Chapter 1O

Online Content: Breadboarding Hints & Tips

1O.1 Solderless breadboards

All of the course labs will be built on solderless breadboards strips: see Fig. 1O.1. These provide spring-loaded, friction-grip contacts to insert components and jumpers into for building circuits.

Each solderless breadboard strip consists of columns of five contacts above and below a central horizontal trench. Four horizontal buses, two on top and two on the bottom, supply power to your circuits. *Never use the horizontal buses for signals.* They are only useful to supply DC power and ground to your circuits.

On some versions of these breadboards the horizontal buses are split in the middle and must be connected in the center externally with wires. You can either use your multimeter to see if jumpers are required or play it safe and just always add them.

You should place ICs (integrated circuits in "DIP" – Dual Inline Packages) over the trench so that you can access the IC's pins via the top and bottom column of contacts. *Pin 1 of the IC should always be in the lower-left corner.* Remember that all five contacts in each vertical column are connected together when building circuits.

1O.2 Two possible breadboard choices

For most of the past five decades, we have used the Global Specialities Model PB-503 (now upgraded to the PB-503A) for all the labs in LAoE. The PB-503 has three breadboard strips mounted on an angled enclosure with three power supplies, a fixed $+5V$ supply along with independently variable 0 to $+15V$ and 0 to $-15V$ supplies. It also includes a number of buttons and switches, LEDs to display logic levels, a speaker, two potentiometers, and a
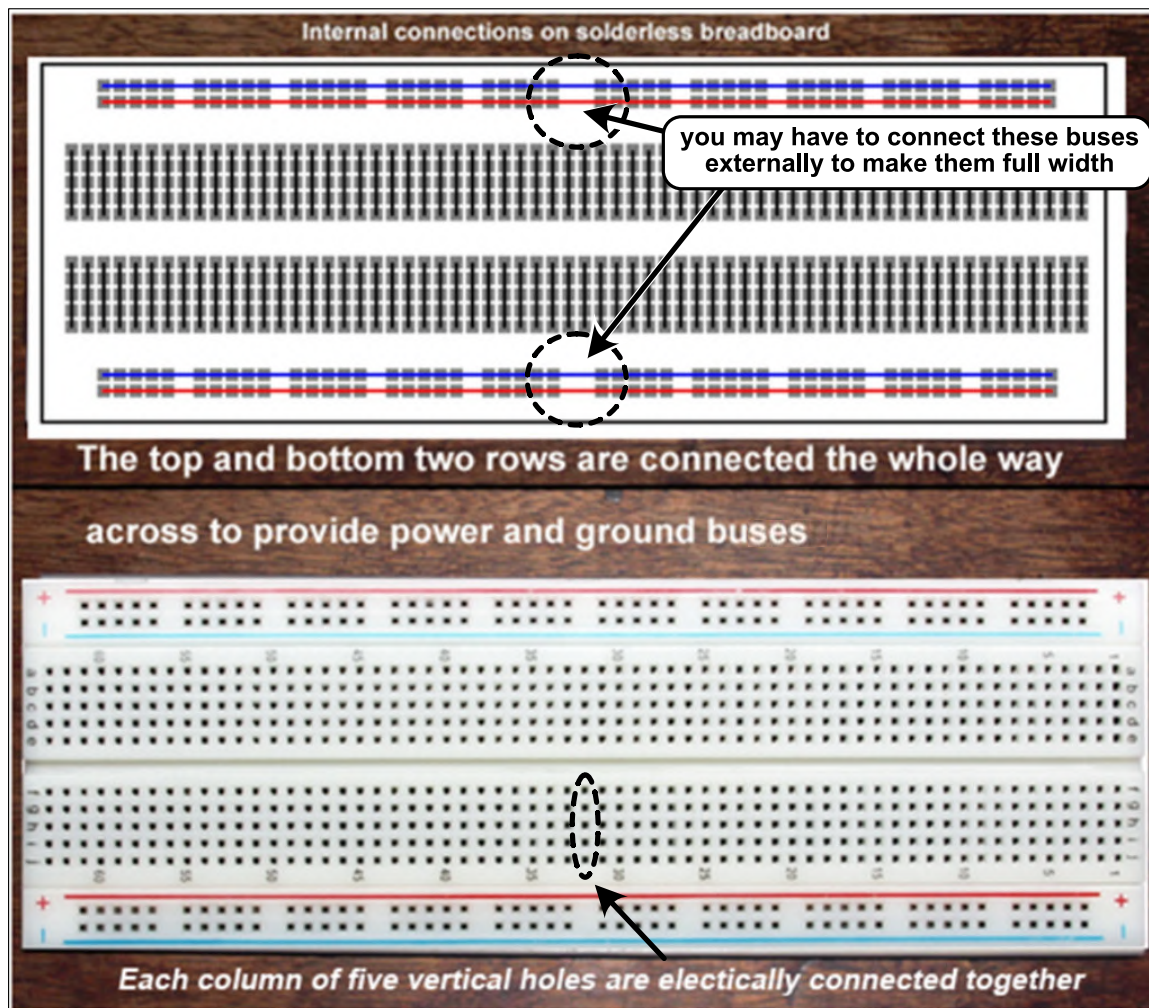
Figure 1O.1: Internal connection configuration of each solderless breadboard strip.

somewhat limited function generator: see https://LAoE.link/PB503.html.

Recently, we have begun using the PB-503 only for the digital labs 14L to 27L and a simpler breadboard for the analog labs. We made this change for several reasons:

- The new FPGA and microcontroller labs require +3.3V power rather than the +5V used in the first edition of LAoE. That means we have to set the variable positive supply to +3.3 and we fix the adjustment knob in place with hot melt glue to make sure we do not damage the expensive FPGA and microcontroller: see §14L.1.2. We do not want to have to undo this for the analog labs each time we teach the course.

- The analog labs do not use the switches and lights on the PB-503 and, for many experiments, we cannot use the onboard function generator because we need either to float the output or we need a variable DC offset.

- The simpler analog breadboard allows us to add an additional breadboard strip so that students can build larger circuits or keep older circuits on the breadboard.

We include here information on both breadboards. You can, of course, continue to use the PB-503 for all the labs if you wish.

1O.2.1   An optional analog only breadboard

Our new analog breadboxes consist of a commercial breadboard mounted on an angled sheet-metal stand with banana jacks to connect to an external power supply: see Fig. 1O.2.[1]

Figure 1O.2: Simple breadboard assembly used for analog labs.

We are using a 3M P/N 922336 four-strip breadboard because it is the only one we found with two dual-bus strips between the breadboards. This allows us to route all four power bus signals (ground, $+5V$, and $\pm15V$) both above and below each breadboard strip. Unfortunately, the 3M breadboard products are quite expensive: see `https://LAoE.link/3M_Breadboard.html`.

You can either make your own breadboard from individual strips mounted on a sheet-metal or wooden base or purchase a much lower cost alternative such as this three-strip one from Adafruit: `https://LAoE.link/Adafruit_Breadboard.html`. You only need three breadboard strips for the analog labs. The Adafruit breadboard does not include the dual bus strips we like, but at one-tenth the price of the 3M part it is much more affordable if you are not outfitting a Harvard lab. It does include an extra two bus strip mounted perpendicular to the normal buses you can use for power routing.

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[1]Design files for the sheet metal base are available in Corel Draw 7, PNG, PDF, and SVG format at `https://LAoE.link/breadboard_base.zip`. Each series of five small holes widthwise indicates a bend line. The four larger holes 1.25 inches in from each edge are used to pop rivet a $\frac{1}{2} \times \frac{1}{2}$ aluminum "L" extrusion stiffener to the base.

You will need a separate power supply if you choose not to use the PB-503. We are using a Rigol bench supply (see below), but our favorite [quiet] triple-output HP supplies, the 6236B and 6327B, can often be found on eBay for about $100. If the low-voltage supply and split-supply have separate grounds, be sure to connect them together (the black wire between the binding posts in Fig. 1O.3).

An intermediate solution between the full PB-503 and an unpowered breadboard is the Circuit Specialties PBB-272C powered breadboard: `https://LAoE.link/CS_Breadboard.html`. This unit consists of three breadboard strips arranged in the same configuration as the Adafruit breadboard, with the addition of a built-in 5V and dual adjustable 0 to ±15V power supplies for about $120.

Configuring the power buses on the analog breadboard: You may need to bridge the gap in the middle of each horizontal bus with a short jumper of the correct color as shown in Fig. 1O.2. Use a multimeter to check if your horizontal buses are connected.

The power supply buses should be color coded as follows:

- Yellow: $+15$ Volts
  We normally make the top horizontal row of contacts on each individual breadboard the $+15$ volt supply. It is indicated by yellow hookup wire.

- Red: $+5$ Volts
  The next horizontal row of contacts is the $+5$ volt supply. It is indicated by red hookup wire.

- Black: Ground
  The second from the bottom horizontal row of contacts is ground. It is indicated by black hookup wire.

- Blue: -15 Volts
  The bottom horizontal row of contacts is the -15 volt supply. It is indicated by blue hookup wire.

