CHAPTER 1

Basic Electronics

Jack Ganssle

DC Circuits

"DC" means *Direct Current*, a fancy term for signals that don't change. Flat lined, like a corpse's EEG or the output from a battery. Your PC's power supply makes DC out of the building's AC (alternating current) mains. All digital circuits require DC power supplies.

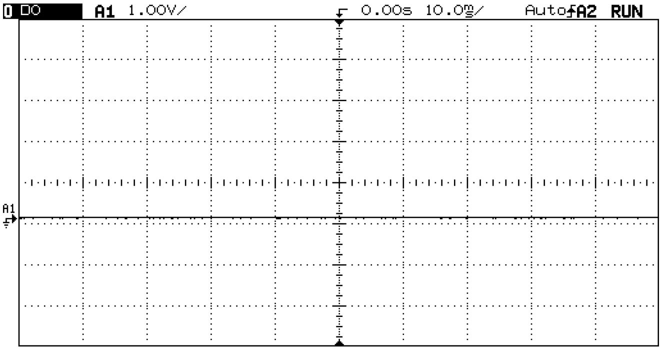


Figure 1-1: A DC signal has a constant, unvarying amplitude.

Voltage and Current

We measure the quantity of electricity using voltage and amperage, but both arise from more fundamental physics. Atoms that have a shortage or surplus of electrons are called *ions*. An ion has a positive or negative charge. Two ions of opposite polarity (one plus, meaning it's missing electrons and the other negative, with one or more extra electrons) attract each other. This attractive force is called the *electromotive force*, commonly known as EMF.

Charge is measured in coulombs, where one coulomb is 6.25×10^{18} electrons (for negative charges) or protons for positive ones.

An ampere is one coulomb flowing past a point for one second. Voltage is the force between two points for which one ampere of current will do one joule of work, a joule per second being one watt.

But few electrical engineers remember these definitions and none actually use them.

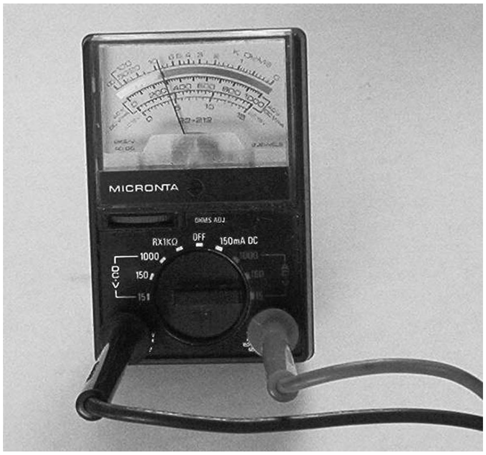


Figure 1-2: A VOM, even an old-fashioned analog model like this $10 Radio Shack model, measures DC voltage as well or better than a scope.

An old but still apt analogy uses water flow through a pipe: current would be the amount of water flowing through a pipe per unit time, while voltage is the pressure of the water.

The unit of current is the ampere (amp), though in computers an amp is an awful lot of current. Most digital and analog circuits require much less. Here are the most common nomenclatures:

Name	**Abbreviation**	**# of amps**	**Where likely found**
amp	A	1	Power supplies. Very high performance processors may draw many tens of amps.
milliamp	mA	.001 amp	Logic circuits, processors (tens or hundreds of mA), generic analog circuits.
microamp	µA	10^{-6} amp	Low power logic, low power analog, battery backed RAM.
picoamp	pA	10^{-12} amp	Very sensitive analog inputs.
femtoamp	fA	10^{-15} amp	The cutting edge of low power analog measurements.

Most embedded systems have a far less extreme range of voltages. Typical logic and microprocessor power supplies range from a volt or two to five volts. Analog power supplies rarely exceed plus and minus 15 volts. Some analog signals from sensors might go down to the millivolt (.001 volt) range. Radio receivers can detect microvolt-level signals, but do this using quite sophisticated noise-rejection techniques.

Resistors

As electrons travel through wires, components, or accidentally through a poor soul's body, they encounter *resistance*, which is the tendency of the conductor to limit electron flow. A vacuum is a perfect resistor: no current flows through it. Air's pretty close, but since water is a decent conductor, humidity does allow some electricity to flow in air.

Superconductors are the only materials with zero resistance, a feat achieved through the magic of quantum mechanics at extremely low temperatures, on the order of that of liquid nitrogen and colder. Everything else exhibits some resistance, even the very best wires. Feel the power cord of your 1500 watt ceramic heater—it's warm, indicating some power is lost in the cord due to the wire's resistance.

We measure resistance in ohms; the more ohms, the poorer the conductor. The Greek capital omega (Ω) is the symbol denoting ohms.

Resistance, voltage, and amperage are all related by the most important of all formulas in electrical engineering. Ohm's Law states:

$$E = I \times R$$

where E is voltage in volts, I is current in amps, and R is resistance in ohms. (EEs like to use "E" for volts as it indicates electromotive force).

What does this mean in practice? Feed one amp of current through a one-ohm load and there will be one volt developed across the load. Double the voltage and, if resistance stays the same, the current doubles.

Though all electronic components have resistance, a *resistor* is a device specifically made to reduce conductivity. We use them everywhere. The volume control on a stereo (at least, the non-digital ones) is a resistor whose value changes as you rotate the knob; more resistance reduces the signal and hence the speaker output.

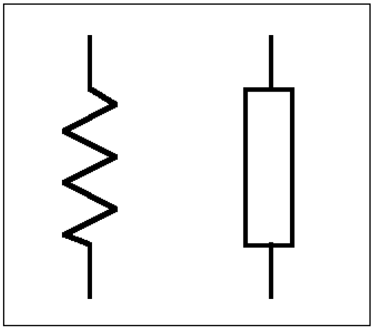


Figure 1-3: The squiggly thing on the left is the standard symbol used by engineers to denote a resistor on their schematics. On the right is the symbol used by engineers in the United Kingdom. As Churchill said, we are two peoples divided by a common language.

Name	Abbreviation	ohms	Where likely found
milliohm	m Ω	.001 ohm	Resistance of wires and other good conductors.
ohm	Ω	1 ohm	Power supplies may have big dropping resistors in the few to tens of ohms range.
hundreds of ohms			In embedded systems it's common to find resistors in the few hundred ohm range used to terminate high speed signals.
kiloohm	k Ω or just k	1000 ohms	Resistors from a half-k to a hundred or more k are found all over every sort of electronic device. "Pullups" are typically a few k to tens of k.
megaohm	M Ω	10^6 ohms	Low signal-level analog circuits.
hundreds of M Ω		10^8++ ohms	Geiger counters and other extremely sensitive apps; rarely seen as resistors of this size are close to the resistance of air.

Table 1-1: Range of values for real-world resistors.

What happens when you connect resistors together? For resistors in series, the total effective resistance is the sum of the values:

$$R_{\mathrm{eff}} = R_1 + R_2$$

For two resistors in parallel, the effective resistance is:

$$R_{\mathrm{eff}} = \frac{R_1 \times R_2}{R_1 + R_2}$$

(Thus, two identical resistors in parallel are effectively half the resistance of either of them: two 1ks is 500 ohms. Now add a third: that's essentially a 500-ohm resistor in parallel with a 1k, for an effective total of 333 ohms).

The general formula for more than two resistors in parallel is:

$$R_{\mathrm{eff}} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + \ldots}$$

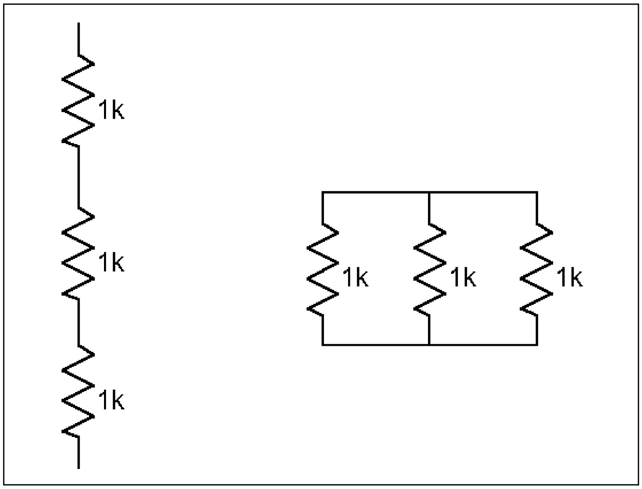


Figure 1-4: The three series resistors on the left are equivalent to a single 3000-ohm part. The three paralleled on the right work out to one 333-ohm device.

