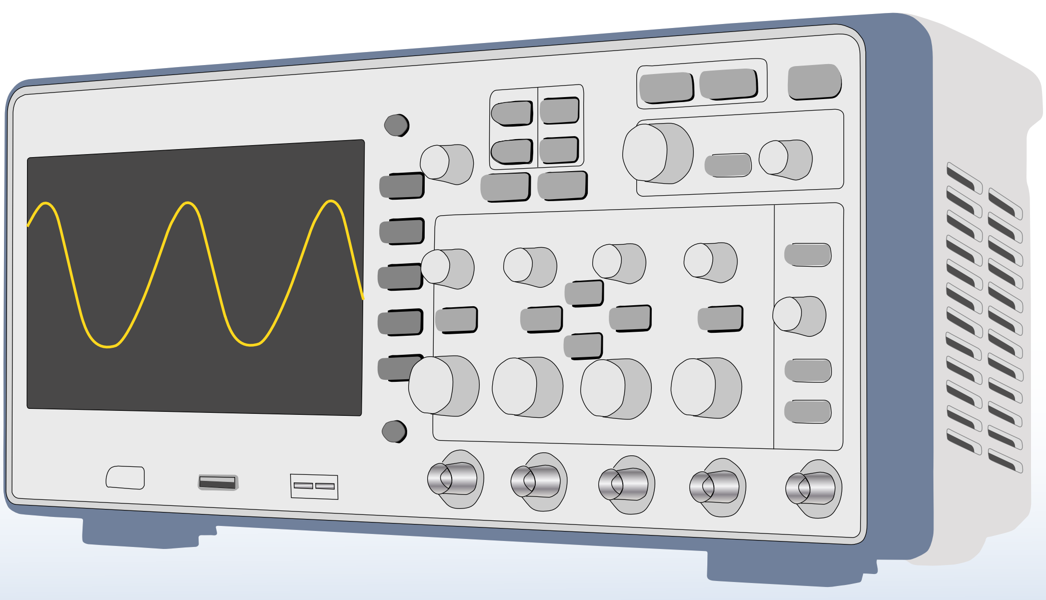
Oscilloscope

Guide



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Introduction

This document is a primer on the use and application of analog and digital oscilloscopes (we'll also call them "scopes"). Most of the material is at an introductory level and aimed at helping you understand some of the key features and aspects about oscilloscopes.

What we'll cover in this document

- Basic characteristics of signals and their terminology
- Two predominant types of oscilloscopes available today: analog and digital
- Typical oscilloscope controls, features, and theory of operation
- Various types of probes available and their use
- Oscilloscope guidelines and safety

A glossary of terms used in the context of oscilloscopes and the use of oscilloscopes is included at the end of this document.

So what exactly is an oscilloscope?

An oscilloscope is an electrical measuring device that displays a graph of a voltage as a function of time. This allows a user to make both voltage and time measurements. Many oscilloscopes can display more than one voltage signal on their screen, which gives us the powerful ability to compare the behavior of these signals. Since our brains are good at recognizing patterns, the oscilloscope lets us see patterns in these voltage versus time plots. These patterns and comparisons are the oscilloscope's benefits over a measuring instrument like a voltmeter that just gives us a number. Since many physical properties of interest can be represented by a voltage, **the oscilloscope helps us understand how the world changes in time**.

Many engineers, scientists, and technicians pick the oscilloscope as their primary measurement tool because of its range and versatility. Visual representations and wide measuring range are probably the major reasons scopes are so widely used. The oscilloscope can display information over roughly 10 orders of magnitudes of time and 3 to 4 orders of magnitude of voltage.

Here's an example of a digital oscilloscope displaying a 1 volt peak-to-peak (Vpp), 1 kHz sine wave:

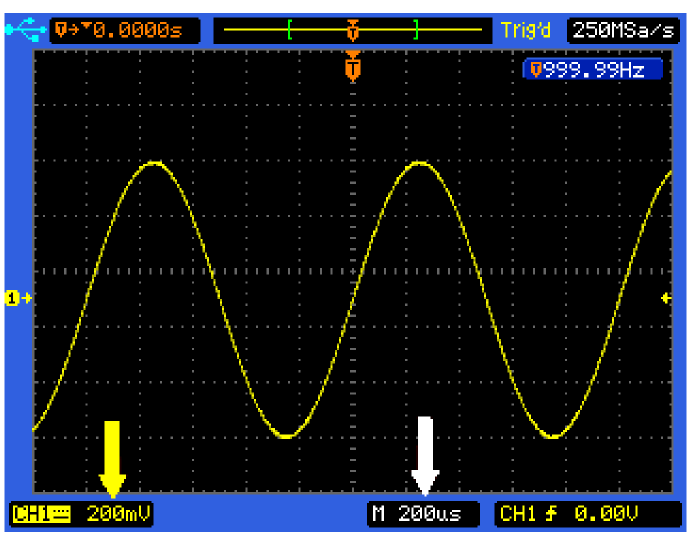

Figure 1

We will look at these pictures in more detail, but two observations are:

- The peak-to-peak voltage of the waveform can be measured along the vertical axis. It is five main divisions and the vertical gain is set to 200 mV/division (see the yellow arrow), which gives a signal amplitude of 1 volt peak-to-peak.
- The horizontal axis is time and the scope is set to 200 µs/division (see the white arrow). One period of the sine wave spans five main divisions, so the period is 1 ms, which means the frequency is 1 kHz. (This particular oscilloscope has a counter that is displaying the signal's frequency in the upper right-hand corner.)

Some of the uses of an oscilloscope are:

- Measure voltages, voltage differences, and time intervals.
- Measure the frequency of a repetitive signal.
- Compare two or more signals varying in time and see their relationships (for example, whether a particular feature on one waveform occurs before or after a feature on the other waveform).
- See the effect of adding or removing a component on a circuit.
- Capture transients, glitches, or surprising behavior, even when no one is around.
- Verify correct operation of a test point in a circuit when troubleshooting or performing a manufacturing test.
- Measure the DC and AC parts of a waveform.
- Measure various characteristics of a waveform, such as peak-to-peak voltage, RMS voltage, period, rise time, fall time, etc.
- Examine the noise on a signal is and how modifications to the circuit or cabling can change the noise.
- Plot one voltage versus another voltage. This is called XY mode and is an exception to the statement that the scope displays a voltage as a function of time.
- Some scopes have the ability to allow the intensity of the trace to be varied by an external signal (z-axis modulation). This gives another "dimension" to the ability of the scope to display information.
- Look for distortion in a circuit by visually comparing its input and output waveforms -- or using the scope to subtract them and look at the mathematical difference.
- Make physical measurements using a transducer that converts a physical behavior into a voltage.

Notation

References to sections and figures can be clicked as hyperlinks. The bookmarks contain links to all of the chapters and subsections. The following fonts and colors are used to identify various things:

Notation	Explanation
CH1	Denotes a control on the front panel of an oscilloscope.
Coupling	Denotes a menu selection in a digital oscilloscope.

The following symbols are used in the text:

Symbol	Meaning
A	amperes
B	bandwidth, Hz
f	frequency in Hz
G	giga-, the SI prefix of 10^{9}
Hz	hertz, the SI unit of frequency, equal to reciprocal seconds
k	kilo-, the SI prefix of 10^{3}
m	milli-, the SI prefix of 10^{-3}
M	mega-, the SI prefix of 10^{6}
n	nano-, the SI prefix of 10^{-9}
p	pico-, the SI prefix of 10^{-12}
s	seconds
s/div	seconds per division, timebase setting (i.e., sweep speed) of an oscilloscope
V	volts
V/div	volts per division, vertical gain of an oscilloscope's vertical amplifier
Vpp	peak-to-peak voltage, V
Vrms	RMS (root mean square) voltage, V
Ω	ohms
μ	micro-, the SI prefix of 10^{-6}

Signals

With regard to the oscilloscope, the term signal means a voltage that may vary in value as a function of time. One distinction is whether the signal is periodic or not. Periodic means that the signal repeatedly takes on the same set of values over various intervals. The sine wave is one example of a periodic waveform. Let's look at some of its features:

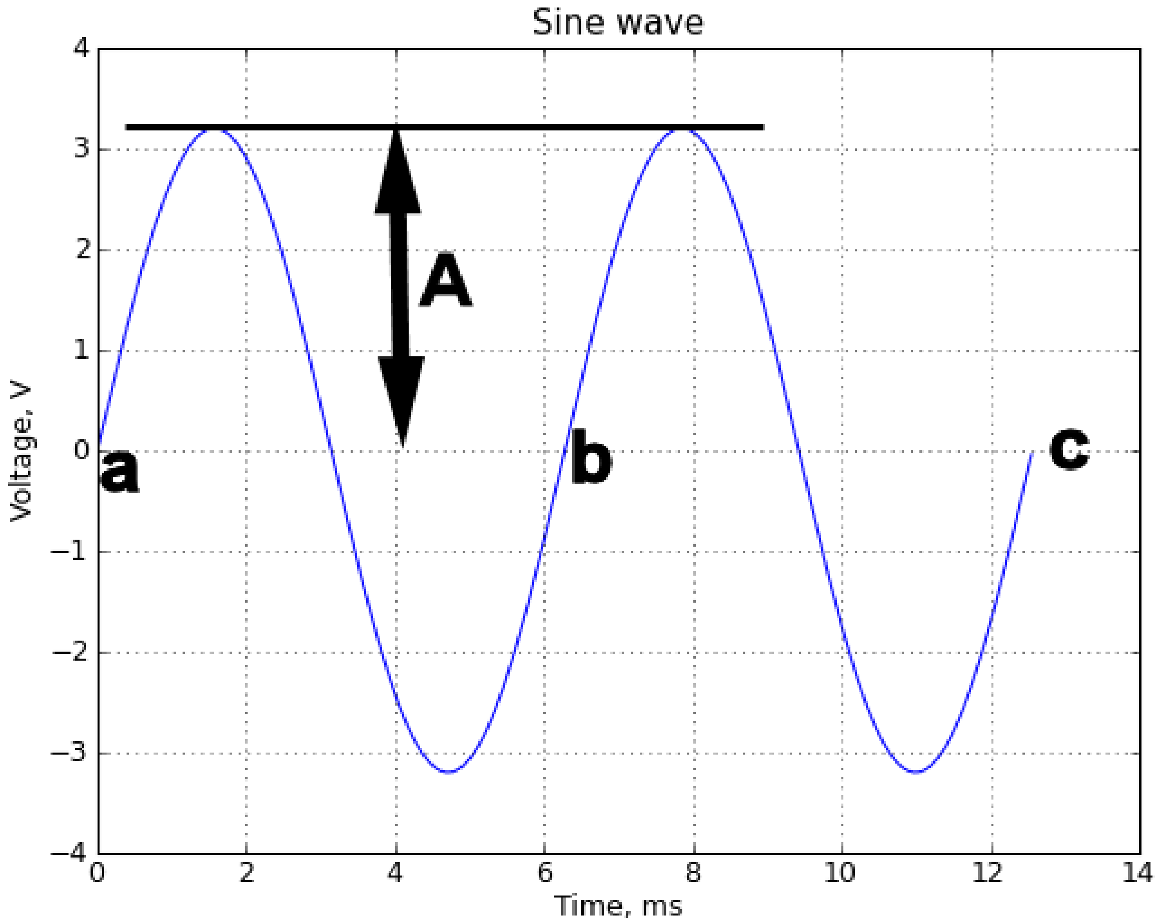

Figure 2

Frequency measurements

Figure 2 shows two periods of a sine wave. A **period** is the set of points consisting of the basic shape of the waveform. The sine wave takes on various values between point a (t = 0) and point b (t = 6.2). The waveform then repeats this set of values from point b to point c. The time from point a to point b is called the period of the waveform. In the figure, you can see that the period is 6.2 ms.

The **frequency** of a signal is the reciprocal of the period:

$$\text{frequency} = \frac{1}{\text{period}}$$

Frequency is measured in Hz (hertz) and is dimensionally equal to reciprocal seconds (s^{-1}). In this document, we'll use the symbol *f* for frequency. Another measure of frequency is **angular frequency** (also called **radian frequency**), which is often denoted by ω and is equal to $2\pi f$. It is used because sine waves and their analysis lead to trigonometric formulas, and are most simply and easily expressed in radian measurement.

The sine wave's amplitude in Figure 2 is shown as the distance '*A*'. The mathematical expression for the sine wave, expressing the voltage as a function of time, is:

$$V = A\sin(\omega t)$$

From the graph, you can see that the period of this sine wave is 6.2 ms. This corresponds to a frequency of 1/(6.2 x 10^{-3} s) or 161 Hz. Then we have $\omega = 2\pi f = 2\pi(161Hz) = 1011$ radian/s. We can also read from the graph that the sine wave's amplitude 'A' is 3.2 volts. Thus, the equation for this particular sine wave is:

$$V = 3.2\sin(1011t)$$

where *t* is measured in seconds and *V* is measured in volts. Here is a graph from an oscilloscope showing such a sine wave produced by a function generator:

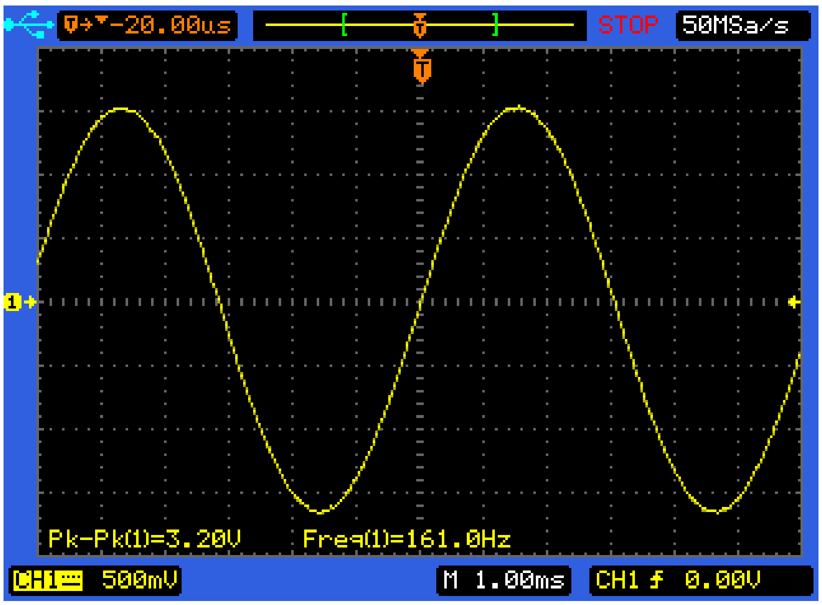

Figure 3

Amplitude measurements

A common measurement of a waveform on an oscilloscope's graph is the peak-to-peak amplitude. This is the vertical distance from the minimum point to the maximum point on the waveform. Here you can see that the minimum point is at -3.3 divisions, measured from the V = 0 axis marked by the yellow 1 and arrow marker on the left. The maximum point is at +3.1 divisions. Hence, the peak-to-peak amplitude is 3.1 - (-3.3) or 6.4 divisions. The scope's vertical channel gain is set to 500 mV per division, so we get a measured peak-to-peak voltage of (6.4 div)x(500 mV/div) = 3.2 volts. Note this measurement is shown by the scope in the lower left corner of the picture and demonstrates that some scopes can be set up to display various waveform measurements of interest.

The period of the waveform is calculated from the two intersections with the V = 0 axis. The first one is -3.2 divisions and the second one is 3.1 divisions. The scope's horizontal axis (called the timebase or sweep speed) is set to 1 ms/div. Thus, the period is [(3.1 div) - (-3.2 div)]x(1 ms/div) = 6.3 ms. The frequency is the reciprocal of this or 159 Hz. The scope has also provided this measurement at 161 Hz. Our measurement from the screen disagrees from the scope's measured value by roughly a percent. We'll have more to say about this later -- but one of the key things to realize about the measurements made from an oscilloscope's screen is that you can, at best, expect a measurement resolution and accuracy of a few percent.

While the amplitude *A* shown in Figure 2 is used in the mathematical expression of the sine wave, it's rarely used in practical measurements. Instead, two other measures are used. We've already discussed the peak-to-peak amplitude and can thus provide the relationship:

$$V_{pp} = 2A \qquad (1)$$

where V_{pp} is the peak-to-peak amplitude. The amplitude *A* is sometimes called the zero-to-peak amplitude.

Another amplitude measure is RMS, which stands for "root mean square". If you have a sequence of *n* discrete voltage measurements V_i (like you would in the above digital oscilloscope measurement) over one period of the waveform, you can calculate the RMS value of this sequence by a formula hinted at by the name:

$$V_{rms} = \sqrt{\frac{\sum_{i=1}^{n} V_i^2}{n}}$$

In other words, square each voltage, add them all together, and divide by *n* to get their mean. Then take the square root. For continuous functions, there's a corresponding definition of the RMS value in terms of an integral.

In this document, we'll often use the units of Vpp and Vrms to denote a peak-to-peak voltage measurement and an RMS voltage measurement. These are read "volts peak-to-peak" and "volts RMS".

One can derive for a sine wave that:

$$A = \sqrt{2}V_{rms} \qquad (2)$$

From equations (1) and (2), one can derive the often-used relationship:

$$V_{pp} = 2\sqrt{2}V_{rms} = 2.82V_{rms} \qquad (3)$$

Remember, this is only true for a sine wave.

In the use of oscilloscopes, the peak-to-peak voltage is often used because it is usually the easiest type of amplitude to measure for a waveform (we're assuming the user has to measure it manually from the screen). The RMS voltage is important because it is used to quantify the electrical power in time-varying waveforms. For a DC circuit, the power dissipated in a resistor is defined as:

$$P = Vi$$

where *V* is the voltage across the resistor in volts, *i* is the current through the resistor in amperes, and *P* is the power being dissipated (i.e., turned into heat) in watts. The RMS measures of the current and voltage are used in the analogous relationship for a time-varying waveform:

$$P_{rms} = V_{rms} i_{rms}$$

Experimentally, it has been established that the heating power of a waveform can be related to a DC situation by the use of RMS measures. Thus, a 1 volt RMS periodic voltage that causes a 1 ampere RMS current through a 1 Ω resistor has an average power dissipated in the resistor of 1 watt. Here, "average" means that the instantaneous power values are averaged over one waveform period or longer. **The use of this relationship applies to any shape of waveform, not just sinusoidal waveforms**.

Non-sinusoidal waveforms

There are other often-encountered waveforms that have special names. The following figure shows some examples:

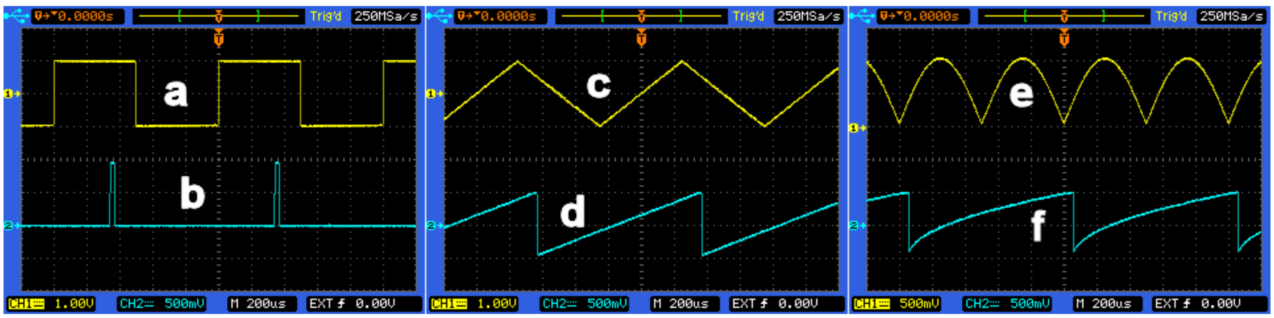

Figure 4

a	Square wave
b	Pulse waveform (note the pulse's minimum values here are 0 volts and the peak voltage is 1 volt)
c	Triangle wave
d	Ramp wave (also called a sawtooth wave)
e	Rectified sine wave ($\lvert\sin(\omega t)\rvert$)
f	Square root wave (amplitude is proportional to the square root of the time from the start of the wave's period)

Analog oscilloscopes

An analog scope is an oscilloscope constructed with analog circuit technology and signals are displayed on a cathode ray tube (CRT), a type of vacuum tube using an electron beam (see the section below on CRTs). Such technology has been evolving since the 1930's when the first commercial oscilloscopes were available. While digital scopes constitute the majority of new oscilloscopes sold, this does not mean there is no demand for analog oscilloscopes. Analog oscilloscopes don't have the feature sets that digital scopes do, but can provide some benefits that digital scopes don't offer. We'll first look at a typical analog scope, the B&K 2125A, and its controls. Then we'll examine an analog scope's theory of operation and look at the operation of the 2125A scope.

Analog scope controls

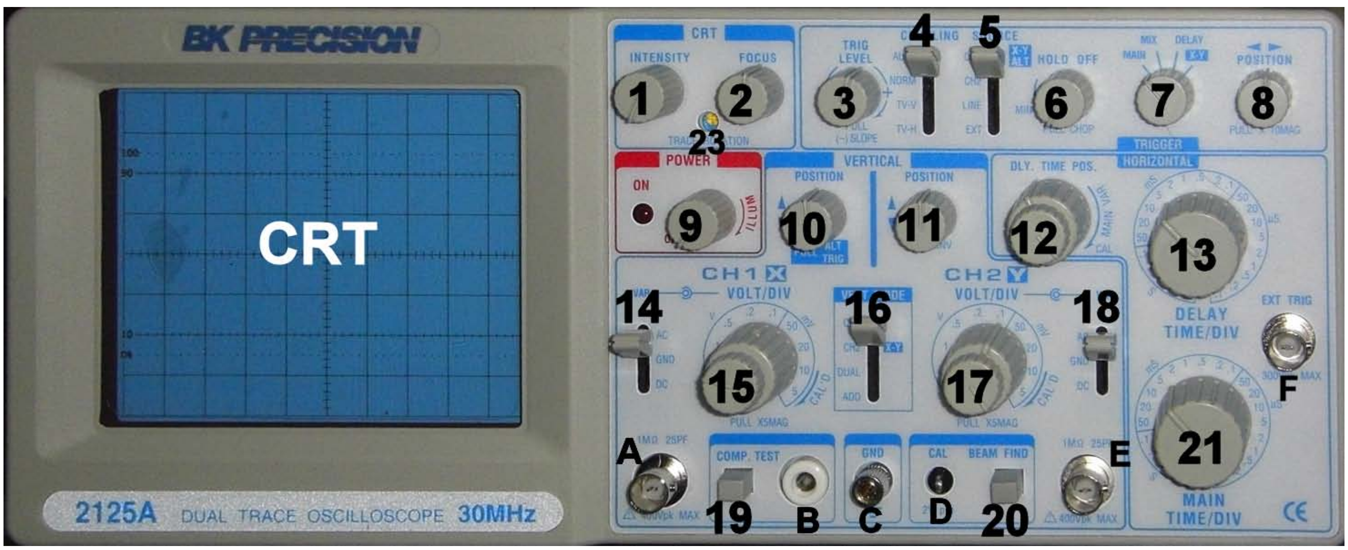

Figure 5

Figure 5 shows the front panel of the 2125A scope. The controls are keyed to the numbers in the following table:

Button Number	Button label	Function
1	Intensity	Changes the brightness of the trace on the screen. This is done by changing the electron beam current in the CRT.
2	Focus	Focuses the electron beam, leading to a thinner trace on the screen.
3	Trig Level	Trigger level. This sets the voltage that the trigger circuit must see in order for a trigger event to occur and, thus, a trace to go across the screen.
4	Coupling	Trigger coupling. The choices are Auto, Normal, TV-V (TV vertical), and TV-H (TV horizontal).
5	Source	Chooses where the triggering signal comes from. The choices are channel 1, channel 2, line (i.e., the AC line), and external.
6	Hold off	Sets the time delay after the electron beam has swept across the screen before the trigger is armed again. This is useful to help with triggering on more complex waveforms.