We strongly suggest you use red, black, yellow, and blue wire only for the power lines indicated. Troubleshooting goes much faster when you know, for example, that a black wire is always connected to ground.

Supplying power to the analog breadboard: On our breadboard assembly, we included four color-coded banana jacks wired to the power busses: see Fig. 1O.2 (rear view). We connect these to our triple-output bench supply with color-coded banana-to-banana jumper cables (e.g., `https://LAoE.link/Banana_Jumpers.html`): see Fig. 1O.3.
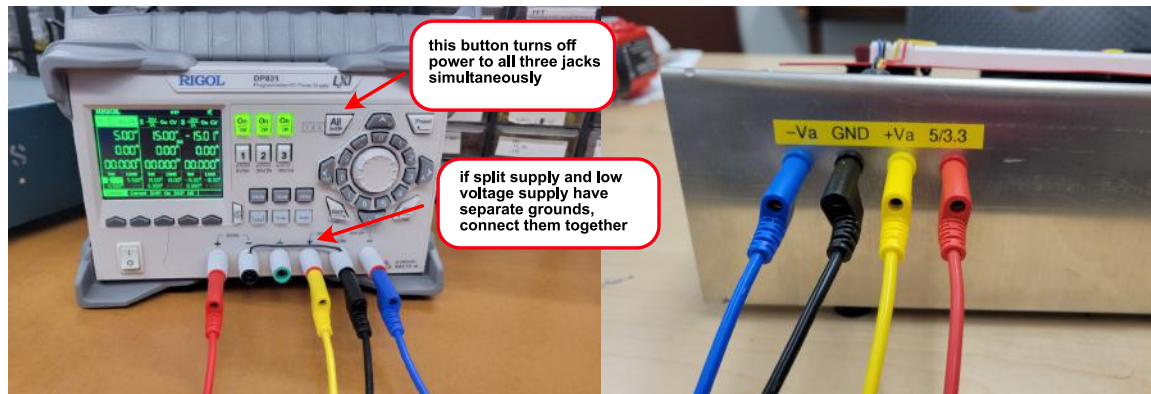
Figure 1O.3: Power supply connections for stand-alone breadboard.

1O.2.2   Configuring the PB-503 breadboard

The Global Specialties PB-503 Digital Workstation provides three solderless breadboard strips to insert components and jumpers into for building circuits, three power supplies, BNC connectors, eight logic level slide switches, two uncommitted slide switches, two debounced pushbutton switches, two potentiometers, eight indicator LEDs, a speaker and a simple function generator. For the analog labs, we only use the power supplies and occasionally the speaker.

The $+5$ and ± 15V volt power supplies built into the breadboard are adequate to power all of the analog labs with the possible exception of the PID lab: see §10L.1.1.3. Your should prewire your breadboard as shown in Fig. 1O.4 to provide power buses for the lab circuits:

You should adjust the variable power supplies to $+15$V and -15V and leave them there unless directed otherwise in the lab instructions.

The power supply buses should be color coded as follows:

- Yellow: $+15$ Volts
- Red: $+5$ Volts
- Black: Ground
- Blue: -15 Volts

1O.3   Building circuits with the solderless breadboard

Turn off the power when inserting components or modifying your circuit. It is easy to damage components or even the power supplies on the PB-503 if you inadvertently short circuit something while building or modifying your circuit. Finding damaged components, particularly if they worked properly before the modification, can be difficult and frustrating.

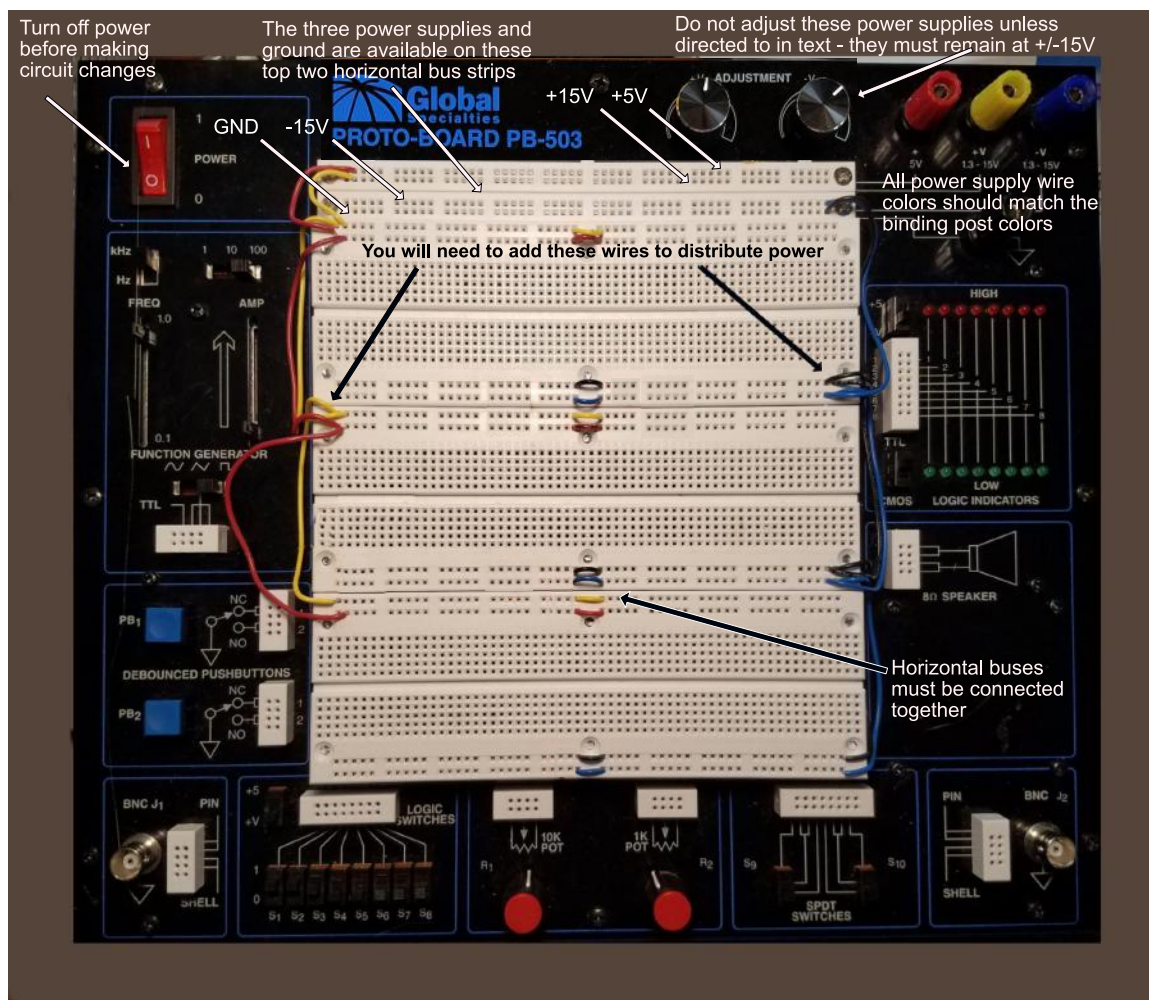You should start every project by setting up your power and ground buses and adding

Figure 1O.4: Power supply connections for PB-503 breadboard analog labs.

bypass capacitors ("caps") first.[2] You may need to move the caps later to make room for components, but it means you will start building and debugging with a solid power scheme.

If you see a supply voltage decrease appreciably when you connect it to your circuit or the current rises significantly, it is probably because your circuit is drawing excessive current (the outputs of the breadboard and bench power supplies are current limited). **Turn the power supply off immediately** and find the problem before powering back on. Also check to see if the power supply is set to limit current below its maximum. **Always turn power off immediately if you see smoke or smell something burning.**

It is helpful to add a piece of partially stripped black hookup wire in the ground bus to provide a place to connect test equipment ground clips to as shown Fig. 1O.5.

While you may be tempted to insert components and hookup wire by hand, some of the connector strips on may be very tight, making insertion difficult. A better method is to use

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[2]See §2N.4.2 for an explanation of bypassing power supplies.
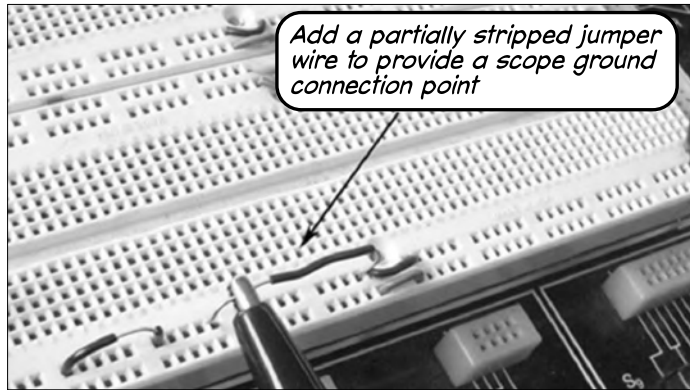
Figure 1O.5: Add a wire to connect your scope ground clip to.

