THE OSCILLOSCOPE

APPENDIX O

The oscilloscope ("scope" for short) is, by far, the most useful and versatile electronic circuit test instrument.[1] As usually used, it lets you "see" voltages in a circuit as a function of time, triggering on a particular point of the waveform so that a stationary display results. Contemporary scopes are almost invariably *digital* (input signals are digitized, processed, and displayed), and they do (and usually *better*) what their analog ancestors did. To understand how to use an oscilloscope, we think it best to start with the traditional (and nearly extinct) 2-channel *analog* scope, for which we've drawn a block diagram (Figure O.1) and typical front panel (Figure O.2). Digital scopes carry forward nearly all of its features, to which they add an impressive array of capabilities (and a few hazards).

O.1 The analog oscilloscope

O.1.1 Vertical

Beginning with the signal inputs, most analog scopes have two channels; that's very useful, because you often need to see the relationship between signals. Each channel has a calibrated gain switch, which sets the scale of **VOLTS/DIVISION** *on the screen*.[2] There's also a **VARIABLE** gain knob (concentric with the gain switch) in case you want to set a given signal to a certain number of divisions. Warning: be sure the variable gain knob is in the "calibrated" position when making voltage measurements! It's easy to forget. The better scopes have indicator lights to warn you if the variable gain knob is out of the calibrated position.

The scope is dc-coupled, an essential feature: what you see on the screen is the signal voltage, dc value and all. Sometimes you may want to see a small signal riding on a large dc voltage, though; in that case you can switch the input to **AC COUPLING**, which capacitively couples the input with a time constant of about 0.1 second. Most scopes also have a grounded input position, which lets you see where zero volts is on the screen. (In **GND** position the signal isn't shorted to ground, just disconnected from the scope, whose input is grounded.) Scope inputs are usually high-impedance (1MΩ in parallel with about 20 pF), as any good voltage-measuring instrument should be.[3] The input resistance of 1 MΩ is an accurate and universal value, so that high-impedance attenuating probes can be used (as will be described later); unfortunately, the parallel capacitance is not standardized, which is a bit of a nuisance when changing probes.

The vertical amplifiers include a vertical **POSITION** control, an **INVERT** control on at least one of the channels, and an **INPUT MODE** switch. The latter lets you look at either channel, their sum (their difference, when one channel is inverted), or both. There are two ways to see both: **ALTERNATE**, in which alternate inputs are displayed on successive sweeps of the trace, and **CHOPPED**, in which the trace jumps back and forth rapidly (0.1–1 MHz) between the two signals. **ALTERNATE** mode is generally better, except for slow signals. It is often useful to view signals both ways, to make sure you're not being deceived.

O.1.2 Horizontal

The vertical signal is applied to the vertical deflection electronics, moving the dot up and down on the screen. The horizontal sweep signal is generated by an internal ramp generator, giving deflection proportional to time. As with the vertical amplifiers, there's a calibrated **TIME/DIVISION** switch and a **VARIABLE** concentric knob; the same warning stated earlier applies here. Most scopes have a **10× MAGNIFIER** and also allow you to use one of the input channels for horizontal deflection (this lets you generate those beloved but generally useless

---

[1] It is sometimes said that practitioners of other engineering disciplines are especially envious of EEs, because we are blessed with such a splendid instrument with which to visualize the happenings in our circuits.

[2] Note that the two channels can be set for different scale factors, offsets, and coupling. This goes also for digital scopes, which commonly have four channels.

[3] Scopes intended for high-frequency measurements, going beyond 100 MHz, say, offer also a 50 Ω input impedance option.

