probes follow, with more emphasis given to the passive probe since this is the probe type that allows you the most flexibility of use.

# Using Passive Probes

Most passive probes have some degree of attenuation factor, such as 10X, 100X, and so on. By convention, attenuation factors, such as for the 10X attenuator probe, have the X after the factor. In contrast, magnification factors like X10 have the X first.

The 10X (read as "ten times") attenuator probe minimizes circuit loading and is an excellent general-purpose passive probe. Circuit loading becomes more pronounced at higher frequencies, so be sure to use this type of probe when measuring signals above 5 kHz. The 10X attenuator probe improves the accuracy of your measurements, but it also reduces the amplitude of the signal seen on the screen by a factor of 10.

Because it attenuates the signal, the 10X attenuator probe makes it difficult to look at signals less than 10 millivolts. The 1X probe is similar to the 10X attenuator probe but lacks the attenuation circuitry. Without this circuitry, more interference is introduced to the circuit being tested. Use the 10X attenuator probe as your standard probe, but keep the 1X probe handy for measuring weak signals. Some probes have a convenient feature for switching between 1X and 10X attenuation at the probe tip. If your probe has this feature, make sure you are using the correct setting before taking measurements.

Many oscilloscopes can detect whether you are using a 1X or 10X probe and adjust their screen readouts accordingly. However with some oscilloscopes, you must set the type of probe you are using or read from the proper 1X or 10X marking on the volts/div control. The 10X attenuator probe works by balancing the probe's electrical properties against the oscilloscope's electrical properties. Before using a 10X attenuator probe you need to

adjust this balance for your particular oscilloscope. This adjustment is called compensating the probe and is further described in the next section. Figure 3 shows a simple diagram of the internal workings of a probe, its adjustment, and the input of an oscilloscope.
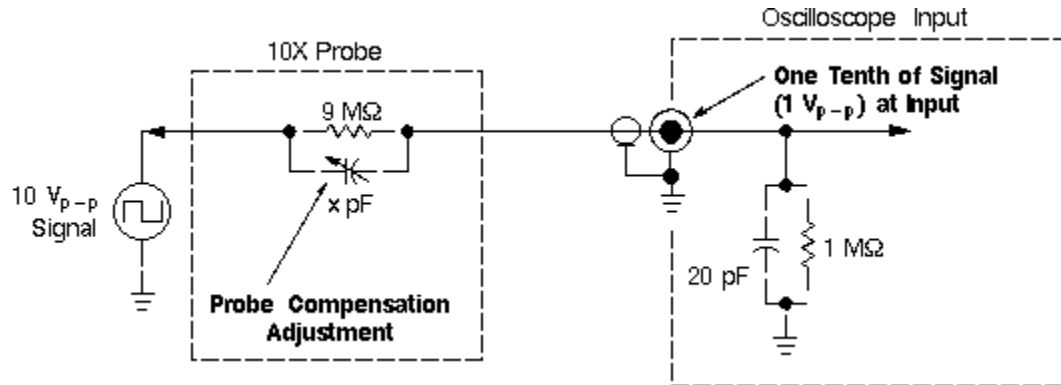


**Figure 3: Typical Probe/Oscilloscope 10-to-1 Divider Network**

Figure 4 shows a typical passive probe and some accessories to use with the probe.
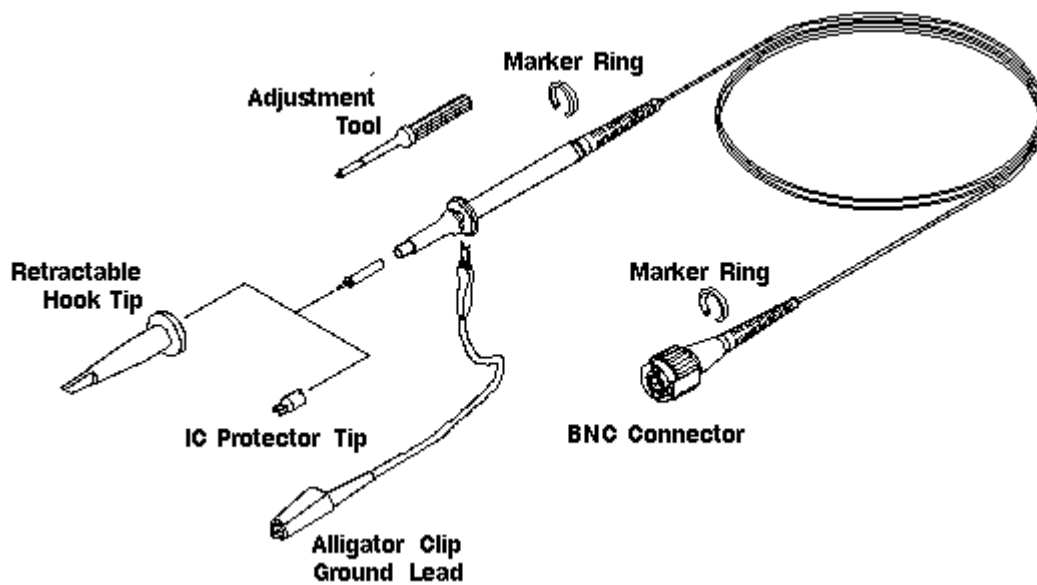


**Figure 4: A Typical Passive Probe with Accessories**

# Using Active Probes

Active probes provide their own amplification or perform some other type of operation to process the signal before applying it to the oscilloscope. These types of probes can solve problems such as circuit loading or perform tests on signals, sending the results to the oscilloscope. Active probes require a power source for their operation.

# Using Current Probes

Current probes enable you to directly observe and measure current waveforms. They are available for measuring both AC and DC current. Current probes use jaws that clip around the wire carrying the current. This makes them unique since they are not connected in series with the circuit; they, therefore, cause little or no interference in the circuit.

# Where to Clip the Ground Clip

Measuring a signal requires two connections: the probe tip connection and a ground connection. Probes come with an alligator-clip attachment for grounding the probe to the circuit under test. In practice, you clip the grounding clip to a known ground in the circuit, such as the metal chassis of a stereo you are repairing, and touch the probe tip to a test point in the circuit.