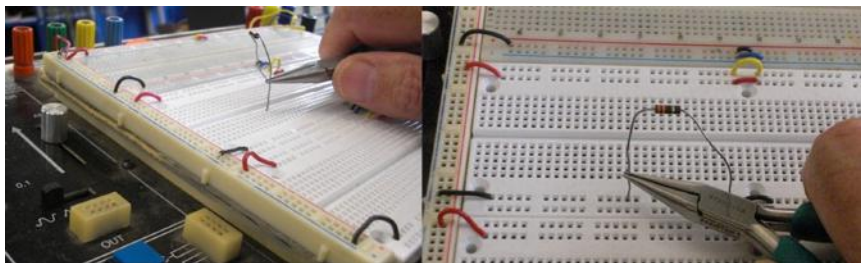needle-nose or long-nose pliers: see Fig. 1O.6

Figure 1O.6: Use pliers to insert components and jumper wires.

Also, bend component leads slightly away from the body of the component rather than right at the component, particularly on resistors, diodes and tubular capacitors, to avoid stress that can cause the leads to break.

Use insulated <u>solid</u> #22 gauge wire to make connections between components on the breadboard. You should use the notch in your wire strippers marked "22" to strip the insulation. Strip at least three-eights of an inch ($.375$in or ≈ 9 mm) of the insulation off the end of the wire before you insert it into the breadboard. Fig. 1O.7 shows what a properly stripped wire will look like (the scale on the left is in mm; inches on the right).

Figure 1O.7: A properly stripped jumper wire.

One of the most frustrating errors you can make in breadboarding is to strip too little

insulation from the end of your wires! While the circuit will look properly built, if the wire is not long enough to reach through the plastic breadboard to the metal connector underneath, the circuit either will not work or it may work intermittently. This error is extremely difficult to find since the defective wire will look like all the others. Here is a parable that you should take to heart:

One semester, two of our students spent forty minutes trying to figure out why their circuit was not working. They called over a Teach Fellow who spent another thirty minutes with no success. Everything looked fine, the circuit appeared to be built correctly and replacing the integrated circuit (which was the component that did not appear to be working) did not solve the problem. Finally, they called us for help. Fig. 1O.8 shows what the relevant portion of the breadboard looked like when we came over.
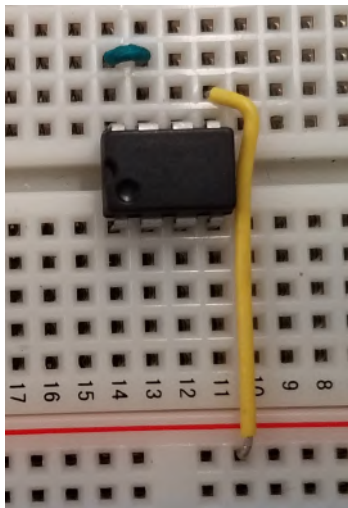

Figure 1O.8: This looked like a properly built circuit at first glance.

We confirmed that the circuit was built correctly but that it was not working correctly. We also confirmed that the integrated circuit (the black rectangular device) was not working as expected, but replacing it did not solve the problem. After about ten minutes of investigation, we decided that the only thing that explained the circuit behavior we saw was that the two pins in the upper left corner were not connected together (even though there was a wire obviously connecting them). So we took out the green jumper and here is what we found: see Fig. 1O.9. The wire was not long enough to reach the metal contacts in the breadboard.

We replaced this defective jumper with one cut properly and the circuit appeared to work – but that was not the end of the story.

We left and a few minutes later the same students came running after us saying that the circuit was only working intermittently. We returned and, now alerted to the students' faulty breadboarding technique, discovered that the yellow jumper providing power to the circuit had the same problem: see Fig. 1O.10.

This *not* a problem you ever want to experience, and the best way to avoid it is to make sure you strip your wires long enough. It is much easier to strip too much off the end of a wire and then trim it back than find a too short wire once it is inserted in the breadboard.

In addition, *do not daisy chain multiple short lengths of hookup wire* to reach between two
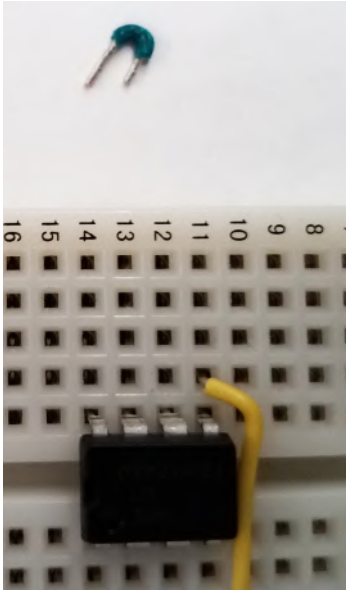
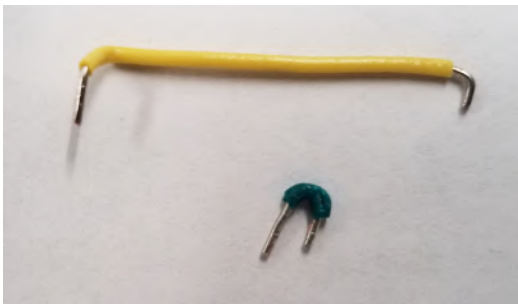Figure 1O.9: Uh-oh. This might explain the problem.

Figure 1O.10: Not a good day. Avoid this problem by stripping your wires correctly.

components as was done in Fig. 1O.11. Each contact introduces a point of failure. If you cannot find a long enough jumper of the correct color, create a new jumper by cutting a wire to the correct length. Also note the color change in the photo below that only adds to the confusion – *all points electrically connected together should use the same color of wire*. Wires connected to power and ground must use the correct color wire to match the power supply binding post. A black wire should *only* be used for ground.

1O.3.1 Build your circuits neatly and document what you build

Always draw a schematic of the circuit you are building and update it as you make changes.

On complicated circuits (and maybe simple ones) always build a portion of the circuit and testing it before building the next section. You will find it much easier to debug small portions of a design than one big mess and you will be less likely to disturb a working section while debugging a non-working section.

While building a circuit from a schematic in the notes (or from your own sketch), use a highlighter pen to mark the components and wires as you complete each item. This helps
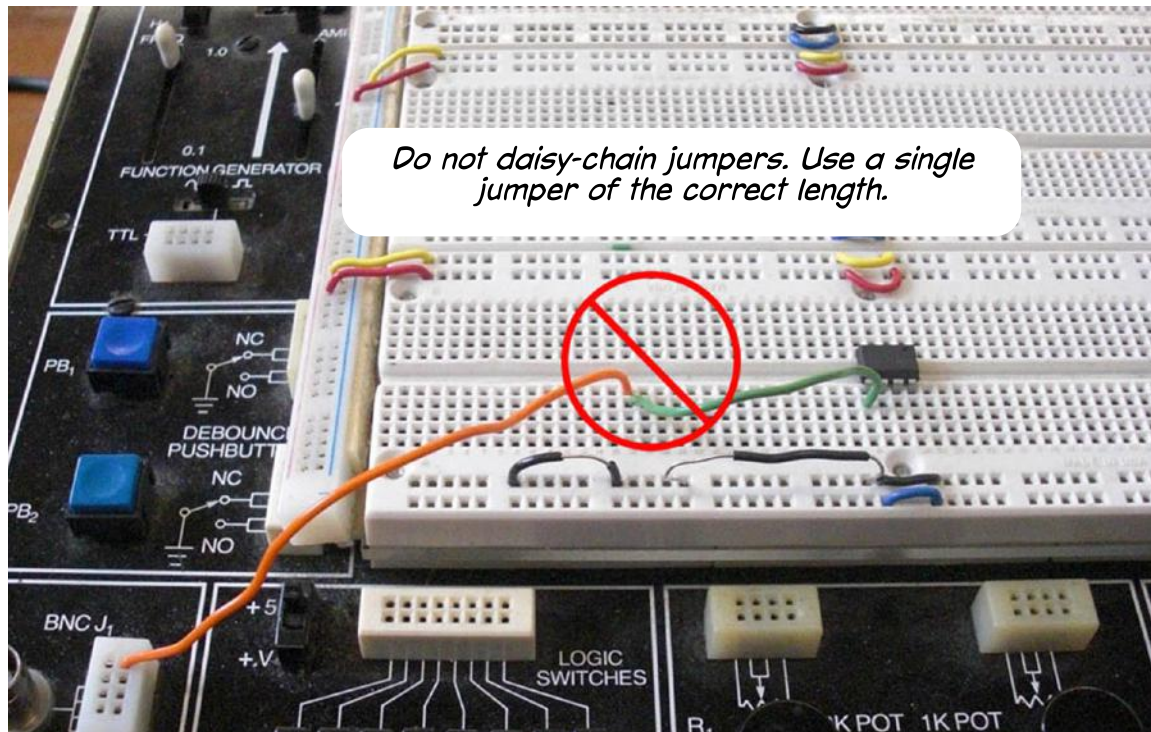
Figure 1O.11: Do not daisy chain jumpers unless there is a device connected at the junction. Do not change wire colors in a daisy chain.

catch missing portions of the circuit and is easier than debugging a non-working circuit only to find you left out a jumper. We often leave out power supply connections and pin numbers on parts with multiple devices in them when we draw schematics of our designs. As we build, we use the device and pins that makes the wiring easiest. If you do not document the pin numbers you use, it becomes very difficult to debug your circuit if it does not work correctly. In Fig. 1O.12, we have started building a simple circuit using an op-amp (the "358") that contains two devices in each package. We have highlighted connections as we wired them, and have documented the power connections necessary for the op-amp to work. We also added pin numbers for the op-amp of the two in the package that we are using in this circuit.