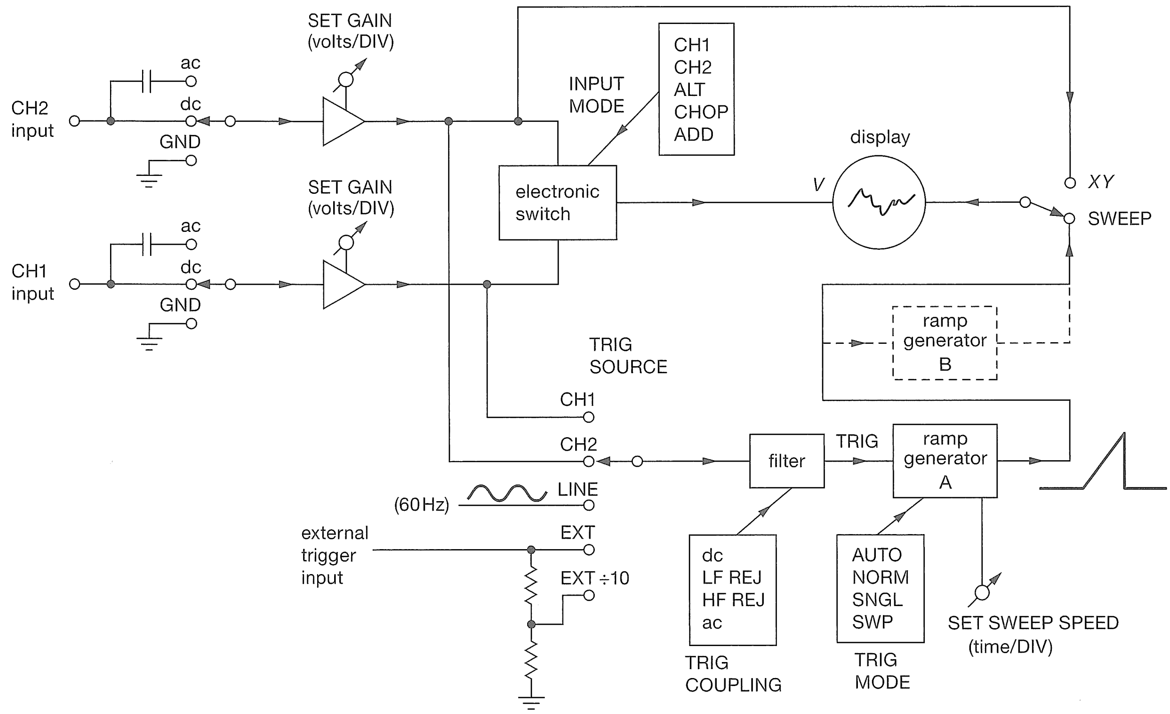

Figure O.1. Block diagram of a 2-channel analog oscilloscope.

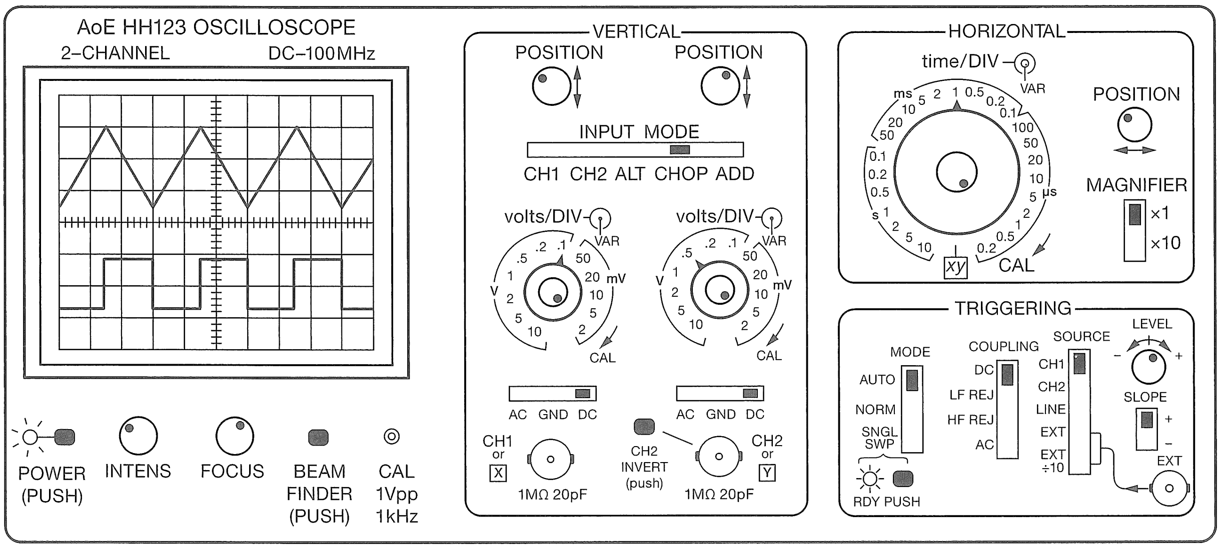

Figure O.2. Portrait of a 2-channel analog scope.