**Compensating the Probe**

Before using a passive probe, you need to compensate it - to balance its electrical properties to a particular oscilloscope. You should get into the habit of compensating the probe every time you set up your oscilloscope. A poorly adjusted probe can make your measurements less accurate. Figure 5 shows what happens to measured waveforms when using a probe not properly compensated.
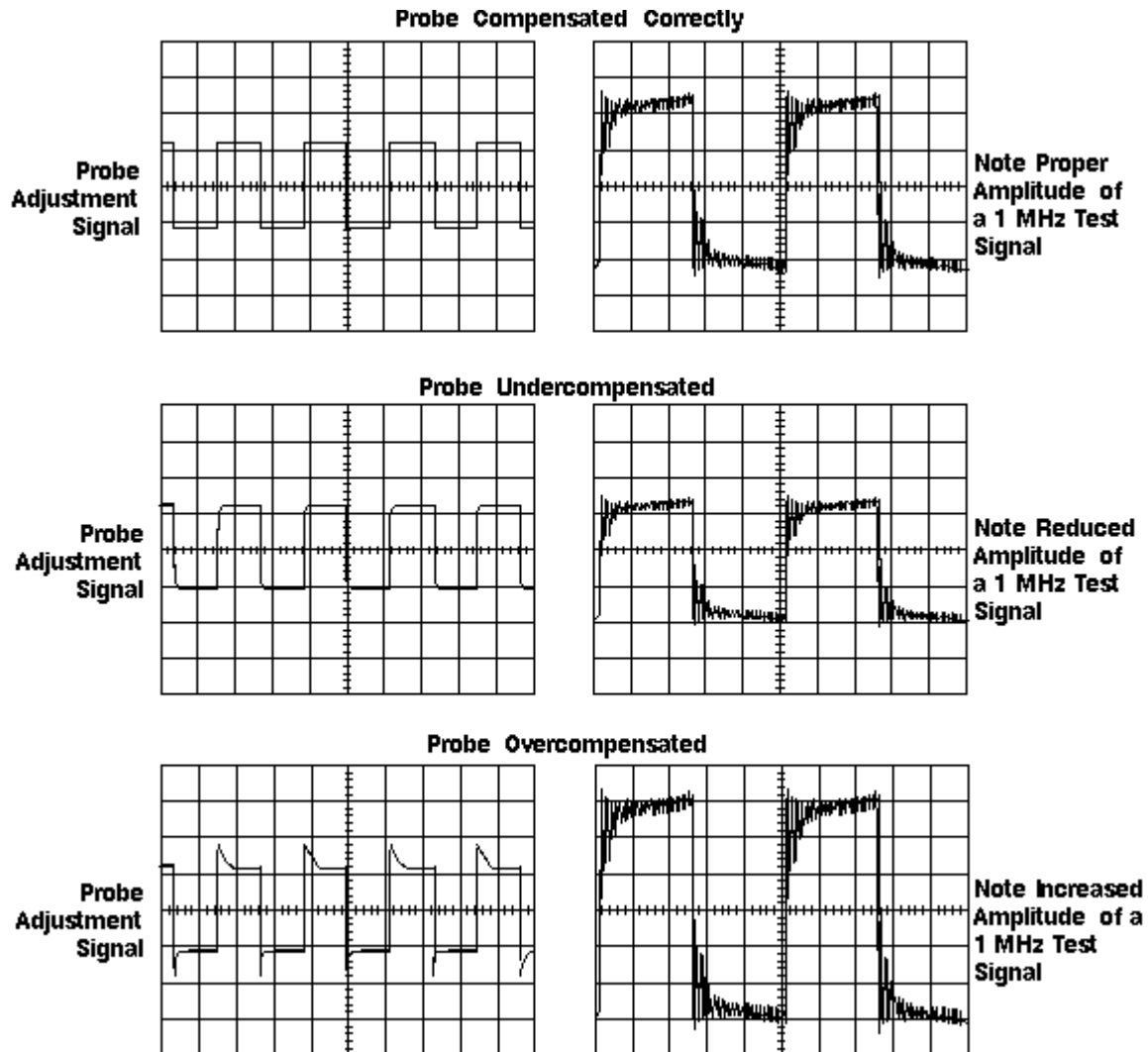


**Figure 5: The Effects of Improper Probe Compensation**

Most oscilloscopes have a square wave reference signal available at a terminal on the front panel used to compensate the probe. You compensate a probe by:

- Attaching the probe to an input connector

- Connecting the probe tip to the probe compensation signal

- Attaching the ground clip of the probe to ground

- Viewing the square wave reference signal

- Making the proper adjustments on the probe so that the corners of the square wave are square

When you compensate the probe, always attach any accessory tips you will use and connect the probe to the vertical channel you plan to use. This way the oscilloscope has the same electrical properties as it does when you take measurements.

### The Controls
This section briefly describes the basic controls found on analog and digital oscilloscopes. Remember that some controls differ between analog and digital oscilloscopes; your oscilloscope probably has controls not discussed here.

### Display Controls
Display systems vary between analog and digital oscilloscopes. Common controls include:

- An intensity control to adjust the brightness of the waveform. As you increase the sweep speed of an analog oscilloscope, you need to increase the intensity level.

- A focus control to adjust the sharpness of the waveform. Digital oscilloscopes may not have a focus control.

- A trace rotation control to align the waveform trace with the screen's horizontal axis. The position of your oscilloscope in the earth's magnetic field affects waveform alignment. Digital oscilloscopes may not have a trace rotation control.

- Other display controls may let you adjust the intensity of the graticule lights and turn on or off any on-screen information (such as menus).

### Vertical Controls
Use the vertical controls to position and scale the waveform vertically. Your oscilloscope also has controls for setting the input coupling and other signal conditioning, described in this section. Figure 1 shows a typical front panel and on-screen menus for the vertical controls.
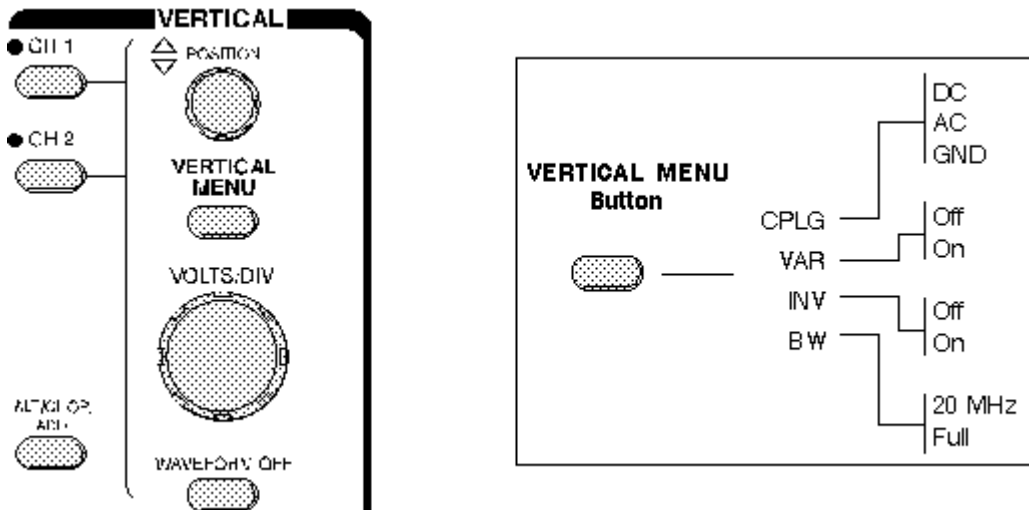


**Figure 1: Vertical Controls**

# Position and Volts per Division

The vertical position control lets you move the waveform up or down to exactly where you want it on the screen.