In general, you should build the breadboard the way the schematic is drawn, from left to right with higher power supply voltages at the top and lower power supply voltages at the bottom.

Label switches and potentiometers on your schematic and on the actual component on the breadboard so you (and a user of your circuit) know what the adjustment does. In the circuit above, you should add a label "OFFSET" on or near the 10k pot. For circuits that you plan to leave constructed for several lessons or one you are building in stages, consider keeping leads and jumper wires short and close to the surface of the wireless breadboard. This will reduce the chance of components or jumpers being pulled out of a working circuit and make debugging new additions much easier.
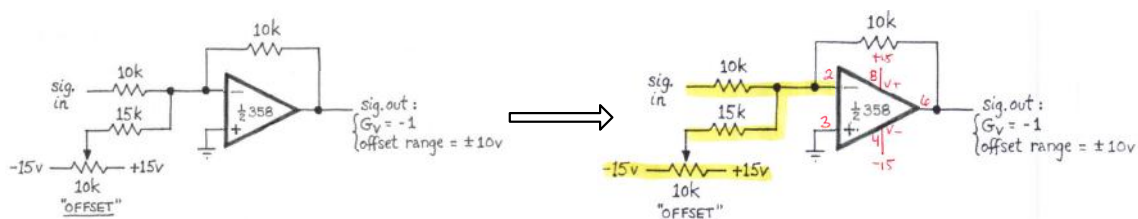
Figure 1O.12: Document your build as you go along. Add pin numbers where you can choose between multiple devices in a package.

Fig. 1O.13 shows an example of a neatly built circuit. Note how the power supply jumpers are color coded (Red: +5, Black: ground), the switches are labeled by function and the jumpers are placed close to the surface of the breadboard and neatly routed to avoid snagging. The resistors are also placed low to the breadboard and are bent away from the body of the component.
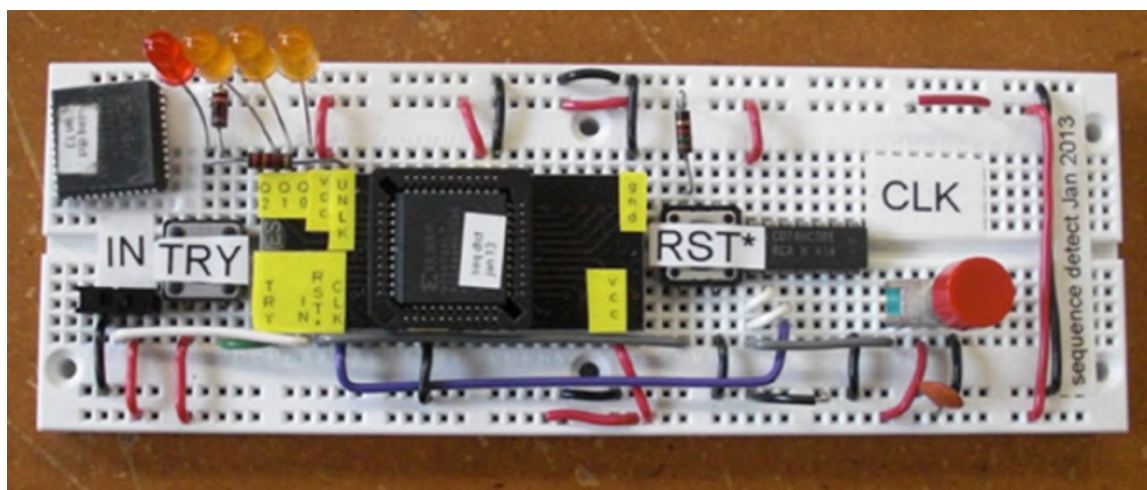

Figure 1O.13: A neatly built circuit.

1O.3.2   Additional breadboarding hints & tips

When you disassemble a circuit, *do not try to remove ICs by hand*, you will bend the leads: see Fig. 1O.14. The U-shaped IC extractor should always be your first choice to remove integrated circuits from the breadboard. It is much easier to use this tool than to have to straighten bent pins on an IC removed by hand. For larger ICs, you can use the green handled screwdriver to gently pry up the IC package. A video showing how to use the IC removal tool is available at `https://LAoE.link/IC_Tool_Demo.html` and using a screwdriver at `https://LAoE.link/IC_Screwdriver_Demo.html`.

If you find an IC in your parts bin that has bent leads do not try to force it into the breadboard. Rather, use your pliers to carefully straighten the pins out before inserting the IC into the breadboard. Be careful – it is very easy to break the pin off entirely, rendering the
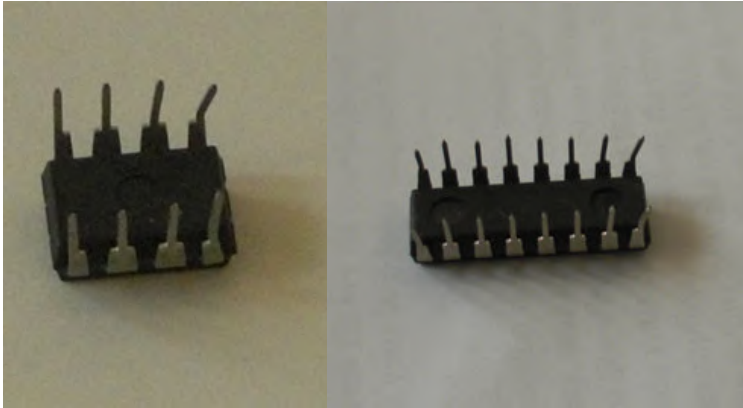
Figure 1O.14: What happens if you try to remove an IC with your fingers.

IC useless. You can align the pins vertically by holding the IC on its side against a hard surface and bending all the leads simultaneously to a right angle to the body of the device.

Be careful with TO-220 packages like the one shown in Fig. 1O.15. The metal tab is connected to one of the device pins. Make sure this does not short out against any other component or wire.
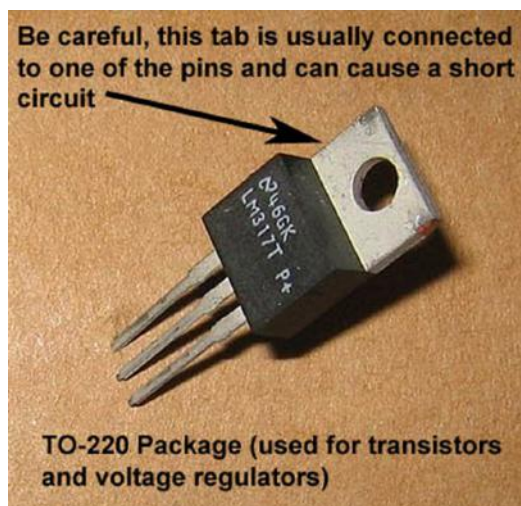

Figure 1O.15: The metal tab on TO220 packages is connected to one of the pins. Be sure it does not short to another device.

We recommend you have the tools shown in Fig. 1O.16 available when you build circuits.

The "T" shaped BNC connector optional. It is useful to split an external signal source output to two inputs.

Rules for the resistor color code: Even if you decide not to memorize the resistor color code (Fig. 1O.17) right away, keep these rules in mind:

A resistor starting with BROWN then BLACK is an order of magnitude value (1K, 10K, 100K, etc.)

- A BROWN third band means 100s of ohms
  BROWN BLACK BROWN = 100 ohms

Useful tools for breadboarding. Use the U-shaped IC extractor to remove integrated circuits from the breadboard without bending the pins. Needle-nose pliers are used to insert components and jumpers and to [carefully] straighten bent IC pins. Wire strippers allow you to create new jumper wires. The BNC "T" connector connects the external function generator to the breadboard BNC input connector and the oscilloscope simultaneously to monitor the circuit input. The thin screwdriver ("green tweeker") can be used to adjust trimpots and remove ICs too big for the IC extractor.

Figure 1O.16: Tools you will need to build your circuits.