"Lissajous figures" featured in elementary books and science fiction movies).

O.1.3 Triggering

Now comes the trickiest part: *triggering*. We've got vertical signals and horizontal sweep; that's what's needed for a graph of voltage versus time. But if the horizontal sweep doesn't catch the input signal at the same point in its waveform each time (assuming the signal is repetitive), the display will be a mess – a picture of the input waveform superimposed over itself at different times. The trigger circuitry lets you select a **LEVEL** and **SLOPE** (+ or −) on the waveform at which to begin the sweep. You can see from the front panel that you have a number of choices about trigger sources and mode. **NORMAL** mode produces a sweep only when the source selected crosses through the trigger point you have set, moving in the direction (**SLOPE**) you have selected. In practice, you adjust the level control for a stable display. In **AUTO** the sweep will "free run" if no signal is present; this is good if the signal sometimes drops to small values, since the display won't disappear and make you think the signal has gone away. It's the best mode to use if you are looking at a bunch of different signals and don't want to bother setting the trigger each time. **SINGLE SWEEP** is used for nonrepetitive signals. **LINE** causes the sweep to trigger on the ac power line, handy if you're looking at hum or ripple in a circuit. The **EXTERNAL** trigger inputs are used if you have a clean signal available at the same rate as some "dirty" signal you're trying to see; it's often used in situations where you are driving some circuit with a test signal, or in digital circuits where some "clock" signal synchronizes circuit operations. The various coupling modes are useful when viewing composite signals; for instance, you may want to look at an audio signal of a few kilohertz that has some spikes on it. The **HF REJ** position (high-frequency reject) puts a low-pass filter in front of the trigger circuitry, preventing false triggering on the spikes. If the spikes happen to be of interest, you can trigger on them instead in **LF REJ** position.

Many scopes now have **BEAM FINDER** and **TRIGGER VIEW** controls. The beam finder is handy if you're lost and can't find the trace; it's a favorite of beginners. Trigger view displays the trigger signal; it's especially handy when triggering from external sources.

O.1.4 Hints for beginners

Sometimes it's hard to get *anything* to show on the scope. Begin by turning the scope on; set triggering for **AUTO**, **DC COUPLING**, **CH 1**. Set sweep speed at 1 ms/div, cal, and the magnifier off (×1). Ground the vertical inputs, turn up the intensity, and wiggle the vertical position control until a horizontal line appears (if you have trouble at this point, try the beam finder).[4] Now you can apply a signal, unground the input, and fiddle with the trigger. Become familiar with the way things look when the vertical gain is far too high, when the sweep speed is too fast or slow, and when the trigger is adjusted incorrectly.

[4] Curiously, some scopes (for example the once-popular Tektronix 400 series) don't sweep on **AUTO** unless the trigger level is adjusted correctly.

O.1.5 Probes

The oscilloscope input capacitance seen by a circuit under test can be undesirably high, especially when the necessary shielded connecting cable is included. The resulting input impedance (1MΩ in parallel with 100 pF or so) is often too low for sensitive circuits and loads it by the usual voltage divider action; for example, at 10 MHz a 100 pF load looks like 160 Ω – ouch! Worse yet, the capacitance may cause some circuits to misbehave, even to the point of going into oscillation. In such cases the scope obviously is not acting like the "low-profile" measurement instrument we expect; it's more like a bull in a china shop.