The volts per division (usually written volts/div) setting varies the size of the waveform on the screen. A good general purpose oscilloscope can accurately display signal levels from about 4 millivolts to 40 volts.

The volts/div setting is a scale factor. For example, if the volts/div setting is 5 volts, then each of the eight vertical divisions represents 5 volts and the entire screen can show 40 volts from bottom to top (assuming a graticule with eight major divisions). If the setting is 0.5 volts/div, the screen can display 4 volts from bottom to top, and so on. The maximum voltage you can display on the screen is the volts/div setting times the number of vertical divisions. (Recall that the probe you use, 1X or 10X, also influences the scale factor. You must divide the volts/div scale by the attenuation factor of the probe if the oscilloscope does not do it for you.)

Often the volts/div scale has either a variable gain or a fine gain control for scaling a displayed signal to a certain number of divisions. Use this control to take rise time measurements.

# Input Coupling

Coupling means the method used to connect an electrical signal from one circuit to another. In this case, the input coupling is the connection from your test circuit to the oscilloscope. The coupling can be set to DC, AC, or ground. DC coupling shows all of an input signal. AC coupling blocks the DC component of a signal so that you see the waveform centered at zero volts. Figure 2 illustrates this difference. The AC coupling setting is handy when the entire signal (alternating plus constant components) is too large for the volts/div setting.
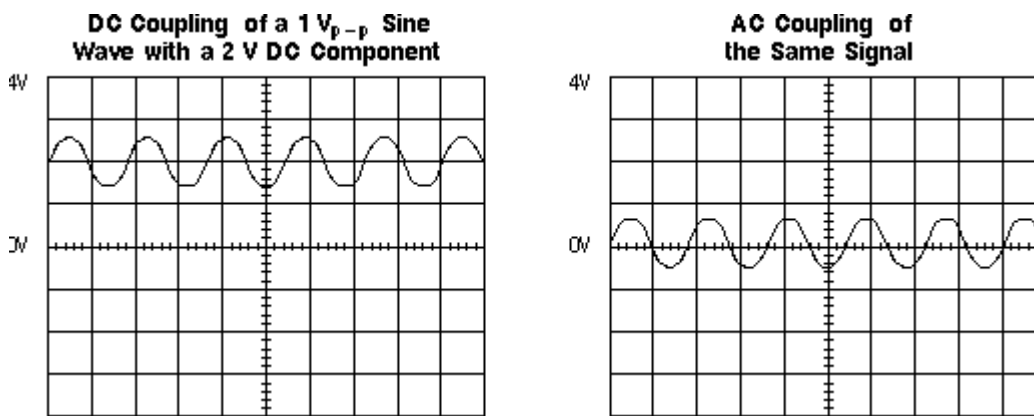


**Figure 2: AC and DC Input Coupling**

The ground setting disconnects the input signal from the vertical system, which lets you see where zero volts is on the screen. With grounded input coupling and auto trigger mode, you see a horizontal line on the screen that represents zero volts. Switching from DC to ground and back again is a handy way of measuring signal voltage levels with respect to ground.

# Bandwidth Limit

Most oscilloscopes have a circuit that limits the bandwidth of the oscilloscope. By limiting the bandwidth, you reduce the noise that sometimes appears on the displayed waveform, providing you with a more defined signal display.

# Channel Invert

Most oscilloscopes have an invert function that allows you to display a signal "upside-down." That is, with low voltage at the top of the screen and high voltage at the bottom.

# Alternate and Chop Display

On analog scopes, multiple channels are displayed using either an alternate or chop mode. (Digital oscilloscopes do not normally use chop or alternate mode.)

Alternate mode draws each channel alternately - the oscilloscope completes one sweep on channel 1, then one sweep on channel 2, a second sweep on channel 1, and so on. Use this mode with medium- to high-speed signals, when the sec/div scale is set to 0.5 ms or faster.

Chop mode causes the oscilloscope to draw small parts of each signal by switching back and forth between them. The switching rate is too fast for you to notice, so the waveform looks whole. You typically use this mode with slow signals requiring sweep speeds of 1 ms per division or less. Figure 3 shows the difference between the two modes. It is often useful to view the signal both ways, to make sure you have the best view.
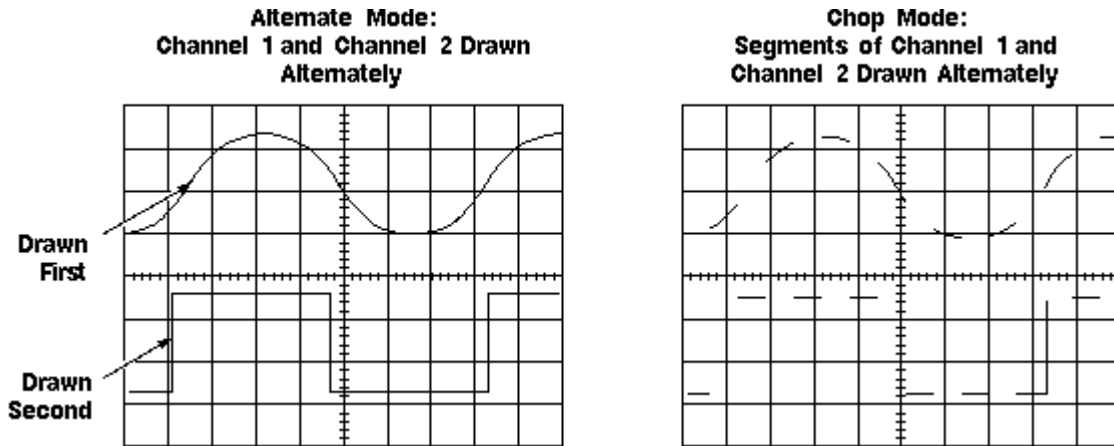
**Figure 3: Multi-Channel Display Modes**