7	--	This switch chooses the display type. The choices are Main, Mix, Delay, and X-Y. We'll discuss each in more detail below.
8	Position	Controls the horizontal position of the trace(s) on the screen.
9	Illum	Turns power on to the scope and controls the illumination of the graticule, the scale printed on the CRT.
10	Position	Adjusts the vertical position of the trace of channel 1's signal.
11	Position	Adjusts the vertical position of the trace of channel 2's signal.
12	Dly. Time Pos.	This is a dual control. The inner (larger diameter control) sets the delay time of the delayed sweep. The outer (smaller diameter control) is used to vary the main timebase sweep speed.
13	Delay time/div	Adjusts the sweep time of the delayed timebase.
14	--	Selects the coupling of channel 1. The choices are DC, AC, and ground.
15	Volt/div	The large (inner) control adjusts the calibrated vertical gain of channel 1. The smaller (outer) control continuously varies the vertical gain (this control is sometimes incorrectly called a vernier). Turn the outer control fully clockwise to have it click and be in the calibrated position. The uncalibrated position is useful for e.g. setting a signal to full screen height, then noting the change in signal amplitude for some physical change in the circuit. It is also used for rise time measurements using the 10%-90% marks on the screen.
16	Vert mode	Chooses which channels of the scope are displayed and how they're displayed. The choices are CH1, CH2, DUAL, X-Y, and Add.
17	Volt/div	Same behavior as 15, except for channel 2.
18	--	Selects the coupling of channel 2. The choices are DC, AC, and ground.
19	Comp. test	A pushbutton switch that turns on component test. We'll discuss this more below.
20	Beam find	A pushbutton switch that helps you figure out which controls need to be adjusted to get a trace onto the screen.
21	Main time/div	Adjusts the sweep time of the main timebase.
22	Trace rotation	This is an adjustment that rotates the trace on the screen so that the trace is parallel to the graticule.

The letters identify the connectors for inputs and outputs from the scope:

ID	**Label**	**Function**
A	--	Channel 1 input
B	--	Component test signal output (see discussion below)
C	GND	Chassis ground connection. The chassis is connected to the power line ground conductor via the power plug.
D	CAL	Probe calibration signal (2 Vpp, 1 kHz square wave). It is used to adjust the compensation of oscilloscope probes.
E	--	Channel 2 input
F	Ext trig	External trigger input

The rear panel has two BNC connectors:

- Y-Axis Output Jack - a buffered signal of one of the channels (channel 2 on the 2125A) is available with an output impedance of 50 Ω. It can act as a preamplifier with the same bandwidth of the scope (one use is to amplify a low-level signal for a frequency counter).
- Z-Axis Input Jack (also called "External Blanking Input") - a voltage can modulate the intensity of the CRT electron beam. The signal levels are often TTL such that 0 volts turns the beam off and 5 volts causes the maximum intensity. Older scientific instruments sometimes used XY mode with the z-axis input to provide a raster-type display similar to how an analog television behaves.

Theory of operation

Cathode ray tube (CRT)

The basis of the operation of an analog oscilloscope is the cathode ray tube (CRT), a special type of vacuum tube. The following picture is a schematic representation of a CRT:

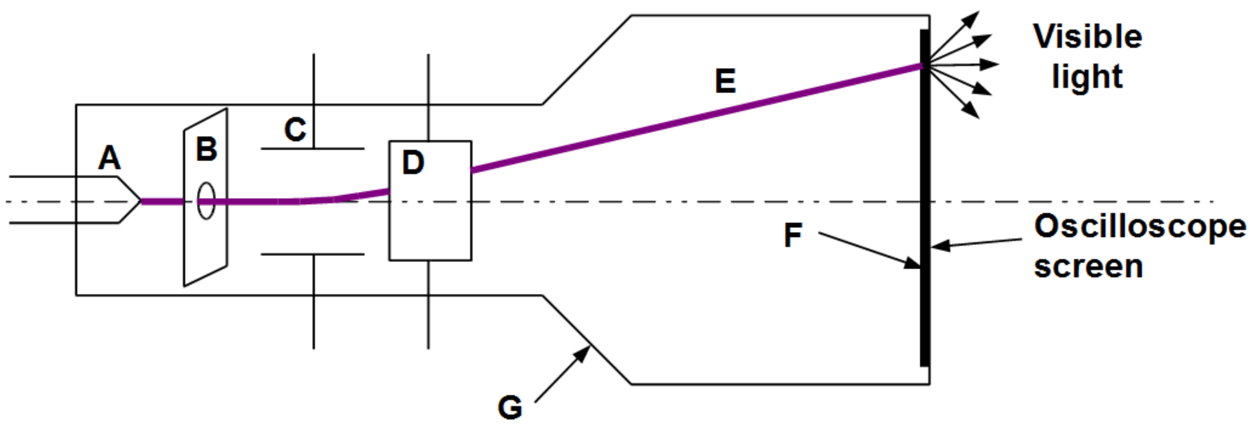

Figure 6

The glass envelope G is the vacuum container; inside the envelope, most of the air is removed to eliminate electron collisions with air molecules. The filament A is heated by current flowing through it. This heated filament causes electrons to be emitted. A positive potential is put on plate B with respect to the filament[1] which accelerates the electrons towards and through the hole in B, resulting in the electron beam E. Voltages on deflecting plates C and D cause the electron beam E to impact at different positions on the phosphor screen F because of electrostatic deflection (more sophisticated designs may use both electrostatic and magnetic deflection). When electrons impact the phosphor's atoms, the atoms change into an excited state. When the excited states decay back to the ground state, the atoms emit photons of visible light. This light is what lets you see the trace on the oscilloscope screen. The light emission from the phosphor happens over a period of time called the **persistence**, which distinguishes phosphorescence from fluorescence, which happens immediately. Since electrons have small mass, the electron beam is capable of being positioned rapidly over the phosphor screen. When this is done rapidly enough, you see a continuous trace of light[2]. The scope's

[1]The filament is called the cathode because of its negative potential with respect to the accelerating plate B. The electron beam can be seen in some tubes because of collisions with residual air molecules. In the late 1800's, these beams were called "cathode rays" -- hence the name "cathode ray tube".

[2]If you have an analog scope, you can measure the point at which your eyes and brain just start to see the trace licker. People see flicker at frequencies from below 30 Hz to 60 Hz or so.

intensity control adjusts the magnitude of the electron beam current -- the more current, the brighter the spot the beam makes on the screen. The accelerating potential on plate B is not adjustable by the user. The voltages on the plates C and D are the responsibility of the horizontal and vertical deflection circuitry as shown in the following block diagram of a scope:

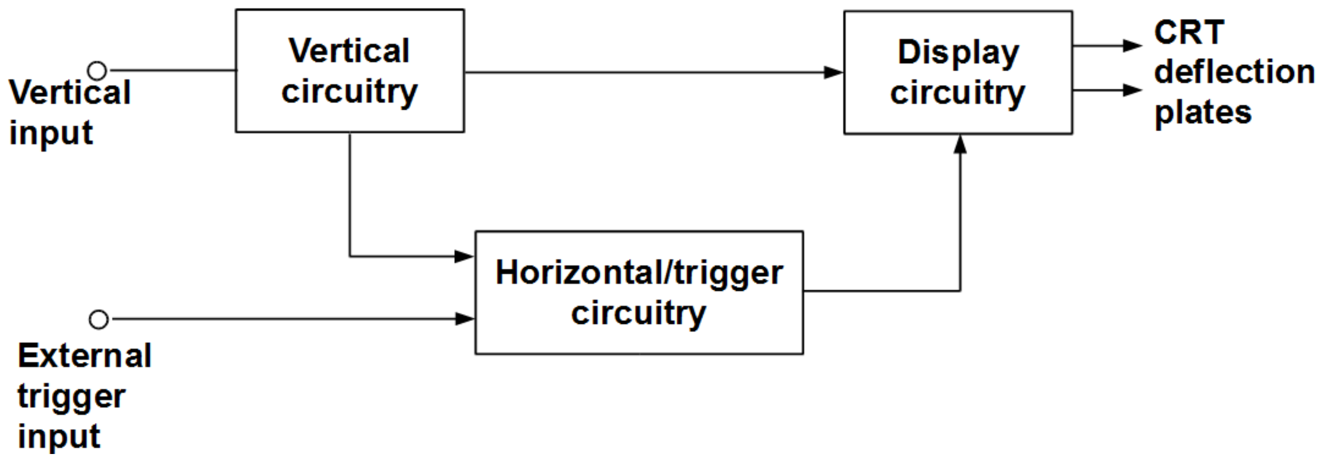

Figure 7

The display circuitry is responsible for generating and adjusting the voltages on the deflection plates.

Vertical circuits

A block diagram of the vertical circuitry is:

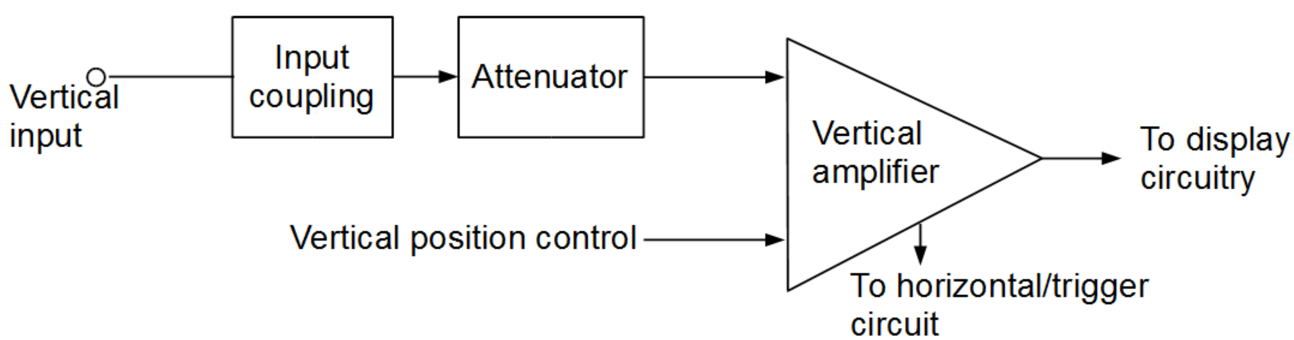

Figure 8

The input coupling choices are ground, AC, and DC. Grounded coupling is used to determine where 0 volts is on the screen. AC coupling is used to couple only the AC component of the signal to the vertical amplifier; it is often done with a coupling capacitor that blocks the DC. This is useful when a small AC signal is riding on a large DC component, such as in a biased transistor circuit. DC coupling allows you to see both the DC and AC components of a signal.

The attenuator is used to reduce the input signal's amplitude with range of the vertical amplifier's capabilities. Typical oscilloscopes offer a wide range of signal gains. The B&K 2125A has vertical amplifier ranges of 5 V/div to 1 mV/div. With a 1X/10X probe, you can measure signals from hundreds of volts to a few millivolts -- roughly 5 orders of magnitude. The attenuators must have flat responses for signals with frequencies from DC to approximately the scope's bandwidth.

Horizontal and trigger circuits

A block diagram for the horizontal and trigger circuitry is:

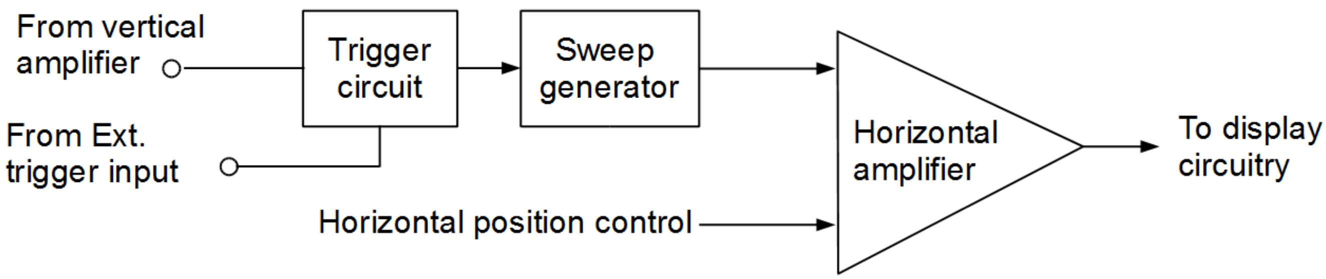

Figure 9

The horizontal and trigger circuits are responsible for the horizontal movement and positioning of the electron beam. The trigger circuit causes the sweep generator to initiate a sweep of the voltage on the horizontal plates in the CRT. This sweep is a sawtooth-shaped voltage that causes the electron beam to sweep uniformly from the left edge to the right edge of the screen. This sawtooth is carefully controlled for constant slope and period so that quantitative measurements of timing can be read from the screen.

The trigger circuit is responsible for generating a sweep at the same point during the period of a periodic signal. If this wasn't done, the screen would be a jumble of different waveforms, none of which start at exactly the same place. The trigger level adjustment control on the front panel sets the voltage on the input waveform at which the trigger event occurs -- and thus causes a single sweep of the electron beam. The slope control allows you to select whether the trigger happens on the rising portion of the signal (positive slope triggering) or the falling portion (negative slope triggering). Besides triggering on the signal from the vertical amplifier, switches allow triggering from the AC line, an external signal, or a TV signal.

The sawtooth waveform of the sweep circuit is as follows:

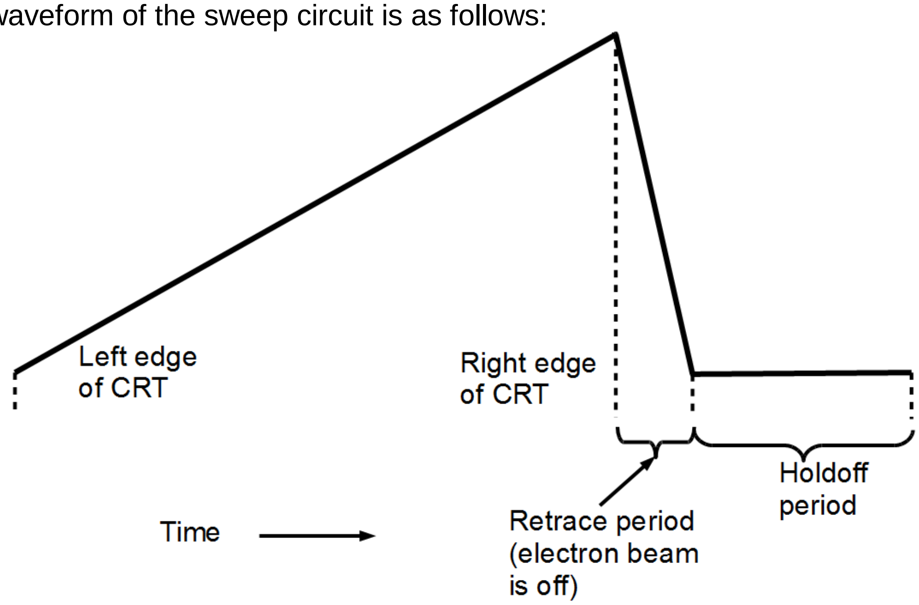

Figure 10

The rising edge of the sawtooth sweeps the beam across the screen (this voltage is on the plates in the CRT that deflect the electron beam horizontally). At the right edge of the CRT, the electron beam is turned off and the voltage goes back to what it was at the left edge of the CRT. The holdoff period (control 6 in Figure 5) allows this period to be adjusted. Increasing the holdoff time can make it easier to get stable displays of complex waveforms.

Graticule

The oscilloscope's screen is covered with a Cartesian coordinate system called the graticule:

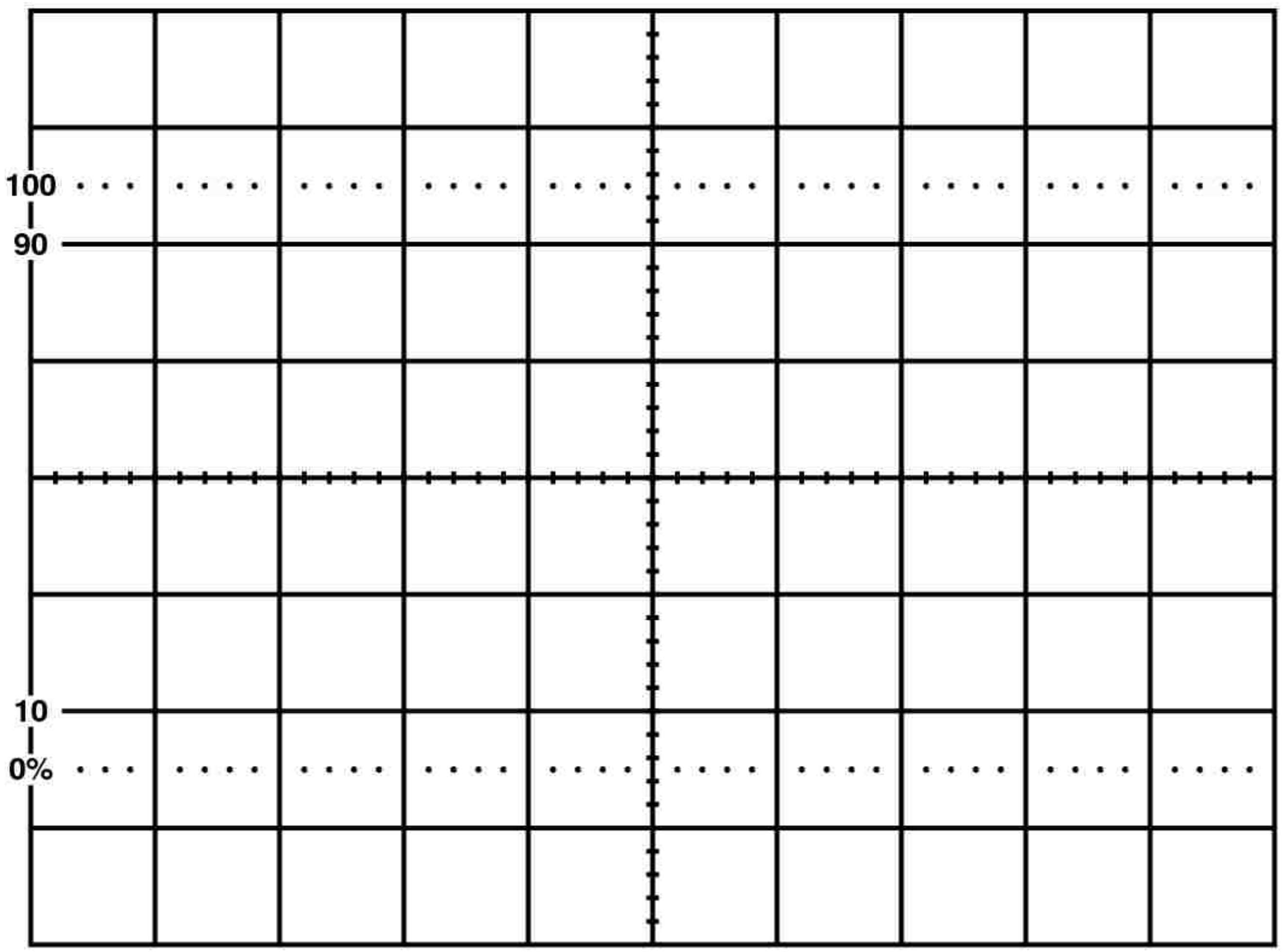

Figure 11

The graticule lets you make measurements of the signal's voltage (vertical axis) and timing (horizontal axis). The percentage marks along the left edge are used to measure rise times. A waveform is positioned so that its vertical extent lies exactly between the 0% and 100% marks. Then the horizontal distance (i.e., time) is read between the 10% and 90% points, as this is a common definition of the rise time of a signal.

Delayed sweep

Some analog oscilloscopes come with a delayed sweep feature that allows a section of the displayed waveform to be magnified in the horizontal direction. This lets you see waveform details while at the same time seeing the whole waveform.

The delayed sweep is a second sawtooth generator that is started an adjustable time after the main sweep's sawtooth starts its vertical ramp. After the adjustable delay, the delayed sweep is allowed to control the sweep of the electron beam. As the delayed sweep is set with a sweep time faster than the main timebase (i.e., smaller time/div setting), the remaining portion of the waveform is expanded. Adjusting the delay (control number 12 in Figure 5) allows you to choose where to start the horizontally-expanded display.