Manufacturers use color codes to denote the value of a particular resistor. While at first this may seem unnecessarily arcane, in practice it makes quite a bit of sense. Regardless of orientation, no matter how it is installed on a circuit board, the part's color bands are always visible.

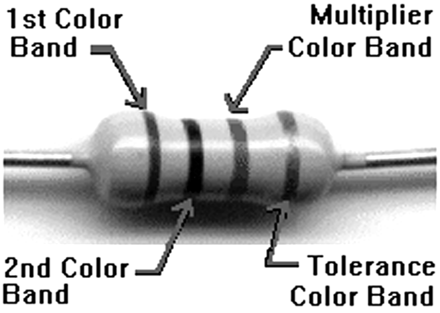


Figure 1-5: This black and white photo masks the resistor's color bands. However, we read them from left to right, the first two designating the integer part of the value, the third band giving the multiplier. A fourth gold (5%) or silver (10%) band indicates the part's tolerance.

Color Band	Value	Multiplier
Black	0	1
Brown	1	10
Red	2	100
Orange	3	1000
Yellow	4	10,000
Green	5	100,000
Blue	6	1,000,000
Violet	7	not used
Gray	8	not used
White	9	not used
Gold (3rd band)		÷10
Silver (3rd band)		÷100

Table 1-2: The resistor color code. Various mnemonic devices designed to help one remember these are no longer politically correct; one acceptable but less memorable alternative is Big Brown Rabbits Often Yield Great Big Vocal Groans When Gingerly Slapped.

The first two bands, reading from the left, give the integer part of the resistor's value. The third is the multiplier. Read the first two band's numerical values and multiply by the scale designated by the third band. For instance: brown black red = 1 (brown) 0 (black) times 100 (red), or 1000 ohms, more commonly referred to as 1k. The following table has more examples.

First band	Second band	Third band	Calculation	Value (ohms)	Commonly called
brown	red	orange	12 x 1000	12,000	12k
red	red	red	22 x 100	2,200	2.2k
orange	orange	yellow	33 x 10,000	330,000	330k
green	blue	red	56 x 100	5,600	5.6k
green	blue	green	56 x 100,000	5,600,000	5.6M
red	red	black	22 x 1	22	22
brown	black	gold	10 ÷10	1	1
blue	gray	red	68 x 100	6,800	6.8k

Table 1-3: Examples showing how to read color bands and compute resistance.

Resistors come in standard values. Novice designers specify parts that do not exist; the experienced engineer knows that, for instance, there's no such thing as a 1.9k resistor. Engineering is a very practical art; one important trait of the good designer is using standard and easily available parts.

Circuits

Electricity always flows in a loop. A battery left disconnected discharges only very slowly since there's no loop, no connection of any sort (other than the non-zero resistance of humid air) between the two terminals. To make a lamp light, connect one lead to each battery terminal; electrons can now run in a loop from the battery's negative terminal, through the lamp, and back into the battery.

There are only two types of circuits: series and parallel. All real designs use combinations of these. A *series circuit* connects loads in a circular string; current flows around through each load in sequence. In a series circuit the current is the same in every load.

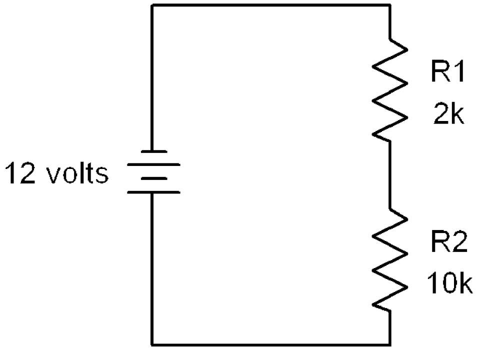


Figure 1-6: In a series circuit the electrons flow through one load and then into another. The current in each resistor is the same; the voltage dropped across each depends on the resistor's value.

It's easy to calculate any parameter of a series circuit. In the diagram above a 12-volt battery powers two series resistors. Ohm's Law tells us that the current flowing through the circuit is the voltage (12 in this case) divided by the resistance (the sum of the two resistors, or 12k). Total current is thus:

$I = V \div R = (12\ volts) \div (2000 + 10{,}000\ ohms) = 12 \div 12000 = 0.001\ amp = 1\ mA$ (remember that *mA* is the abbreviation for milliamps).

So what's the voltage across either of the resistors? In a series circuit the current is identical in all loads, but the voltage developed across each load is a function of the load's resistance and the current. Again, Ohm's Law holds the secret. The voltage across R1 is the current in the resistor times its resistance, or:

$$V_{R1} = I_{R1} = 0.001\ amps \times 2000\ ohms = 2\ volts$$

Since the battery places 12 volts across the entire resistor string, the voltage dropped on R2 must be 12 – 2, or 10 volts. Don't believe that? Use Mr. Ohm's wonderful equation on R2 to find:

$$V_{R2} = I_{R2} = 0.001\ amps \times 10{,}000\ ohms = 10\ volts$$

It's easy to extend this to any number of parts wired in series.

Parallel circuits have components wired so both pins connect. Current flows through both parts, though the amount of current depends on the resistance of each leg of the circuit. The voltage, though, on each component is identical.

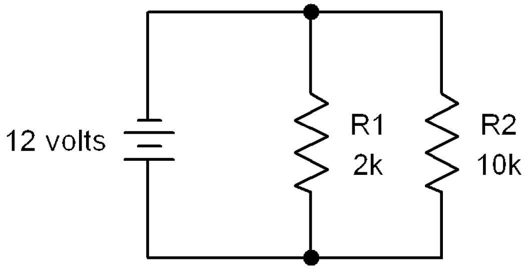


Figure 1-7: R1 and R2 are in parallel, both driven by the 12 volt battery.

We can compute the current in each leg much as we did for the series circuit. In the case above the battery applies 12 volts to both resistors. The current through R1 is:

$$I_{R1} = 12 \ \mathit{volts} \div 2{,}000 \ \mathit{ohms} = 12 \div 2000 = 0.006 \ \mathit{amps} = 6 \ \mathit{mA}$$

Through R2:

$$I_{R2} = 12 \ \mathit{volts} \div 10{,}000 \ \mathit{ohms} = 0.0012 \ \mathit{amps} = 1.2 \ \mathit{mA}$$

Real circuits are usually a combination of series and parallel elements. Even in these more complex, more realistic cases it's still very simple to compute anything one wants to know.

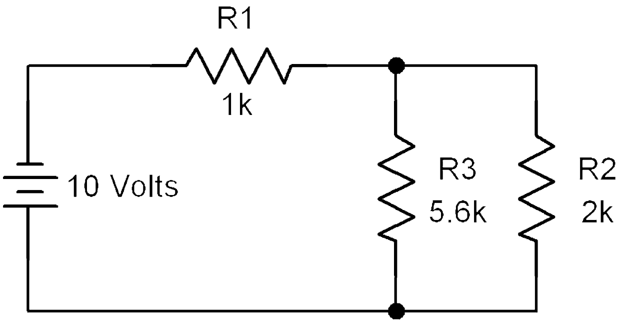


Figure 1-8: A series/parallel circuit.

Let's analyze the circuit shown above. There's only one trick: cleverly combine complicated elements into simpler ones. Let's start by figuring the current flowing out of the battery. It's much too hard to do this calculation till we remember that two resistors in parallel look like a single resistor with a lower value.