# Math Operations

Your oscilloscope may also have operations to allow you to add waveforms together, creating a new waveform display. Analog oscilloscopes combine the signals while digital oscilloscopes mathematically create new waveforms. Subtracting waveforms is another math operation. Subtraction with analog oscilloscopes is possible by using the channel invert function on one signal and then use the add operation. Digital oscilloscopes typically have a subtraction operation available. Figure 4 illustrates a third waveform created by adding two different signals together.
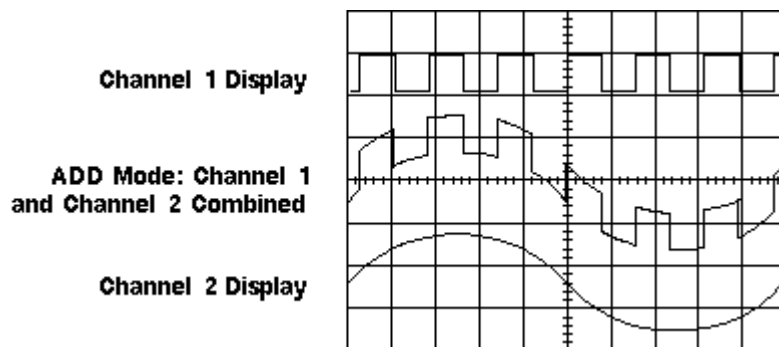
**Figure 4: Adding Channels**

**Horizontal Controls**

Use the horizontal controls to position and scale the waveform horizontally. Figure 5 shows a typical front panel and on-screen menus for the horizontal controls.
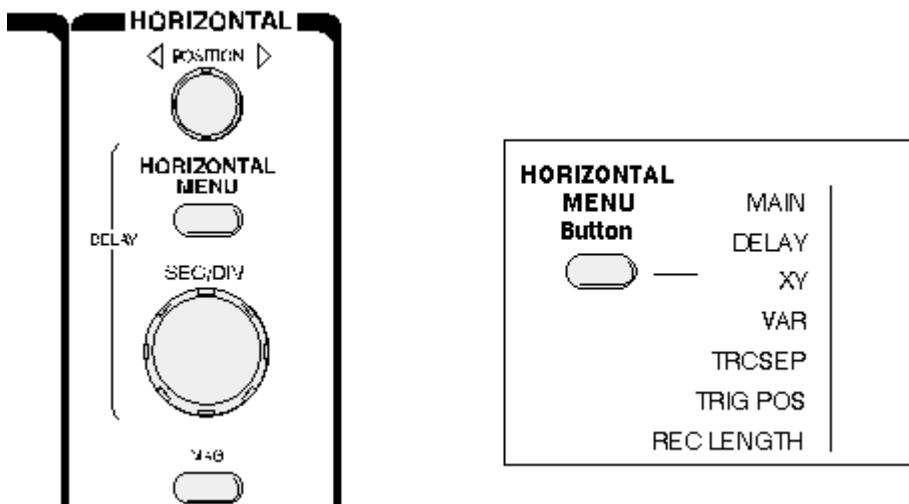
**Figure 5: Horizontal Controls**

# Position and Seconds per Division

The horizontal position control moves the waveform from left and right to exactly where you want it on the screen.

The seconds per division (usually written as sec/div) setting lets you select the rate at which the waveform is drawn across the screen (also known as the time base setting or sweep speed). This setting is a scale factor. For example, if the setting is 1 ms, each horizontal division represents 1 ms and the total screen width represents 10 ms (ten divisions). Changing the sec/div setting lets you look at longer or shorter time intervals of the input signal.

As with the vertical volts/div scale, the horizontal sec/div scale may have variable timing, allowing you to set the horizontal time scale in between the discrete settings.

# Time Base Selections

Your oscilloscope has a time base usually referred to as the main time base and it is probably the most useful. Many oscilloscopes have what is called a delayed time base - a time base sweep that starts after a pre-determined time from the start of the main time base sweep. Using a delayed time base sweep allows you to see events more clearly or even see events not visible with just the main time base sweep.

The delayed time base requires the setting of a delay time and possibly the use of delayed trigger modes and other settings not described in this book. Refer to the manual supplied with your oscilloscope for information on how to use these features.

# Trigger Position

The trigger position control may be located in the horizontal control section of your oscilloscope. It actually represents "the *horizontal* position of the trigger in the waveform record." Horizontal trigger position control is only available on digital oscilloscopes.

Varying the horizontal trigger position allows you to capture what a signal did *before* a trigger event (called *pretrigger viewing*).

Digital oscilloscopes can provide pretrigger viewing because they constantly process the input signal whether a trigger has been received or not. A steady stream of data flows through the oscilloscope; the trigger merely tells the oscilloscope to save the present data in memory. In contrast, analog oscilloscopes only display the signal after receiving the trigger.

Pretrigger viewing is a valuable troubleshooting aid. For example, if a problem occurs intermittently, you can trigger on the problem, record the events that led up to it and, possibly, find the cause.

# Magnification

Your oscilloscope may have special horizontal magnification settings that let you display a magnified section of the waveform on-screen.

# XY Mode

Most oscilloscopes have the capability of displaying a second channel signal along the X-axis (instead of time). This is called XY mode; you will find a longer discussion later in this book.