The B&K 2125A scope demonstrates its delayed sweep in the following screen photograph (converted to grayscale):

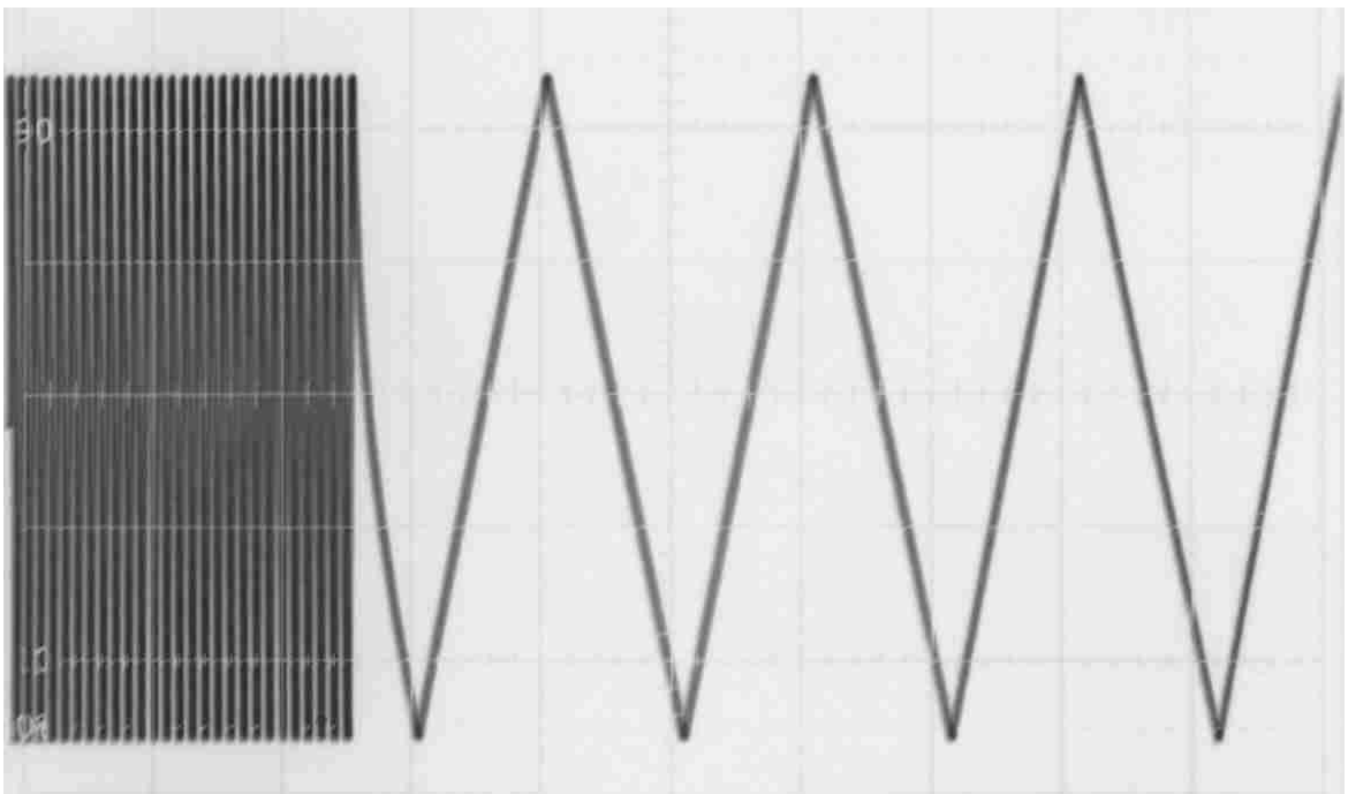

Figure 12

The bunched waveform on the left was a 1 volt peak-to-peak 10 kHz triangle wave. The main timebase was set to 1 ms/div, which meant each division held 10 periods of the wave. The expanded section was created by setting the display mode to MIX and setting the delayed sweep to 50 µs/div. You can see there are two horizontal divisions between the waveform's peaks in the delayed sweep portion. This means the period of the waveform is 100 µs, which implies a frequency of 10 kHz.

Some analog oscilloscopes display a second trace for the delayed sweep rather than combine them as the 2125A does.

Operation of an analog scope

We'll use the B&K 2125A as an example analog scope. It is a popular two-channel 30 MHz scope. A special feature of the scope is that it provides a component tester, which we'll look at in more detail. Over the years there have been a variety of other features provided with analog scopes, such as both digital and analog storage, counters, and digital voltmeters.

While the control panel of an analog scope may look intimidating to a newcomer, this will quickly pass after some experience with using the scope. The 2125A scope is quite easy to set up to look at an unknown waveform.

The basic strategy is to apply the signal to an AC-coupled channel, using auto triggering and set the timebase control to about the middle of its adjustment range. Once an auto-triggered trace is seen, you can adjust the vertical gain and timebase controls to get an acceptable display. Below is a general procedure (numbers and letters in parentheses refer to Figure 5 above):

1. Set all lever switches to their uppermost position. Make sure the COMP TEST button (19) is not pressed in.
2. Set control 7 to MAIN.
3. Set all potentiometer knobs so that their indicator is vertical. The exceptions are to leave the HOLD OFF control (6) fully counterclockwise and the three variable adjustments (12, 15, and 17) fully clockwise until they click.
4. Set the scope's timebase control (21) to 1 ms/div.
5. You should see a flat horizontal trace across the screen.
6. If you don't, press the BEAM FIND button (20). This should show you a compressed view of the horizontal line. If it doesn't, you may not have the intensity control (1) turned up high enough. Also adjust the focus control (2) to get a sharp line.
7. If the beam find button does show you the waveform, adjust control 10 to vertically position the horizontal line on the screen.
8. Connect a signal to the scope via channel 1's BNC jack (A). You can also use an oscilloscope probe. If you have a probe, you can connect the probe's center conductor to the scope's CAL waveform at (D).
9. Adjust the vertical gain knob (the inner knob of (15)) to display the waveform on the screen. Adjust the timebase (21) to get a few periods of the waveform displayed.

This procedure should result in a waveform being displayed on the screen. If it doesn't, it's possible that the signal is changing too slowly to be displayed easily on an analog oscilloscope (this is an advantage of digital oscilloscopes, as they can capture and display slow waveforms that are difficult to see on an analog scope).

One thing you'll notice from using an analog scope is that once you're familiar with the control layout, it's often faster to change scope settings than for an equivalent operation with a digital scope. This is one reason why troubleshooters often prefer an analog scope: the control is right there and there's no navigating a menu to enable or adjust it. The B&K 2125A has 21 controls on its control panel (three controls are double potentiometers and 7 of the knobs can be pulled out to switch something). In contrast, the B&K 254xB scopes have 29 buttons and 8 knobs. Most of the functionality in the digital scopes is accessed through menus, which require more button presses. While this is only natural because the digital scopes have more features, it may be slower than doing an equivalent task on an analog scope.

Vertical coupling

Control 14 in Figure 5 sets the type of coupling to use with the channel 1 signal. It is AC coupling in the up position. This is used to block the DC component of the signal and lets you e.g. observe a small AC voltage riding on top of a DC bias. For example, you might want to look at the AC signal in a transistor amplifier and AC coupling would help you see it in spite of the DC bias on the transistor. However, AC coupling can cause waveform distortion at low frequencies.

The GND position of the coupling switch is used to ground the input. This allows you to use the vertical position control (10) to set the position of the 0 volts line on the screen. Despite the name, this switch position doesn't ground the input; rather, it disconnects it from the scope and grounds the scope's vertical amplifier.

The DC position is used when you want to see the DC and AC components of a waveform. If the DC component is large and the AC component is small, it may be difficult to position the waveform on the screen and see the AC details. In this case, you should switch to AC coupling.

Variable adjustments

The vertical gain control (15) has a potentiometer that can be used to adjust the gain in a variable fashion. When the control is in its fully clockwise position, the vertical gain is calibrated. This allows you to make voltage measurements from the screen.

The variable control is used to adjust the displayed amplitude of the signal so it can fit on the screen. This allows relative measurements. Here's an example. You want to find the 3 dB down point of an amplifier. You view the output signal on the scope and use the variable gain and position controls to adjust the peaks of the waveform to just touch the top and bottom lines of the graticule. Then the frequency of the test signal is changed and the amplitude is monitored. When the peak-to-peak amplitude has dropped to 70.7% of the full screen amplitude, this is the 3 dB point.

Analogous measurements are made in the time domain by adjusting the variable timebase control (12). While the time/div is uncalibrated if the control is not in the fully clockwise position, you can still make time measurements relative to features on the waveform such as its period.

Trigger controls

The primary trigger controls in Figure 5 are 3, 4, 5, and 6. Control 4 (trigger coupling) determines the type of triggering: auto, normal, or two types of video triggering. Auto triggering is the same as normal triggering with the additional feature that if a trigger doesn't occur in a reasonable amount of time, the scope triggers itself. This lets the scope trigger normally on varying signals, but e.g. also trigger on DC signals. In the normal trigger mode, the scope won't trigger on a DC signal and you won't see a trace. The voltage level where the trigger occurs is set by the TRIG LEVEL knob 3. It lets you adjust the trigger voltage level from the maximum screen voltage to the minimum screen voltage. Thus, for example, if the vertical amplifier was set to 0.1 V/div, the trigger level adjustment would range from +0.4 V to -0.4V (assuming the screen has 8 divisions vertically).

The SOURCE switch 5 tells the oscilloscope which signal you want to trigger from. The choices are channel 1, channel 2, line, and external. Normally, to get a stable view of channel 1's signal, you'd set switch 2 to the CH1 position and adjust the trigger level appropriately. If the signal on channel 1 was synchronized with the AC line frequency, you could instead switch to LINE and trigger from the AC line frequency. If the display is stable when triggering from the line, the input signal is probably derived from the line frequency.

If you have an external synchronization signal from the circuit being tested, it can be used to trigger the scope in the external trigger mode. One example of such use would be to view logic signals in a digital circuit -- the scope could be triggered from the clock signal so that the displayed signals would be stable.

Trigger holdoff 6 is used to adjust the amount of time delay between subsequent triggers. With zero trigger holdoff, the scope is triggered after the trace ends and time is allowed for the electron beam to be positioned at the beginning position (retrace time).

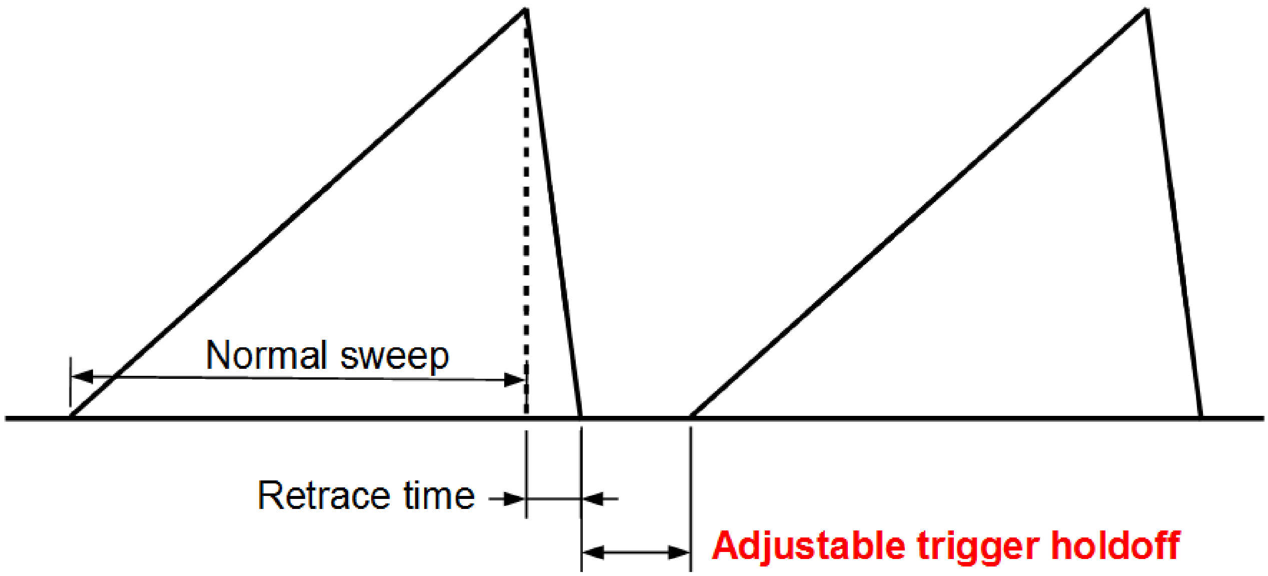

Figure 13

This holdoff adjustment can be valuable in helping you trigger on signals that would otherwise be difficult to trigger on.

Slow waveforms

One of the more challenging tasks in using an analog scope can be to get pictures of waveforms with slow repetition rates. With a little practice, you can get pictures of waveforms that take perhaps 10 s or so to cross the screen. This requires a tripod and a dark room or a hood to block out extraneous light because of the need to keep the camera's shutter open while the electron beam is moving across the screen.

Conversely, it can also be challenging to get pictures of rapid waveforms -- the electron beam moves quickly over the phosphor and produces correspondingly less light.

XY display mode

By putting the oscilloscope into XY display mode, the voltage on channel 1 is plotted along the horizontal axis and the voltage on channel 2 is plotted along the vertical axis. Turn knob 7 to XY and set switches 5 and 16 to XY. This lets you plot one voltage against another.

A common use of this mode is to display two sine waves against each other. When the frequencies of the two sine waves have a ratio that is a rational number, then a stationary pattern called a Lissajous figure is seen on the display. These figures can be quite sensitive to small frequency differences in the two signals. For example, on a 2125A, two 1 MHz sine waves can differ in frequency by 1 part in 10^7 and the Lissajous pattern will move on the screen, telling you the frequencies are slightly different.

The 2125A in component test mode uses the XY display mode.

Component test

The B&K 2125A oscilloscope provides a component test banana jack. This jack enables a user to quickly test components in-circuit (the circuit must be powered off). Both passive components like resistors, capacitors, and inductors can be tested as well as many active semiconductor components. Applying the component test signal from the scope (about 6.3 Vrms) to a component results in the scope displaying the applied voltage along the horizontal axis of the screen and the current through the component on the vertical axis. For more details, do a web search on "octopus tester" and you will find a number of circuits that demonstrate the technique.

The COMP TEST switch puts the scope into XY mode. This results in a current versus voltage plot. The pattern seen on the scope helps identify the type of component and determine whether it is working correctly or not.

Some of the patterns (sometimes called “analog signatures”) you might see on the screen are:

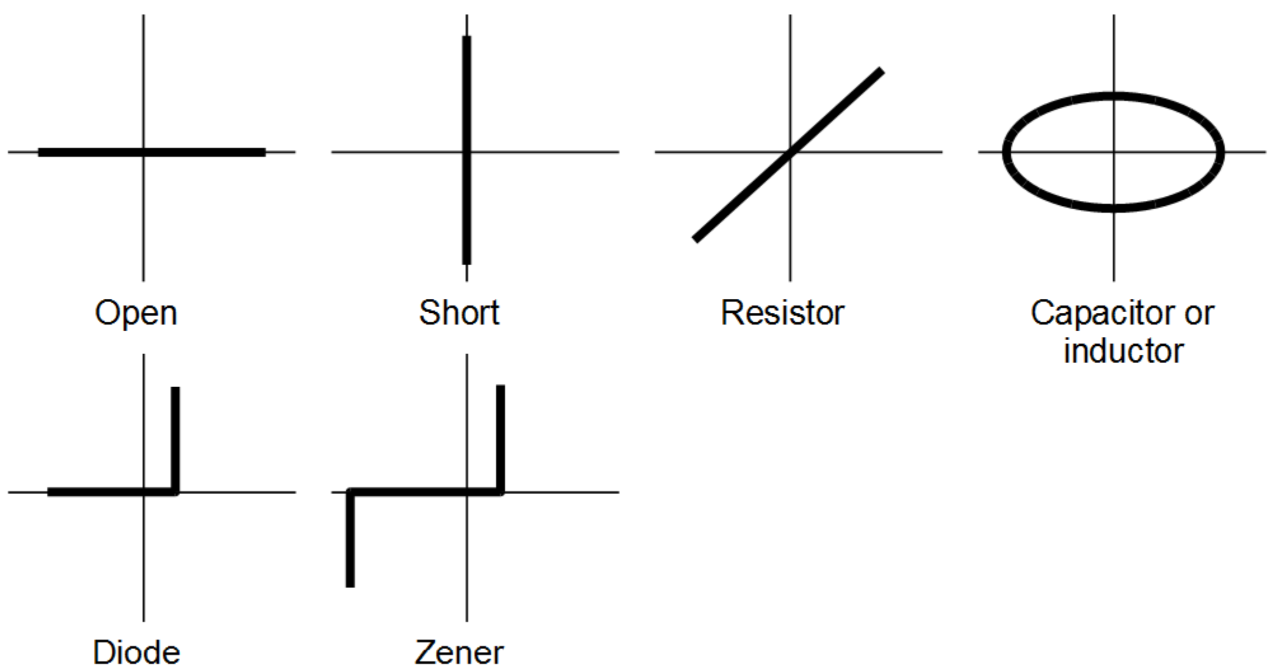

Figure 14

If the expected pattern isn't seen on the scope, that component is suspect or out of the measurement range of the component test feature.

The 2125A's measurement capabilities are:

Quantity	**Useful measurement range**	**If outside range, looks like**
Resistance	10 Ω to about 10 kΩ	< 10 Ω→ short > 10 kΩ → open
Capacitance	0.33 µF to 330 µF	< 0.33 µF → open > 330 µF → short
Inductance	50 mH to 5 H	< 50 mH → short > 5 H → open

As an example, a 1 H inductor might look like the ellipse in Figure 14 and a 10 H inductor would look like an open circuit.

The component tester limits the current through the device. The short circuit current will be on the order of 10 mA, so it will be difficult to damage a component. However, since the peak-to-peak voltage is around 18 volts, you may not want to use the component tester on sensitive low voltage semiconductors.

The component tester can test combinations of components too. This is valuable when troubleshooting, especially if you have a known-good circuit to compare the behavior to. If the suspect circuit matches the signature of the known-good circuit, the tested subcircuit of the suspect circuit is probably good. Conversely, if they don't match, that section of the circuit may deserve more in-depth troubleshooting examination.

Digital oscilloscopes

We'll use the B&K 2542B-GEN as an example scope. This scope is a two-channel 100 MHz digital scope with a built-in function generator and arbitrary waveform generator. Here's a picture of the front of the scope:

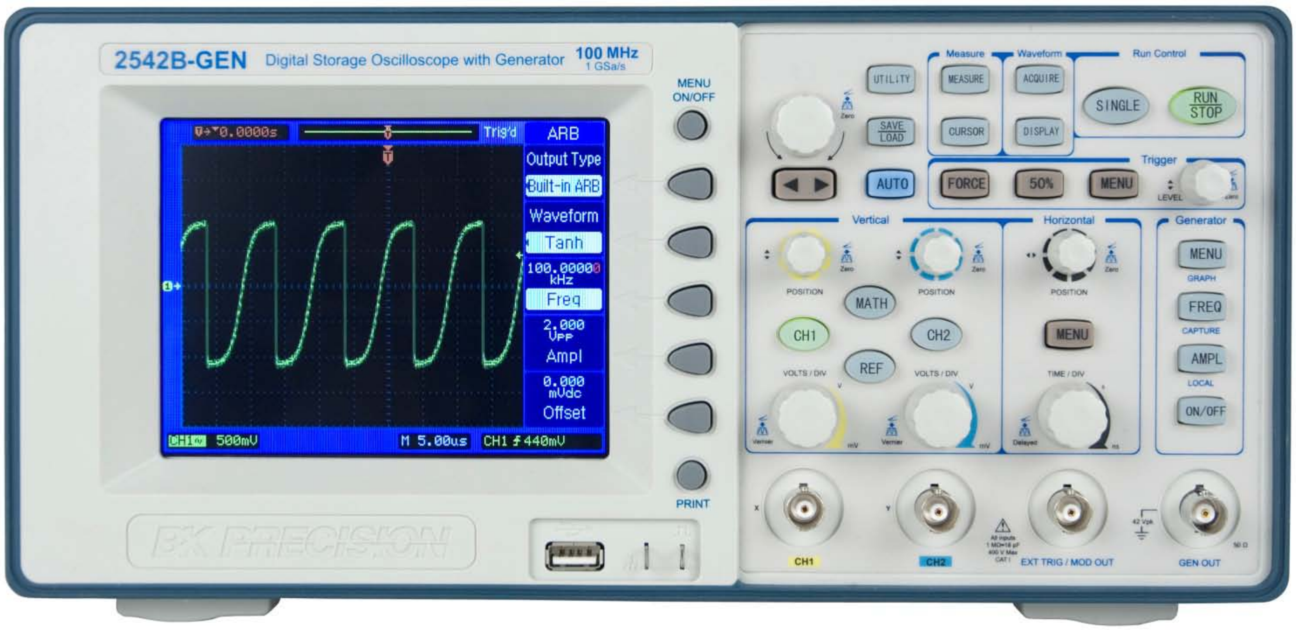

Figure 15

The display window of the scope is showing a hyperbolic tangent waveform that is output from the built-in arbitrary waveform generator (connecting cables aren't shown). The right part of the display screen shows the menu that annotates what the five menu buttons (sometimes called soft keys) to the right of the menu will do when they are pressed.

Digital scope controls

Here's a more detailed view of the controls with numbers to identify the controls along with their explanations in the following table:


Measure
Waveform
Run Control
MENU ON/OFF
Trigger
LEVEL
Vertical
Horizontal
Generator
POSITION
POSITION
POSITION
GRAPH
CAPTURE
LOCAL
VOLTS / DIV
VOLTS / DIV
TIME / DIV
Vernier
Vernier
Delayed
PRINT
CH1
CH2
EXT TRIG / MOD OUT
GEN OUT
42 Vpk

Figure 16

Number	Button label	Function
F	None	Soft keys. Their function is shown at the right side of the screen. The button 27 (MENU ON/OFF) can be used to turn the menu on and off.
1	Print	When pressed, the displayed waveforms are saved into a file in external memory (e.g., a USB thumb drive). You can choose to either save the waveforms as either a CSV (comma-separated values) or four types of bitmap images (8 bit BMP, 24 bit BMP, GIF, or PNG).
2	CH1	Input male BNC terminal for channel 1's vertical amplifier.
3	CH2	Input male BNC terminal for channel 2's vertical amplifier.
4	EXT TRIG/MOD OUT	External trigger input for scope operation or, if the function generator is supplying a modulated waveform, this terminal outputs the modulation waveform.
5	GEN OUT	Output terminal for the function generator.
6	VOLTS/DIV	Adjusts the vertical sensitivity (gain) of channel 1.
7	VOLTS/DIV	Adjusts the vertical sensitivity (gain) of channel 2.
8	TIME/DIV	Adjusts the horizontal time base in seconds per division (or SI multiples).
9	ON/OFF	Turns the output of the function generator on and off.
10	CH1	Accesses channel 1's menu and turns channel 1 on. Pressed again, it turns channel 1 off.
11	REF	Turns the reference waveform menu on and off.
12	MATH	Turns the math menu on and off. This menu allows you to perform mathematical functions with two waveforms: add, subtract, or multiply. It also lets you calculate the FFT (fast Fourier transform) of channel 1 or 2.
13	CH2	Accesses channel 2's menu and turns channel 2 on. Pressed again, it turns channel 2 off.
14	MENU	Access the horizontal menu.
15	AMPL	Adjust the amplitude of the function generator.
16	FREQ	Adjust the frequency of the function generator.
17	POSITION	Channel 1's vertical position on the screen.
18	POSITION	Channel 2's vertical position on the screen.
19	POSITION	Horizontal position of the trace(s) on the screen.
20	MENU	Function generator menu.
21	◄ ►	When the knob 28 is used for some adjustments, these two buttons are used to select which digit is to be adjusted. Also used when displaying help screens.
22	AUTO	Initiates an automated measurement sequence (this is called the Autoset function). This will automatically set the controls to display the signals on channel 1 or channel 2 or both.
23	FORCE	Immediately forces the oscilloscope to trigger. This is useful when the trigger mode is set to NORMAL in the absence of a trigger signal, as you can see where the trace is on the screen.