The usual solution is the use of high-impedance "probes." In simplified form,[5] the popular 10× probe works as shown in Figure O.3. At dc it's just a 10× voltage divider. By adjusting C_1 to be $\frac{1}{9}$th the parallel capacitance of C_2 and C_3, the circuit becomes a 10× divider at all frequencies, with input impedance of 10MΩ in parallel with a few picofarads. In practice, you adjust the probe by looking at a square wave of about 1 kHz, available on all scopes as **CALIB**, or **PROBE ADJ**, setting the capacitor on the probe for a clean square wave without overshoot. Sometimes the adjustment is cleverly hidden; on some probes you twist the body of the probe and lock it by tightening a second threaded part. One drawback: a 10× probe makes it difficult to look at signals of only a few millivolts; for these situations use a "1× probe," which is simply a length of low-capacitance shielded cable with the usual probe hardware (wire "grabber," ground clip, handsome knurled handle, etc.). The 10× probe should be the standard probe, left connected to the scope, with the 1× probe used when necessary. Some probes feature a convenient choice of 1× or 10× attenuation, switchable at the probe tip.

Even with a 10× probe, the circuit loading may be unacceptable; after all, its improvement is just the same factor of ten by which it attenuates the input signal. You *can* get 100× probes, with correspondingly higher input

[5] In practice the cable itself is made from resistance wire, to damp transmission-line effects (frequency peaking and transient reflections, see Appendix H), an elegant 1959 invention by Kobbe and Polits (US Patent 2,883,619); you also see tricks such as a series *RC* across the scope terminals (e.g., 500 Ω and a trimmer capacitor), to provide a transmission-line match at high frequencies.

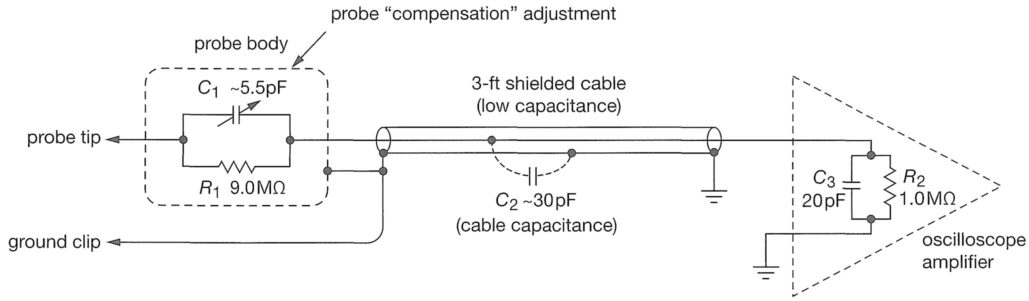

Figure O.3. A 10× passive scope probe attenuates signals by a factor of ten at all frequencies, conveniently raising the input impedance by the same factor. (In practice additional tricks are used to suppress transmission-line effects, see text.)

impedance (e.g., the Tektronix P5100 series), but these are intended primarily for viewing high-voltage signals (the scope itself is usually limited to a maximum of ±400 V at the input connector), and they do not excel in important features such as small physical size. What you do, instead, is to use an *active probe*, which uses a FET follower at the tip to achieve an input capacitance <1 pF.[6] Active probes, being intended for wideband use, are intended to drive a 50 Ω input (available on most high-speed scopes; if not, attach a 50 Ω pass-through terminator); they require a source of power, available at the scope's input connector (on digital scopes), or provided by a stand-alone box like the Tektronix 1103.

Any discussion of probes would be incomplete without a mention of *current* probes: these handy devices, when clipped around a wire in some circuit, convert the circuit's current to a voltage waveform that's displayed on the scope. The simplest current probes are inherently ac-coupled (they wrap a secondary winding around a magnetic split core that surrounds the one-turn wire "primary") and thus do not sense dc current; the fancier types use a combination of Hall effect and transformer coupling to achieve response down to dc. Examples of the latter are the Tektronix A622 (dc to 100 kHz) and the TCP312A (dc to 100 MHz); the latter requires the matching TCPA300 amplifier.

O.1.6 Grounds

As with most test instruments, the oscilloscope input is referred to the instrument ground (the outer connection of the input BNC connectors), which is usually tied electrically to the case. That, in turn, connects to the ground lead of the ac power line, via the 3-wire power cord. This means that you cannot measure voltages between the two arbitrary points in a circuit, but are forced to measure signals relative to this universal ground.

