Breadboard Circuit Implementation

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Building reliable circuits and connections on a breadboard, and debugging these practical circuits when things don't work as expected, is often a source of difficulty. So, after watching many students work in the lab, I decided to write down my opinions on how I would approach these problems in the lab for the most reliable results. Reliable circuit implementation is crucial in a practical product, but it's also crucial in research and education. If you want to design a circuit, and assess the performance of the circuit that you've designed, then reliable and consistent implementation of that circuit is crucial, or it will only lead to frustration and not any learning about your experimental circuit.

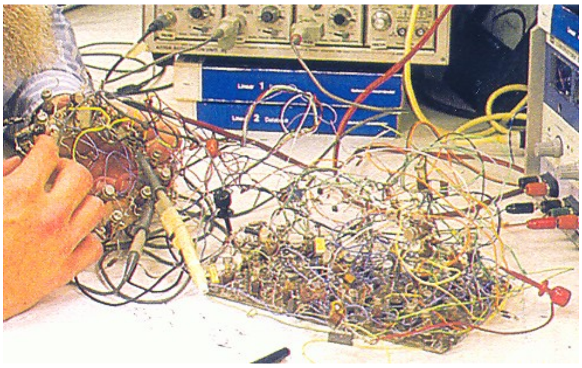

Figure 1: No.

This is a bad circuit implementation on a breadboard. *I don't care* if that's how Bob Pease does it, don't do this. When making a reliable and easily debuggable circuit layout on a breadboard, I suggest a few basic rules.

1. Make your breadboard layout as neat as possible.

2. Plan the layout of your breadboard circuit in a rational way that corresponds to the schematic diagram.

3. Keep components close together.

4. Use 22AWG solid wire for jumper wires.

5. Minimise the number of jumper wires used.

6. Keep all jumper wires as short as possible.

7. Trim long component leads, where possible.

I've never seen a textbook that covers these practical tools and techniques of tangible circuit implementation well - even the famous Horowitz and Hill [1] don't really cover this - they just assume that everybody can make the leap from a schematic diagram to a real-world physical experiment, and "solder" or "breadboard" does not appear in its index.

[1] Horowitz, P., & Hill, W. (2015). *The Art of Electronics*, 3rd ed.
One of my favourite reference books, and highly recommended!

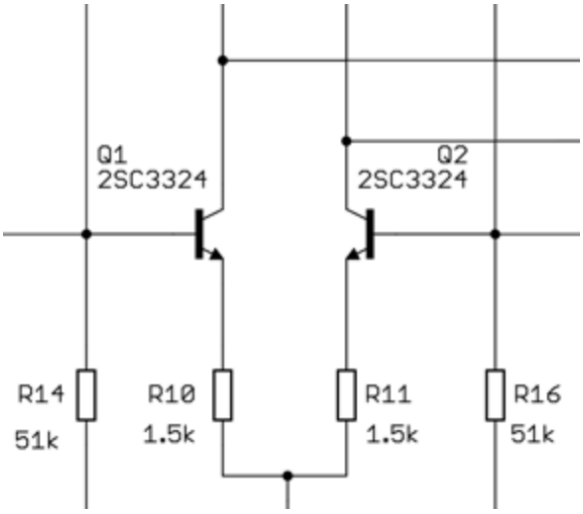

Figure 2: Ideal wires

Schematic diagrams that you're familiar with show components such as resistors and BJTs connected to each other with ubiquitous straight lines. But what are these lines, really?

Let's call them "ideal wires". These lines are assumed to have no resistance, no inductance, no capacitance to ground, no voltage drop, no ohmic heating, no limitation to their current-carrying capability, no insulation breakdown at high voltages, no loose connections, no coupling into other circuits, etc. It is assumed that one line is *one circuit node* and the voltage is always exactly the same at any point along this line at any time.

In reality, there is no ideal wire. But in low-power, low-current, low-speed systems, this model is OK. As with everything in engineering, this is always a tradeoff. It's time consuming to lay out and fabricate a bespoke PCB for every experiment and to do it again if you want to try a different circuit, so a solderless breadboard is one candidate tool (there are others) which helps to provide a decent tradeoff of rapid, flexible experimentation for circuits that are low-current systems at low speeds without tight demands on signal integrity.