**Trigger Controls**

The trigger controls let you stabilize repeating waveforms and capture single-shot waveforms. Figure 6 shows a typical front panel and on-screen menus for the trigger controls.
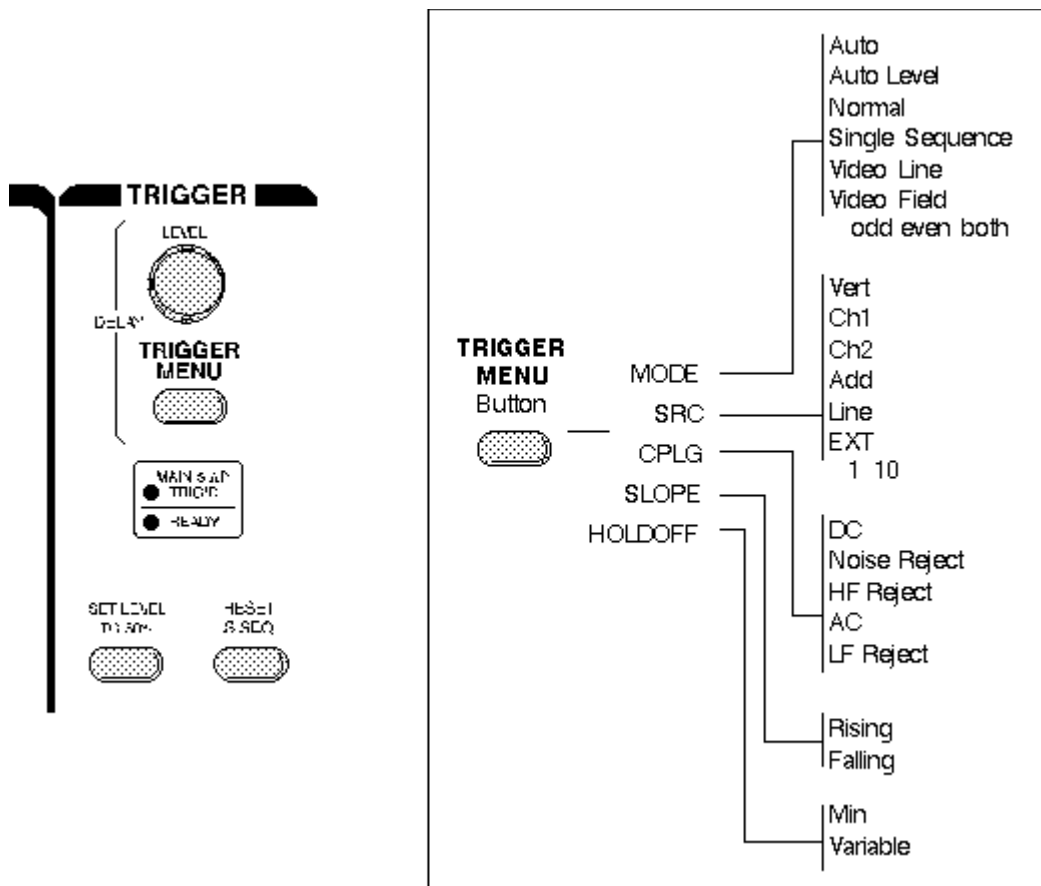


**Figure 6: Trigger Controls**

The trigger makes repeating waveforms appear static on the oscilloscope display. Imagine the jumble on the screen that would result if each sweep started at a different place on the signal (see Figure 7).
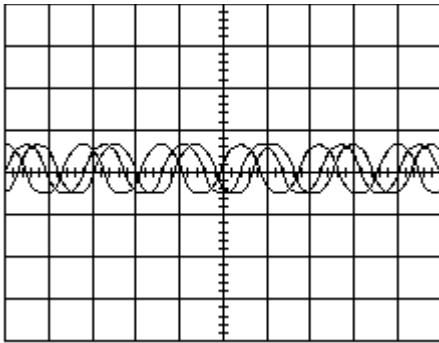
**Figure 7: Untriggered Display**

# Trigger Level and Slope

Your oscilloscope may have several different types of triggers, such as edge, video, pulse, or logic. Edge triggering is the basic and most common type and is the only type discussed in this book. Consult your oscilloscope instruction manual for details on other trigger types.

For edge triggering, the trigger level and slope controls provide the basic trigger point definition.

The trigger circuit acts as a comparator. You select the slope and voltage level of one side of the comparator. When the trigger signal matches your settings, the oscilloscope generates a trigger.

- The slope control determines whether the trigger point is on the rising or the falling edge of a signal. A rising edge is a positive slope and a falling edge is a negative slope.

- The level control determines where on the edge the trigger point occurs.

Figure 8 shows you how the trigger slope and level settings determine how a waveform is displayed.
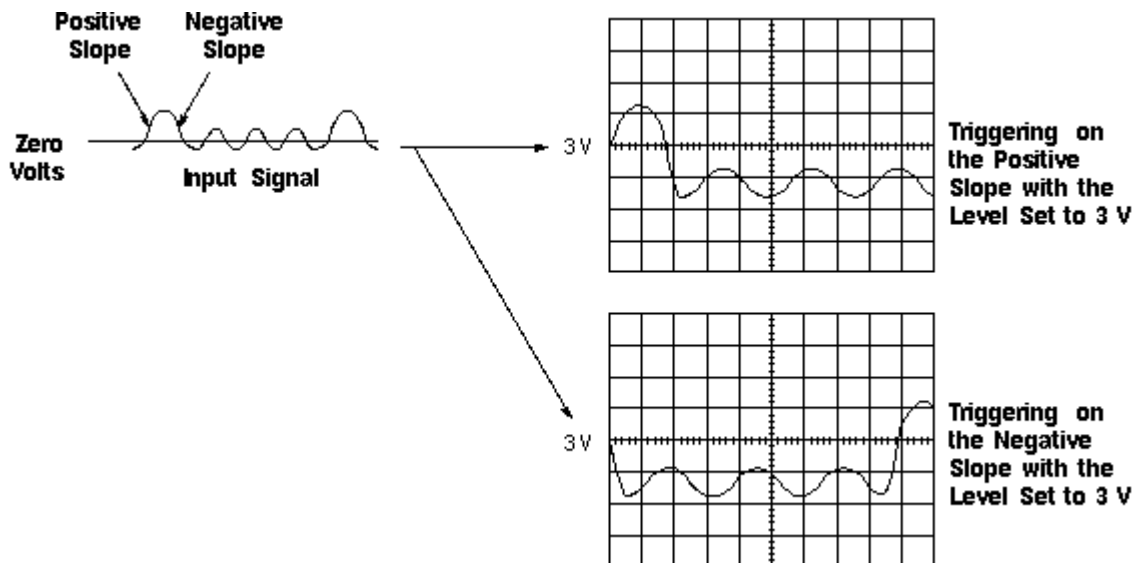


**Figure 8: Positive and Negative Slope Triggering**

# Trigger Sources

The oscilloscope does not necessarily have to trigger on the signal being measured. Several sources can trigger the sweep:

- Any input channel

- An external source, other than the signal applied to an input channel

- The power source signal

- A signal internally generated by the oscilloscope

Most of the time you can leave the oscilloscope set to trigger on the channel displayed.
Note that the oscilloscope can use an alternate trigger source whether displayed or not. So you have to be careful not to unwittingly trigger on, for example, channel 1 while displaying channel 2.

# Trigger Modes

The trigger mode determines whether or not the oscilloscope draws a waveform if it does not detect a trigger. Common trigger modes include *normal* and *auto*.

In normal mode the oscilloscope only sweeps if the input signal reaches the set trigger point; otherwise (on an analog oscilloscope) the screen is blank or (on a digital oscilloscope) frozen on the last acquired waveform. Normal mode can be disorienting since you may not see the signal at first if the level control is not adjusted correctly.
Auto mode causes the oscilloscope to sweep, even without a trigger. If no signal is present, a timer in the oscilloscope triggers the sweep. This ensures that the display will not disappear if the signal drops to small voltages. It is also the best mode to use if you are looking at many signals and do not want to bother setting the trigger each time.
In practice, you will probably use both modes: normal mode because it is more versatile and auto mode because it requires less adjustment.
Some oscilloscopes also include special modes for single sweeps, triggering on video signals, or automatically setting the trigger level.