An important caution is in order here: if you try to connect the ground clip of an oscilloscope probe to a point in the circuit that is at some voltage relative to ground, you will end up shorting it to ground. This can have disastrous consequences to the circuit under test; in addition, it can be downright dangerous with circuits that are "hot to ground" (for example line-powered switching power supplies). If it is imperative to look at the signal between two points, you can make a differential measurement by inverting one input channel and switching to ADD, or you can use an external differential preamp (e.g., the LeCroy DA1855A). In desperate situations we have been known to "float" the scope by lifting the ground lead at the power cord, but this is *not recommended*, unless you really know what you're doing (and agree to waive any liability on our part).

Another caution about grounds when you're measuring weak signals or high frequencies: be sure the oscilloscope ground is the same as the circuit ground where you're measuring. The best way to do this is by connecting the short ground wire on the probe body directly to the circuit ground,[7] then checking by measuring the voltage of "ground" with the probe, observing no signal. One problem with this scheme is that those short ground clips are usually missing, lost! Keep your probe accessories in a drawer somewhere.

O.1.7 Other analog scope features

Many scopes have a **DELAYED SWEEP** that lets you see a segment of a waveform occurring some time after the trigger point. You can dial the delay accurately with a multiturn adjustment and a second sweep-speed switch. A delay

[6] One of our favorites is the Tektronix P6243, <1 pF and 1 GHz bandwidth.

[7] See the illustrations in Figure 12.32

mode known as **A INTENSIFIED BY B** lets you display the whole waveform at the first sweep speed, with the delayed segment brightened; this is handy during setup. Scopes with delayed sweep sometimes have "mixed sweep," in which the trace begins at one sweep speed, then switches to a second (usually faster) speed after the selected delay. Another option is to begin the delayed sweep either immediately after the selected delay or at the next trigger point after the delay; there are two sets of trigger controls, so the two trigger points can be set individually. (Don't confuse delayed sweep with "signal delay." All good analog scopes have a delay in the signal channel, so you can display the event that caused the trigger; it lets you look a little bit backward in time! See the photographs of the analog delay lines in Figures H.19 and H.21).

A common feature of analog scopes is a **TRIGGER HOLDOFF** control; it inhibits triggering for an adjustable interval after each sweep, and it is very useful when viewing complicated waveforms without the simple periodicity of, say, a sinewave. The usual case is a digital waveform with a complicated sequence of 1s and 0s, which won't generate a stable display otherwise (except by adjustment of the sweep-speed vernier, which means you don't get a calibrated sweep).

All scopes (analog and digital) include some **BANDWIDTH LIMIT** vertical amplifier options (for simplicity, not shown in Figures O.1 and O.2), useful for reducing the amount of wideband "fuzz" on the displayed trace when you're working with relatively slow signals.

During the height of the analog scope era, you could get scopes with on-screen "storage" (for single-shot capture) and scopes with an impressive array of plug-in modules that let you do lots of interesting stuff, including display of eight traces, or spectrum analysis, or accurate (digital) measurements of voltage and time on waveforms, and so on. Happily, these functions and many others (e.g., looking far backward in time from the triggering event) are now embodied in the dominant oscilloscope species, the *digital* oscilloscope. Let's take a look.

O.2 The digital oscilloscope

Analog scopes are easy to use, but they are seriously limiting in what you can do. For example, (a) it's hard to see a "single-shot" event; (b) you can't store a trace, or compare a live trace with an earlier trace; (c) you can't extract a trace for measurement or illustration; and (d) you can't look back in time to see what happened before the triggering event.

Digital scopes effortlessly provide these and many other capabilities; and, because of the stunning capability and low cost of digital conversion and processing, they are, ironically, less expensive than an analog scope (if you can find one) of comparable bandwidth. The transition to usable and friendly digital scopes was rocky at first, but they are now ubiquitous and universal.