Start by figuring the current flowing out of the battery and through R1. We can turn this into a series circuit (in which the current flowing is the same through all of the components) by replacing R3 and R2 by a single resistor with the same effective value as these two paralleled components. That's:

$$R_{EFF} = \frac{R2 \times R3}{R1 + R3} = \frac{5600 \times 2000}{5600 + 2000} = 1474\ ohms$$

So the circuit is identical to one with two series resistors: R1, still 1k, and R_{EFF} at 1474 ohms. Ohm's Law gives the current flowing out of the battery and through these two resistors:

$$i = \frac{V}{R1 + R_{EFF}} = \frac{10}{1000 + 1474} = 0.004\ \ amps = 4\ \ mA$$

Ohm's Law remains the font of all wisdom in basic circuit analysis, and readily tells us the voltage dropped across R1:

$$V = iR1 = 0.004\ amps \times 1000\ ohms = 4\ volts$$

Clearly, since the battery provides 10 volts, the voltage across the paralleled pair R2 and R3 is 6 volts.

Power

Power is the product of voltage and current and is expressed in watts. One watt is one volt times one amp. A milliwatt is a thousandth of a watt; a microwatt a millionth.

You can think of power as the total amount of electricity present. A thousand volts sounds like a lot of electricity, but if there's only a microamp available that's a paltry milliwatt—not much power at all.

Power is also current^2 times resistance:

$$\mathrm{P} = I^2 \times R$$

Electronic components like resistors and ICs consume a certain amount of volts and amps. An IC doesn't move, make noise, or otherwise release energy (other than exerting a minimal amount of energy in sending signals to other connected devices), so almost all of the energy consumed gets converted to heat. All components have maximum power dissipation ratings; exceed these at your peril.

If a part feels warm it's dissipating a reasonable fraction of a watt. If it's hot but you can keep your finger on it, then it's probably operating within specs, though many analog components want to run cooler. If you pull back, not burned but the heat is too much for your finger, then in most cases (be wary of the wimp factor; some people are more heat sensitive than others) the device is too hot and either needs external cooling (heat sink, fan, etc.), has failed, or your circuit exceeds heat parameters. A burn or near burn, or discoloration of the device, means there's trouble brewing in all but exceptional conditions (e.g., high energy parts like power resistors).

A PC's processor has so many transistors, each losing a bit of heat, that the entire part might consume and eliminate 100+ watts. That's far more than the power required to destroy the chip. Designers expend a huge effort in building heat sinks and fans to transfer the energy in the part to the air.

The role of heat sinks and fans is to remove the heat from the circuits and dump it into the air before the devices burn up. The fact that a part dissipates a lot of energy and wants to run hot is not bad as long as proper thermal design removes the energy from the device before it exceeds its max temp rating.

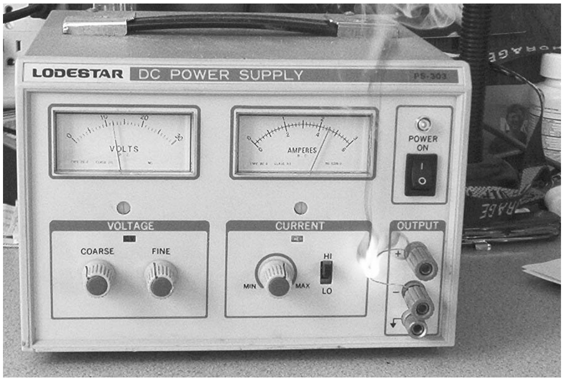


Figure 1-9: This 10-ohm resistor, with 12 volts applied, draws 833 mA. $P = I^2R$, so it's sucking about 7 watts. Unfortunately, this particular part is rated for ¼ watt max, so is on fire. Few recent college grads have a visceral feel for current, power and heat, so this demo makes their eyes go like saucers.

AC Circuits

AC is short for *alternating current*, which is any signal that's not DC. AC signals vary with time. The mains in your house supply AC electricity in the shape of a sine wave: the voltage varies from a large negative to a large positive voltage 60 times per second (in the USA and Japan) or 50 times (in most of the rest of the world).

AC signals can be either *periodic*, which means they endlessly and boringly repeat forever, or *aperiodic*, the opposite. Static from your FM radio is largely aperiodic as it's quite random. The bit stream on any address or data line from a micro is mostly aperiodic, at least over short times, as it's a complex changing pattern driven by the software.

The rate at which a periodic AC signal varies is called its *frequency*, which is measured in *hertz* (Hz for short). One Hz means the waveform repeats once per second. 1000 Hz is a kHz (kilohertz), a million Hz is the famous MHz by which so many microprocessor clock rates are defined, and a billion Hz is a GHz.

The reciprocal of Hz is *period*. That is, where the frequency in hertz defines the signal's repetition rate, the period is the time it takes for the signal to go through a cycle. Mathematically:

$$\text{Period in seconds} = 1 \div \text{frequency in Hz}$$

Thus, a processor running at 1 GHz has a clock period of 1 nanosecond—one billionth of a second. No kidding. In that brief flash of time even light goes but a bare foot. Though your 1.8 GHz PC may seem slow loading Word®, it's cranking instructions at a mind-boggling rate.

Wavelength relates a signal's period—and thus its frequency—to a physical "size." It's the distance between repeating elements, and is given by:

$$\text{Wavelength in meters} = \frac{c}{\mathit{frequency}} = \frac{300{,}000{,}000\ \mathit{meters / second}}{\mathit{frequency\ in\ Hz}}$$

where *c* is the speed of light.

An FM radio station at about 100 MHz has a wavelength of 3 meters. AM signals, on the other hand, are around 1 MHz so each sine wave is 300 meters long. A 2.4-GHz cordless phone runs at a wavelength a bit over 10 cm.

As the frequency of an AC signal increases, things get weird. The basic ideas of DC circuits still hold, but need to be extended considerably. Just as relativity builds on Newtonian mechanics to describe fast-moving systems, electronics needs new concepts to properly describe fast AC circuits.

Resistance, in particular, is really a subset of the real nature of electronic circuits. It turns out there are three basic kinds of resistive components; each behaves somewhat differently. We've already looked at resistors; the other two components are capacitors and inductors. Both of these parts exhibit a kind of resistance that varies depending on the frequency of the applied signal; the amount of this "AC resistance" is called reactance.

Capacitors

A capacitor, colloquially called the "cap," is essentially two metal plates separated from each other by a thin insulating material. This insulation, of course, means that a DC signal cannot flow through the cap. It's like an open circuit.

But in the AC world strange things happen. It turns out that AC signals can make it across the gap between the two plates; as the frequency increases the effective resistance of this gap decreases. This resistive effect is called *reactance*; for a capacitor it's termed *capacitive reactance*. There's a formula for everything in electronics; for capacitive reactance it's:

$$X_c = \frac{1}{2\pi fc}$$

where:

X_c = capacitive reactance

f = frequency in Hz

c = capacitance in farads

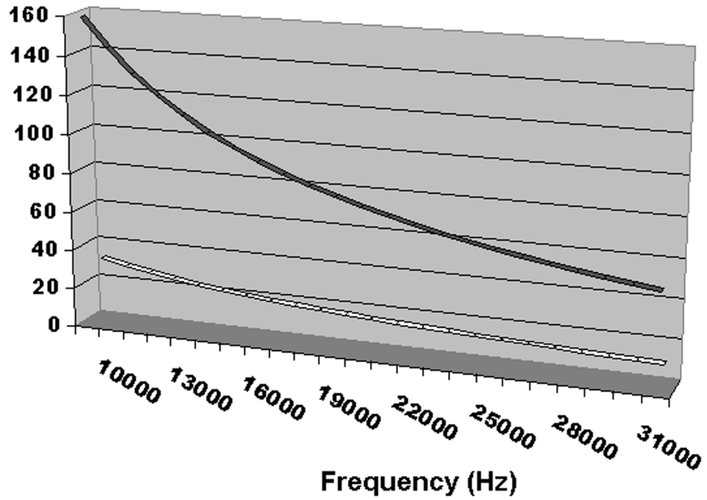


Figure 1-10: Capacitive reactance of a 0.1 µF cap (top) and a 0.5 µF cap (bottom curve). The vertical axis is reactance in ohms. See how larger caps have lower reactances, and as the frequency increases reactance decreases. In other words, a bigger cap passes AC better than a smaller one, and at higher frequencies all caps pass more AC current. Not shown: at 0 Hz (DC), reactance of all caps is essentially infinite.