- A RED third band means kiloohms
  BROWN BLACK RED = 1k ohms

- An ORANGE third band means 10s of kiloohms
  BROWN BLACK ORANGE = 10k ohms

- A YELLOW third band means 100s of kiloohms
  BROWN BLACK YELLOW = 100k ohms

A very common mistake is using a resistor that is several orders of magnitude away from what you thought you were using. *A few minutes memorizing these third band rules now may save you a lot of troubleshooting time later.*

One of the few ways you can hurt yourself (or others) in the lab: The voltages we use in the lab are too low to present an electrocution hazard. However, *pay careful to polarity* when inserting components such as diodes and electrolytic capacitors. Fig. 1O.18 shows

Figure 1O.17: Reading the Resistor Color Code. Courtesy of Backward Workshop (William Hunt and Joel Phillips) / CC BY-NC-ND 3.0

what was left of an electrolytic capacitor that was inserted backwards by a student in one of our courses. It exploded with a bang that sounded like a firecracker going off. The student was stung by flying shrapnel, but luckily was not permanently injured. Even if you do not get an explosion, a reversed or incorrectly inserted component can lead to odd circuit behavior that is difficult to diagnose. It is better to take your time building a circuit than to waste time debugging it.
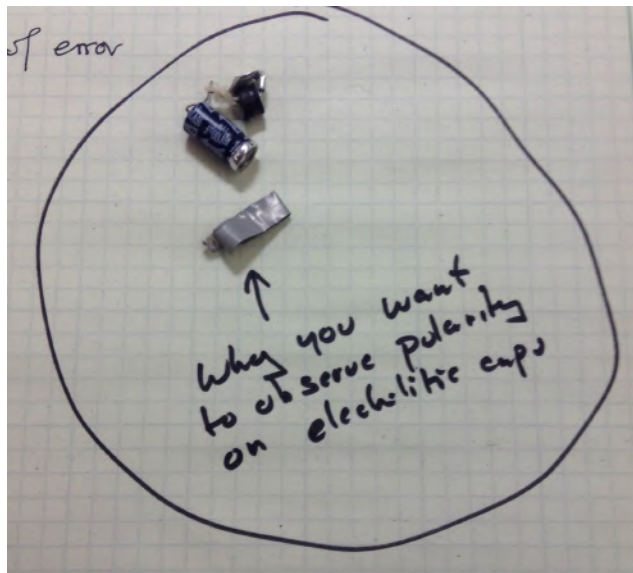

Figure 1O.18: The remains of an electrolytic capacitor that exploded when it was inserted with reverse polarity.

1O.4   Test equipment hints & tips

While the following describes the equipment we use in our lab, many of the the hints and tips apply to other similar equipment.
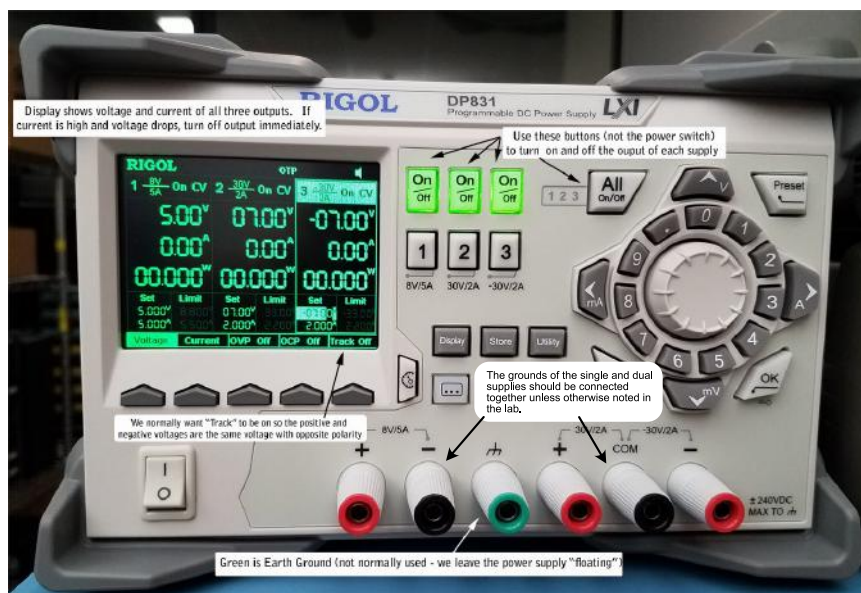
Figure 1O.19: The Rigol DP831 triple-output lab power supply.

1O.4.1 Configuring and using the laboratory power supply

The Rigol DP831 power supply we use (Fig. 1O.19) is capable of supplying three voltages simultaneously: a split supply (variable from 0 to $\pm30V$) used for analog circuits, and a low (0 to 8V) voltage typically used for digital circuitry.[3] In general, we will set the low voltage supply to $+5$ volts or $+3.3V$ and the split supply to somewhere between ±6 to ±15 volts depending on the circuit. We will almost always use the split supply in "tracking mode," meaning that the plus and minus supply are at the same (but opposite polarity) voltage.

Make sure the power supply voltages are set correctly before connecting them to your breadboard. In particular, most analog components are not rated to withstand the maximum ±30 volts available from the split supply. Be sure to press the "All On/Off" button to turn off all voltage outputs before making changes to your circuit.

The outputs of the DP831 are "floated." That means they are not referenced to earth ground, nor is output 1 (the low voltage supply) referenced to the other two outputs. The low voltage output has a negative binding post output separate from the split supply common output. Normally, we will connect the low voltage "8V/5A" minus terminal to the split supply "COM" terminal to create a single ground reference for our circuit. However, we do not connect this common ground to the green earth ground binding post at the power supply. Rather, we will let the oscilloscope probe ground lead make that connection. That means that if you forget to connect the scope ground lead to your circuit ground, you will not get meaningful traces on the oscilloscope.

The current at each of the three outputs can be adjusted from zero to the DP831 maximums

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[3]Rigol offers a similar power supply, the DP832A, which separates the split supplies so they can be used independently at the same price. This offers more flexibility at the expense of a bit more complexity. In addition, the low voltage supply is limited to 5V, but the higher voltage supplies are rated at 3A rather than the 2A of the DP831.

of 5A and 2A on the low voltage output and the split supply respectively. If the current limit is set to less than that drawn by your circuit, the output voltage will drop. If you do not get the output voltage you set when you connect to your circuit, disconnect the power supply and check the current limit settings. If they are set high enough, you probably have a short circuit in your breadboard. The "LIMIT" displays show the current limit settings of each output of the supply. We normally set the split supply to a current limit of 300mA and the low voltage current limit to 500mA. That is adequate for most of the circuits we build and allows us to catch wiring errors with less chance of destroying components and/or generating smoke. (The built-in PB-503 breadboard power supplies do not have adjustable current limits.)
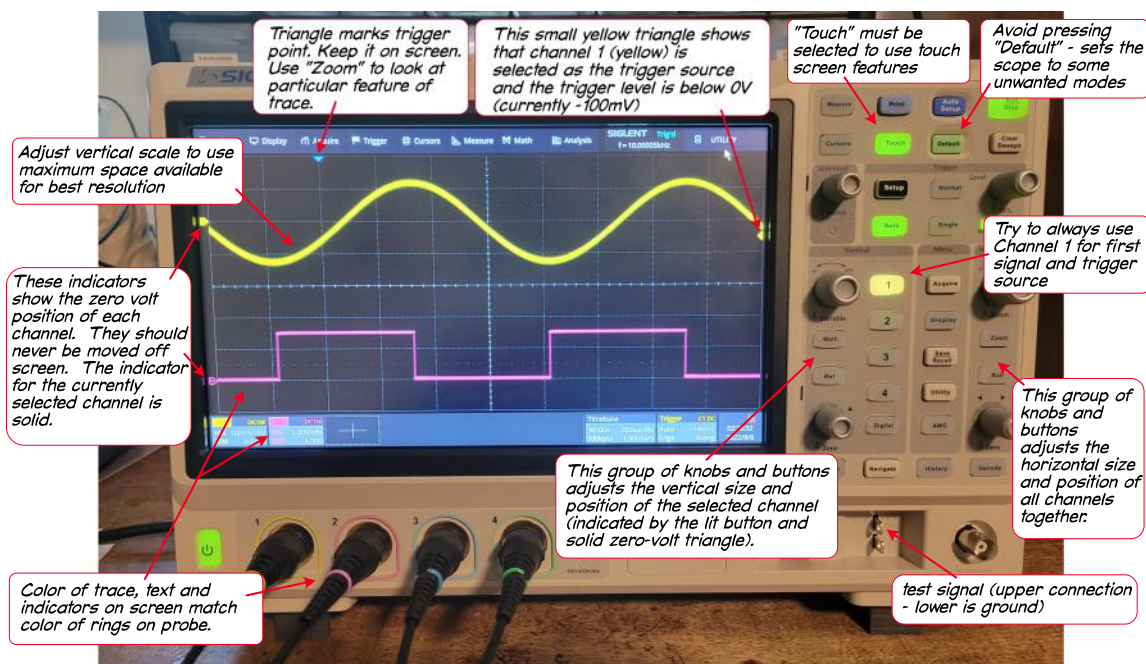
1O.4.2   Configuring and using the digital oscilloscope

Figure 1O.20: Some hints about using the oscilloscope.

Our lab is equipped with Siglent SDS2204X Plus four-channel digital storage oscilloscopes.[4] These scopes use digital memory to store the trace data which is displayed on a Liquid Crystal Display (LCD) screen. Unlike an analog scope, this means it is easy to capture a single occurrence of a rare signal. It also means the scope can take measurements of signal amplitude, frequency or period and do calculations such as Root Mean Squared (RMS) or display the Fourier Transform of an input signal. However, it also adds complexity that you will need to master in order to navigate the instrument.

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[4]This is a mid-level 200MHz scope, but you can get by with a low-end 70- to 100MHz scope for most of the experiments in the book. If you can afford it, four channels are much better than two for looking at complex circuits like the PID controller and the lock-in amplifier.