The basic scheme (Figure O.4) is to digitize the incoming signal after the frontend stages of programmable gain and bandwidth limiting, capture the samples in a fast circular buffer memory, and then use a processor (or multiple processors) to do all the signal processing, measurements, conversion to a meaningful display, user interface, and I/O. We'll keep this section brief, and merely run through some capabilities of digital scopes.

O.2.1 What's different?

In no particular order:

Front-end: The signal emerging from the (variable-gain) input amplifiers is digitized at some sampling rate f_{samp} (typically 1 Gsps or more, but always above the minimum Nyquist rate of $2f_{max}$ when the scope is set at fast enough sweep rates to resolve the scope's bandwidth f_{max}. But – **important** – see "aliasing," below). The digital samples, typically of 8 bits resolution, are stored at full speed into a *sample memory* (or "capture memory"), often of length 1 Mpt or more per channel (and reaching 1 Gpt at the high end). Note that, even though digital scopes let you zoom in after a trace is captured, the resolution depends on the vertical scale factor, because of the fixed bit depth of conversion.

Simultaneous on all channels: Digital scopes digitize all channels simultaneously; there's no "alternate" or "chop." Most digital scopes come in 2- or 4-channel flavors, augmented in "mixed-signal" scopes by sixteen or more 1-bit (i.e., logic-level) channels.

Pre-trigger: Because digitized input signals are pouring into memory, you can set a trigger condition (most simply, level and slope; but see "Smart trigger," below) and, when it is satisfied, you've got substantial pre-history in the sample memory. From the user's point of view, you can simply set the displayed trigger pointer to the right portion of the screen to reveal what came before. And you can walk backward or forward to your heart's content through a saved single-shot capture (see "Single-shot capture," below).

Display: The time interval between points on the *displayed* waveform (the "waveform interval") is typically longer (often much longer) than the sampling interval

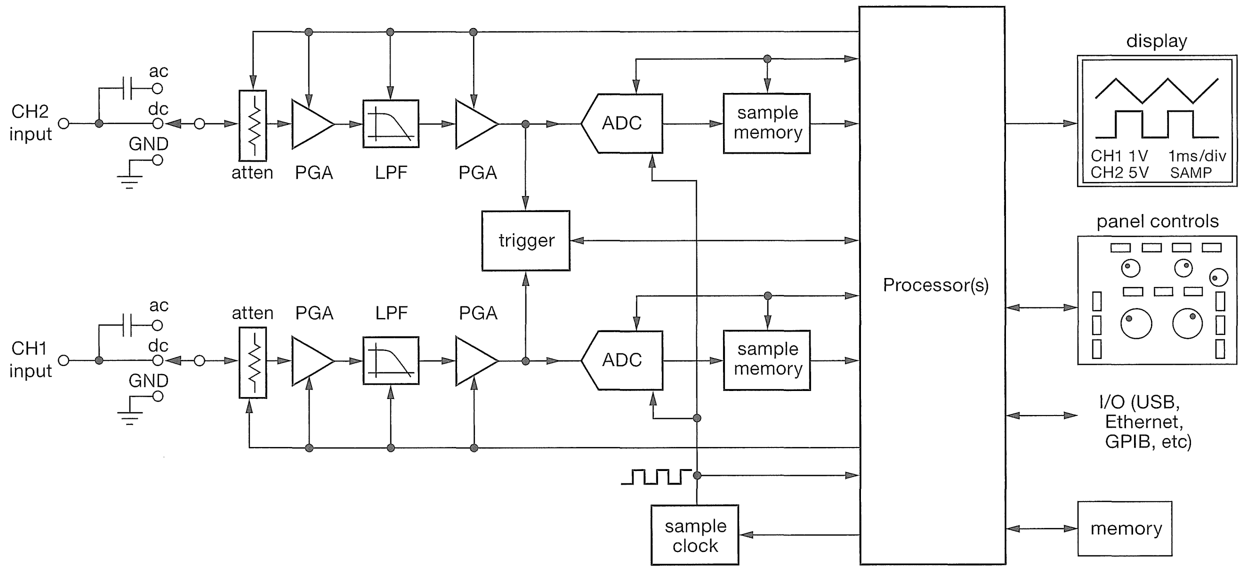

Figure O.4. Block diagram of a 2-channel digital oscilloscope.