Capacitors thus pass only *changing* signals. The current flowing through a cap is:

$$I = \frac{dV}{dt}$$

(If your calculus is rusty or nonexistent, this simply means that the current flow is proportional to the change in voltage over time.)

In other words, the faster the signal changes, the more current flows.

Name	Abbreviation	farads	Where likely found
picofarad	pF	10^{-12} farad	Padding caps on microprocessor crystals, oscillators, analog feedback loops.
microfarad	µF	10^{-6} farad	Decoupling caps on chips are about .01 to .1µF. Low freq decoupling runs about 10µF, big power supply caps might be 1000µF.
farad	F	1 farad	One farad is a huge capacitor and generally does not exist. A few vendors sell "supercaps" that have values up to a few farads but these are unusual. Sometimes used to supply backup power to RAMs when the system is turned off.

Table 1-4: Range of values for real-world capacitors.

In real life there's no such thing as a perfect capacitor. All leak a certain amount of DC and exhibit other more complex behavior. For that reason, there's quite a range of different types of parts.

In most embedded systems you'll see one of two types of capacitors. The first are the polarized ones, devices which have a plus and a minus terminal. Connect one backwards and the part will likely explode!

Polarized devices have large capacitance values: tens to thousands of microfarads. They're most often used in power supplies to remove the AC component from filtered signals. Consider the equation of capacitive reactance: large cap values pass lower frequency signals efficiently. Typical construction today is from a material called "tantalum"; seasoned EEs often call these devices "tantalums." You'll see tantalum caps on PC boards to provide a bit of bulk storage of the power supply.

Smaller caps are made from a variety of materials. These have values from a few picofarads to a fraction of a microfarad. Often used to "decouple" the power supply on a PCB (i.e., to short high frequency switching from power to ground, so the logic signals don't get coupled into the power supply). Most PCBs have dozens or hundreds of these parts scattered around.

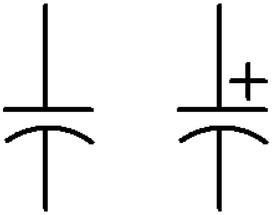


Figure 1-11: Schematic symbols for capacitors. The one on the left is a generic, generally low-valued (under 1 µF) part. On the right the plus sign shows the cap is polarized. Installed backwards, it's likely to explode.

We can wire capacitors in series and in parallel; compute the total effective capacitance using the rules opposite those for resistors. So, for two caps in parallel sum their values to get the effective capacitance. In a series configuration the total effective capacitance is:

$$C_{eff} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \ldots}$$

Note that this rule is for figuring the total capacitance of the circuit, and *not* for computing the total reactance. More on that shortly.

One useful characteristic of a capacitor is that it can store a charge. Connect one to a battery or power supply and it will store that voltage. Remove the battery and (for a perfect, lossless part) the capacitor will still hold that voltage. Real parts leak a bit; ones rated at under 1 µF or so discharge rapidly. Larger parts store the charge longer.

Interesting things happen when wiring a cap and a resistor in series. The resistor limits current to the capacitor, causing it to charge slowly. Suppose the circuit shown in the following diagram is dead, no voltage at all applied. Now turn on the switch. Though we've applied a DC signal, the sudden transition from 0 to 5 volts is AC.

Current flows due to the $I = \frac{dV}{dt}$ rule; dV is the sudden edge from flipping the switch. But the input goes from an AC-edge to steady-state DC, so current stops flowing pretty quickly. How fast? That's defined by the circuit's *time constant***.**

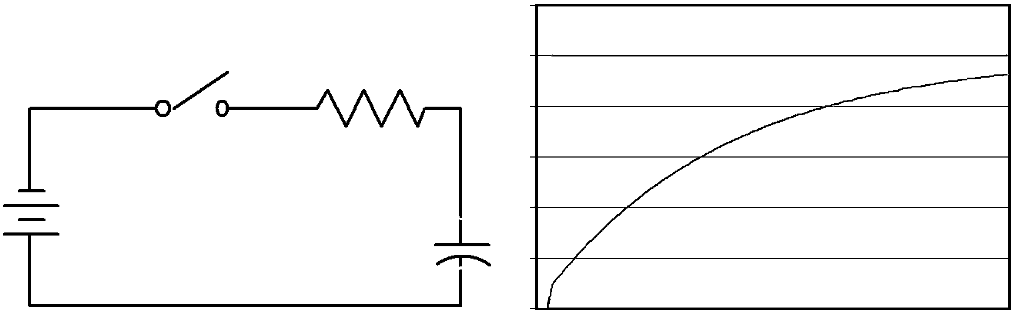


Figure 1-12: Close the switch and the voltage applied to the RC circuit looks like the top curve. The lower graph shows how the capacitor's voltage builds slowly with time, headed asymptotically towards the upper curve.

A resistor and capacitor in series is colloquially called an RC circuit. The graph shows how the voltage across the capacitor increases over time. The time constant of any circuit is pretty well approximated by:

$$t = RC$$

for *R* in ohms, *C* in farads, and *t* in seconds.

This formula tells us that after *RC* seconds the capacitor will be charged to 63.2% of the battery's voltage. After another *RC* seconds another 63.2%, for a total now of 86.5%.

Analog circuits use a lot of RC circuits; in a microprocessor it's still common to see them controlling the CPU's reset input. Apply power to the system and all of the logic comes up, but the RC's time constant keeps reset asserted low for a while, giving the processor time to initialize itself.

The most common use of capacitors in the digital portion of an embedded system is to *decouple* the logic chips' power pins. A medium value part (0.01 to 0.1 µF) is tied between power and ground very close to the power leads on nearly every digital chip. The goal is to keep power supplied to the chips as clean as possible—close to a perfect DC signal.

Why would this be an issue? After all, the system's power supply provides a nearly perfect DC level. It turns out that as a fast logic chip switches between zero and one it can draw immense amounts of power for a short, sub-nanosecond, time. The power supply cannot respond quickly enough to regulate that, and since there's some resistance and reactance between the supply and the chip's pins, what the supply provides and what the chip sees is somewhat different. The decoupling capacitor shorts this very high frequency (i.e., short transient) signal on Vcc to ground. It also provides a tiny bit of localized power storage that helps overcome the instantaneous voltage drop between the power supply and the chip.

Most designs also include a few tantalum bulk storage devices scattered around the PC board, also connected between Vcc and ground. Typically these are 10 to 50 µf each. They are even more effective bulk storage parts to help minimize the voltage drop chips would otherwise see.

You'll often see very small caps (on the order of 20 pF) connected to microprocessor drive crystals. These help the device oscillate reliably.

Analog circuits make many wonderful and complex uses of caps. It's easy to build integrators and differentiators from these parts, as well as analog hold circuits that memorize a signal for a short period of time. Common values in these sorts of applications range from 100 pF to fractions of a microfarad.

Inductors

An inductor is, in a sense, the opposite of a capacitor. Caps block DC but offer diminishing resistance (really, reactance) to AC signals as the frequency increases. An inductor, on the other hand, passes DC with zero resistance (for an idealized part), but the resistance (reactance) increases proportionately to the frequency.

Physically an inductor is a coil of wire, and is often referred to as a *coil.* A simple straight wire exhibits essentially no inductance. Wrap a wire in a loop and it's less friendly to AC signals. Add more loops, or make them smaller, or put a bit of ferrous metal in the loop, and inductance increases. Electromagnets are inductors, as is the field winding in an alternator or motor.

An *iron core* inductor is wound around a slug of metal, which increases the device's inductance substantially.

Inductance is measured in henries (H). *Inductive reactance* is the tendency of an inductor to block AC, and is given by:

$$X_L = 2\pi L f$$

where:

X_L = Inductive reactance

f = frequency in Hz

L = inductance in henries

Clearly, as the frequency goes to zero (DC), reactance does as well.