# Trigger Coupling

Just as you can select either AC or DC coupling for the vertical system, you can choose the kind of coupling for the trigger signal.

Besides AC and DC coupling, your oscilloscope may also have high frequency rejection, low frequency rejection, and noise rejection trigger coupling. These special settings are useful for eliminating noise from the trigger signal to prevent false triggering.
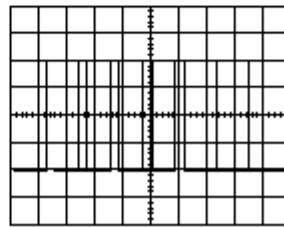
# Trigger Holdoff

Sometimes getting an oscilloscope to trigger on the correct part of a signal requires great skill. Many oscilloscopes have special features to make this task easier.

Trigger *holdoff* is an adjustable period of time during which the oscilloscope cannot trigger. This feature is useful when you are triggering on complex waveform shapes, so that the oscilloscope only triggers on the first eligible trigger point. Figure 9 shows how using trigger holdoff helps create a usable display.
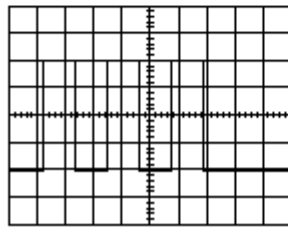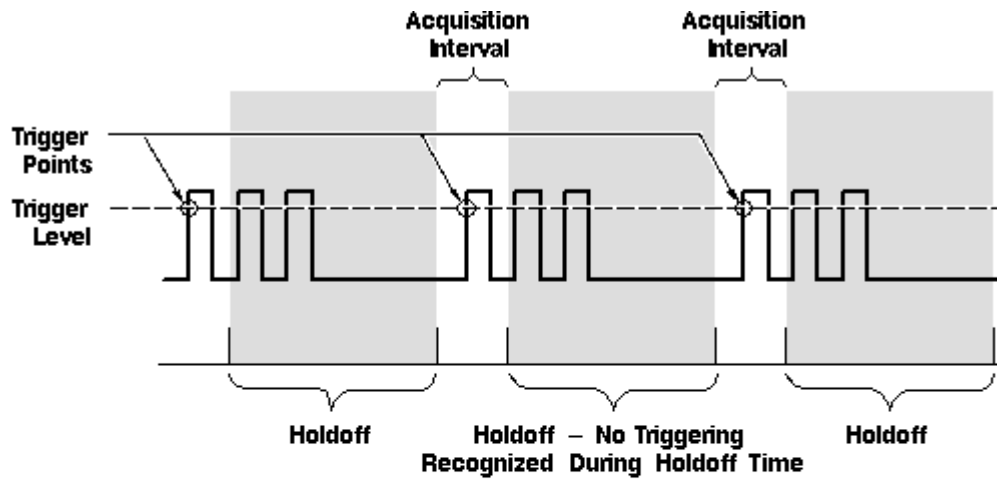
**Figure 9: Trigger Holdoff**

**Acquisition Controls for Digital Oscilloscopes**

Digital oscilloscopes have settings that let you control how the acquisition system processes a signal. Look over the acquisition options on your digital oscilloscope while you read this description. Figure 10 shows you an example of an acquisition menu.
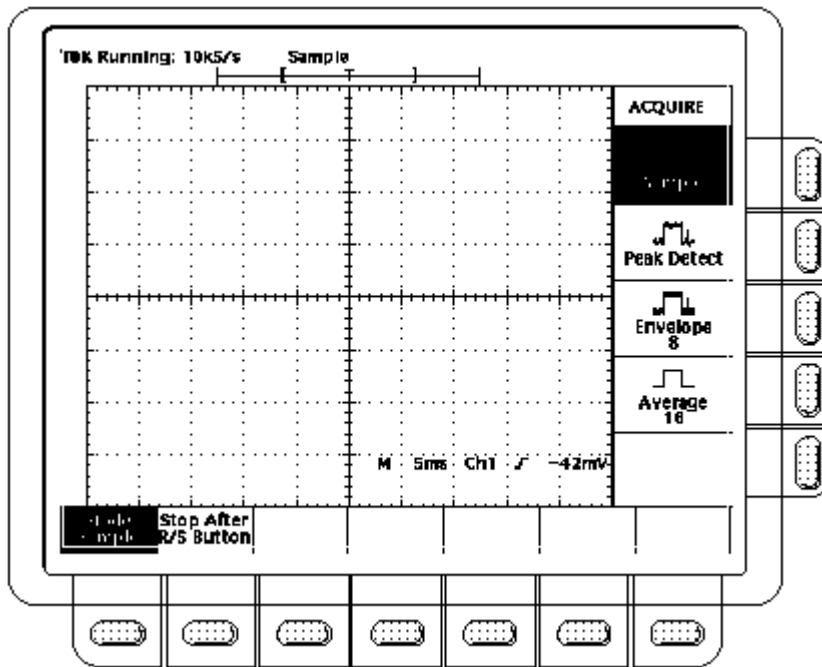
**Figure 10: Example of an Acquisition Menu**

# Acquisition Modes

Acquisition modes control how waveform points are produced from sample points. Recall from the first section that sample points are the digital values that come directly out of the Analog-to-Digital-Converter (ADC). The time between sample points is called the sample interval. Waveform points are the digital values that are stored in memory and displayed to form the waveform. The time value difference between waveform points is called the waveform interval. The sample interval and the waveform interval may be but need not be the same. This fact leads to the existence of several different acquisition modes in which one waveform point is made up from several sequentially acquired sample points. Additionally, waveform points can be created from a composite of sample points taken from multiple acquisitions, which leads to another set of acquisition modes. A description of the most commonly used acquisition modes follows.

- Sample Mode: This is the simplest acquisition mode. The oscilloscope creates a waveform point by saving one sample point during each waveform interval.

- Peak Detect Mode: The oscilloscope saves the minimum and maximum value sample points taken during two waveform intervals and uses these samples as the two corresponding waveform points. Digital oscilloscopes with peak detect mode run the ADC at a fast sample rate, even at very slow time base settings (long waveform interval), and are able to capture fast signal changes that would occur between the waveform points if in sample mode. Peak detect mode is particularly useful for seeing narrow pulses spaced far apart in time.

- Hi Res Mode: Like peak detect, hi res mode is a way of getting more information in cases when the ADC can sample faster than the time base setting requires. In this case, multiple samples taken within one waveform interval are averaged together to produce one waveform point. The result is a decrease in noise and an improvement in resolution for low speed signals.