$1/f_{\text{samp}}$. This allows for various modes of processing the sampled points to produce the displayed waveform, in particular:

sample one sample point per waveform interval is displayed; the rest are discarded. Simple, but susceptible to aliasing, see below.

peak detect the highest and lowest sampled points in two successive waveform intervals are displayed. Produces a thicker waveform, but no short spikes are lost.

envelope similar to peak detect, but combines min/max from multiple triggered acquisitions. Useful for seeing excursions from an ideal repetitive waveform.

average each point in the displayed waveform is the calculated average of single samples (as in sample mode) over many (a settable number, e.g, 2, 4, 8, ...512) triggered acquisitions. Greatly reduces noise, without reducing bandwidth, but requires a repetitive signal.

high resolution each displayed point is calculated as the average value of the multiple samples captured within one waveform interval. Provides higher resolution, and does not require a repetitive signal, but reduces bandwidth.[8]

[8] You can think of this as a "horizontal average" along one waveform capture, as compared with the "vertical averaging" of single sample points in successive stacked waveforms in *average* mode.

Persistence: Engineers with gray beards wax poetic about the beautiful gradations of intensity with which analog scopes display waveforms. Digital scopes took a while to catch up, but now they trumpet their ability to do the same, with terms like "digital phosphor," "persistence trace," and "digital persistence."

Single-shot capture: Digital scopes excel in single-shot capture. You can troll through the sampled data post-capture, either manually (by turning knobs for scrolling and magnifying) or with some helpful automated search tools (e.g., Tektronix's "Wave Inspector" – the name says it all).

Slow sweep: Analog scopes are hopeless when you want to view a waveform that takes many seconds; digital scopes couldn't care less. Use "rolling mode" at slow sweep rates.

Save/Recall: You can save one or more waveforms to memory, bring them back for comparison, etc. You can also save the scope's *state* (i.e., settings).

Measurements: The data's all there, so digital scopes have no problem measuring period, frequency, amplitude, time interval, duty cycle, etc. These measurements usually update continuously, and you can use settable horizontal and vertical cursors to define the measurement regions and intervals.

Math: Going further, digital scopes let you calculate products (e.g., to measure power from voltage and current), quotients (to normalize a waveform), jitter, histograms, frequency spectra, etc. Almost limitless possibilities, but you may prefer to extract the data and do the math offline.

I/O: You can send waveforms and data out (via connected Ethernet or whatever), and you can control the scope's operations remotely. A networked data-acquisition system!

Mixed-signal: Many digital scopes come with a bunch of 2-level channels (typically 16 or 32) along with the usual 2 or 4 full-resolution channels; so it works as a logic analyzer, but augmented by a few channels of clear waveform view. As with a traditional logic analyzer, you can trigger on a defined set of levels, and it can do bus decoding, bus triggering, and other fancy stuff for you.

Smart trigger: Good digital scopes let you trigger on just about any condition you can imagine: pulse width $<$, $>$, $=$, or $\neq$ to some value; runt pulses and glitches; setup or hold time violations; specified range of rise-times or falltimes; specified conditions or violations on serial buses; trigger after n events; and so on. (check-out the enjoyable reading in a datasheet from Tektronix, LeCroy, Keysight/Agilent, or Rohde & Schwarz)

Limit/Mask testing: You can set up a template and detect out-of-spec waveforms, for Go/No-Go testing on a production line; ditto for jitter and other measurable parameters.

Autoset: It's easy to get lost in this multi-dimensional wilderness; digital scopes provide a rescue button (autoset, autoscale, or some linguistic variant, depending on manufacturer), which will at least get something going on the screen (but see the Cautions, next).

Probe skew: When you're using several different probing systems (e.g., passive 10× probe, active FET probe, current probe) the signal delays can vary by tens of nanoseconds or more, completely disrupting the fidelity of the multichannel display (hey, you may be tricked into thinking you've got a violation of causality – effect precedes cause![9]).