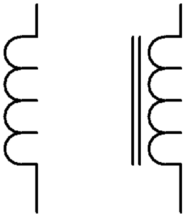


Figure 1-13: Schematic symbols of two inductors. The one on the left is an "air core"; that on the right an "iron core."

Inductors follow the resistor rules for parallel and series combinations: add the value (in henries) when in series, and use the division rule when in parallel.

Inductors are much less common in embedded systems than are capacitors, yet they are occasionally important. The most common use is in switching power supplies. Many datacomm circuits use small inductors (generally millihenries) to match the network being driven.

Power supplies usually have a *transformer* which reduces the AC mains (from the wall) to a lower voltage more appropriate for embedded systems.

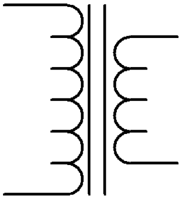


Figure 1-14: The schematic symbol for a transformer.

Transformers are two inductors wrapped around each other, with an iron core. The input AC generates a changing magnetic field, which induces a voltage in the output ("secondary") inductor.

If both inductors have the same number of wire loops, the output voltage is the same as the input. If the secondary has fewer loops, the voltage is less.

Sometimes signals, especially those flowing off a PC board, will have a *ferrite bead* wrapped around the wire. These beads are small cylinders (a few mm long) made of a ferromagnetic material. Like all inductors they help block AC so are used to minimize noise of signal wires.

Active Devices

Resistors, capacitors and inductors are the basic *passive* components, passive meaning "dumb." The parts can't amplify or dramatically change applied signals. By contrast, *active* parts can clip, amplify, distort and otherwise change an applied signal.

The earliest active parts were vacuum *tubes*, called “valves” in the UK.

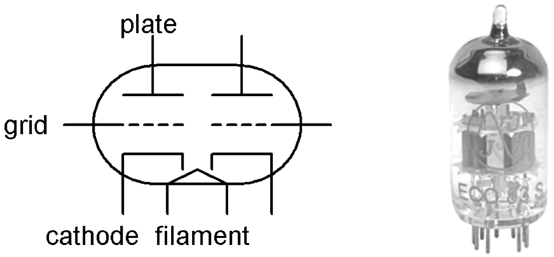


Figure 1-15: On the left, a schematic of a dual triode vacuum tube. The part itself is shown on the right.

Consider the schematic above, which is a single tube that contains two identical active elements, each called a “triode,” as each has three terminals. Tubes are easy to understand; let’s see how one works.

A *filament* heats the cathode, which emits a stream of electrons. They flow through the grid, a wire mesh, and are attracted to the plate. Electrons are negatively charged, so applying a very small amount of positive voltage to the grid greatly reduces their flow. This is the basis of amplification: a small control signal greatly affects the device’s output.

Of course, in the real world tubes are almost unheard of today. When Bardeen, Brattain, and Shockley invented the *transistor* in 1947 they started a revolution that continues today. Tubes are power hogs, bulky and fragile. Transistors—also three-terminal devices that amplify—seem to have no lower limit of size and can run on picowatts.

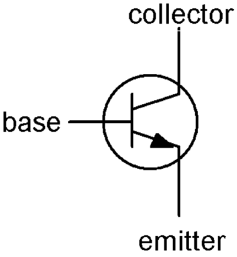


Figure 1-16: The schematic diagram of a bipolar NPN transistor with labeled terminals.

A transistor is made from a single crystal, normally of silicon, into which impurities are doped to change the nature of the material. The tube description showed how it’s a voltage controlled device; bipolar transistors are current controlled.

Writers love to describe transistor operation by analogy to water flow, or to the movement of holes and carriers within the silicon crystal. These are at best poor attempts to describe the quantum mechanics involved. Suffice to say that, in the picture above, feeding current into the base allows current to flow between the collector and emitter.

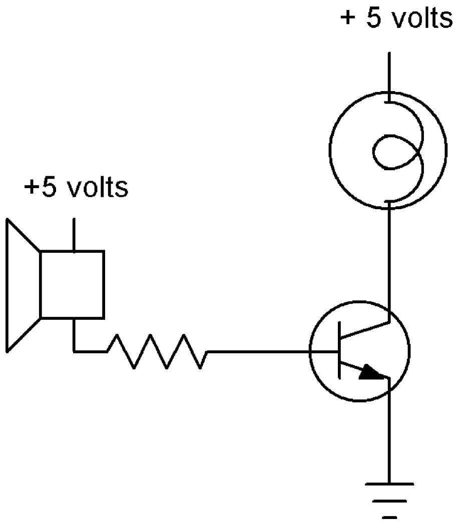


Figure 1-17: A very simple amplifier.

And that's about all you need to know to get a sense of how a transistor amplifier works. The circuit above is a trivialized example of one. A microphone—which has a tiny output—drives current into the base of the transistor, which amplifies the signal, causing the lamp to fluctuate in rhythm with the speaker's voice.

A real amplifier might have many cascaded stages, each using a transistor to get a bit of amplification. A radio, for instance, might have to increase the antenna's signal by many millions before it gets to the speakers.

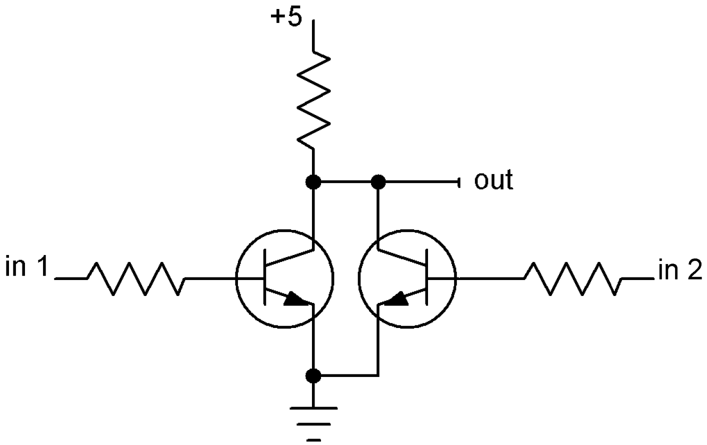


Figure 1-18: A NOR gate circuit.

Transistors are also switches, the basic element of digital circuits. The previous circuit is a simplified—but totally practical—NOR gate. When both inputs are zero, both transistors are off. No current flows from their collectors to emitters, so the output is 5 volts (as supplied by the resistor).

If either input goes to a high level, the associated transistor turns on. This causes a conduction path through the transistor, pulling "out" low. In other words, any input going to a one gives an output of zero. The truth table below illustrates the circuit's behavior.

in1	in2	out
0	0	1
0	1	0
1	0	0
1	1	0

It's equally easy to implement any logic function.

The circuit we just analyzed would work; in the 1960s all "RTL" integrated circuits used exactly this design. But the gain of this approach is very low. If the input dawdles between a zero and a one, so will the output. Modern logic circuits use very high amplification factors, so the output is either a legal zero or one, not some in-between state, no matter what input is applied.

The silicon is a conductor, but a rather lousy one compared to a copper wire. The resistance of the device between the collector and the emitter changes as a function of the input voltage; for this reason active silicon components are called *semiconductors*.

Transistors come in many flavors; the one we just looked at is a bipolar part, characterized by high power consumption but (typically) high speeds. Modern ICs are constructed from MOSFET—Metal Oxide Semiconductor Field Effect Transistor—devices, or variants thereof. A mouthful? You bet. Most folks call these transistors FETs for short.

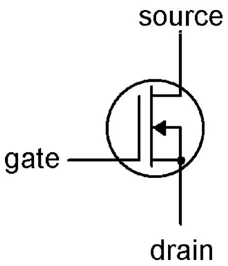


Figure 1-19: The schematic diagram of a MOSFET.

A FET is a strange and wonderful beast. The gate is insulated by a layer of oxide from a silicon channel running between the drain and source. No current flows from the gate to the silicon channel. Yet putting a bias voltage (like a tube, a FET is a voltage device) on the gate creates an electrostatic field that reduces current flow between the other two terminals. Again, *no current flows from the gate*. And when turned on, the source-drain resistance is much lower than in a bipolar transistor. This means the part dissipates little power, a critical concern when putting millions of these transistors on a single IC.