24	50%	Sets the trigger level to 50% of the amplitude of the waveform being used to trigger the scope. This is useful when NORMAL trigger mode is selected and the scope is not triggering because the trigger level isn't set correctly.
25	MENU	Turns on trigger menu.
26	LEVEL	Adjusts trigger voltage level. Press the knob to set it to 0 volts.
27	MENU ON/OFF	For any displayed menu, turns the menu on and off.
28	None	This knob is the general-purpose adjustment knobs for numerical settings and menu choices in menus. When you've turned the knob to choose a selection in the menu, press the knob to select that menu item (it will click). When this knob is active, a green arrow in a circular pattern is illuminated above the knob, alerting you that the knob will adjust something. If the arrow is not visible, then the knob will adjust the scope's intensity.
29	SAVE/LOAD	Toggles the SAVE/LOAD menu. Save or load setups and traces (waveforms) from internal or external memory.
30	CURSOR	Toggles the CURSOR menu. Can turn cursors on, select their type, and select what they measure.
31	DISPLAY	Toggles the DISPLAY menu. Sets various display features such as vector or single points, persistence, trace intensity, grid (graticule) type, grid brightness, color scheme, and how long menus are displayed.
32	SINGLE	Arms the scope to capture a single waveform after a trigger has occurred.
33	RUN/STOP	Turns waveform acquisition on and off. A common use is that you see something unusual on the screen and you press this button to stop the scope from updating the displayed waveform so you can examine things more carefully.
34	UTILITY	Toggles the UTILITY menu. Lets you set up which input/output interface to use (serial, LAN, or USB), set up how the PRINT button (#1) works, system setup features, language to use, various service functions, set up PASS/FAIL testing, and perform calibrations.
35	MEASURE	Toggles the MEASURE menu. This menu lets you choose to display various voltage and time metrics, such as RMS amplitude, peak-to-peak amplitude, frequency, rise time, etc.
36	ACQUIRE	Toggles the ACQUIRE menu. Lets you set normal, averaging, or peak-detect acquisition modes and select between real-time and equivalent sampling.

A 1 kHz sine wave is displayed on the oscilloscope's screen in the following figure:

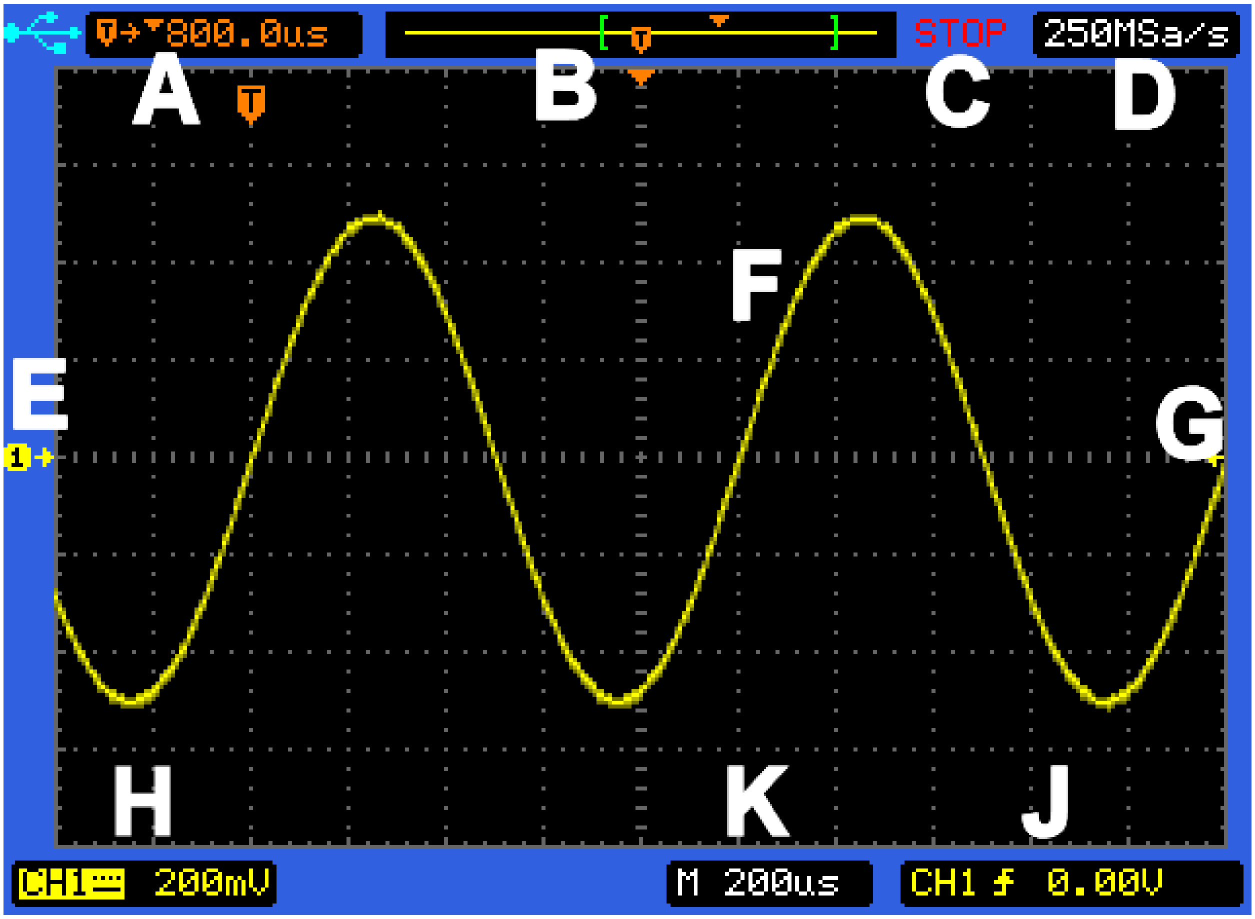

Figure 17

The various display elements are keyed by letters:

Element	Description
A	The cyan-colored symbol indicates that the USB connection is enabled and a flash thumb drive is connected to the scope. The T in the orange polygon indicates the location of the trigger point in the displayed waveform. The 800.0 us indicates that the trigger point is displayed 800 µs before the center of the screen; this positioning was gotten by turning the horizontal position control (19 in Figure 13).
B	This small graphic encapsulates information about the display. The horizontal yellow line represents the time extent of the digitized waveform. The left and right green square brackets indicate the part of the waveform that is shown on the screen. The T indicates where the trigger point is on the screen. The inverted orange triangle indicates the center of the screen.
C	This indicates the state of the scope. STOP means the RUN/STOP button has been pushed to stop waveform acquisition. WAIT will be blinking when the scope is waiting for a trigger event. Trig'd will be displayed when the scope is free-running and is being triggered.
D	Shows the digital sampling rate. This number is changed by the timebase knob (8 in Figure 16).

E	The yellow 1 indicates the vertical position of 0 volts for channel 1. A similar cyan 2 indicator shows 0 volts for channel 2 when it is displayed.
F	The displayed waveform for channel 1 shown in yellow. Channel 2 is displayed in cyan.
G	The small yellow arrow (partially occluded by the letter G) shows that the scope is being triggered on channel 1 and the vertical position with respect to channel 1's zero volts point indicates the trigger level's voltage. In the figure, the trigger voltage is zero.
H	The yellow graphic shows that channel 1 is DC-coupled and that the volts per division setting is 200 mV/div (also called the vertical gain). A similar display would be given in cyan for channel 2 if it was turned on.
J	This information shows the trigger settings. The trigger source, trigger type (here, an edge trigger), and trigger voltage are displayed.
K	This number indicates the time per division setting of the scope. The M indicates the main timebase. If you enable the delayed timebase, its time/div setting will be above the M setting and will be prefixed by the letter Z.

Other types of digital oscilloscopes

While this document is focused on the traditional oscilloscope in a box with controls and a display screen, there are a number of other types of digital oscilloscopes. We'll briefly describe them.

Mixed signal oscilloscope (MSO)

When designing electronic equipment, the designer often makes use of digital technology. Digital electronic devices are also analog devices, insofar as the same issues like propagation delay, distortion, glitches, etc. can complicate designs just like they can in analog designs. The digital engineer often uses a logic analyzer to analyze the digital behavior of a system. Occasionally, the digital system doesn't behave as expected and an analog tool is needed to look at the signals.

This is the domain of the mixed signal oscilloscope (MSO). These products typically have two to four analog oscilloscope channels for viewing the analog nature of digital signals and perhaps 8 to 16 digital channels for the logic analyzer. They are conveniently, two tools in one package -- and the digital and analog systems can work together. For example, a complex digital pattern trigger from the logic analyzer can be used to trigger the analog scope operation.

USB oscilloscope

USB oscilloscopes interface with a computer, which provides the controls and display. The interface with the computer is usually the USB interface. These devices are often used with laptop computers and have the advantage of providing their functionality in a small package because the display and user control electronics don't need to be present, as they're done in software on the computer. Some of these tools can provide an oscilloscope, logic analyzer, and function generator, all in the same surprisingly small package. Some of them support the decoding of serial data streams like SPI, I2C, and RS-232.

Handheld oscilloscopes

Handheld oscilloscopes provide the same basic functionality as bench scopes, but in a handheld package. These are popular with field service people. They can be more expensive than their bench scope counterparts. Some offer isolated and floating inputs, which are advantages in industrial environments because it means the scope can be used like a digital multimeter (i.e., you don't have to worry that a probe's ground lead will e.g. short out a non-ground potential in a circuit).

For budget-minded hobbyists, there are numerous low-cost microcontroller-based projects that let you construct your own oscilloscope.

Theory of operation

The architecture of a typical digital scope is as follows:

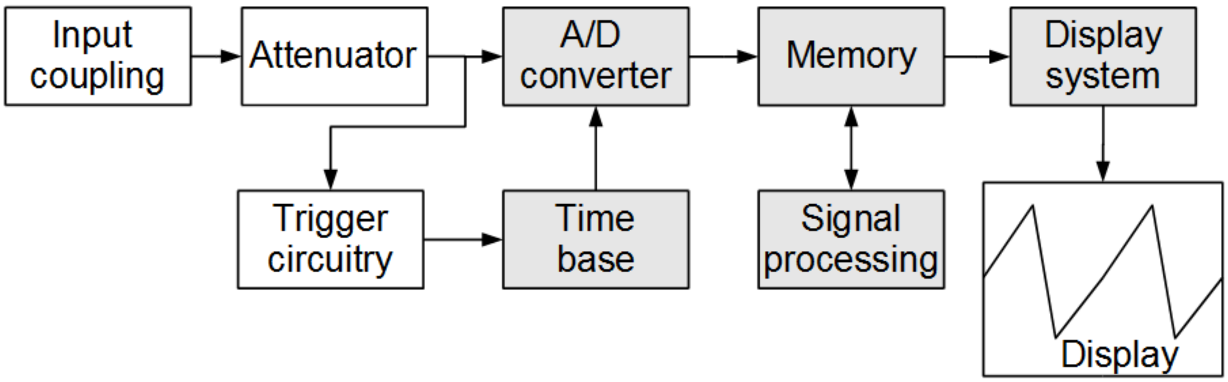

Figure 18

The input circuitry, attenuator, and parts of the trigger circuitry may be similar to an analog scope. The fundamental difference from an analog scope is that the sections with the gray backgrounds are digital in architecture and operation.

The key task of the digital scope is to digitize the waveform, which means to convert it to a sequence of numbers. This is done by the A/D (analog to digital) converter that allows the digitized information to be stored in digital memory, manipulated, displayed, and saved to a file. The A/D converter is characterized by how many bits of resolution it has. A common resolution is 8 bits, giving 256 different voltage levels that the scope can measure. Some scopes have higher resolutions.

This digitizing is characterized by the **sampling rate**, S, in samples per second. An important relationship between the sampling rate and the measured signal is given by the following sampling theorem:

> If a function x(t) contains only frequencies less than B hertz, it is completely determined by giving its ordinates at a series of points spaced 1/(2B) seconds apart.

In the real world of measurements, it is rare that the signal being input to the oscilloscope is band-limited per the sampling theorem's assumption -- you usually don't know much about the signal's frequency content. Because of this, you have to be aware that frequencies in the signal that are higher than the sampling frequency can cause **aliasing**, something we'll look at in more detail below.

You can see the sampling frequency given as 250 MSa/s (megasamples per second) in Figure 17 above. A careful digital oscilloscope user is always conscious of what the sampling frequency is and its impact on the signals he or she is examining.

Sampling

Because the idea of sampling is so fundamental to the operation of a digital oscilloscope, let's look at it in more detail.

An analogy for sampling is to think of the A/D converter as a camera that takes a picture of the amplitude of the waveform. The "shutter time" is very short and the camera "assumes" that the waveform is constant over the time that the "shutter" is open.

As an example, you might behave like this "sampling camera" if you were monitoring the outside air temperature with a thermometer. You'd look at your watch, write down the time, then write down the thermometer's reading.

If your thermometer was near the exhaust of a heat engine, the air temperature could vary more rapidly than your thermometer is capable of responding. You would reconstruct the temperature waveform as a function of time by using your samples -- and, depending on your knowledge of what you were measuring, you may or may not be aware that your reconstruction of the waveform might not accurately represent the "real" air temperature. The term "real" has quotes around it because we can only know it through measurement -- and different measurement methods have different capabilities, leading to different "versions" of reality.

Let's look at two cases of sampling, one where the sampling is adequate and one where it is not. These qualitative examples will give you a feel for what good sampling can be like. Here's a waveform that was constructed by a program that used 1000 points to display the waveform. The "Adequate sampling" waveform shows the sampling points taken by the "camera" at 1 out of every 20 points in the waveform. The "Inadequate sampling" waveform was 1 out of every 10 points.

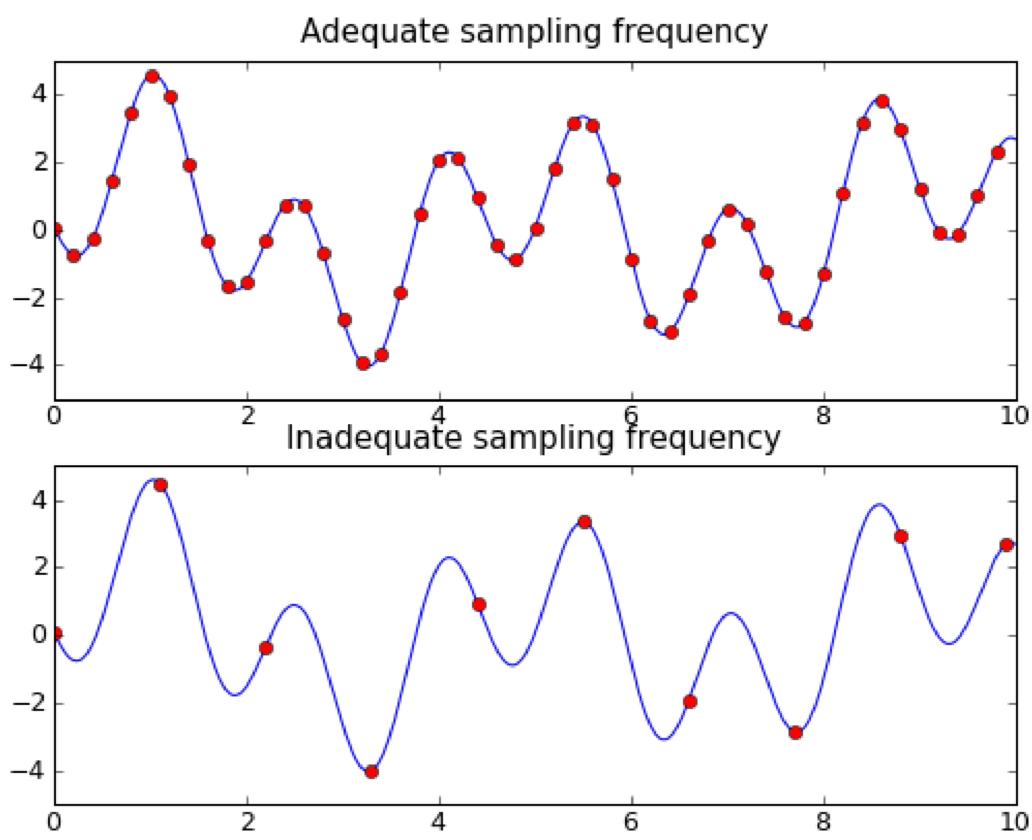

Figure 19

The next plot shows the waveform reconstructions using linear interpolation (i.e., drawing a straight line between each point):

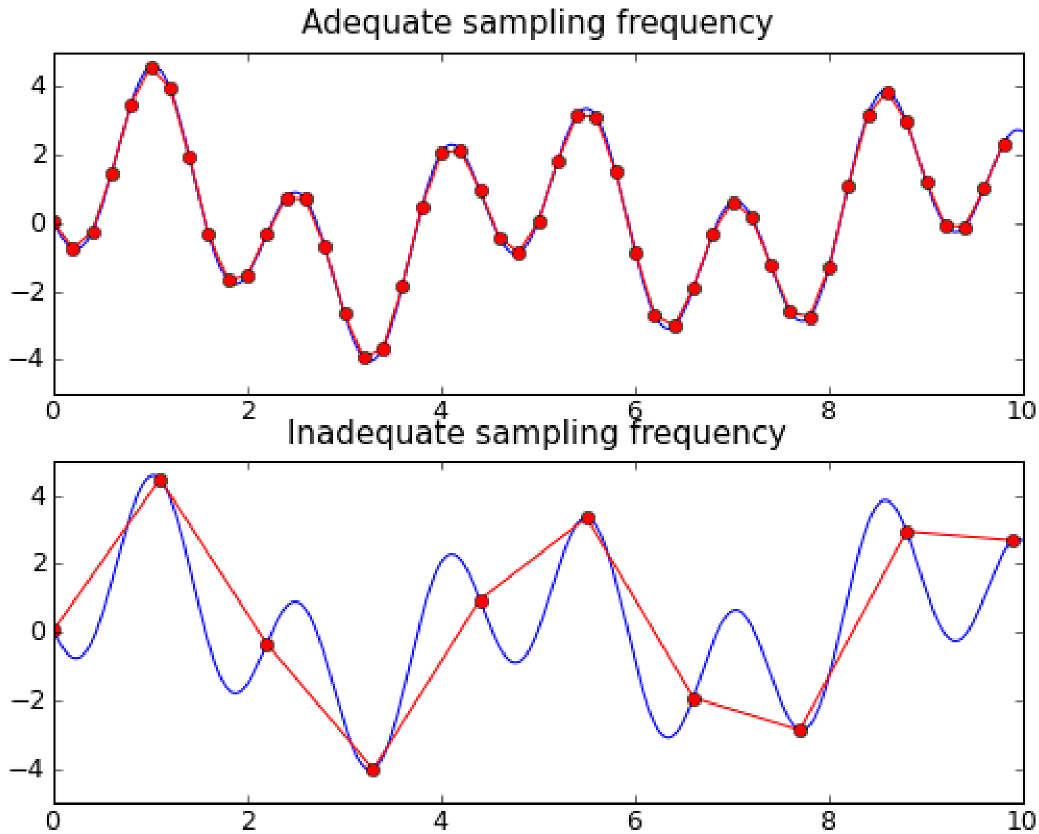

Figure 20

The "Adequate sampling" samples reproduce the waveform adequately. With some suitable low pass filtering, this could be an excellent reconstruction of the original waveform. However, the "Inadequate sampling" reconstruction **misses important details in the waveform**. With some low pass filtering to remove the sharp corners, you'd probably conclude the original waveform was about one-third the frequency of the actual waveform. Other waveform measurements would be in error too.

Exactly this situation can occur when you're using a digital oscilloscope -- and you won't be aware of it unless you're careful, worry about these things, and look for clues that such things are happening. In reality, accurate reconstruction of a signal depends on both the sample rate and the interpolation method used to fill in the spaces between the samples. Some oscilloscopes may let you select either sin (x)/x interpolation for measuring sinusoidal signals, or linear interpolation for square waves, pulses and other signal types.

Note a particular behavior in the inadequate sampling reconstruction in Figure 20. If you squint your eyes at the waveform the connected points make, you might estimate that it was approximately a sine wave with a period of about 6.5 units on the horizontal axis. This is a behavior called **aliasing**, where a signal "appears" that isn't really in the actual signal -- it's an artifact of the sampling, caused by frequency components in the signal higher than the sampling frequency. If you were using a digital oscilloscope, the red curve suitably smoothed is what you'd see on the screen and you would be hard-pressed to know from that picture alone whether what you were looking at was the real waveform or not. The aliased signal is at a frequency that is the difference between the sampling frequency and the relevant frequency component in the signal.

In order to accurately reconstruct a signal and avoid aliasing, Nyquist theorem says that the signal must be sampled at least twice as fast as its highest frequency component. This theorem, however, assumes an infinite record length and a continuous signal. Since no oscilloscope offers infinite record length and by definition, glitches are not continuous, sampling at only twice the rate of highest frequency component is usually insufficient.

Many people have seen the effects of aliasing, although they may not be aware of it. If you've watched a western movie and seen the stagecoach's wheels go backwards while the horses are galloping, you're seeing an artifact of aliasing: the stagecoach wheels' spokes are turning too fast for the 25 to 30 frame-per-second camera to accurately record their position.

There are two popular types of sampling used with digital oscilloscopes: **real-time sampling** and **equivalent-time sampling**.

Real-time sampling is the sampling method shown above -- the method is best used for signals with bandwidths less than half the sampling frequency of the oscilloscope. It is the method that must be used when you have "one shot" at capturing a waveform and its characteristics are illustrated by the above figures.

Equivalent-time sampling is used when the waveform being measured is periodic. Fortunately, many of the signals measured in the real world are periodic, so equivalent-time sampling is often used. The concept is to take many "snapshots" of a waveform over many periods and "piece" them together to create a picture of the waveform. The benefit is that the method can recreate periodic signals with frequencies higher than the scope's sampling frequency. Here's how it works.

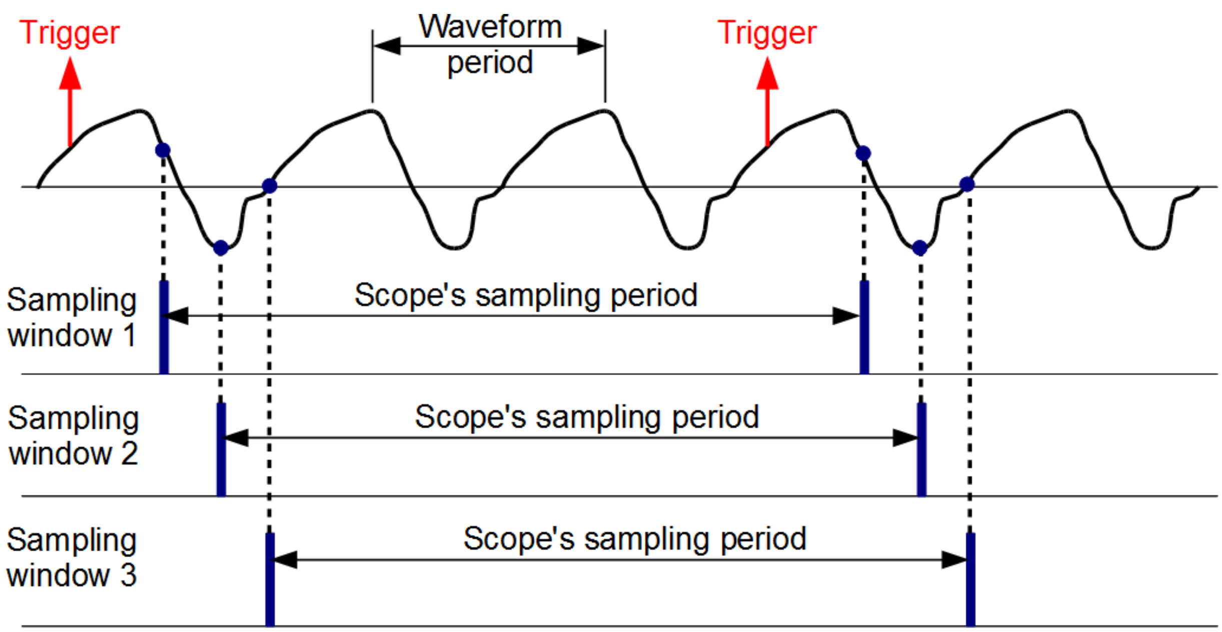

Figure 21

Suppose the waveform to be measured has a period that is roughly one-third of the shortest sampling period of the scope. Further suppose the scope's electronics triggers at the indicated positions on the waveform. The scope's first sampling window samples the waveform at the points labeled 1, the second window at the points labeled 2, etc. The sampling points are asynchronous with the waveform so the sampled points are not at the same place in each waveform cycle. Thus, over many sampling periods, a substantial number of sample points of the waveform's period are constructed in the oscilloscope's memory.