- Envelope Mode: Envelope mode is similar to peak detect mode. However, in envelope mode, the minimum and maximum waveform points from multiple acquisitions are combined to form a waveform that shows min/max changes over time. Peak detect mode is usually used to acquire the records that are combined to form the envelope waveform.

- Average Mode: In average mode, the oscilloscope saves one sample point during each waveform interval as in sample mode. However, waveform points from consecutive acquisitions are then averaged together to produce the final displayed waveform. Average mode reduces noise without loss of bandwidth but requires a repeating signal.

# Stopping and Starting the Acquisition System

One of the greatest advantages of digital oscilloscopes is their ability to store waveforms for later viewing. To this end, there are usually one or more buttons on the front panel that allow you to stop and start the acquisition system so you can analyze waveforms at your leisure. Additionally, you may want the oscilloscope to automatically stop acquiring after one acquisition is complete or after one set of records has been turned into an envelope or average waveform. This feature is commonly called single sweep or single sequence and its controls are usually found either with the other acquisition controls or with the trigger controls.

# Sampling Methods

In digital oscilloscopes that can use either real-time sampling or equivalent-time sampling as described earlier, the acquisition controls will allow you to choose which one to use for acquiring signals. Note that this choice makes no difference for slow time base settings and only has an effect when the ADC cannot sample fast enough to fill the record with waveform points in one pass.

### Other Controls

So far we have described the basic controls that a beginner needs to know about. Your oscilloscope may have other controls for various functions. Some of these may include:

- Measurement cursors

- Keypads for mathematical operations or data entry

- Print capabilities

- Interfaces for connecting your oscilloscope to a computer

Look over the other options available to you and read your oscilloscope's manual to find out more about these other controls.

**Measurement Techniques**

This section teaches you basic measurement techniques. The two most basic measurements you can make are voltage and time measurements. Just about every other measurement is based on one of these two fundamental techniques.

This section discusses methods for taking measurements visually with the oscilloscope screen. Many digital oscilloscopes have internal software that will take these measurements automatically. Knowing how to take the measurements manually will help you understand and check the automatic measurements of the digital oscilloscopes.

**The Display**

Take a look at the oscilloscope display. Notice the grid markings on the screen - these markings create the *graticule*. Each vertical and horizontal line constitutes a *major division*. The graticule is usually laid out in an 8-by-10 division pattern. Labeling on the oscilloscope controls (such as volts/div and sec/div) always refers to major divisions. The tick marks on the center horizontal and vertical graticule lines (see Figure 1) are called minor divisions.

Many oscilloscopes display on the screen how many volts each vertical division represents and how many seconds each horizontal division represents. Many oscilloscopes also have 0%, 10%, 90%, and 100% markings on the graticule (see Figure 1) to help make rise time measurements, described later.

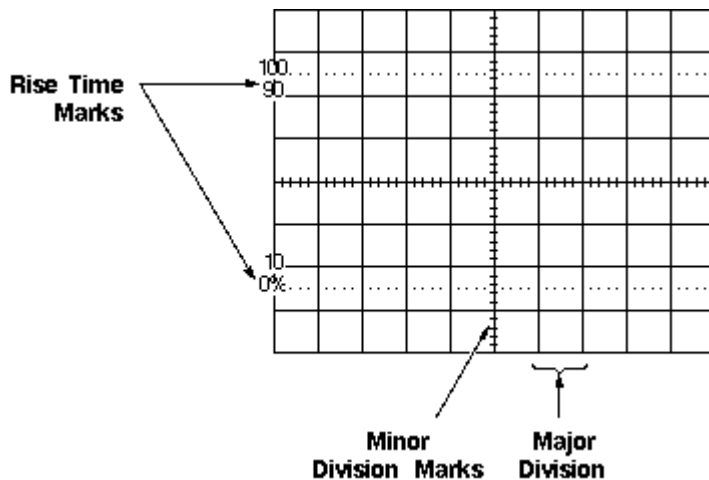**Figure 1: An Oscilloscope Graticule**

**Voltage Measurements**

Voltage is the amount of electric potential, expressed in volts, between two points in a circuit. Usually one of these points is ground (zero volts) but not always. Voltages can also be measured from peak-to-peak - from the maximum point of a signal to its minimum point. You must be careful to specify which voltage you mean.

The oscilloscope is primarily a voltage-measuring device. Once you have measured the voltage, other quantities are just a calculation away. For example, Ohm's law states that voltage between two points in a circuit equals the current times the resistance. From any two of these quantities you can calculate the third. Another handy formula is the power law: the power of a DC signal equals the voltage times the current. Calculations are more complicated for AC signals, but the point here is that measuring the voltage is the first step towards calculating other quantities.

Ohm's Law:

$$\text{Voltage} = \text{Current} \text{ times } \text{Resistance}$$

$$\text{Current} = \frac{\text{Voltage}}{\text{Resistance}}$$

$$\text{Resistance} = \frac{\text{Voltage}}{\text{Current}}$$

Power Law:

$$\text{Power} = \text{Voltage} \text{ times } \text{Current}$$

Figure 2 shows the voltage of one peak - V[p] - and the peak-to-peak voltage - V[p-p] -, which is usually twice V[p]. Use the RMS (root-mean-square) voltage - V[RMS] - to calculate the power of an AC signal.
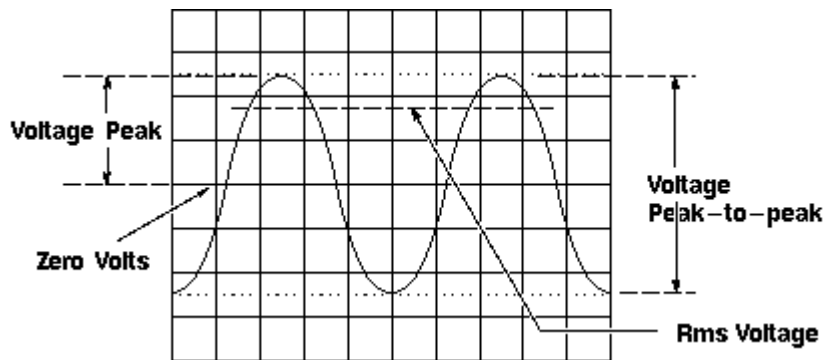
**Figure 2: Voltage Peak and Peak-to-peak Voltage**