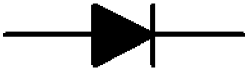


Figure 1-20: The schematic symbol for a diode.

A *diode* is a two-terminal semiconductor that passes current in one direction only. In the picture above, a positive voltage will flow from the left to the right, but not in the reverse direction. Seems a little thing, but it's incredibly useful. The following circuit implements an OR gate without a transistor:

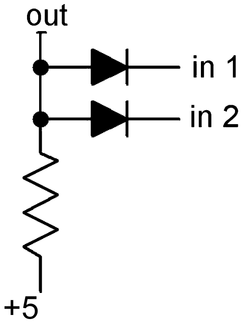


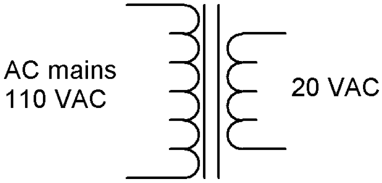
Figure 1-21: A diode OR circuit.

If both inputs are logic one, the output is a one (pulled up to +5 by the resistor). Any input going low will drag the output low as well. Yet the diodes insure that a low-going input doesn't drag the other input down.

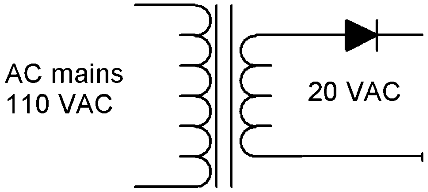
Putting it Together—a Power Supply

A power supply is a simple yet common circuit that uses many of the components we've discussed. The input is 110 volts AC (or 220 volts in Europe, 100 in Japan, 240 in the UK). Output might be 5 volts DC for logic circuits. How do we get from high voltage AC input to 5 volts DC?

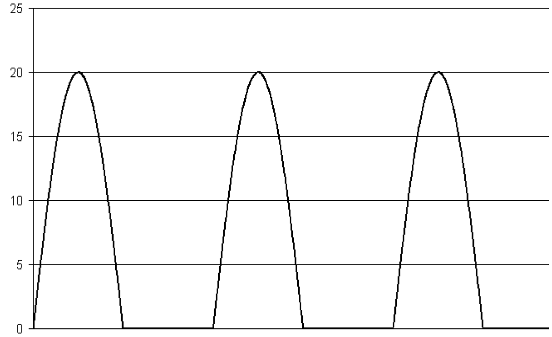
The first step is to convert the AC mains to a lower voltage AC, as follows:



Now let's turn that lower voltage AC into DC. A diode does the trick nicely:

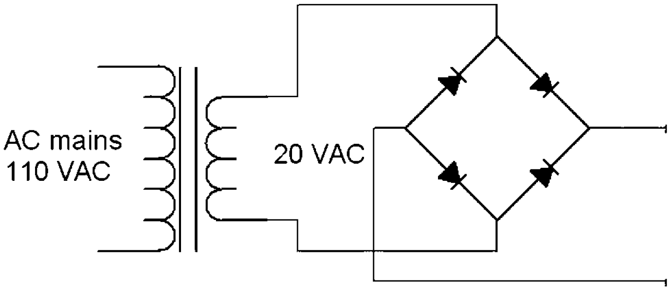


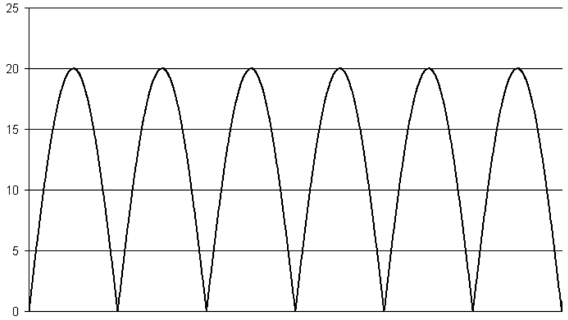
The AC mains are a sine wave, of course. Since the diode conducts in one direction only, its output looks like:



This isn't DC… but the diode has removed all of the negative-going parts of the waveform.

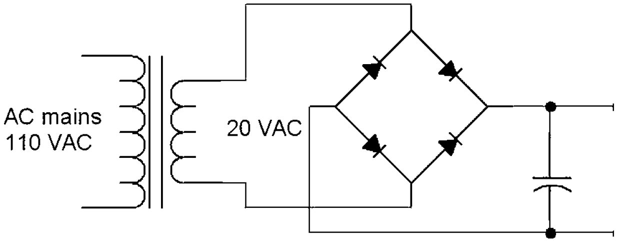
But we've thrown away half the signal; it's wasted. A better circuit uses four diodes arranged in a *bridge* configuration as follows:





The bridge configuration ensures that two diodes conduct on each half of the AC input, as shown above. It's more efficient, and has the added benefit of doubling the apparent frequency, which will be important when figuring out how to turn this moving signal into a DC level.

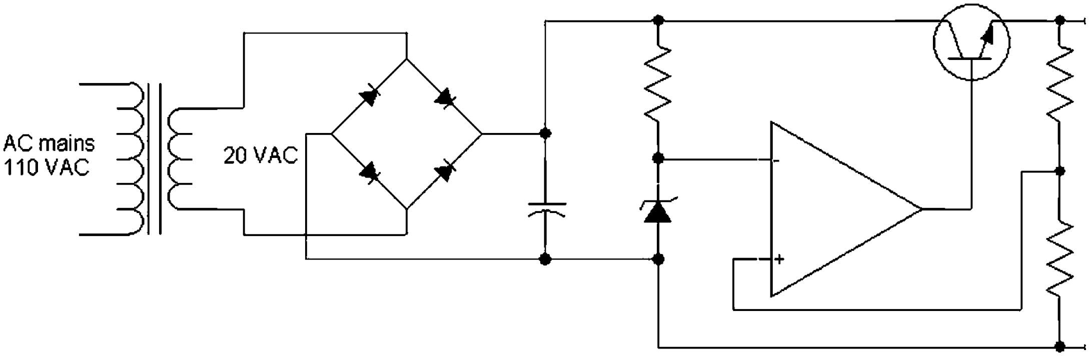
The average of this signal is clearly a positive voltage, if only we had a way to create an average value. Turns out that a capacitor does just that:



A huge value capacitor filters best—typical values are in the thousands of microfarads.

The output is a pretty decent DC wave, but we're not done yet. The load—the device this circuit will power—will draw varying amounts of current. The diodes and transformer both have resistance. If the load increases, current flow goes up, so the drop across the parts will increase (Ohm's Law tells us $E = IR$, and as I goes up, so does E). Logic circuits are very sensitive to fluctuations in their power, so some form of *regulation* is needed.

A regulator takes varying DC in, and produces a constant DC level out. For example:



The odd-looking part in the middle is a *zener diode*. The voltage drop across the zener is always constant, so if, for example, this is a 3-volt part, the intersection of the diode and the resistor will *always* be 3 volts.

The regulator's operation is straightforward. The zener's output is a constant voltage. The triangle is a bit of magic—an error amplifier circuit—that compares the zener's constant voltage to the output of the power supply (at the node formed by the two resistors). If the output voltage goes up, the error amplifier applies less bias to the base of the transistor, making it conduct less… and lowering the supply's output. The transistor is key to the circuit; it's sort of like a variable resistor controlled by the error amp.

If, say, 20 volts of unregulated DC goes into the transistor from the bridge and capacitor, and the supply delivers 5 volts to the logic, there's 15 volts dropped across the transistor. If the supply provides even just two amps of current, that's 30 watts (15 volts times two amps) dissipated by that semiconductor—a lot of heat! Careful heatsinking will keep the device from burning up.