Since this measured waveform will be a high frequency, thousands of sampling windows can be used to generate thousands of sample points per period -- and thus, the periodic waveform can be accurately displayed by the oscilloscope.

Thus, equivalent-time sampling effectively increases the scope's sampling frequency for periodic waveforms. However, be aware that the scope's vertical amplifier bandwidth will likely be the deciding factor on what you're able to see with the scope.

Another important component of the digital oscilloscope is the waveform memory. The amount of this memory determines the length of a sample that can be captured and displayed by the oscilloscope. The relationship is:

$$t = \frac{M}{S}$$

where

t = captured time, seconds
S = sampling rate of scope, Hz
M = number of points of waveform storage memory

For example, when displaying a 1 kHz square wave, the B&K 2542B scope has a sampling rate of 25 MSa/s (million samples per second) when the timebase is set to 2 ms/division. Since the scope's memory can store 1.2 million points at this sampling rate, the time extent of a single captured waveform by pressing the SINGLE button is $(1.2 \times 10^6 \text{samples})/(25 \times 10^6 \text{samples/s}) = 48\text{ms}$.

The reciprocal of the sampling frequency gives you the time between points in the waveform. In the previous example, the time between sample points is $1/(25 \times 10^6 \text{samples/s}) = 40\text{ns}$.

Dead time

A scope user should be cognizant of the notion of "dead time" (also called blind time). This is the time during which the signal is not being sampled and displayed by the oscilloscope. Let's look at an example situation. The scope acquires the waveform at a particular sampling rate during the time occupied by the black area in the following diagram:

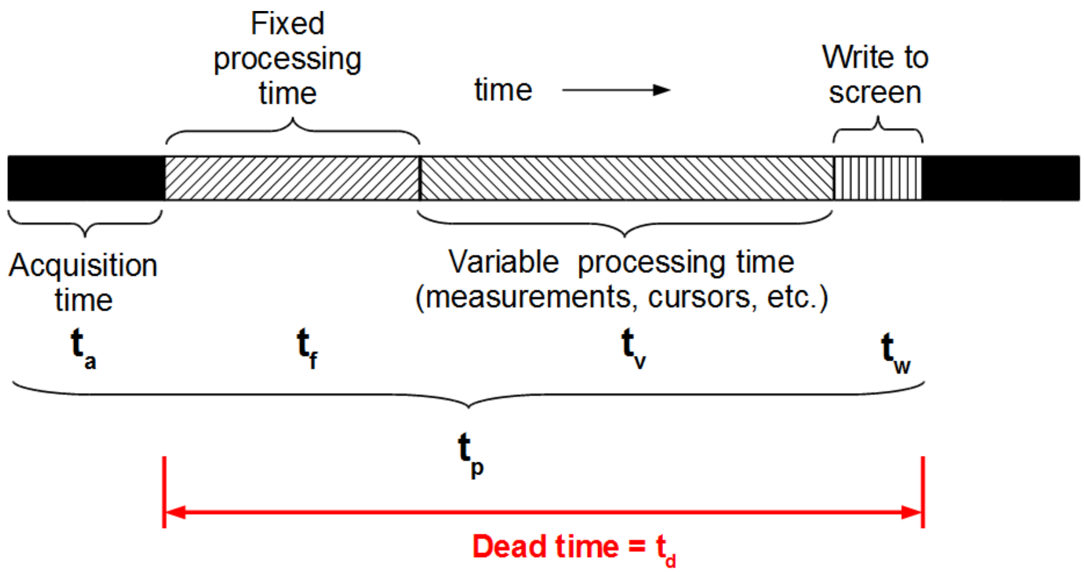

Figure 22

The acquisition time t_a is determined by the sampling rate, memory depth, and the details of how the scope works. The scope takes a fixed amount of time t_f to perform the basic calculations needed to display the acquired signal on the screen. If the user has certain features enabled, such as making waveform measurements or placing cursors on the waveform, extra computing time t_v will be needed to make the requisite calculations (a non-minimum holdoff time can contribute to t_v also). Then it takes a time of t_w to write the information to the screen (one could argue that the time to write to the screen could be included in the fixed processing time).

The maximum rate that the scope can display waveforms is determined by the total processing time $t_p$where:

$$t_p = t_a + t_f + t_v + t_w = t_a + t_d$$

Thus, assuming the times are measured in seconds, the maximum display rate is $1/t_p$ Hz.

The three times that are hatched in the figure comprise the **dead time** t_d of the scope. **Any changes to the signal that occur during the dead time are invisible to the user of the oscilloscope**. The dead time of a scope is typically not specified by manufacturers for basic general-purpose oscilloscopes, so please don't assume the relative times as shown in Figure 22 are meaningful.

Here's another aspect of viewing waveforms on a scope. Suppose your scope's timebase is set to 1 µs/division. Further suppose that the scope displays a trace every 1 ms (i.e., one thousand traces per second). Since the typical screen width is about 10 divisions, the screen represents 10 µs of time. Then the "duty cycle" of the display is $\frac{10\mu s}{1\text{ms}}$ or 0.01. This “duty cycle” could vary because of the scope’s architecture, deep memory, processing and display strategies, etc. Thus, on the surface, there's a 99% chance that a single transient event will be missed by the scope (unless you triggered the scope on the transient event). You could calculate this duty cycle more correctly if you knew the waveform display rate, but this is typically not specified.

Analog scopes have a dead time too. This is typically the retrace time of the electron beam and any holdoff time set by the user. It will, however, typically be shorter than a digital scope's dead time at a given sweep speed. But there's a more subtle problem with analog scopes: if a waveform feature occurs for only a short period, you may not be able to see it on the screen because of the limited amount of light. This can be affected by the electron beam's intensity, the ambient light in the room, and the user's attention level.

Every scope will thus have the notion of dead time and this dead time determines the events you can and can't see. Since the dead time is typically not specified, you would have to experimentally measure it to determine it.

Operation and features

This section gives an overview of using a digital oscilloscope and uses the B&K 254xB scopes as examples. The control numbers will be as indicated in Figure 16.

The basic method of operating a digital oscilloscope is the same as the analog oscilloscope: you need to set the vertical coupling, set the vertical gain to display the whole signal, set the timebase to a suitable value to display one or more periods of the waveform, and choose trigger settings to allow the scope to trigger. While this can be done in the same fashion as is done with an analog scope, the digital scope provides an automatic measurement button.

The AUTO button

One of the biggest time-saving features of a digital oscilloscope is the AUTO button 22. This button tells the oscilloscope to measure the signals on channels 1 and 2 and display them appropriately. The scope manual will tell you what signals the scope will be able to measure automatically (or some experimentation with a function generator will show you). The 254xB scopes require a signal of 50 Hz or greater, a duty cycle of greater than 0.5%, and an amplitude of at least 10 mVpp to successfully display a signal using the AUTO button. Knowing your scope's auto measuring capabilities for different types of waveforms may prove useful in future investigations.

The auto measurement feature is convenient to working engineers and technicians, but may not be desirable in an educational environment -- the instructor might want the students to learn how to set a scope up manually. In such cases, the 254xB scopes can have their auto measurement capability turned off.

Because the AUTO button can be accidentally pressed, a nice feature is to have a menu item to restore the previous settings. This provides a useful method of measuring a second signal: disconnect signal 1 from channel 1, connect signal 2 to channel 1, press the AUTO button, write down any relevant measurements from the second signal (or store the waveform), reconnect signal 1 to channel 1, and press the Undo Autoset menu button to restore the settings you had for signal 1.

Quick help

The 254xB oscilloscopes have a quick help system that provides descriptions of the functionality of keys and menu selections. Press and hold the key down for one or more help screens describing the topic. For example, holding down the AUTO button 22 provides the following information on two screens:

Press this key to get best waveform display by setting vertical, horizontal and trigger controls automatically. The setups are as follows:

- Display type: Main
- Coupling: DC or AC
- Acquisition mode: Normal
- Vertical scale: Adjust to applicable scale
- Vertical position: Adjust to middle
- Bandwidth limit: Off
- Digital filter: Off
- Invert: Off
- Trigger type: Edge
- Trigger source: Channel with active signal
- Trigger mode: Auto
- Trigger coupling: DC
- Trigger level: 50% amplitude level of the trigger source waveform
- Trig-offset: Reset delay time to zero
- Holdoff: Reset holdoff time to default 100 ns

This quick help feature can be invaluable to a new user to help them understand the various features of the scope.

Vertical gain

This adjustment controls the volts per division setting on the vertical scale of the oscilloscope. The settings change in a 1-2-5 sequence. When this control is pressed, a click is felt and the variable adjustment feature is turned on for the vertical gain. The adjustments then decrease or increase in 1% steps of the starting value. The behavior of this adjustment is substantially the same as an analog scope's; see ***Variable adjustments*** for more details.

The gain of both channels is shown in the lower-left portion of the display. Some digital scopes with the ability to display color will color-code the data to make it easier to identify.

Vertical coupling

This feature works substantially the same as on an analog scope; see **Vertical coupling** for more details.

Trigger controls

A digital oscilloscope has an edge trigger that is nominally the same as an analog scope's. Thus, read the section **Trigger controls** for an overview.

The digital scope may have more triggering features than an analog scope. For example, the B&K 254xB scopes also have a trigger sensitivity adjustment that adjusts an internal sensitivity and can help you trigger the scope on more difficult waveforms. In addition, other triggering modes may be available, such as pulse width triggering or TV triggering. While an analog scope may have the ability to trigger on video signals, the digital scope will typically provide more features, such as triggering on a particular video line.

The trigger level adjustment 26 works like it does on an analog scope. A short-cut feature is that pressing the knob until it clicks sets the trigger voltage to zero.

Pulse width triggering is a feature that allows the scope to trigger on a signal's width. While the name implies a digital pulse, this triggering mode can be used with any signal. The typical criteria used to determine when to trigger are:

1. Pulse width less than a given value
2. Pulse width greater than a given value
3. Pulse width equal to a given value
4. Pulse width not equal to a given value

These conditions can be chosen for either the negative-going portion of the waveform or the positive-going. The width of the pulse is measured at the current setting of the trigger level (knob 26). For the equal and not equal settings, the width of the acceptance interval is typically around ±10% of the center of the interval.

Delayed timebase

The delayed timebase on a digital scope operates approximately the same as on an analog scope (see the **Delayed sweep** section). However, the screen can be more expressive. Here's a 2542B screen with the delayed sweep turned on:

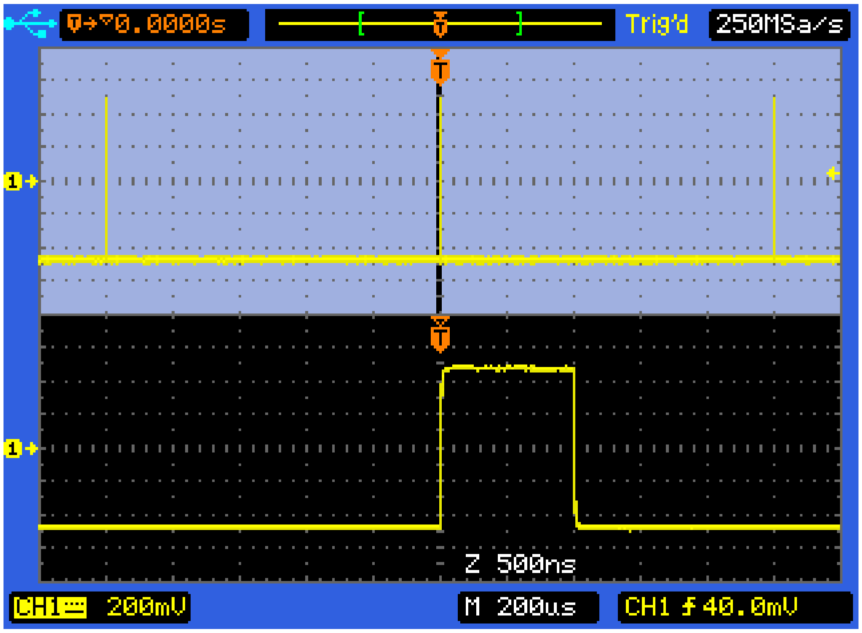

Figure 23

The center of the upper display is the main trace with a narrow black window around the section of the main trace that is expanded in the delayed sweep, the lower trace. The "Z" shows that the delayed timebase is set to a sweep speed of 500 ns/div, or 400 times faster than the main timebase. Thus, we're able to see much more detail in the waveform.

The delayed sweep may be able to show you things not easily seen with the main timebase. For example, if you display a 1 kHz square wave, the delayed sweep can show you the jitter in the position of the square wave's edges (switch to real-time sampling to see it). You can use the horizontal position adjustment to measure the width of the envelope of the jitter by positioning the envelope over a vertical graticule.

XY display mode

This feature is nominally the same as the XY display mode of an analog scope.

Saving waveforms and data

Saving a waveform is a valuable feature that analog scopes don't have. There are two primary ways this can be done: a computer program can download the digital information from the scope or the scope can store the waveform on a flash drive.

A computer program like WaveXpress® can download the currently displayed waveform from the oscilloscope, display it, and transform it in a variety of ways.

Saving a waveform to a flash drive is done by inserting a flash driven into the USB jack on the front panel of the scope. On the B&K 254xB scopes, The Utility button can be pressed and the Print Setup menu accessed to determine what file type will be saved when the Print button is pressed. The choices are CSV (comma separated values, an ASCII data file format that can be imported by a spreadsheet), 8-bit BMP, 24-bit BMP, GIF, and PNG. The last four are bitmap image formats. When a flash drive is plugged into the scope and the Print button is pressed, the screen image is saved in the chosen format (the file name is automatically chosen; subsequent saves increment a number in the file name).

The ability to press a button and store a captured waveform or screen image is valuable for documenting investigative and development work. With an analog scope, the user needs to stop and set things up to take a photograph. Contrast this to the digital scope, which just needs a button press and typically less than 2 seconds to capture a screen image. This makes it more likely the user won't be distracted from their work task.

Network operation

This describes the networking feature for the B&K Precision 254xB oscilloscopes. Other scopes will likely have similar features but differ in operational details.

To connect to the scope over the network, you need to configure the IO settings. This is most easily done if you have a DHCP (Dynamic Host Configuration Protocol) server available. This is often provided with network devices such as cable routers, routers and switches, and company LANs (and private networks can have a workstation set up to perform this task). The scope is told to use DHCP and contacts the server to get an IP address for the scope. In the 254xB scope, you just press the OK button in the configuration menu and, after a few seconds, the scope's display shows it has received an IP address.

You can also configure the LAN settings manually. You'll have to supply an IP address, subnet mask, gateway address, and DNS (domain name server).

Then all that's needed is to connect a web browser to the scope's IP address. If the scope had the IP address of 192.168.1.13, you'd type http://192.168.1.13 into your browser and you should be able to connect to your scope. Note: Some browsers such as Firefox may not work. If you're unable to connect, try a recent version of Microsoft's Internet Explorer.

Once the browser is connected to the scope, you can view the scope's screen and a simulated control panel:

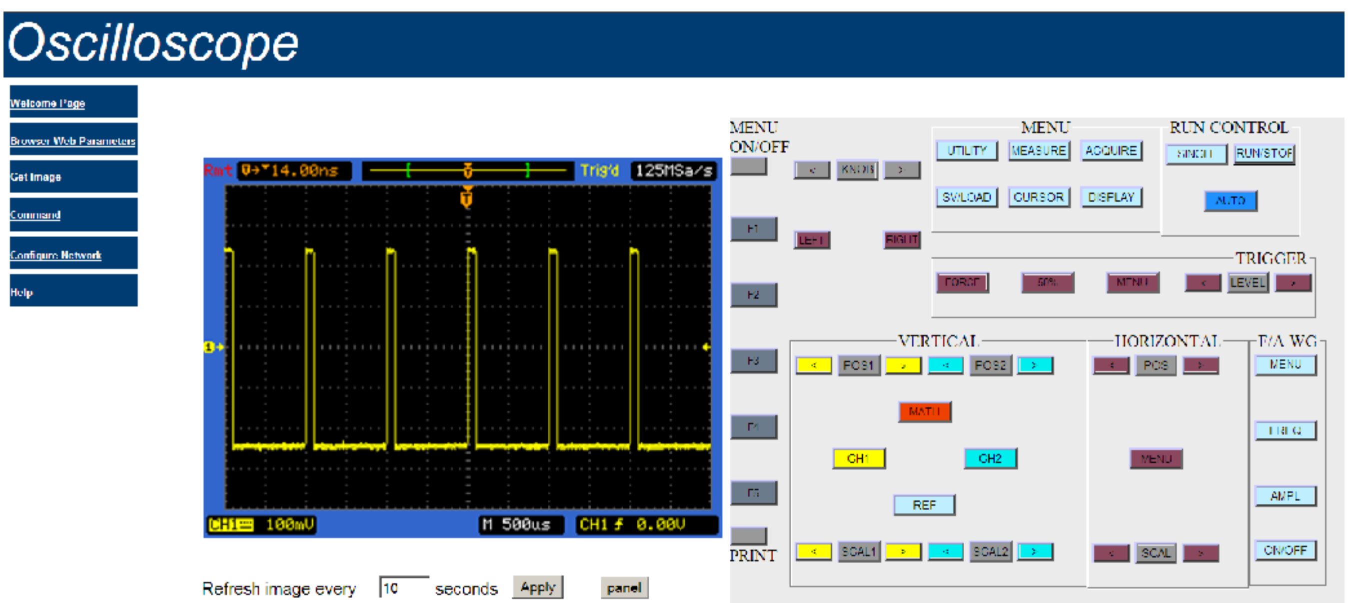

Figure 24

The scope's display shows a red Rmt in the upper left corner to alert you that a connection has been made to the scope.

The buttons on the control panel mirror the buttons on the scope and you can operate the scope remotely. This is a powerful tool, as the scope can be across the room or half-way around the world.

The web browser should let you save the displayed image of the scope's screen. This is typically done by right clicking the image with the mouse and saving to a file or copying the image to the clipboard.

To return to local control by the oscilloscope's keyboard, you'll have to press a button to disconnect the LAN connection (a similar thing occurs when the scope is remotely controlled over a USB connection). For the B&K 254xB scopes, the button to press is the AMPL button.

Math calculations

Digital scopes allow mathematical operations to be applied to the waveforms. The choices are typically A+B, A-B, AxB, and FFT (fast Fourier transform). Here, A and B denote the source channels and are usually set so that A is channel 1 and B is channel 2. However, you can do such things as set the math operation to AxB and set both A and B to be channel 1 and see the square of the waveform being measured on channel 1.

The subtraction operation lets you look at the difference between two signals and is often used as the "poor man's differential amplifier".

The product AxB can be used to show the instantaneous power waveform across a circuit element if one channel measures the voltage and the other channel measures the current. Unless you have a current probe that provides a signal referenced to ground, you'll probably need a differential amplifier to make such a measurement in general.

The math display is toggled on and off by pressing the MATH button 12. The following picture shows a clipped 1 kHz sine wave with its FFT displayed:

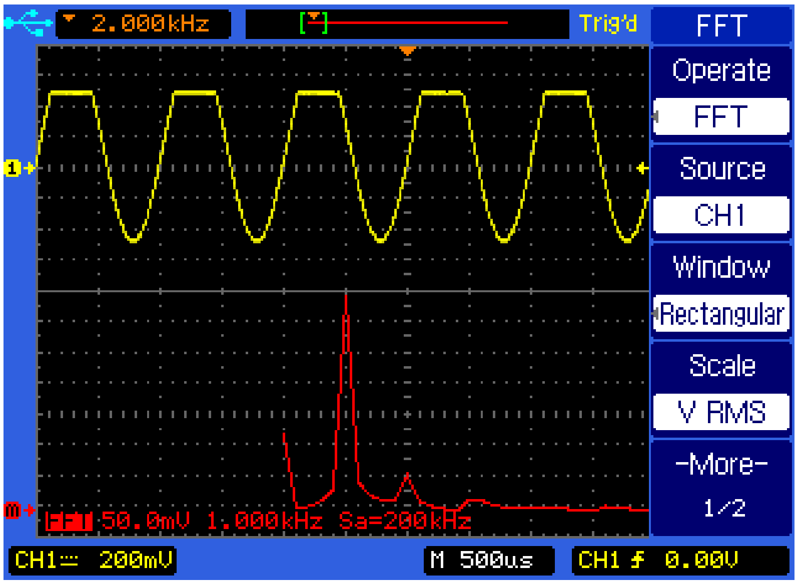

Figure 25

The FFT is shown in red and the vertical scale of the FFT is linear (the other scale choice is logarithmic). The horizontal position knob was used to position the FFT trace so that the second peak was measured at 2 kHz, making it the second harmonic.

Recording transient events

One of the most important advantages of a digital oscilloscope over an analog oscilloscope is the ability of the digital scope to capture transient (i.e., one-time or infrequent) events and display them.

As mentioned above, this is necessarily done with real-time sampling. The steps to acquire a transient waveform are:

1. Set the scope's vertical amplifier(s) to the desired gain and coupling configuration.
2. Set the scope to trigger on the signal you wish to capture.
3. Set the timebase to capture the temporal detail you want.
4. Arm the scope's trigger and wait for it to trigger.
5. After the scope has triggered, analyze or save the captured waveform.

While this description of the measurement process sounds straightforward, in practice it can sometimes be difficult to set up the trigger circuit appropriately. This can be caused when you don't know much about the waveform's characteristics and the waveform occurs infrequently.

Video triggering

Most modern oscilloscopes have the ability to trigger on video signals from various video standards. Perhaps the most common are the NTSC and PAL/SECAM signals used on the original black and white or color televisions, although these are being used less because of the newer digital formats.