You take voltage measurements by counting the number of divisions a waveform spans on the oscilloscope's vertical scale. Adjusting the signal to cover most of the screen vertically, then taking the measurement along the center vertical graticule line having the smaller divisions, makes for the best voltage measurements. The more screen area you use, the more accurately you can read from the screen.
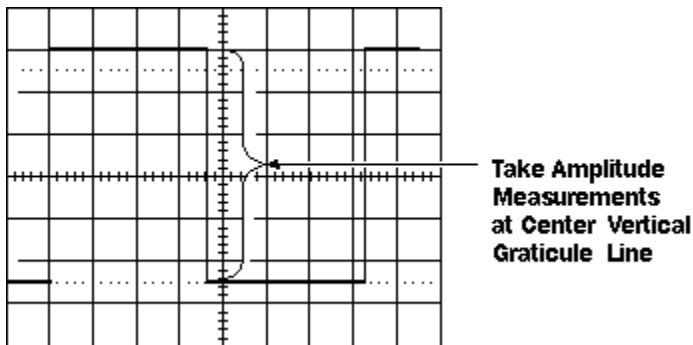


**Figure 3: Measure Voltage on the Center Vertical Graticule Line**

Many oscilloscopes have on-screen *cursors* that let you take waveform measurements automatically on-screen, without having to count graticule marks. Basically, cursors are two horizontal lines for voltage measurements and two vertical lines for time measurements that you can move around the screen. A readout shows the voltage or time at their positions.

**Time and Frequency Measurements**

You take time measurements using the horizontal scale of the oscilloscope. Time measurements include measuring the period, pulse width, and timing of pulses. Frequency is the reciprocal of the period, so once you know the period, the frequency is one divided by the period. Like voltage measurements, time measurements are more accurate when you adjust the portion of the signal to be measured to cover a large area of the screen. Taking time measurement along the center horizontal graticule line, having smaller divisions, makes for the best time measurements. (See Figure 4.)
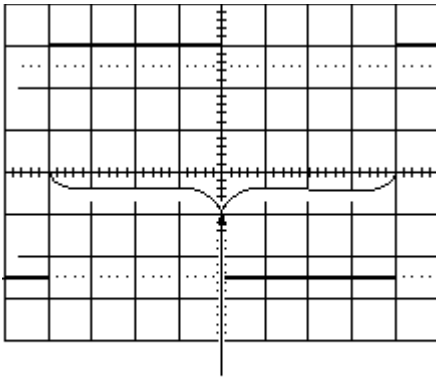
Take Time Measurements
at Center Horizontal Graticule Line

**Figure 4: Measure Time on the Center Horizontal Graticule Line**

**Pulse and Rise Time Measurements**

In many applications, the details of a pulse's shape are important. Pulses can become distorted and cause a digital circuit to malfunction, and the timing of pulses in a pulse train is often significant.

Standard pulse measurements are *pulse width* and *pulse rise time*. Rise time is the amount of time a pulse takes to go from the low to high voltage. By convention, the rise time is measured from 10% to 90% of the full voltage of the pulse. This eliminates any irregularities at the pulse's transition corners. This also explains why most oscilloscopes have 10% and 90% markings on their screen. Pulse width is the amount of time the pulse takes to go from low to high and back to low again. By convention, the pulse width is measured at 50% of full voltage. See Figure 5 for these measurement points.
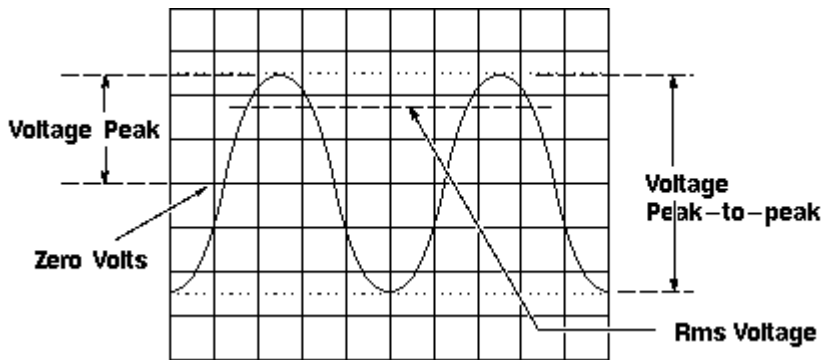


**Figure 5: Rise Time and Pulse Width Measurement Points**

Pulse measurements often require fine-tuning the triggering. To become an expert at capturing pulses, you should learn how to use trigger holdoff and how to set the digital oscilloscope to capture pretrigger data, as described earlier in the Controls section. Horizontal magnification is another useful feature for measuring pulses, since it allows you to see fine details of a fast pulse.

**Phase Shift Measurements**

The horizontal control section may have an XY mode that lets you display an input signal rather than the time base on the horizontal axis. (On some digital oscilloscopes this is a display mode setting.) This mode of operation opens up a whole new area of phase shift measurement techniques.

The phase of a wave is the amount of time that passes from the beginning of a cycle to the beginning of the next cycle, measured in degrees. Phase shift describes the difference in timing between two otherwise identical periodic signals.

One method for measuring phase shift is to use XY mode. This involves inputting one signal into the vertical system as usual and then another signal into the horizontal system. (This method only works if both signals are sine waves.) This set up is called an XY measurement because both the X and Y axis are tracing voltages. The waveform resulting from this arrangement is called a Lissajous pattern (named for French physicist Jules Antoine Lissajous and pronounced LEE-sa-zhoo). From the shape of the Lissajous pattern, you can tell the phase difference between the two signals. You can also tell their frequency ratio. Figure 6 shows Lissajous patterns for various frequency ratios and phase shifts.
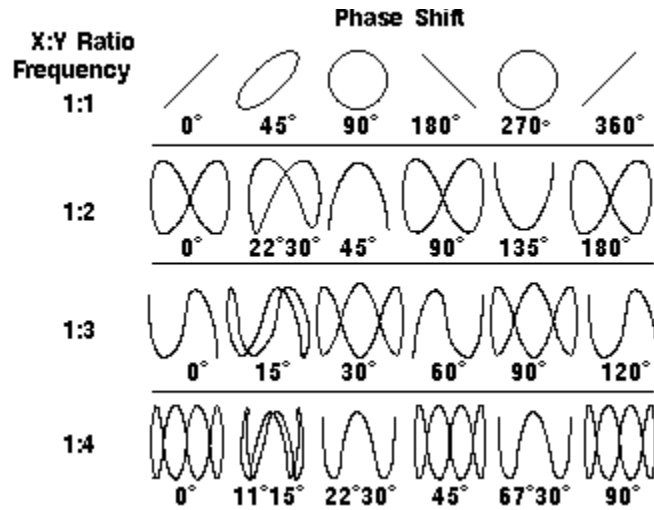


**Figure 6: Lissajous Patterns**