Probe readout, Probe power: Probes for use with contemporary digital scopes have extra connections by which they communicate their attenuation factor (×1, ×10, ×100) and other useful scale factor information (e.g., the amps/div of a current probe); they use such connections also to send power to the probe (needed, for example, with FET active voltage probes or Hall-effect current probes). This can be an annoyance, though, if your scope's input connectors are of the wrong format (which happens even within one manufacturer's scope offerings).

O.2.2 Some cautions

There's not much not-to-like about digital oscilloscopes. But here are a few cautions, ways in which a digital scope can trick the unwary.

A. Aliasing

This one can fool even the experienced scope user: digital scopes are designed such that the *maximum* sample rate is always adequate for signals up to the scope's full bandwidth; but when you are running at a slower sweep rate in "sample" mode (i.e., one sample per displayed waveform point) the effective sample rate is much lower. So you may see some serious nonsense (jittery unstable signal, inability to trigger, weird change of waveform when sweep rate is changed, etc.) if there's a high frequency signal present.[10]

If you suspect aliasing, try speeding up the sweep, or changing to **PEAK DETECT** mode. Aliasing can be really annoying when you're dealing with signals that combine timescales (the classic one was analog television, with a 3.59 MHz color carrier on a ~15 kHz horizontal line frequency).

B. Dead time

For human visual perception it's necessary to update the scope display at only ~100 times per second or so. If the scope captures input waveform data only at that rate, the fraction of time that it's sensitive to important signal events (like a glitch or timing violation) may be exceedingly low. For example, at a middling sweep rate of 1 μs/div (thus 10 μs per sweep) a scope that's updating 100 times/second is active only 0.1% of the time.

When scope users became aware of this ugly secret, scope manufacturers went at it, and they now provide some measure of true update rate (usually in the form of "waveforms per second," typically in the range of 100,000–1,000,000). Be careful when evaluating such metrics, because there's more than a little "specsmanship" going on.[11]

[9] As does the protagonist in Asimov's delightful short story from 1960: *Thiotimoline and the Space Age*.

[10] Dare we admit? One of the authors was testing a circuit that operates at frequencies in the kilohertz range, driving it with a digital function generator at 1.0 kHz. Go out to lunch, come back, look at the waveform – the scope is broken, won't trigger, jittery waveform sliding left and right. Weird. Tried everything. Then noticed that the generator had defaulted to its 1.0 *mega*hertz setting. Ha! Problem solved (and I won't ever tell anyone how dumb I was).

[11] Ask your scope salesperson, they love to flame the lying competition.

C. Lost in a multidimensional vector space

Analog scopes are simple, and you can see the full state of the instrument just by looking at the knobs and indicators. No such luck with the immense capabilities of digital scopes. Early digital scopes were particularly troublesome, lacking annunciators and (mostly) knobs. They've improved enormously,[12] but it's still awfully easy to be sitting in front of a scope that just isn't triggering, or showing significant vital signs. It takes some keen intuition to know which menu to pull down (horizontal? trigger? mode?) to get to the problem. It may be as simple as triggering on the wrong channel; or it might be that you've left the display in **AVERAGING** mode, and lack of a stable repetitive trigger produces a bunch of garbage. And you can even waste a minute not realizing that the thing is in **SINGLE-SWEEP** or **STOP** mode.

[12] We are particularly fond of the "QuickMenu" feature that was introduced by Tektronix in their original TDS3000-series "lunchbox" scopes. Inexplicably, this highly useful feature has been eliminated (despite our howls of protest) in Tek's successor scopes. We've been badgering them ever since.

D. The scope is lying to you

When observing signals with a digital scope, you may be victimized by a blessing (a vast array of measurement capabilities and settings) that becomes a curse (the scope's settings are not what you think). It's easy to forget some obscure but important settings that falsify the measurements you think you're making. For example, it's easy to forget (we've done it, often) that you've left an earlier **PROBE SKEW** compensation in effect, or that some channels still have **BANDWIDTH LIMIT** set. Such oversights corrupt your measurements in less-than-obvious ways that you may not notice for quite a while; and when you do, you're sentenced to serve time repeating the measurements properly.