The typical trigger synchronization abilities for video triggering are: odd fields, even fields, all lines, and line number. The following picture shows an example of a single video line from an NTSC video signal:

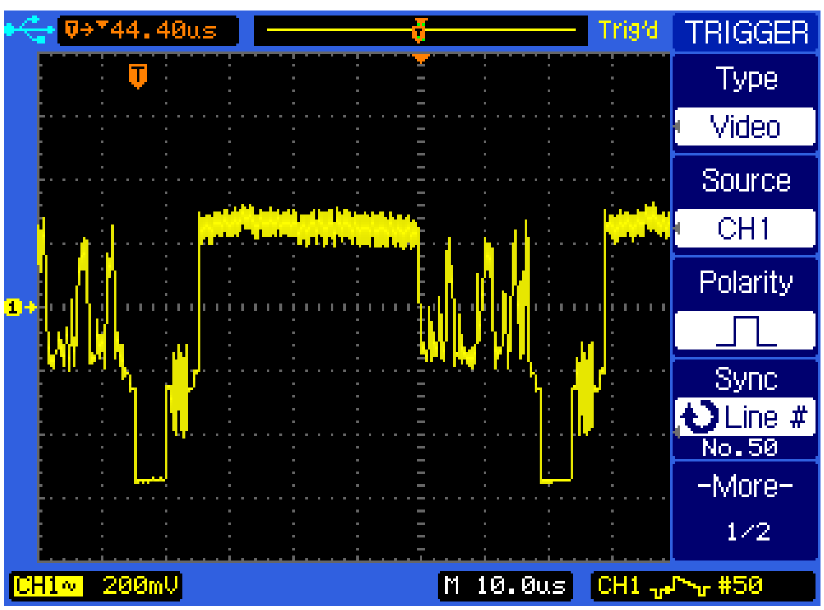

Figure 26

Averaging

A measurement mode of digital oscilloscopes allows you to average a set of readings together, which can reduce the effects of random noise on signals. The typical digital oscilloscope lets you average from 2 times to 256 times (in steps of powers of 2) and then display the resulting waveform.

The following picture demonstrates the ability of the scope to average out random noise:

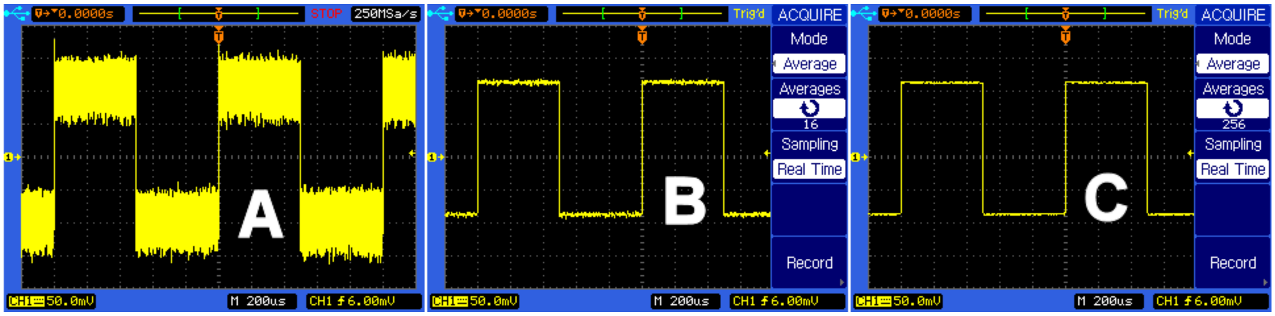

Figure 27

The signal at A was a 200 mV square wave with substantial random noise. At B, the signal has been averaged 16 times and the noise is substantially reduced. At C, 256 waveforms have been averaged and the noise is essentially gone.

Averaging can only be used on periodic signals, but since these are often measured, averaging finds frequent use in day-to-day oscilloscope measurements.

Peak detection

Measuring narrow-width pulses using a slow sweep speed can be challenging with an analog oscilloscope, even if the scope can trigger on the pulses. A digital scope can use peak detect mode to show these narrow pulses. Peak detection shows the highest and lowest values from multiple triggers and thus uses the techniques of equivalent-time sampling. The advantage of peak detection is that it can show these narrow pulses at slow sweep speeds.

An example of where peak detection is useful is shown in the following picture:

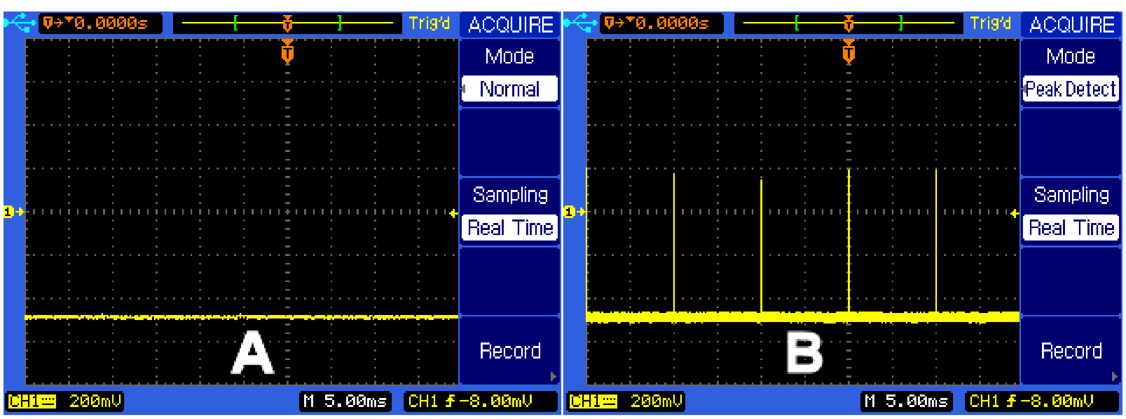

Figure 28

The waveform was a 100 Hz pulse stream with 10 ns wide pulses (this is a 0.0001% duty cycle pulse train). At A, normal acquisition mode was used and the pulses are not visible, yet the scope had triggered. At B, peak detection acquisition mode has been turned on and the pulses become visible. An analog scope would have a difficult time displaying these pulses.

Automatic Measurements

An advantage of the digital oscilloscope is its ability to make measurements on the displayed waveforms. This provides three benefits:

1. It saves time because the user doesn't have to measure positions on the screen and perform a calculation.
2. It reduces errors, as it's not unusual for a user to do the requisite calculations in their head and make a mistake.
3. The measurements can typically be made at a higher precision than the user can get from the screen.

Modern digital oscilloscopes provide a variety of amplitude-related and time-related measurements of waveforms. Some of the measurements that can be made are:

Voltage	Time
Peak-to-peak voltage	Frequency
Average	Period
Maximum	Rise and fall times
Minimum	Width
Overshoot and undershoot	Duty cycle

A handy feature is a "measure all" function, which displays a table of measurements:

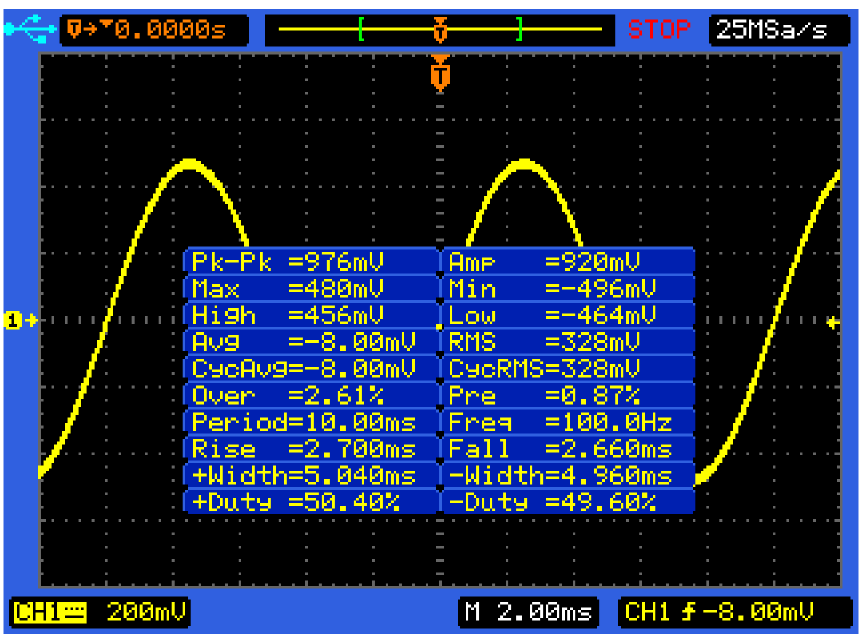

Figure 29

This measurement feature can be used to get a quick "feel" for the waveform displayed on the screen.

The measurements to be displayed are chosen by the user and displayed on the screen (typically, there is room for three measured numbers). The following picture shows two sine waves being displayed on the screen:

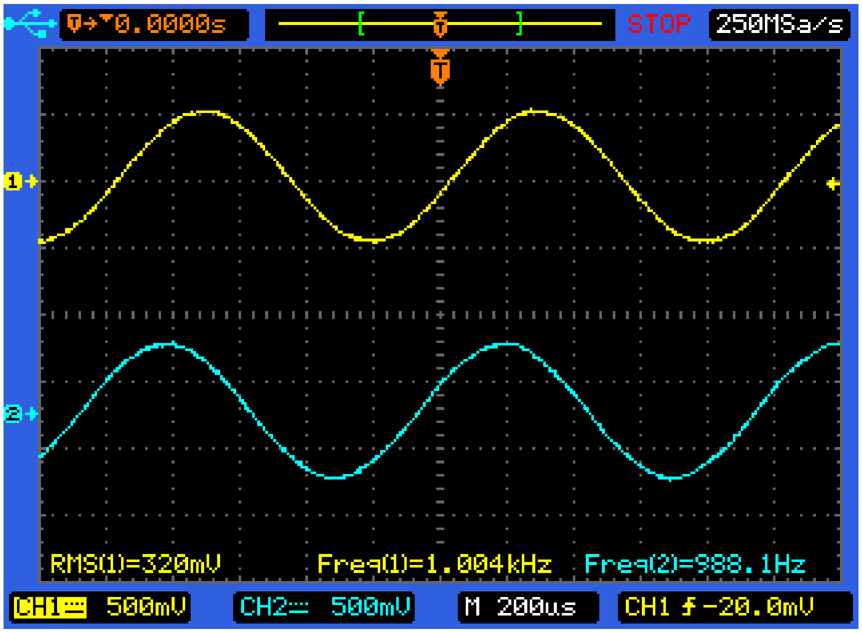

Figure 30

The three displayed measurements at the bottom of the screen are the RMS voltage of the channel 1 signal (yellow) and its frequency. The frequency of the channel 2 signal is displayed in blue.

The two frequency measurements show that these sine waves differ by 12 Hz in frequency. This would be hard to discern at this level by making measurements on the screen.

These measurements were taken with a B&K 2542B scope. This scope also has a hardware counter that will display the frequency of the trigger signal to five significant figures. This hardware counter has substantially higher resolution than the 0.5% resolution of the frequency measurement displayed on the screen in Figure 30.

Reference waveform

The reference waveform feature allows a signal to be recorded and stored as a reference waveform. This allows the reference waveform to be recalled later so that another waveform can be compared to it. An example of the use of a reference waveform would be in a manufacturing environment. The oscilloscope is used to measure the response of a circuit to a test signal. The scope could measure and store the response of a "gold standard" circuit. Then the manufactured circuits could have their response to the test signal compared to the gold standard circuit. The manufacturing person could e.g. accept or reject the circuit or use the reference waveform to adjust the circuit's response to look like the reference waveform.

An example of a reference waveform is shown in the following picture:

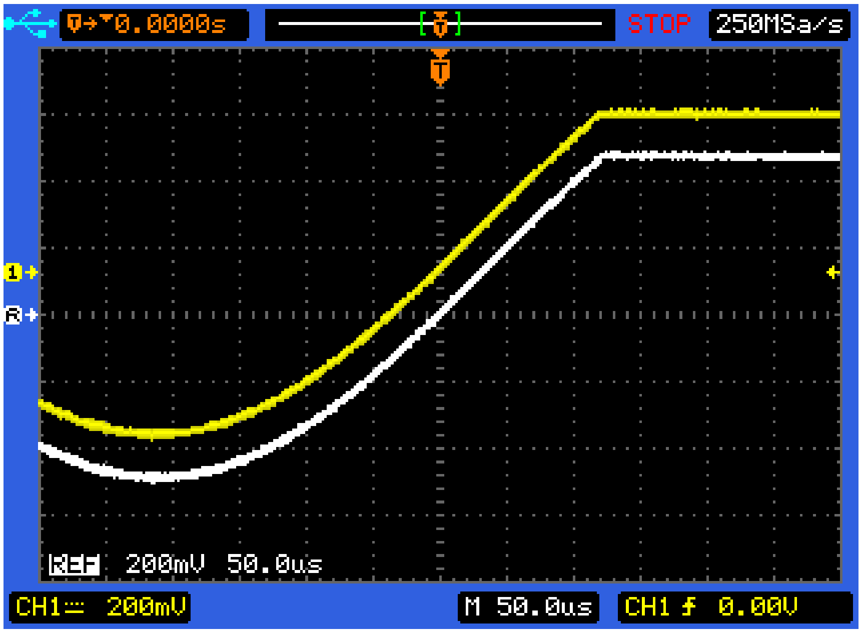

Figure 31

The white trace is the reference waveform that was saved to internal memory (a reference waveform can also be saved to a flash drive). The yellow trace is the signal on channel 1 of the scope. The easiest way to compare these two signals is to adjust the vertical position of channel 1's signal. In the situation shown in the picture, the two signals are exact matches. A signal amplitude change of 1% is discernible and a 2% change is easy to see.

Recording waveforms

We've seen that the digital oscilloscope can capture and display a signal. However, it can happen that the signal changes over a time substantially longer than the captured time. The oscilloscope may include a recording feature which will record and save sequential waveforms. This can let you see how a waveform trace changes over time. Here's a pictorial representation of how it works, where w_i is a single capture waveform:

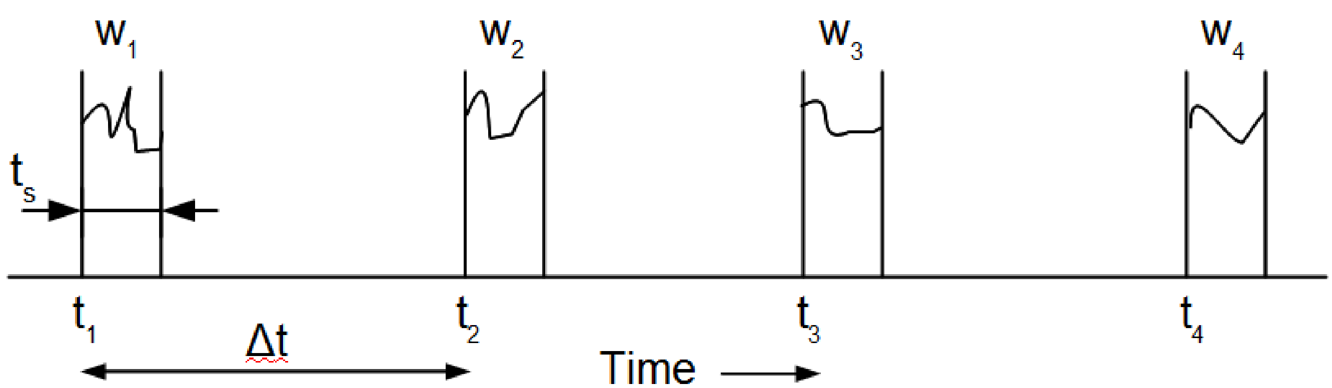

Figure 32

You pick a time Δt that you wish to have between stored waveforms and set the scope to a sweep time t_s ($t_s < \Delta t$). When you start the recording process, the scope waits for a trigger. When triggered, it records waveform w_1, waits for a period of Δ t, rearms the trigger, and waits to capture the next waveform w_2. Each recorded waveform is called a frame. The B&K 2542B scope lets you set Δt to values between 1 ms and 1000 s and record from 1 to 1000 frames.

You can save the recorded frames to internal or external storage (such as a thumb drive). This lets you review the recorded frames at a later time.

You can turn the scope's general-purpose knob and "page" through the frames looking for unusual behavior. Or, you can watch a "movie" of the recorded traces by letting the scope automatically sequence through the frames (the B&K 254xB scopes can play this movie at up to about 20 frames per second). This can compress lots of information into a small time, allowing you to spot rare or anomalous behavior. If you find one or more frames of interest, you can save them to a bitmap or CSV file or have WaveXpress® download them for further processing (see WaveXpress® below).

Recording mode can let the oscilloscope emulate a chart recorder. Suppose you were interested in seeing if an intermittent signal occurs overnight from a system you are studying. Using the B&K 254xB scope, you'd set channel 1 to the proper gain to record the signal and set it to auto trigger. Suppose we want to monitor the circuit from 5 pm today to 9 am tomorrow morning. This is 16 hours or 57,600 seconds. Since we can record 1000 frames, we'd need to record 57.6 seconds per frame to monitor this period. There are 12 horizontal divisions on the scope's screen, choosing 5 s/div gives us 60 s of recording per sweep. We'd set the recording system up to record 1000 frames, each separated by 60 s and be able to examine the data in the morning.

A detail is that the scope will have a short period between the frames to allow it to save the data to memory, arm the trigger, etc. (this is analogous to the scope's dead time in normal operation). Thus, there can be small windows where a signal might be missed, so the emulation of a chart recorder isn't perfect.

Digital filter

A digital oscilloscope may include the ability to filter the vertical channel with a digital filter. This can be useful to get rid of unwanted portions of the signal.

Here's an example of the operation of the digital filter in the B&K 2542B oscilloscope. WaveXpress® was used to create a sine wave with another sine wave of 10 times the frequency added to it. This was then sent to an arbitrary waveform generator and displayed at 1 kHz, as shown at A in the following figure:

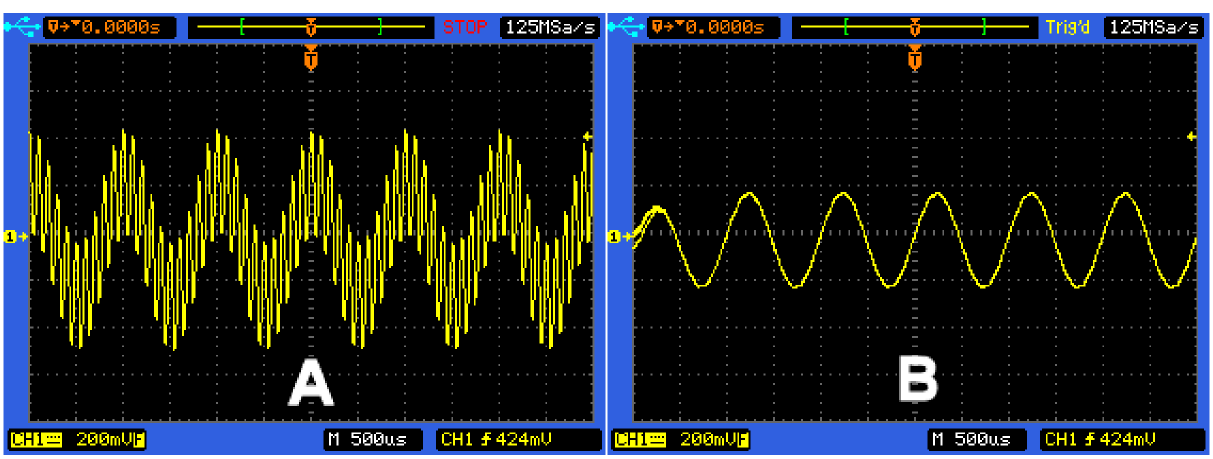

Figure 33

The scope's digital filter was set to be a low-pass filter with a cutoff frequency of 1.2 kHz. This effectively removed the higher signal component and lets us measure the amplitude of the fundamental. The generator was set to 1 Vpp and you can see that is approximately the peak-to-peak amplitude in waveform A. You can estimate that the peak-to-peak amplitude of the fundamental in A is about 400 mV and this is confirmed in trace B.

The typical filtering modes are low-pass, high-pass, band-pass, and band-reject.

Pass/fail testing

Some digital scopes provide pass/fail testing capabilities. This feature lets you define an acceptance region on the scope's display for a signal. If a subsequent signal falls within this acceptance region, the test is considered passed and a pass counter is incremented (and the scope may have an output port that can produce a hardware signal indicating this fact). Otherwise, the test is failed and the failure counter is incremented.

Here's an example of a pass/fail screen from a B&K 2542B oscilloscope:

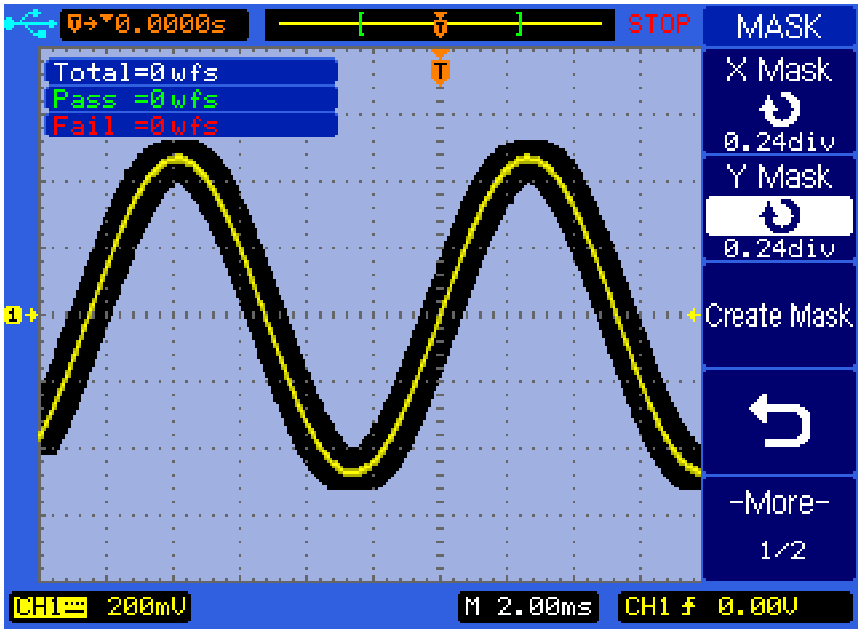

Figure 34

The black area around the yellow waveform shows the acceptance region (this is created with the use of the mask controls shown in the picture). The counters at the top left of the screen show how many total tests have been run and the number of passes and failures. A test is run every time the scope is triggered. For example, in a manufacturing environment, a circuit board under test could be inserted into a fixture, a DC power supply turned on, and a test button could be pressed that would provide the needed input signal(s) and trigger the scope to measure the output signal. The scope's output pass/fail signal could be used to control hardware such as a robot that moved the circuit board to the next station (or e.g. put it into a failure queue for subsequent analysis).