The Scope

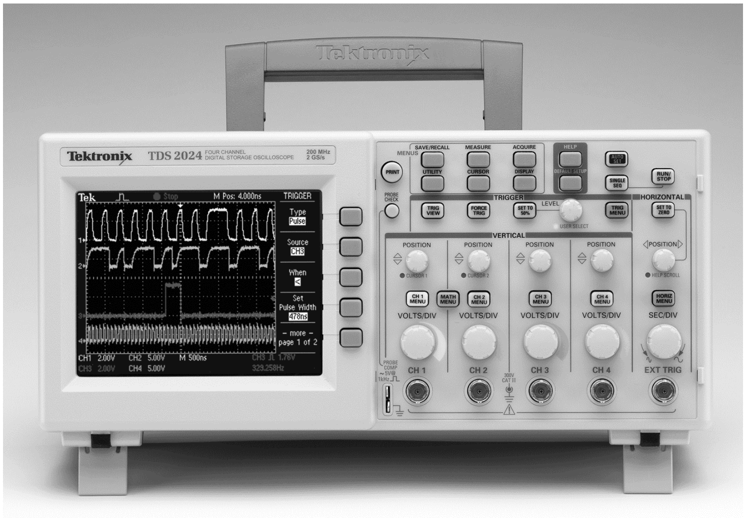


Figure 1-22: A sea of knobs. Don't be intimidated. There's a logical grouping to these. Master them and wow your friends and family. Photo courtesy of Tektronix, Inc.

The oscilloscope (colloquially known as the "scope") is the most basic tool used for troubleshooting and understanding electronic circuits. Without some understanding of this most critical of all tools, you'll be like a blind person trying to understand color.

The scope has only one function: it displays a graph of the signal or signals you're probing. The horizontal axis is usually time; the vertical is amplitude, a fancy electronics term for voltage.

Controls

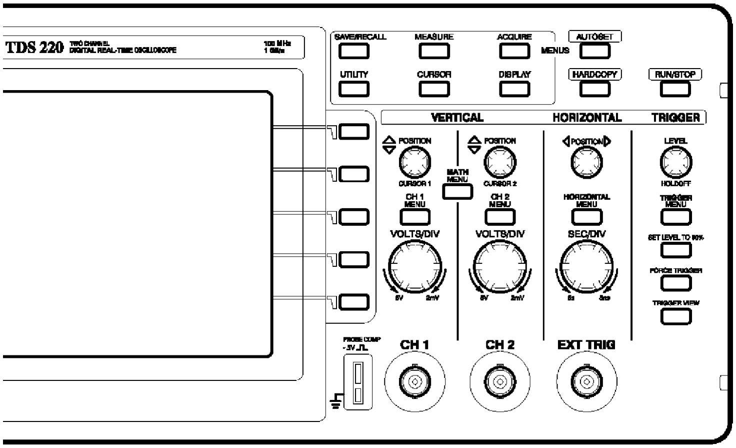


Figure 1-23: Typical oscilloscope front panel. Picture courtesy Tektronix, Inc.

In the above picture note first the two groups of controls labeled “vertical input 1” and “vertical input 2.” This is a two-channel scope, by far the most common kind, which allows you to sample and display two different signals at the same time.

The vertical controls are simple. “Position” allows you to move the graphed signal up and down on the screen to the most convenient viewing position. When looking at two signals it allows you to separate them, so they don’t overlap confusingly.

“Volts/div” is short for volts-per-division. You’ll note the screen is a matrix of 1 cm by 1 cm boxes; each is a “division.” If the “volts/div” control is set to 2, then a two volt signal extends over a single division. A five-volt signal will use 2.5 divisions. Set this control so the signal is easy to see. A reasonable setting for TTL (5 volt) logic is 2 volts/div.

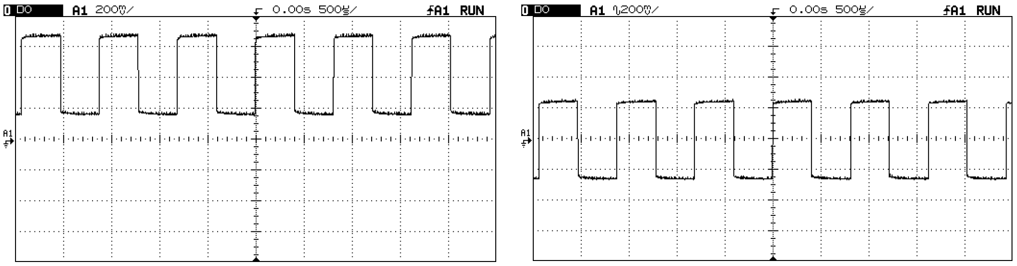


Figure 1-24: The signal is an AC waveform riding on top of a constant DC signal. On the left we’re observing it with the scope set to DC coupling; note how the AC component is moved up by the amount of DC (in other words, the total signal is the DC component + the AC). On the right we’ve changed the coupling control to “AC”; the DC bias is removed and the AC component of the signal rides in the middle of the screen.

The “coupling” control selects “DC”—which means what you see is what you get. That is, the signal goes unmolested into the scope. “AC” feeds the input through a capacitor; since caps cannot pass DC signals, this essentially subtracts DC bias.

The “mode” control lets us look at the signal on either channel, or both simultaneously.

Now check out the horizontal controls. These handle the scope’s “time base,” so called because the horizontal axis is always the time axis.

The “position” control moves the trace left and right, analogously to the vertical channel’s knob of the same name.

“Time/div” sets the horizontal axis’ scale. If set to 20 nsec/div, for example, each cm on the screen corresponds to 20 nsec of time. Figure 1-25 shows the same signal displayed using two different time base settings; it’s more compressed in the left picture simply because at 2000µsec/div more pulses occur in the one cm division mark.

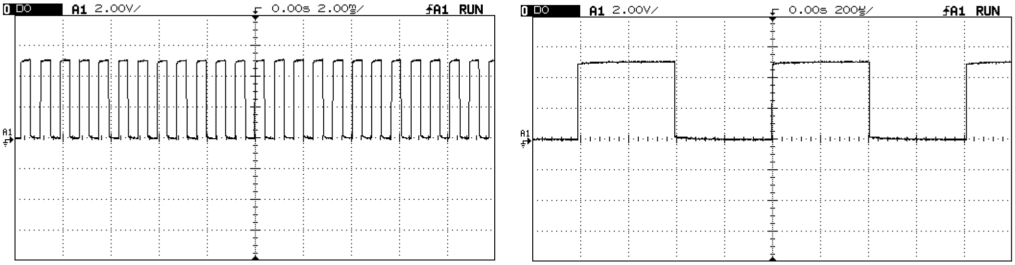


Figure 1-25: The left picture shows a signal with the time base set to 2000 µsec/division; the right is the same signal but now we’re sweeping at 200 µsec/division. Though the data is unchanged, the signal looks compressed. Also note that the 5-volt signal extends over 2.5 vertical boxes, since the gain is set to 2 volts/div. The first rule of scoping is to know the horizontal and vertical settings.

The last bank of knobs—those labeled “trigger”—are perhaps the most important of all. Though you see a line on the screen, it’s formed by a dot swept across from left to right, repeatedly, at a very high speed. How fast? The dot moves at the speed you’ve set in the time/ div knob. At 1 sec/div the dot takes 10 seconds to traverse the normal 10 cm-wide scope screen. More usual speeds for digital work are in the few microseconds to nanosecond range, so the dot moves faster than any eye can track.

Most of the signals we examine are more or less repetitive: it’s pretty much the same old waveform over and over again. The trigger controls tell the scope when to start sweeping the dot across the screen. The alternative—if the dot started on the left side at a random time—would result in a very quickly scrolling screen, which no one could follow.

Twiddling the “trigger level” control sets the voltage at which the dot starts its inexorable left-to-right sweep. Set it to 6 volts and the normal 5-volt logic signal will never get high enough that the dot starts. The screen stays blank. Crank it to zero and the dot runs continuously, unsynchronized to the signal, creating a scrambled mess on the scope screen.

Set trigger-level to 2 volts or so, and as the digital signal traverses from 0 to 5 volts the dot starts scanning, synchronizing now to the signal.

It's most dramatic to learn this control when sampling a sine wave. As you twirl the knob clockwise (from a low trigger voltage to a higher one) the displayed sine wave shifts to the left. That is, the scan starts later and later since the triggering circuit waits for an ever-increasing signal voltage before starting.