The Siglent scopes have a touchscreen, but you may find they are easier to control with a mouse. Many of the features controlled by buttons and knobs can also be set with the touch screen or mouse. (However, many menu selections can only be accessed from the touch-screen or mouse.) You can also plug in a USB drive to save screen images and settings. A measurement function and screen cursors allow you to make measurements without counting boxes onscreen. Many other digital scopes have similar features. Be sure to spend some time learning the features of these powerful instruments.

The oscilloscope probes are connected to the input channels. The probes have color coded tags that match the color of the trace on the screen. (I.e., the probe on channel 1 which displays in yellow has a small yellow collar on it.) Some labs may direct you to remove the probes to connect a BNC cable directly to your breadboard. Twist the black knurled ring at the base of the probe to the left then pull to remove it. Handle probes gently, they are somewhat expensive and delicate.

Note that the oscilloscope ground, which includes the ground clip on the scope probe, is connected to earth ground. It is not floated like the power supplies. This is normally not a problem, but if you are testing a circuit that is deliberately floated (i.e. disconnected) from earth ground you may need to use two scope channels and subtract one signal from the other.

Connecting the oscilloscope to your circuit: *Do not remove the spring-loaded tip on the probe and/or try to push the sharp point of the probe into the breadboard.* The probe end is too large and will deform the breadboard contacts. Instead, connect a short length of hookup wire to the probe spring hook and push that into the breadboard: see Fig. 1O.21. If you try to hook a component directly, the weight of the probe often pulls the part out of the breadboard. Also, try to connect the probe ground lead to a ground point close to the point you are measuring to minimize noise pickup.
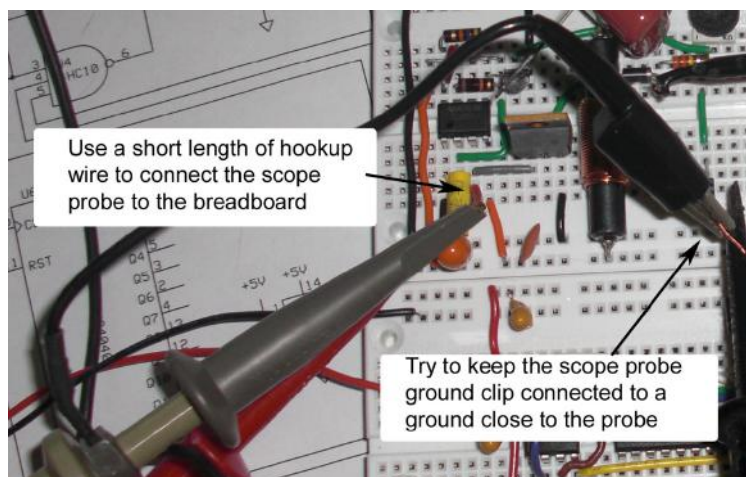

Figure 1O.21: The easy way to connect the scope probe to your circuits.

Set your probe to 10X mode: If your oscilloscope probe is switchable between times one ("1X") and times ten ("10X"), leave it in the times ten position (Fig. 1O.22) and make

sure your [digital] oscilloscope knows that is what you are using so it displays the correct vertical scale. The times ten position provides much higher input impedance so your scope loading has less effect on your circuit (see §3N.2). The only time you want to use the times one setting is when you need the highest sensitivity and the higher loading will not effect your circuit.
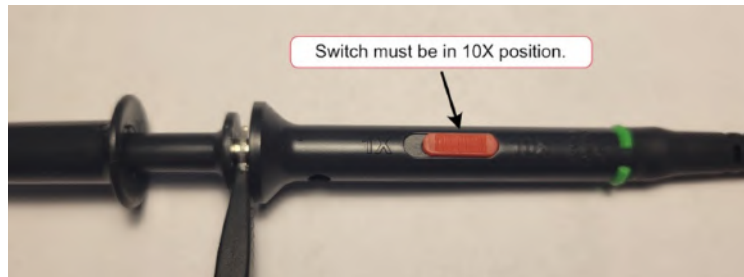

Figure 1O.22: Your scope probe should be left in the 10X position.

However, a 10X probe must occasionally be checked to see that the probe is properly frequency compensated in order to provide the same response (i.e., amplitude gain) to signals from low frequency up to the limit of the scope (200Mhz for our scopes). The instruction manual for the oscilloscope or probe should describe how to check this (look for a section titled "Probe Compensation"). If you connect your probe to a known good square wave (the "CAL" or "calibration" test signal on the front panel) and the waveform is distorted (see Fig.1O.23), you will need to adjust the compensation.
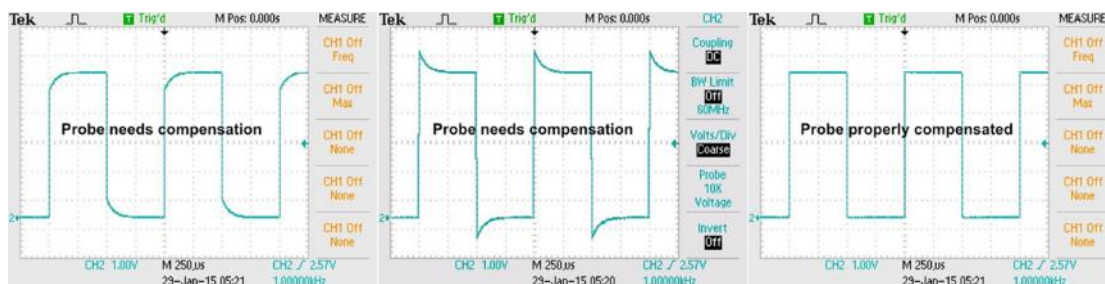

Figure 1O.23: If the calibration waveform is not square, the probe compensation needs to be adjusted.

Use Channel 1 for the trigger signal: If you are only using one channel of the scope, always use Channel 1 (CH 1 - YELLOW). Otherwise you will have to change the triggering and other adjustments. By always connecting channel 1 to the signal you are triggering on, you will spend less time fiddling with the scope controls.

When using more than one channel, use Channel 1 for a source that you can trigger on. If the input signal is large enough that you can trigger on it, use Channel 1 for your input and triggering source and use Channels 2 - 4 for output and/or intermediate signals. If your scope includes an external trigger input (often in the rear), you can look at four signals and trigger on a fifth if necessary.

If your oscilloscope has four channels – use them: We often see students moving a single probe from test point to test point. This makes no sense, particularly if there is a relationship between multiple signals, as is often the case. You will want to look at the input, intermediate signals and output of a circuit simultaneously to see if it is working properly. Use all the channels you have available. Depending on the relationship between the signals, you may want to display them either one above the other or overlaid. See examples below.

Always adjust the traces to show the maximum signal possible: Many of the measurements you will make on the oscilloscope will be done by eye. Even if you are letting the scope make the measurement, you will get the best accuracy if you use the full screen.

In the left-hand image of Fig. 1O.24, half the screen is going to waste vertically. This means that identifying features visually will be difficult and automatic measurements will be less accurate. The image on the right shows many identical cycles of the waveform, making it difficult to accurately make time-based measurements.
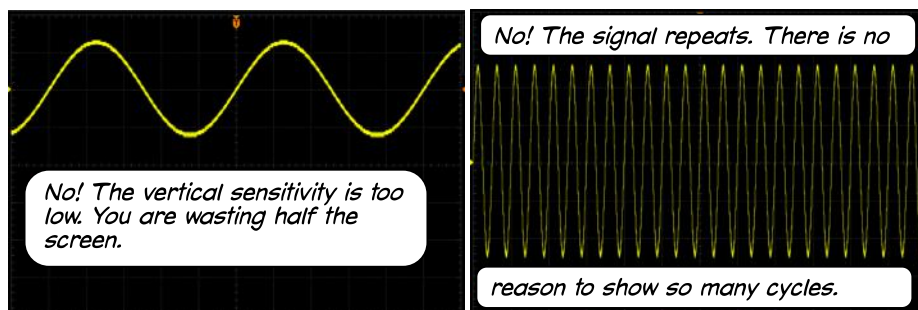

Figure 1O.24: Don't do this.

In Fig. 1O.25, the zero voltage location and the vertical scaling have been adjusted so that the signal takes up most of the vertical screen area. (If your circuit only runs on a single supply, the zero reference should always be near the bottom of the scope display since the signals can never go below ground.) In addition, the horizontal timebase (scale) has been adjusted so that only about two cycles are displayed.
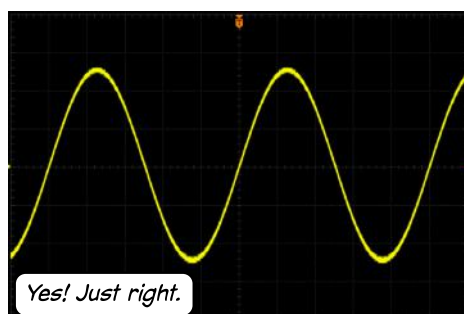

Figure 1O.25: Do adjust the signal to fill most of the screen vertically and only show a few cycles horizontally.

When displaying multiple signals, arrange them in a way that provides the most information. In general, if one signal is a processed or modified version of another, it makes sense to superimpose them to show the difference between the input and output.