WaveXpress®

Since a digital oscilloscope can have an interface to allow a computer to communicate with it, a program running on a computer can be used to upload and download information to an oscilloscope. B&K Precision provides the WaveXpress® program free of charge for this purpose (see http://www.bkprecision.com/wavexpress.html). WaveXpress® allows you to download captured waveforms from B&K digital oscilloscopes, save them to your computer's disk drive, modify them, and upload them to B&K's arbitrary waveform generators. This provides a powerful set of tools for stimulus/response testing and can be a great benefit when using B&K oscilloscope models that include arbitrary waveform generators (254xB-GEN models). The download, modification, and upload of waveforms can be done in a matter of a few seconds, allowing for fast test-fix cycles.

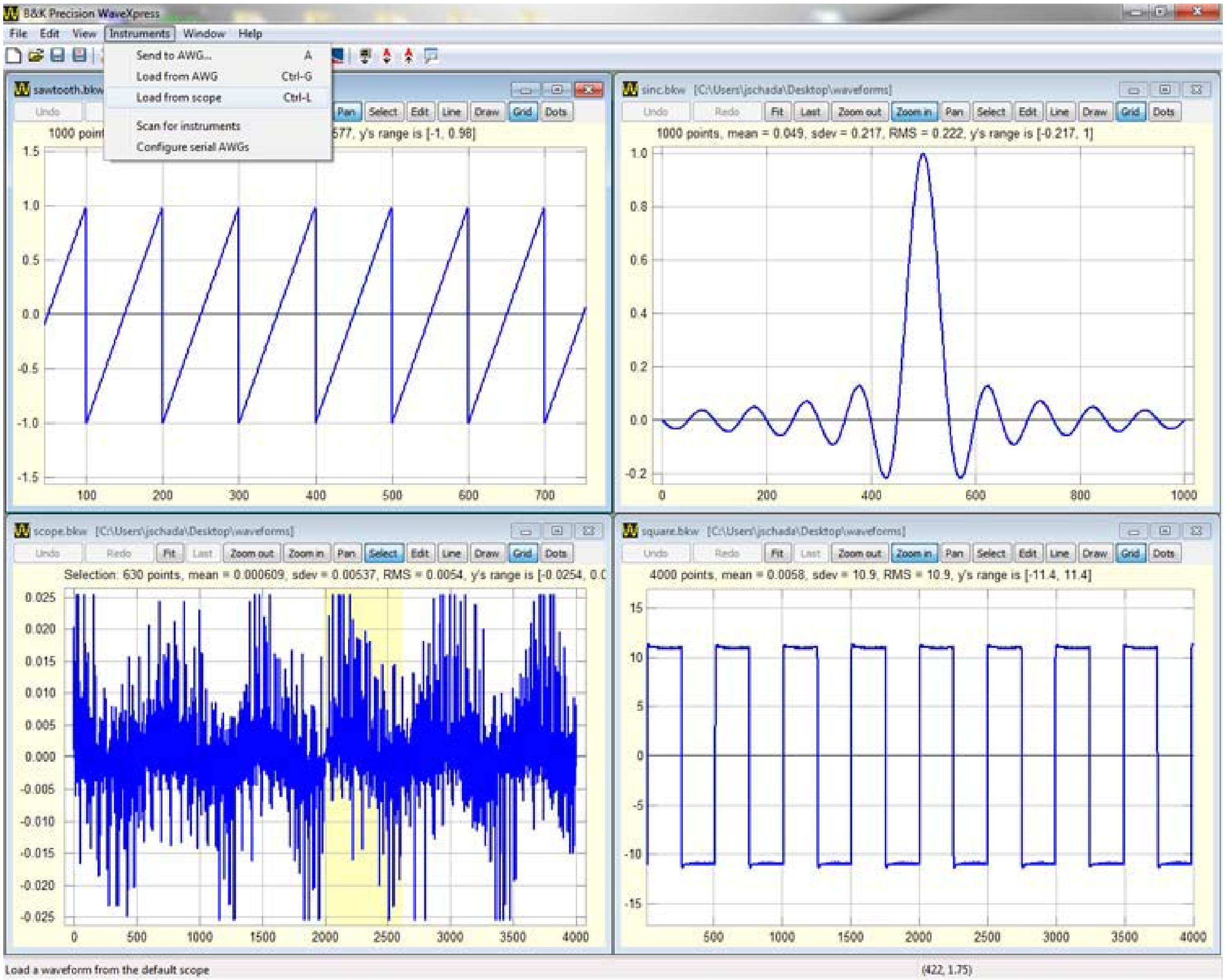

Figure 35

Probes

Probes are the most common methods for connecting the oscilloscope to the circuit of interest. There are two basic types of probes available,active and passive. An active probe contains active circuitry (i.e.., semiconductors and perhaps an external power supply). These probes can give the highest performance, but can be substantially more expensive than passive probes. By far the most commonly used probes are passive probes, which contain no active circuitry and use only passive components in their construction. The majority of the following material will focus on passive probes.

The circuits that need to be probed have a variety of effective input impedances. The best strategy for the scope and probe is to appear as a high impedance because this minimizes the loading of the circuit. While this is easy to say, it may not be easy to do in a high-frequency circuit.

A user's first pass at a probe design would be to connect a bare wire to the circuit to be tested from the scope's input. This works fine for DC and low frequencies (say, audio), but suffers from the problem of picking up substantial noise. Next, the user would think to use a shielded coaxial cable, as this can cut down on picked-up noise, but the coaxial cable introduces a new problem - high distributed capacitance. This distributed capacitance can be significant with respect to the scope's input capacitance. The popular RG-58 coaxial cable has a distributed capacitance of about 80 to 100 pF per meter. This distributed cable capacitance leads to signal degradation as the frequency is increased because the capacitance shunts the scope's input resistance (see the right-hand side of Figure 36 below).

Probe designers use coaxial cables that have substantially smaller distributed capacitance. An additional method of reducing this degradation is to insert a resistor in series with the probe cable. This offsets the degradation due to the cable capacitance, but at the cost of a reduced signal at the scope. Below is a schematic of a typical 10X probe. Note the distributed capacitance of the cable C_c is in parallel with the scope's input capacitance C_s.

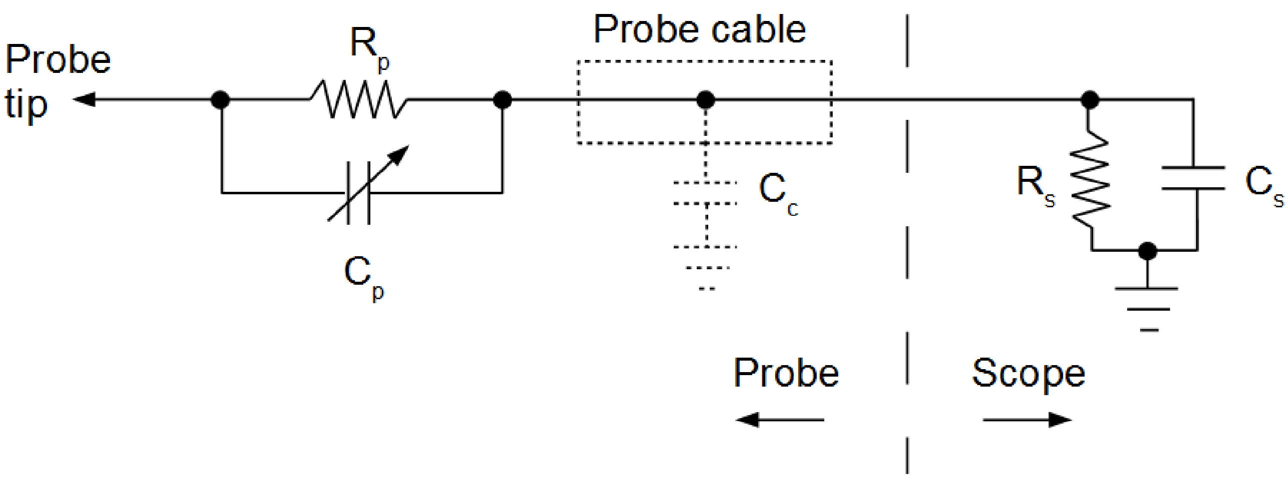

Figure 36

The resistor R_p is typically 9 MΩ. At DC, this means the input to the scope is through a voltage divider made up of R_p and R_s. At DC, the capacitors are effectively open circuits. Oscilloscope manufacturers have standardized on using 1 MΩ input resistances for their scopes. This standardization is important because it allows other manufacturer's probes that are designed for 1 MΩ inputs to be used, giving the consumer more choices. The scope's input also has a capacitance of roughly 10 to 30 pF, depending on the scope. Since R_S is 1 MΩ, the total input resistance is 10 MΩ and the voltage divider ratio is:

$$\frac{1\text{M}\Omega}{(9+1)\text{M}\Omega} = 0.1$$

This is why the probe is called a 10X probe as it attenuates the signal by 10 times. You'll also see them called X10 probes. The cable's distributed capacitance and the scope's input capacitance will shunt the signal around R_s at higher frequencies -- this leads to the basic fact that **a passive probe's impedance at its rated bandwidth can be more than four orders of magnitude smaller than its DC resistance**. Keep this in mind when measuring signals with high frequencies as your probe will likely be loading your circuit significantly. A common technique to see if a probe is loading a circuit is to connect another identical probe to the scope, then connect this second probe to where the first is probing. If the signal from the first probe changes, then circuit loading is a significant issue.

For example, a 150 MHz probe was measured to have a distributed cable capacitance of 58 pF. With a 20 pF typical scope input capacitance, this means a capacitance of about 80 pF. At 150 MHz, the capacitive reactance of this capacitor is 13 Ω, so you can see that this effectively shorts out the 1 MΩ input resistance of the scope. Though the capacitive reactances are low, the capacitances still behave as a capacitive divider and attenuate the signals appropriately. To see this is approximately true, the adjustable capacitor is on the order of 10 pF and $C_c + C_s$ is 80 pF -- almost 90 pF. If it was 90 pF, the reactances as impedances would have a voltage divider ratio exactly the same as the resistances (the $2\pi f$ terms for the reactances are factored out and we're ignoring the much larger resistances which are effectively open circuits).

$$\frac{\frac{1}{90}}{\frac{1}{90}+\frac{1}{10}} = 0.1$$

You may wonder what the adjustable capacitor C_p is for. This capacitance is used to compensate the probe. Compensation means to adjust the capacitance so that the probe has the correct amplitude response for different signal frequencies. The compensation capacitor C_p is adjusted to make the time constant R_pC_p equal to the time constant of the distributed cable capacitance and scope's capacitance of $R_s(C_c + C_s)$. This yields a circuit with minimal distortion of the signal. A typical passive probe has an adjustment between 10 to 30 pF.

For higher frequency passive probes, the equivalent circuit may be more complex -- and compensation may be more complicated than simply adjusting a single capacitor. In fact, probes and their circuits need to be analyzed as transmission lines -- and such analysis will show that probe design is not a trivial task.

You can measure your probe's DC attenuation with a digital multimeter, but you'll have to calculate the probe's voltage drop from knowing the digital multimeter's input resistance. For example, with a 10X probe and a digital multimeter with a measured 10.05 MΩ input resistance, an 11.44 volt DC signal was measured with a probe. The digital multimeter read 6.05 volts using the probe. The relevant voltage divider is the 10 MΩ input resistance of the digital multimeter in series with the 9 MΩ of the probe. Thus, the calculated voltage that the digital multimeter should have measured is:

$$\frac{10.05}{9+10.05} 11.44 = 6.035 \text{ volts}$$

This probe's measured attenuation was within 0.24% of its expected value.

A probe's rise time t_p can be measured with a fast-rising pulse. Since the oscilloscope also has a rise time t_s, the measured rise time t needs to be corrected:

$$t_p = \sqrt{t^2 - t_s^2}$$

You can calculate the scope's rise time $t_s$in ns from:

$$t_s = \frac{350}{B}$$

where *B* is the scope's bandwidth in MHz.

Probe compensation

Probe compensation is the process of matching the probe's electrical characteristics to the scope's. The result is that signals viewed by the scope using the probe will be accurately depicted (excluding the roll-off due to the probe's bandwidth).

Probe compensation is usually done with a square wave signal provided on the scope's front panel. This is usually a 1 to 2 Vpp square wave at 1 kHz (and, hence, the compensation is termed low-frequency compensation). The user hooks the probe to the scope and connects the probe's center conductor to the square wave. A non-conductive screwdriver is used to adjust a small capacitor on the probe so that the waveform on the screen matches a square wave signal with no undershoot or overshoot.

The key take-away about probe compensation is that **a poorly-compensated probe exposes you to measurement errors** -- and you won't know you're making an error unless you check for it.

A probe's compensation should be checked when it is first connected to the scope. If you've used that probe with the scope's different channels and know the compensation is good for all the channels, then you might relax that requirement if you know no one else has used the probe. Even so, it's probably good practice to check your probe compensation at the start of every day. If the probe might have been used with another scope, always check the compensation.

Probe types

Many different scope probes are available. Passive probes are the biggest sellers because they are lower cost and more robust. Probably the most common probe is the 10X probe with the bandwidth the user needs. 1X/10X probes are also popular, as they contain a switch in the probe body that lets you switch between the 1X position, 10X position, and a position where the input line is connected to the ground line. However, a disadvantage of a 1X/10X probe is that you can accidentally leave it in the 1X position when you need it to be in the 10X position. This can result in qualitative and quantitative measurement errors because the attenuation is not what you expect and the frequency response is substantially different than in the 10X position.

100X and 1000X passive probes are also available. These can be useful because they reduce the capacitive effects even more, but at the cost of more signal attenuation. They are often made to withstand voltages into the kilovolt ranges. For example, the Cal Test GE3225 100X probe has a 200 MHz bandwidth, 5 pF of capacitance, and a 2 kV CAT I voltage rating.

Active probes are used for differential measurements and probes with high frequency response with minimal circuit loading.

A passive probe and its accessories

Let's look at a typical passive probe. The following picture shows a B&K Precision PR37AG 150 MHz 1X/10X switchable probe and its 15 cm ground clip that ends in an alligator clip (the scale is graduated in mm):

Figure 37

The orange switch has positions X1, X10, and REF. The REF position grounds the center conductor and disconnects the input, allowing you to see the position of 0 volts on the oscilloscope's screen.

Note the tip is a sharp point and that a band of metal is a few mm behind the tip (the probe comes with one replacement tip). This metal band is connected to the probe's ground and is used to ground high frequency measurements. The left end of the grounding lead plugs into the probe about 1 cm to the right of the orange switch (i.e., just to the right of the finger guard) and clips in place.

Using this probe as shown is not recommended, as it's too easy to accidentally short a conductor with the grounded band of metal. Instead, accessories such as the following are placed over the tip:

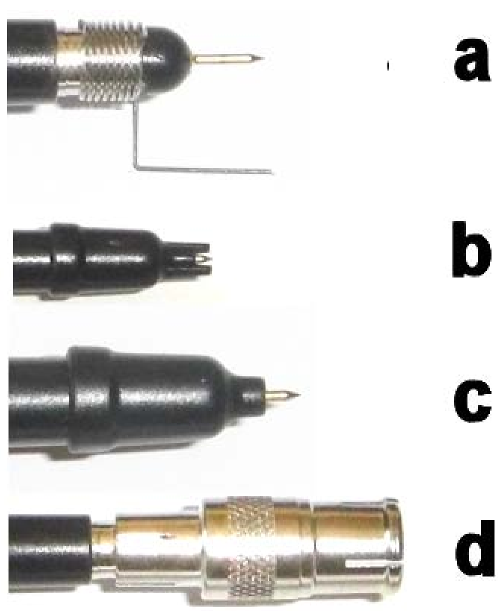

Figure 38

The device at **a** is called a bayonet-mount spring tip. It is used on high frequency circuits because it eliminates the long ground lead inductance and reduces ringing.

The tip at **b** allows the user to probe IC pins. The tip at **c** is for general-purpose probing and insulates the tested circuit from the grounded band of metal. The adapter at **d** allows the probe to be plugged into a BNC female connector. This makes for a convenient connection to test equipment and to BNC test ports on circuits.

A common tip not shown in the picture is a sprung hook. This has a spring-loaded hook that can be clipped over a wire. The spring helps hold the probe tip onto the wire.

Here's a picture of the end of the probe with the BNC male connector that plugs into the scope:

Figure 39

The hole in the plastic body is where you insert the small plastic screwdriver (supplied with the probe) to adjust the probe's compensation.

Note the yellow band around the probe and the probe's end in Figure 37 and Figure 39. These are used to help identify the probe when you have a number of probe connections (i.e., you don't have to trace the wire from the scope to the probe tip). The probe comes with four pairs of colored rings.

The specifications for this probe are:

Position 10X:

Attenuation ratio	10X (10:1)
Bandwidth	DC to 150 MHz (-3 dB)
Rise time	2.3 ns
Input resistance	10 MΩ (when used with oscilloscope with 1 MΩ input)
Input capacitance	13 pF
Compensation range	10-30 pF
Max. input voltage	600 V CAT I, 300 V CAT II (DC + peak AC) derated with frequency (see figure below) Pollution Degree 2

Position REF:

Probe tip opened, oscilloscope input grounded.

Position 1X:

Attenuation ratio	1X (1:1)
Bandwidth	DC to 6 MHz (-3 dB)
Rise time	58 ns
Input resistance	1 MΩ (oscilloscope input resistance)
Input capacitance	56 pF (plus oscilloscope capacitance)
Max. input voltage	300 V CAT I, 150 V CAT II (DC + peak AC) derated with frequency (see figure below) Pollution Degree 2
Max. operating temperature	0 °C to 50 °C
Humidity	85% RH or less (at 35 °C)
Cable length	1.2 m (48")
Max. float voltage	30 Vrms (between reference lead and earth ground)

Some definitions are also given:

Measurement Category II	CAT II is for measurements performed on circuits directly connected to the low voltage installation. Examples are measurements on household appliances, portable tools, and similar equipment.
Pollution Degree 2	Refers to an operation environment where normally only dry non-conductive pollution occurs. Occasionally, a temporary conductivity caused by condensation must be expected.

The probe's operating voltage is derated as the frequency is increased:

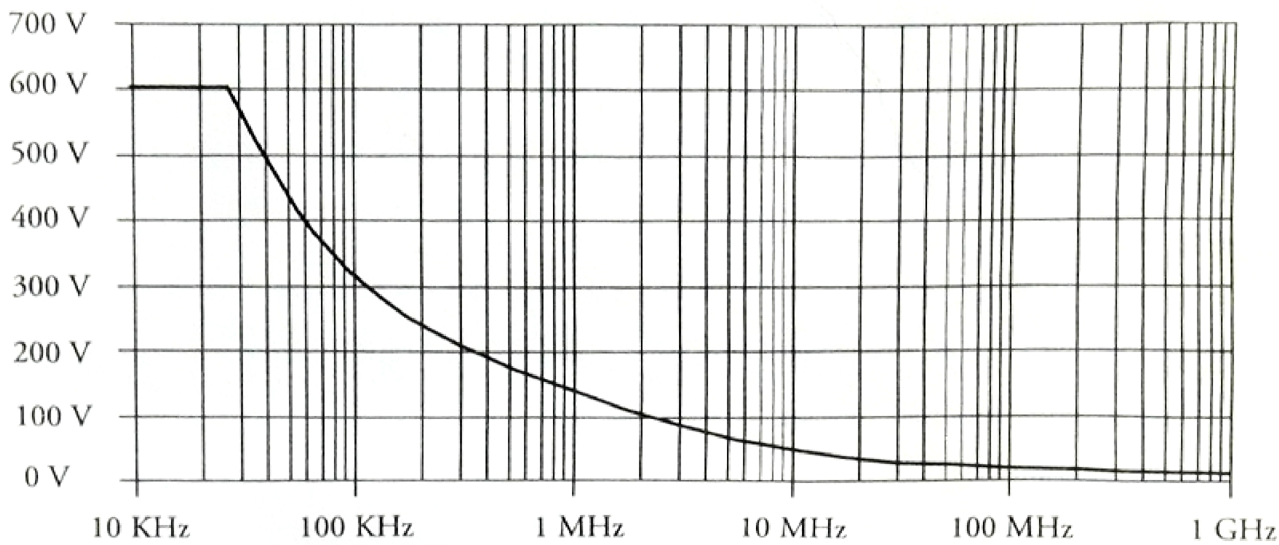

Figure 40

Floating a scope

Some people choose to "float" a scope so they can make a differential measurement with a probe. This is done to remove the connection between the scope's chassis (and the outside of the BNC jacks) to the power line ground. Then the user reasons that they can connect the probe and the probe's ground lead into a circuit to e.g. measure the voltage across a resistor (a common technique to look at the current in a circuit). Normally, the probe's ground wire is at power line ground potential and this would cause a short unless the point the probe ground was connected to was already at ground potential. If the scope is floated, then this eliminates the problem with the short. Isolating the scope from the power line's ground conductor is done with a 3-to-2 wire adapter or an isolation transformer.

Floating a scope is not recommended because it can put the user at a safety risk. The risk is that dangerous voltages can appear on the scope's chassis and the metal of the BNC connectors. It can happen that the user only learns about this problem when they try to make a differential measurement and end up with a blown circuit breaker, damaged circuit, or damaged probe -- or worse, getting a shock. While the principle will be obvious to a user who sees a schematic of the situation, the exercise drives the point home in a way that theoretical knowledge sometimes doesn't, especially when you realize that the exercise's innocuous small battery voltage could have been a 120 or 240 VAC line voltage -- and you may have inadvertently exposed yourself to these dangerous voltages.

If you need to make measurements that require a floating scope, either use an appropriately-isolated differential amplifier or a battery-operated scope that is specified for such floating measurements.

Good measurement practices

These are provided as guidelines of good practice, but may not be true in all situations.