"Trigger Menu" calls up a number of trigger selection criterion. Select "trigger on positive edge" and the scope starts sweeping when the signal goes from a low level through the trigger voltage set with the "Trigger Level" knob. "Trigger on negative edge" starts the sweep when the signal falls from a high level through the level.

Every scope today has more features than normal humans can possibly remember, let alone use. Various on-screen menus let you do math on the inputs (add them, etc), store signals that occur once, and much, much more. The instrument is just like a new PC application. Sure, it's nice to read the manual, but don't be afraid to punch a lot of buttons and see what happens. Most functions are pretty intuitive.

Probes

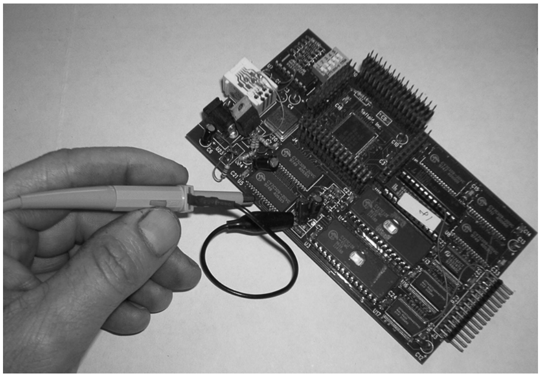


Figure 1-26: Always *connect the probe's ground lead to the system.*

A "probe" connects the scope to your system. Experienced engineers' fingers are permanently bent a bit, warped from too many years holding the scope probe in hand while working on circuit boards. Though electrically the probe is just a wire, in fact there's a bit of electronics magic inside to propagate signals without distortion from your target system to the scope.

So too for any piece of test equipment. The tip of the scope probe is but one of the two connections required between the scope and your target system. A return path is needed, a ground. If there's no ground connection the screen will be nutso, s swirling mass of meaningless scrolling waveforms.

Yet often we'll see engineers probing nonchalantly without an apparent ground connection. Oddly, the waves look fine on the scope. What gives? Where's the return path?

It's in the lab wall. Most electric cords, including the one to the scope and possibly to your target system, have three wires. One is ground. It's pretty common to find the target grounded to the scope via this third wire, going through the wall outlets. Of one thing be sure: even if this ground exists, it's ugly. It's a marginal connection at best, especially when dealing with high-speed logic signals or low level noise-sensitive analog inputs. Never, ever count on it even when all seems well. Every bit of gear in the lab, probably in the entire building, shares this ground. When the Xerox machine on the third floor kicks in, the big inductive spike from the motor starting up will distort the scope signal.

No scope will give decent readings on high-speed digital data unless it is *properly* grounded. I can't count the times technicians have pointed out a clock improperly biased 2 volts above ground, convinced they found the fault in a particular system, only to be bemused and embarrassed when a good scope ground showed the signal in its correct zero to five volt glory. Ground the probe and thus the scope to your target using the little wire that emits from the end of the probe. As circuits get faster, shorten the wire. The very shortest ground lead results in the least signal distortion.

Yet most scope probes come with crummy little lead alligator clips on the ground wire that are impossible to connect to an IC. The frustrated engineer might clip this to a clip lead that has a decent "grabber" end. Those extra 6–12 inches of ground may very well trash the display, showing a waveform that is not representative of reality. It's best to cut the alligator clip off the probe and solder a micrograbber on in its place.

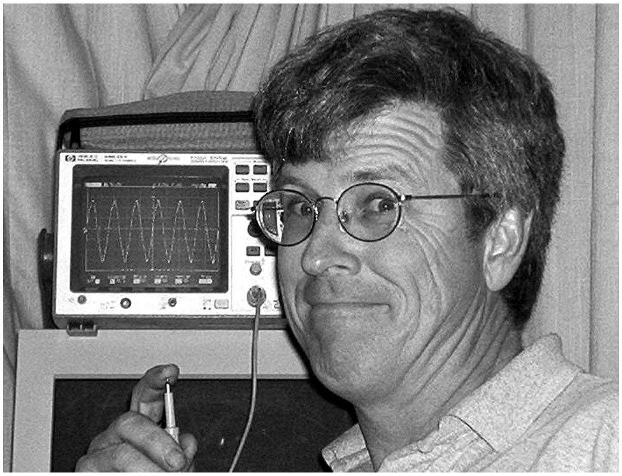


Figure 1-27: Here we probe a complex non-embedded circuit. Note the displayed waveform. A person is an antenna that picks up the 60 Hz hum radiated from the power lines in the walls around us. Some say engineers are particularly sensitive (though not their spouses).

One of the worst mistakes we make is neglecting probes. Crummy probes will turn that wonderful 1-GHz instrument into junk. After watching us hang expensive probes on the floor, mixed in with all sorts of other debris, few bosses are willing to fork over the $150 that Tektronix or Agilent demands. But the $50 alternatives are junk. Buy the best and take good care of them.

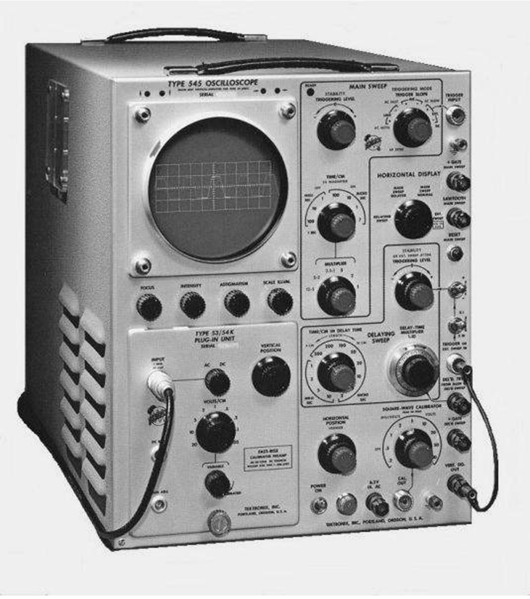


Figure 1-28: Tektronix introduced the 545 scope back in the dark ages; A half-century later many are still going strong. Replace a tube from time to time and these might last forever. About the size of a two drawer file cabinet and weighing almost 100 pounds, they're still favored by Luddites and analog designers.

CHAPTER 2

Logic Circuits

Jack Ganssle

Coding

The unhappy fact that most microprocessor books start with a chapter on coding and number systems reflects the general level of confusion on this, the most fundamental of all computer topics.

Numbers are existential nothings, mere representations of abstract quantitative ideas. We humans have chosen to measure the universe and itemize our bank accounts, so have developed a number of arbitrary ways to count.

All number systems have a *base*, the number of unique identifiers combined to form numbers. The most familiar is decimal, base 10, which uses the ten symbols 0 through 9. Binary is base two and can construct any integer using nothing more than the symbols 0 and 1. Any number system using any base is possible and in fact much work has been done in higher-order systems like base 64—which obviously must make use of a lot of odd symbols to get 64 unique identifiers. Computers mostly use binary, octal (base 8), and hexadecimal (base 16, usually referred to as "hex").

Why binary? Simply because logic circuits are primitive constructs cheaply built in huge quantities. By restricting the electronics to two values only—on and off—we care little if the voltage drifts from 2 to 5. It's possible to build trinary logic, base 3, which uses a 0, 1 and 2. The output of a device in certain ranges represents each of these quantities. But defining three bands means something like: 0 to 1 volt is a zero, 2 to 3 volts a 1, and 4 to 5 a 2. By contrast, binary logic says anything lower than (for TTL logic) 0.8 volts is a zero and anything above 2 a one. That's easy to make cheaply.

Why hex? Newcomers to hexadecimal find the use of letters baffling. Remember that "A" is as meaningless as "5"; both simply represent values. Unfortunately "A" viscerally means something that's not a number to those of us raised to read.

Hex combines four binary digits into a single number. It's compact. "8B" is much easier and less prone to error than "10001011."

Why octal? Base 8 is an aberration created by early programmers afraid of the implications of using letters to denote numbers. It's a grouping of three binary digits to represent the quantities zero through seven. It's less compact than hex, but was well suited to some early