Figure 1O.26 shows a scope image an input signal (yellow) and an output signal (blue) displayed in a way that makes the relationship between them very hard to see. Both signals are displayed at 2V/div and this presentation makes it look like they may be identical. (This is how the automatic display feature of your scope would most likely display the signals.)

Figure 1O.26: It may be difficult to determine the time relationship of traces stacked vertically.

However, if you overlay the same signals (by placing the zero reference points for each signal at the same vertical location), we can see that the output is slightly out of phase (i.e., delayed) from the input: see Fig. 1O.27.
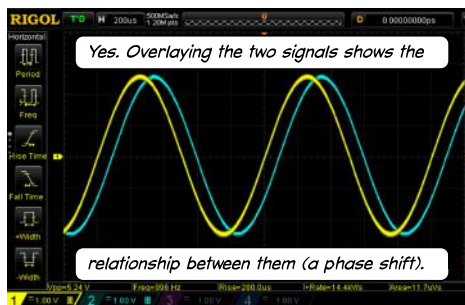

Figure 1O.27: Overlaying the traces makes it much easier to see the time relationship between them. Here it looks like the output from Fig. 1O.26 is the input delayed by about 100μs.

The "AUTO" button is your friend (sort of): On our scopes, this is the button in the upper right corner printed in reverse white on blue lettering. Once your probes are connected to signal sources, press the AUTO SETUP button to automatically adjust the vertical gain, horizontal timebase and triggering to display the signals. However, if you press AUTO SETUP with nothing connected to a channel, the vertical gain will be set to the maximum and you will see only electrical noise. Once autoset is complete, you will still need to adjust the vertical scale and position to use the maximum amount of screen to display the signal as described above.

The "DEFAULT" button is NOT your friend: If you scope has a "default" or "reset" button, pressing it resets the scope to factory settings. This will undo any changes you have made to the factory defaults (such as expanding horizontally around the trigger point, not the center of the screen) which may be better choices. The DEFAULT button is like a fire alarm – don't press it unless it is an emergency.

Do not use scope probes for anything other than oscilloscope input signals: One term, a student could not understand why nothing was coming out of the function generator connected with a scope probe: see Fig. 1O.28. This will not work! You cannot use a scope probe for an output signal. (If you are curious why – see §3N.2.)
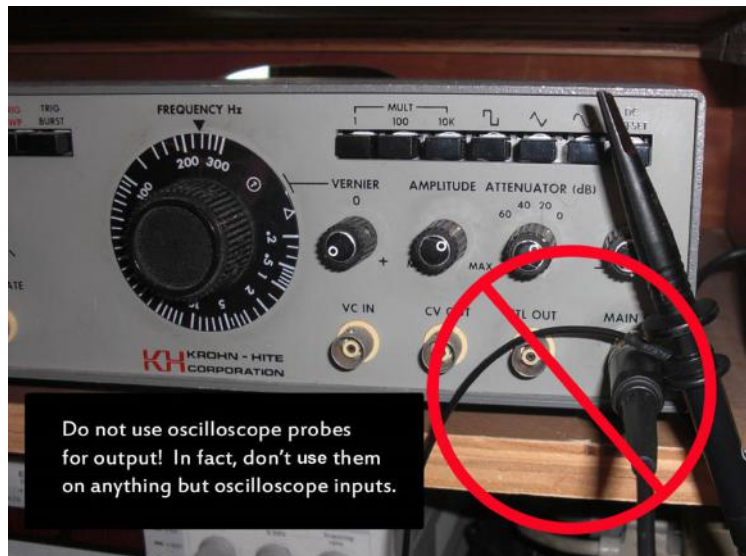

Figure 1O.28: This will not work. Scope probes are for oscilloscopes.

1O.4.3   Configuring and using a digital function generator

Each bench in our lab includes a Siglent SDG1032X Function/Arbitrary Waveform Generator (AWG): see Fig. 1O.29. While powerful, this instrument is menu driven and thus more complicated than the analog Khron-Hite function generator we used to use. Most functions are accessed through the set of six reconfigurable "soft keys" located just below the display. We use this instrument to generate continuous pulses, square waves and sine waves.

Certain functions display two legends above the soft keys. For example, a button might show both the words "FREQUENCY" and "PERIOD", however only one of these will be highlighted at a time. Pressing a button the first time selects the highlighted field. Once selected the parameter is shown with a blue background. Pressing it a second time switches to the alternate method of entering the controlling parameter.

To select a waveform type: Press the "Waveforms" button to display the waveform choices. A second page allows you to select a DC level as the output waveform. This is convenient when you need a specific DC value with high accuracy but do not need to output much power (i.e. not much current). "ARB" means an arbitrary waveform. Many are built in, but you can also use a PC and an editing program to create your own waveforms. We will not need arbitrary waveforms in any of our labs.

To set the frequency: Press the "FREQUENCY" soft key and use the keypad or the knob to adjust the magnitude of the desired frequency. Then select the desired units soft key.
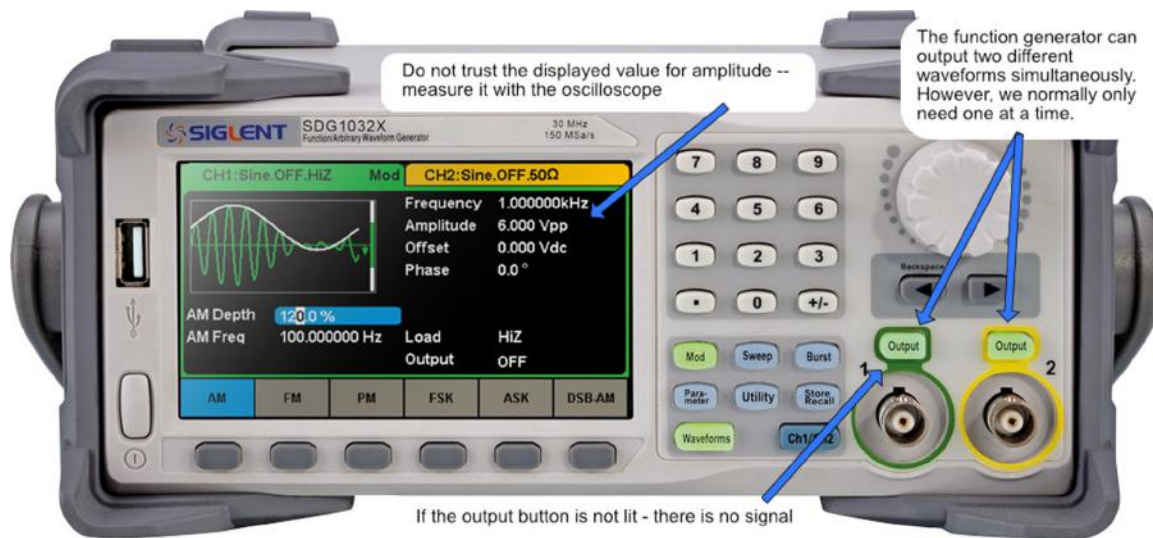
Figure 1O.29: Siglent two channel digital arbitrary waveform generator.

Alternatively, you can set the frequency by setting the period between signal repetitions.

To set the output amplitude: Press the "AMPLITUDE" soft key and use the keypad or knob to adjust the magnitude of the desired output. Then select the desired units soft key. *Many of the circuits in this course can be damaged by excess voltage. You should always measure the output with your oscilloscope to make sure you properly set the value you expect before connecting to your circuit!*

To adjust the DC offset voltage: Press the "OFFSET" soft key and use the keypad or knob to adjust the magnitude of the desired offset. Then select the desired units soft key. To make a signal unipolar, set the offset to one-half the output amplitude.

To set the high and low level output values: On square waves and pulses used with digital circuits, we often want to adjust the amplitude to give a 0 to 5 volt (or 3.3V) signal. The function generator allows you to set the high-level and low-level output values directly rather than having to set the amplitude and offset. Press the "AMPLITUDE" soft key to select it. Press the "AMPLITUDE" soft key a second time to toggle to "HIGHLEVEL." Note that the "OFFSET" soft key now shows "LOWLEVEL" highlighted. Use the keypad or dial to adjust the high output level. Then press the "LOWLEVEL" soft key and adjust the low level.

Other adjustments and features: The Siglent function generator can also be used as a frequency counter by selecting "COUNTER" from the "UTILITY" menu.

The function generator output is designed to drive either a high impedance load or a 50 ohm load. (Note that the displayed value for voltage and offset will be incorrect unless

"high-Z" mode is selected if you are not driving a 50 ohm load. That is why we insist that you measure the output before connecting it to any voltage sensitive circuit.) For higher frequency signals (which include almost any pulse or square wave) you will get less distortion by making sure the load impedance is around 50 ohms. However, this is rarely a concern in the circuits we build in this book.

One of the more complex uses of the function generator is to set up a sweep output. This is used to see the response of a circuit to multiple frequencies. In sweep mode, you set a starting frequency, an ending frequency and the time to sweep from the lowest frequency to the highest. You can also select if the frequency changes linearly with time or logarithmically. The latter simulates the way we draw frequency domain graphs. While you can sweep any waveform, the only one that makes sense in testing frequency response is a sine wave.