1. Divide the bandwidth by 10 to get a rough idea of the fundamental frequency of an arbitrary periodic signal that your scope will be able to reasonably reproduce.
2. Time measurements are generally relative with oscilloscopes -- thus, you usually subtract two times measured on the screen to get a time difference. This is because there's no inherent notion of time t = 0 (unless you define the trigger event as t = 0). This principle may not be applicable to digital scopes, as they have more sophisticated time measurement features than analog scopes.
3. Voltage measurements are referenced to power line ground for the majority of non-battery-operated scopes.
4. If you measure voltages and times on the scope's screen, make the signal take up as much space on the screen as possible in both directions to get the best measurement resolution and accuracy.
5. Scope probes become part of the circuit they're measuring and thus load the circuit, especially at higher frequencies. The impedance of a passive scope probe can drop by three or four orders of magnitude from DC to the probe's rated bandwidth.
6. An uncompensated scope probe is a measurement error waiting to happen: the measured waveform may be distorted and you may get incorrect amplitude measurements.
7. A scope probe's rated maximum voltage can drop by two or more orders of magnitude from DC to its rated bandwidth.
8. Never connect the ground lead of a scope probe to anything except a point that is at ground potential or an isolated point in a circuit that can be at ground potential.
9. Do not use a grounding lead/clip on a scope probe at frequencies above roughly 100 MHz. Use the probe's spring clip (bayonet-style) or a coaxial probe socket on a printed circuit board.
10. For a non-battery-operated scope, do not float the scope above ground potential by the use of a 3-to-2 wire adapter or an isolation transformer. If you need to float a battery-operated scope, consult the scope's user manual as to whether this is appropriate.
11. Learning the screen annotations for your digital scope well (and the control locations and positions of your analog scope) will help you quickly understand the measurement conditions.
12. Every time you connect a probe to a scope, compensate it and make sure the probe's attenuation is set properly in the corresponding channel's menu. If appropriate, make sure the probe's attenuation switch is in the position you need.
13. If you use coaxial cables for making connections, get in the habit of using pass-through terminations for the scope's inputs, as this may help avoid measurement mistakes in the future.
14. Noise can't be distinguished from the signal unless the noise spectrum and the signal spectrum have an intersection of zero. The best strategy is to not let the noise into the system in the first place if possible.
15. If you're using an arbitrary waveform generator for stimulation of a circuit or system, put in a short, tall pulse in the waveform if the system will allow it. This pulse can make it easier to trigger a scope to get a stable display. If this isn't possible, but your scope supports e.g. pulse triggering, you can put in a low amplitude narrow pulse and try to trigger on that waveform. If your arbitrary waveform generator has a marker signal output, use the marker signal as the external trigger for the scope.
16. You can estimate the standard deviation of a signal using a digital scope. Here are two possible ways. First, turn on persistence and measure the overall envelope of the waveform for a time interval. The maximum and minimum values of this envelope will give you the range. You can then estimate the standard deviation, either by assuming the distribution or using a non-parametric method. The second way is to measure the RMS value. The RMS value of a waveform is the same as the population standard deviation of the waveform with the DC component subtracted out.

Oscilloscope safety

Remember that your safety (and often the safety of others working near you) is ultimately your responsibility. Take this responsibility seriously and be methodical about it. Don't engage in horseplay. Use checklists to remind you of things that need to be done. The cost and effort of safety training and practicing its rules will seem like a trivial expense compared to the human cost of an accident or a death after the fact.

1. Don't expose high voltages needlessly in the equipment under test. Remove housings and covers only when necessary. Turn off equipment while making test connections in high-voltage circuits. Discharge high-voltage capacitors after removing power.
2. If possible, familiarize yourself with the equipment being tested and the location of its high voltage points. However, remember that high voltage may appear at unexpected points in defective equipment.
3. Use an insulated floor material or a large, insulated floor mat to stand on, and an insulated work surface on which to place equipment; make certain such surfaces are not damp or wet.
4. Use the time-proven "one hand in the pocket" technique while handling an instrument probe. Be particularly careful to avoid contacting a nearby metal object that could provide a good ground return path.
5. When using a probe, touch only the insulated portion. Never touch the exposed tip portion.
6. When testing ac powered equipment, remember that ac line voltage is usually present on some power input circuits such as the on-off switch, fuses, power transformer, etc. any time the equipment is connected to an ac outlet, even if the equipment is turned off.
7. Some equipment with a two-wire ac power cord, including some with polarized power plugs, is the "hot chassis" type. This includes most recent television receivers and audio equipment. A plastic or wooden cabinet insulates the chassis to protect the customer. When the cabinet is removed for servicing, a serious shock hazard exists if the chassis is touched. Not only does this present a dangerous shock hazard, but damage to test instruments or the equipment under test may result from connecting the ground lead of most test instruments to a "hot chassis". To make measurements in "hot chassis" equipment, always connect an isolation transformer between the ac outlet and the equipment under test. To be on the safe side, treat all two wire ac powered equipment as "hot chassis" unless you are sure it has an isolated chassis or an earth ground chassis.
8. Never work alone. Someone should be nearby to render aid if necessary. Training in CPR (cardiopulmonary resuscitation) first aid is recommended.
9. Use shrouded BNC coaxial cables if possible. Unshrouded BNC connectors may have significant voltages on the outside metal, especially on instruments that use floating BNC connections.
10. Know about Category ratings (see CAT I in the glossary) and how they apply to your scope and probes. Don't use these measurement tools on circuits that require higher category ratings than your scope and probes provide.

Preventing damage to the oscilloscope

1. On an analog oscilloscope, don't leave the oscilloscope set at high brightness for long intervals. A bright spot or line left in one position can permanently burn the CRT's phosphor.
2. Keep the ventilation holes clear.
3. Avoid dusty environments or spilling liquids onto the oscilloscope.
4. Don't apply excessive voltage to the scope's input jacks. Voltage limits are clearly stated in your operating manual and usually on the scope itself.
5. Connect the ground clip of a scope probe only to earth ground or isolated common in the equipment under test.
6. Keep the scope away from direct sunlight, high temperature/humidity, mechanical vibration, electrical noise, and strong magnetic fields.

Glossary

AC	Alternating current. It refers to a voltage or current that is periodically changing over time. It can also refer to the type of electrical coupling to a scope's vertical amplifier or trigger circuitry. AC coupling means that the DC component of a waveform is blocked.
accelerating voltage	The potential used to accelerate the electrons in a scope's CRT. This gives the electrons enough kinetic energy to excite the atoms in the tube's phosphor, causing light to be emitted from the phosphor, resulting in an oscilloscope trace.
ADC	Analog to digital converter. It is an electronic circuit used to digitize analog signals for further digital processing.
aliasing	The false appearance of non-existent signal frequencies in signals that aren't sampled correctly. Related phenomena are Moire patterns and wagon wheel spokes in movies that don't appear to move at the right speed or direction.
alternate sweep	In analog oscilloscopes, this is a method of generating a dual-trace display at higher sweep speeds. One entire trace is drawn, then the other, in an alternating fashion. Contrast to chopped sweep.
alternate trigger	A dual-trace triggering scheme in which the channel 1 signal triggers the channel 1 trace, and the channel 2 signal triggers the channel 2 trace in an alternating pattern. Each signal becomes its own trigger source and a synchronized display can be obtained even if the two signals have no time relationship.
analog	When describing an oscilloscope, it means an oscilloscope that uses predominantly analog circuitry to process and display waveforms. When describing electronics, it means circuitry that uses a wide variety of voltage or current values. Contrast this with digital electronics, which deals with two voltage values. In some cases, digital signals must be regarded as analog (which, in fact, they are physically) in order to obtain correct operation or explain certain behaviors.
ARB	Abbreviation for arbitrary waveform generator.
arbitrary waveform generator	A signal generator that can generate waveforms with an arbitrarily defined shape other than the standard Sine, Square, or Ramp waveforms found on function generators.
armed	In referring to an oscilloscope's trigger section, the trigger is armed when the scope is waiting for a trigger signal and, when one is found, causes a single sweep of the timebase. Thus, with a digital scope, a common scenario is to set the scope up for a single sweep to capture a transient event. This is done on the B&K 254X/253X scopes by pressing the SINGLE button. This arms the trigger. After a trigger event occurs, the trigger goes into the unarmed state.
attenuation	The process of decreasing the amplitude of a signal.
averaging	A smoothing process achieved by summing more than one measured value and divided by the number of values summed. Because noise on electrical signals often has a zero average (i.e., oscillates randomly about zero volts), averaging waveform data is a valuable way of removing the noise from a signal. For good signal fidelity, the signal must not change its underlying behavior over the averaging period.
AWG	Initialism for arbitrary waveform generator.

bandwidth	In the context of oscilloscopes, this is the upper frequency rating of the oscilloscope's vertical amplifier(s) (the scope's lower frequency rating is 0 Hz, as it can measure DC voltages). The rating is usually the 3 dB point, which means the measured amplitude of a constant-amplitude sine wave is 3 dB below that of a lower frequency sine wave of the same amplitude at, say, half of the bandwidth.
blanking	In an analog scope with a CRT, this is the process of turning off the electron beam immediately after the trace reaches the end of the screen. The beam current is off while the horizontal deflection plate control signals are set to return the beam to the start of the trace and the trigger circuit is waiting for a trigger.
blind time	Same as dead time.
BNC	Type of coaxial connector commonly used on measuring equipment. The initials stand for Bayonet Neill–Concelman (the last two names of the inventors).
CAT I, CAT II, CAT III, CAT IV	These are "installation category" ratings and indicate the type of hazards a user of test equipment is exposed to and that the test equipment can withstand safely. Refer to the IEC 1010 and related standard for more details. Informally, CAT I means equipment connected to AC power, but where the user is isolated by e.g. a transformer. CAT II can mean environments like on an engineer's bench. CAT III can mean the voltages found inside a building's circuit breaker panel. CAT IV can mean connections to primary incoming power from the power company's equipment. The differences in ratings come from the types and severity of voltage and current transients the user can be exposed to from the circuit being worked on. For example, a user working in a CAT IV environment might be exposed to transients of many kilovolts and kiloamperes (due to lightning strikes or inductive spikes from power interrupts). Test equipment needs to be able to protect the user from the effects of these transients. For example, you'll find sophisticated and expensive fuses in digital multimeters to contain the dangerous plasma that can result from a multi-kiloampere transient, thus protecting the user from shocks and burns.
channel	One of the vertical amplifiers on an oscilloscope used to display one trace.
chopped sweep	In analog oscilloscopes, a method of generating a dual-trace display at lower sweep speeds. One trace is drawn for a fraction of the screen, then the other trace is drawn for another short fraction. You can see the chopping by decreasing the time base setting.
CMRR	Common mode rejection ratio, a measure of the ability of a differential amplifier to ignore a signal common to both inputs.
compensation	In the context of an oscilloscope probe, it's the adjustment of a small variable capacitor so that the scope has no overshoot or undershoot when looking at fast rise time edges (e.g., square waves). This is a critical adjustment to be made for each probe, as it also ensures that correct voltage measurements can be made with the probe, especially at higher frequencies.
component test	A feature on the B&K 2125A scope that allows a user to display a voltage versus current waveform for a component. It is capable of identifying and testing capacitors, inductors, resistors, and semiconductors.
coupling	In the use of an oscilloscope, this describes the electrical coupling between the input signal and the scope's circuit. It is typically used in context with the vertical amplifiers and the trigger circuit. See AC coupling and DC coupling.
cross talk	Sometimes referred to as channel isolation or channel separation. The undesired effect that a signal present on one channel has on another channel. Less crosstalk means that the channels are better electrically isolated from one another. Usually expressed in dB.

CRT	Cathode ray tube. It is the vacuum tube with a thermionic emitter and electrostatic deflection plates (some may also contain deflection coils) that accelerates electrons that impact on the phosphor screen, producing light. A CRT is used with virtually all analog oscilloscopes.
cursor	A marker (usually a horizontal or vertical dotted line) on a scope that can be used to make measurements by lining up the marker with a waveform feature.
DC	Direct current. The general use means a voltage or current whose value is constant.
DDS	Stands for direct digital synthesis, a digital architecture used in many modern function generators.
dead time	The time that the scope is not capturing the signal. This applies to both analog and digital scopes and is not usually specified.
decibel	A dimensionless number used to represent a ratio between two quantities of the same type. If the two quantities are a and b, then their ratio in decibels is defined to be $10\log_{10}\frac{a}{b}$. It is often used to represent the ratio of two powers. When used to represent the ratio of two voltages or currents, the expression $20\log_{10}\frac{a}{b}$ is usually used because the power is proportional to the squares of these quantities.
delayed time base	A secondary time base in an oscilloscope that is used to display a smaller section of the trace shown with the main time base. Its trigger position and time width are adjustable to allow inspection of different portions of the main trace at various horizontal magnifications.
digitize	The process of converting an analog signal to a sequence of digital values by an analog to digital converter.
division	A major mark in the graticule (grid) of a scope's display screen. Common numbers of divisions are 10 or 12 horizontal by 8 vertical.
DSO	Digital storage oscilloscope. An oscilloscope that acquires signals with digital sampling.
dual trace	A scope with two vertical channels that is capable of displaying the voltage versus time of two waveforms at the same time.
duty cycle	In a pulse train waveform, the fraction of the pulse train's period that is the width of the pulse.
envelope	A curve joining the peaks of an oscillating signal. This term is often used in the context of amplitude modulation, where the envelope is usually easy to see with an oscilloscope.
equivalent time sampling	A sampling method of a digital oscilloscope that can only be used on periodic signals. It allows the scope to digitize waveforms with frequencies higher than the sampling frequency by sampling one or a few points in many periods of the waveform and combining the sampled data.
extrinsic noise	Noise in an electrical circuit that is caused by physical processes outside of (or extrinsic to) the circuit. An example is an AC voltage induced in the circuit's wiring by an external changing magnetic field.
fall time	The time it takes for a signal to fall from a higher level to a lower level in value. Opposite of rise time.
focus	An adjustment on an analog oscilloscope that allows the trace to be adjusted from a fine line to a wide line.
frequency	The number of periods per unit time of a waveform. Usually expressed in hertz, Hz, often with an SI multiplier. It is equal to the reciprocal of period.
gain	The amount of gain in the vertical amplifier of an oscilloscope.

glitch	An unexpected signal or portion of a repetitive waveform that is unlike the other parts of the waveform. Glitches tend to be of short duration compared to the signal of interest. Other terms that can indicate unexpected signals are spike, runt pulse, or ringing.
graticule	The marked grid on an oscilloscope's screen that is used to make quantitative measurements of a waveform's voltage and time characteristics.
grid	A synonym for graticule.
ground	A voltage reference in a circuit. The term derives from being connected to the Earth, which is usually taken as a point of zero electrical potential.
intensity	An adjustment on an oscilloscope that controls how bright the trace is to the user's eye.
interpolation	The method used to connect the points in a sampled waveform for display.
intrinsic noise	Noise that is caused by fundamental physical causes internal to a circuit. Examples are the thermal (Johnson) noise of a resistor or the shot noise of current flow.
linearity	A measure of how closely a relationship between two variables falls on a straight line. In an analog scope, you want the sweep to be very linear so that the time is directly proportional to the distance from the beginning of the trace.
Lissajous figure	A figure displayed on an oscilloscope in XY display mode. The horizontal and vertical signals are typically sine waves. If their frequency ratio is a rational number, then the display is stable.
loading	A measure of how much a signal is changed by connecting another circuit to it. In the context of oscilloscopes, it refers to either the scope's effect on being connected to the circuit or the effect of connecting a scope probe to a circuit.
main time base	The primary time base in an oscilloscope.
mixed signal oscilloscope	A scope that combines the features of a digital oscilloscope and a logic analyzer.
noise	A variation in a signal that is (usually) unwanted and conveys essentially no useful information.
oversampling	A sampling scheme where the sampling frequency is higher than the Nyquist limit of 2B, where B is the bandwidth of the signal to be sampled. Oversampling can reduce aliasing.
peak detection	An acquisition mode of a digital oscilloscope that lets you see the peak values of a signal. This is useful for getting an idea of the true peak-to-peak voltage of a waveform over many sweeps.
peak-to-peak	The maximum voltage minus the minimum voltage of a waveform displayed on an oscilloscope.
period	The time for a periodic signal to repeat itself. It is equal to the reciprocal of frequency.
persistence	The time it takes for an analog oscilloscope's phosphor to stop emitting light after being excited by the electron beam. The longer the persistence, the easier it is to view slow waveforms. However, a long persistence can be an annoyance when one needs to view rapid changes in a waveform, so a compromise needs to be struck when picking the phosphor and its persistence.
phase	In an oscilloscope display of periodic signal, it measures the time offset of a waveform from a reference point. If two signals have the same period, then these signals can be shifted in time between reference points in a period. This is referred to as phase shift or phase difference and is often measured in degrees with 360 degrees representing a phase shift of one period.

phosphor	A chemical used to coat the inside of a CRT. When struck by fast-moving electrons, the orbital electrons of the phosphor are excited to higher energy levels using the kinetic energy of the incoming electrons. When the atoms decay back to their lower energy states (usually, the ground state), they release a photon. This photon escapes the glass CRT and registers as an oscilloscope trace on a human's eye.
post-trigger	The time period after the trigger event.
post-trigger data	The digitized waveform data collected after the trigger event.
pre-trigger	The time period before the trigger event.
pre-trigger data	The digitized waveform data collected before the trigger event.
probe	An oscilloscope accessory device used to couple the oscilloscope's input channel to a circuit to be measured.
pulse	A rapid, transient change in the amplitude of a signal from a baseline value to a higher or lower value, followed by a rapid return to the baseline value.
pulse period	The time that a periodic pulse train repeats itself.
pulse train	A sequence of one or more pulses.
pulse width	The width of a pulse, measured while the pulse's value is at the non-baseline value.
ramp	A voltage that linearly increases or decreases from a starting value, then quickly returns to the starting value. The horizontal (time axis) deflection voltage in an analog oscilloscope's CRT is a ramp voltage.
raster	The representation of a two-dimensional image by turning small sections of the display screen (pixels or picture elements) on and off. In the analog world, it refers to the rapid scanning back and forth of an electron beam, each line displaced vertically a small amount from the last line, and resulting in a displayed image. This is the way analog televisions and older computer displays worked.
real time sampling	A sampling method of digital scopes where the signal is directly sampled. It is used to measure and display transient, non-repeating signals. Contrast to equivalent-time sampling.
record length	The number of data points representing a trace on a digital oscilloscope.
rise time	The time required for a signal to rise from 10% to 90% of its maximum amplitude (other percentages can be specified, such as 20% to 80%). With a fast rise time pulse, the rise time specification of the oscilloscope can be measured. An oscilloscope's rise time specification is directly related to its bandwidth: $\text{risetime in a scope in ns} = \frac{350}{\text{bandwidth in MHz}}$
RMS	Root mean square. It is a positive measure of the amplitude of a periodic waveform and used to predict the power dissipation in a resistive element. The analog definition involves an integral. For a sampled waveform, the RMS value is the square root of the mean of the squares of the data values (i.e., square each value, take their sum, divide by the number of values, and then take the square root).
sampling	The process of taking samples of a waveform at regular intervals. This converts a continuous analog signal into a sequence of numbers. The term can also refer to equivalent time sampling methods.
sampling rate	A fundamental measure of the digitizing abilities of a digital scope, as in the context of the sampling theorem. It is the frequency in Hz (or it can be expressed in samples per second Sa/s) of the samples being taken.
sampling scope	An oscilloscope that uses equivalent time sampling methods to display high frequency signals that lie beyond the sampling rate of the oscilloscope.

screen	The visual display area of an oscilloscope. It can be a CRT (a phosphor-coated electron beam tube), an LCD (liquid crystal display), or an LED (light emitting diode) display.
single sweep	A mode of operation of a digital scope where the scope is "armed" to wait for a trigger event. When the trigger event occurs, the post-trigger data is collected, the waveform is displayed, and the trigger is "disarmed".
single-shot	Used to describe the nature of capturing a transient (one time) event on an oscilloscope.
slope	The rise over the run of a waveform. A positive sloping waveform goes up and to the right. A negative sloping waveform goes down and to the right (assuming the normal sweep direction is from left to right on the screen).
sweep	An older term describing the movement of the electron beam across the screen, caused by electrostatic and magnetic fields inside of the CRT.
sweep magnifier	An analog oscilloscope feature that magnifies the trace in the horizontal (time) direction. The magnification is usually 10 times.
sweep speed	The amount of time it takes for an electron beam to "sweep" across the screen on an analog scope. It is given in units of time per division on the graticule. More modern usage is to refer to the horizontal sweep circuit as the time base.
TCO	Total cost of ownership. The concept of accounting for all the costs involved in using an instrument like an oscilloscope over the useful life of that instrument.
thermionic emission	When certain materials are heated to a hot enough temperature, electrons can be freed from the material and will flow in a circuit with an accelerating potential to overcome the material's work function (the energy required to break the electrons free of the surface). The current increases essentially as the square of the absolute temperature of the material. This is how all thermionic vacuum tubes like television and oscilloscope CRTs work.
time base	The circuitry used to generate the sweep of the oscilloscope (this is in the context of an analog scope). For digital scopes, the time base controls the sampling rate. Both circuits change the time per division setting of the scope (i.e., how much time a unit horizontal distance on the screen represents).
trace	The display of a single waveform on an oscilloscope's screen.
transient	A signal that only occurs once or infrequently.
trigger	In an analog oscilloscope, the event or signal that causes the CRT beam to begin its sweep across the display. In a digital oscilloscope, it's the event around which the storage process is referenced. Some digital oscilloscopes place the trigger in the center of the storage memory, so that there are equal amounts of pre-trigger and post-trigger data. In both analog and digital scopes, versatile triggering is provided by setting the trigger type, source, level, and slope.
trigger holdoff	An adjustable time between the end of a sweep and the moment that the trigger circuit is armed for the next sweep. This can be valuable to get stable displays of complex signals. The usual method is to set the holdoff to slightly longer than the signal's period.
trigger level	The voltage level that the trigger is set to. If the trigger slope is positive, a trigger event is generated when the trigger signal goes from less than to greater than the trigger level. If the trigger slope is negative, a trigger event is generated when the trigger signal goes from greater than to less than the trigger level.
trigger mode	The mode used to trigger the scope. Two common modes are auto and normal. Auto trigger is the same as normal triggering except when no trigger signal is present, the scope automatically triggers itself.
trigger slope	Determines whether the scope triggers on a rising edge (positive slope) or a falling edge (negative slope).

TV sync	See video sync.
unarmed	In referring to an oscilloscope's trigger section, an unarmed trigger is when the trigger is not armed. The scope will not trigger in the unarmed state.
vertical attenuator	The attenuator used on a vertical channel of a scope.
vertical gain	The gain setting of the vertical amplifier. Usually given in volts per graticule division. Changing the vertical gain determines the vertical extent of a waveform on the screen.
vertical sensitivity	The signal level required to cause a single division of vertical deflection. For example, for a vertical gain (attenuator) setting of 1 V/div, a 1 V peak-to-peak signal will be one division high on the oscilloscope's screen.
video sync	A triggering method to synchronize with television signals to allow the scope to view and measure signal characteristics. Sometimes referred to as TV sync. This feature allows vertical (TV V) or horizontal (TV H) video sync pulses to be selected for triggering. Vertical sync pulses are selected to view vertical fields or frames of video and horizontal sync pulses are selected for viewing horizontal lines of video.
WaveXpress®	A B&K Precision software tool that can create and modify waveforms. The software can communicate with B&K scopes and arbitrary waveform generators to upload and download waveforms for experimentation. The tool can be downloaded from http://www.bkprecision.com/wavexpress.html.
x-axis	The horizontal (time) axis of the oscilloscope. It is also called the x-axis in XY display mode.
XY display	An oscilloscope display mode where two voltage signals are displayed simultaneously. One voltage signal drives the horizontal position (x-axis) and the other signal drives the vertical position (y-axis).
y-axis	The vertical (voltage) axis of the oscilloscope.
z-axis	In some scopes (predominantly analog scopes), the z-axis input can be used to control the intensity of the electron beam. This allows specialized display capabilities. For example, a third parameter can be used to modulate the intensity of a trace, transmitting more information to the user. In XY display mode, the z-axis input can be used to cause dots to appear on the screen as the beam sweeps across the screen. This is essentially the mechanism of how an analog television works.

References

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