One problem with frequency sweep is displaying the sweep (and your circuit's output) on the oscilloscope. Since the output sine wave is a constant amplitude but changing frequency, there is no way for the scope to trigger on the sweep output at the start of a sweep. Luckily, the function generator puts out a signal (a low to high 0 to 5V signal) at the start of the sweep on an output on the back of the unit marked "Aux In/Out": see Fig. 1O.30.[5] Connect this output to a second channel on the scope (or the external trigger input on the scope if available) and use it to trigger the display when using the sweep function.

Figure 1O.30: Use the function generator trigger output signal to trigger the scope on a sweep waveform.

On the Siglent 1032X, you will need to enable the aux output in the function generator sweep setup menu by setting "Trig Out" to "On" to use this trigger: see Fig. 1O.31.

Figure 1O.32 shows the function generator sweep and trigger outputs on the oscilloscope.

1O.4.4 Using the handheld multimeter

We use a variety of multimeter makes and models in our labs. They are all very similar. Some are auto-ranging, but many require you to guess what the amplitude range of your signal will be. It is better to start on a higher range and decrease it than to subject the input to a much higher signal than it is expecting. (The multimeter is designed to withstand excess voltage or current but you may blow a fuse that temporarily renders the multimeter

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[5]On some function generators this output may be labeled "external trigger" or "trigger out."
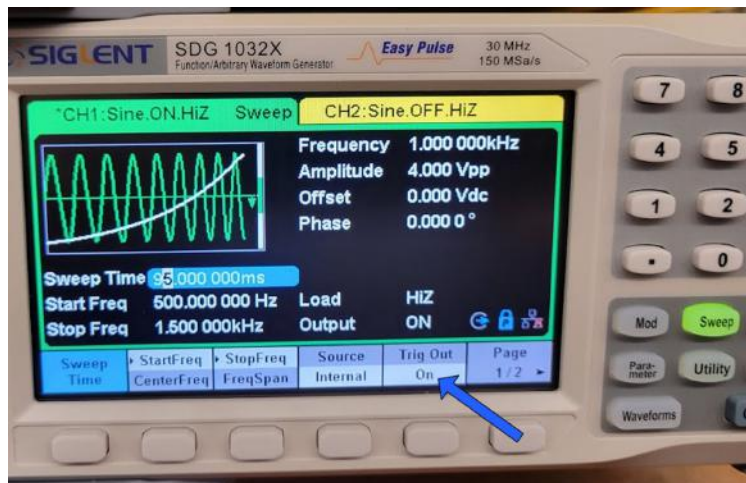
Figure 1O.31: On some function generators you may have to enable the trigger output.
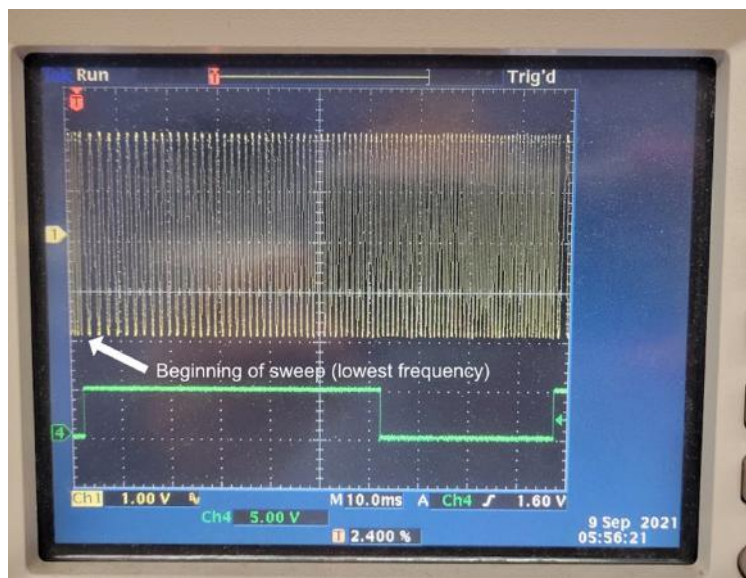

Figure 1O.32: Function generator sweep (yellow) and trigger (green) outputs.

unusable.) The newest are the Etepon WH5000A digital multimeters: see Fig. 1O.33. This model is sold under a number of different names on Amazon, but all have the same model number, WH5000A.

Warning: Do not connect the meter to a voltage source if the probe is connected to either of the current inputs marked in Fig. 1O.33. If you apply a voltage to the "uA mA" current input you will blow the internal fuse and be unable to use the current range again until you find a replacement fuse. In general, it is safer to always keep the red probe in the right hand "INPUT" jack and read the voltage across a shunt resistor to determine the current flowing through a circuit.

In addition to reading both DC and AC voltage, this multimeter can read resistance, capacitance, frequency and duty cycle. It also can provide audible indication of continuity and show both the polarity and forward voltage of diodes.[6] It is very useful for double-

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[6]The meter can also show the current gain of bipolar transistors (called "hFE" or "Beta").

This button is used to select between Ohms, continuity and diode measurements.

You will mostly be using these three ranges to measure DC voltage, resistance, continuity and capacitance

Be careful not to connect these current inputs of the multimeter to a voltage source. If you do, you may blow the meter's fuses.
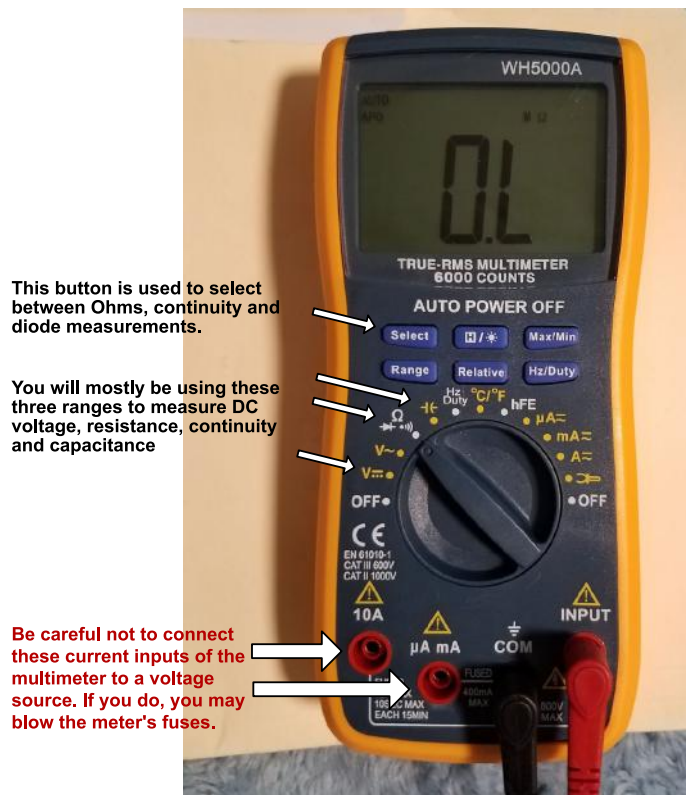
Figure 1O.33: WH5000A digital multimeter.

checking that a component is the value you think it is, particularly on hard-to-read metal film resistors and the "secret-handshake" value code on some capacitors.

You should insert the probes into the "COM" and "INPUT" jacks. Make sure the black probe goes into the COM input. The probes come with plastic shield that only expose the very tip of the probe. You may find it easier to use the multimeter if you remove these (they snap on) and use alligator leads to connect your circuit to the probes. Again, be sure to maintain the color codes for common and input.

This meter is auto-ranging, meaning it will select the best range for the input signal. Occasionally, you may find this distracting. You can use the meter in manual mode by pressing the "Range" button repeatedly to select a specific range you would like to use. Press and hold the "Range" button to return to auto-ranging mode.

Most of the time you will be using the three ranges highlighted in Fig. 1O.33. The left most range is used to measure DC voltage. Be sure the black probe is connected to ground so that polarity reads correctly. The next indicated range is used for three different measurements. The Ohms mode reads resistance. Note that you cannot read resistance when the resistor is in a circuit; at least one end of the resistor must be disconnected to read its value. This range is also used to test continuity (i.e., to see if two points are electrically connected together). If there is continuity, a buzzer will sound. Finally, this range is also used to measure the forward voltage drop of a diode. Be sure the red lead is connected to the diode anode. You sequence through these three modes by pressing the select switch. The third highlighted range measures capacitance. If the capacitor is polarized, the red lead must be

connected to the positive terminal. It may take several seconds for the reading to stabilize for larger value capacitors. Again, one end of the capacitor must be disconnected to read its value.

Be very careful when using the low current range input labeled "uA mA." If you accidentally blow out the fuse, you will not be able to make any low current measurements until it is replaced. Always move the probe back to the INPUT jack when you are done measuring current. If you connect the 10A input to a voltage source, the meter will short the source. If it is not current limited, it may blow the fuse or damage the source.

While the meter can also measure frequency and duty cycle, it makes more sense to use your oscilloscope to measure these, since the scope also allows you to visually make sure the signal is correct.

Please send comments or corrections to: authors@LAoE.link