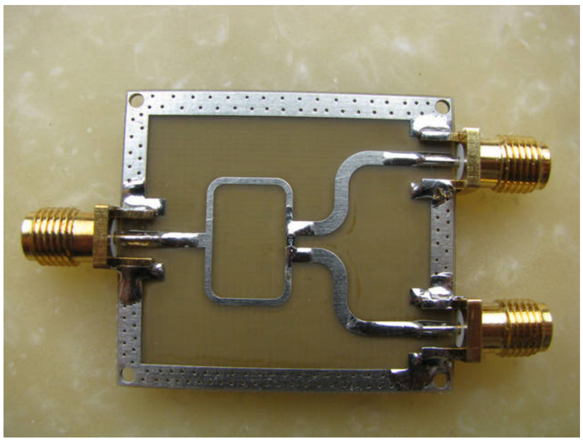

Figure 3: A strange (and elegant) wire.

Real wires need to be treated carefully as a crucial component of electronic design, not just an unimportant line on a schematic. Sometimes, when handled correctly, real wires can be put to work in interesting ways. Consider the circuit in the photo above, which consists of a wire, and a resistor. We have port 1, at left, and port 2 and port 3 at right. A wire connects port 1 to port 2 and port 3.[2]

There's a tiny surface-mount 100Ω resistor connected between port 2 and port 3. What happens to this resistor? So all three ports are always at the same potential. Right? Are they the same circuit node?
What does this circuit *do*, anyway?
Wires don't do what you think wires do.

[2]This is well outside the scope of a core course in electronic circuits - but it's cool.

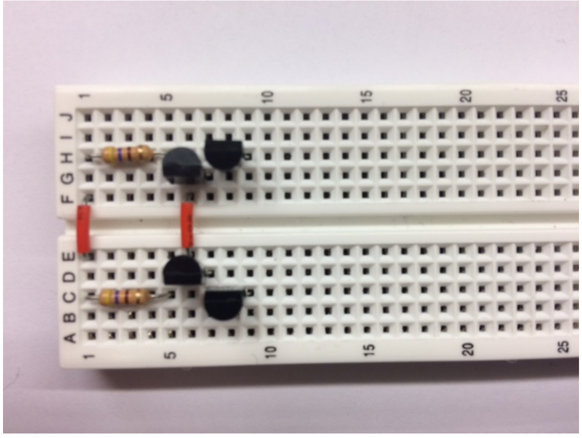

Figure 4: A good breadboard layout.

Figure 5: Resistor prepared for breadboard use.

A typical 1/4W through-hole resistor like this can be bent with its leads 0.4″ (10.16 mm) apart, leaving a sensible amount of bend radius after the leads have come out from the resistor body.

Figure 6: Bad breadboard wires.

Don't buy wires that look like the above. Avoid using these wires. They often make loose connections, and they're all quite long. With no short wires, your circuit will end up looking like an unwieldy mess of long wires all over the place. This makes your circuit really difficult to trace out and follow, making debugging almost impossible if a connection is loose or wrong - not to mention wires getting caught and falling out or coming loose.

When laying out a circuit on a breadboard, minimise the number of jumper wires used, and minimise the length of the jumper wires used. This minimises parasitic inductance or capacitance, and makes the breadboard circuit more mechanically robust, since shorter, lighter wires are less likely to be pulled out or fall out.

One "grid unit" on a breadboard is 0.1″ (2.54 mm), so a resistor bent like above will span four grid spaces on the breadboard. For example, in the above image you can see that one resistor has a lead in hole H1 and the other lead in hole H5. (Small components such as 1N4148 diodes can be bent at an 0.3″ pitch if you like, and resistors can be bent a bit wider, say 0.6″, if you want to connect two breadboard points further apart.) Then, cut off the vertical part of the resistor leads, leaving about 8 mm of height for the breadboard.

One of my favourite tools is a component lead-bending tool (for example SparkFun `TOL-13114`), which can be used for a clean, consistent 0.4″ resistor fold every time, without getting the spacing wrong or overstressing the wire with a tight bend.[3]

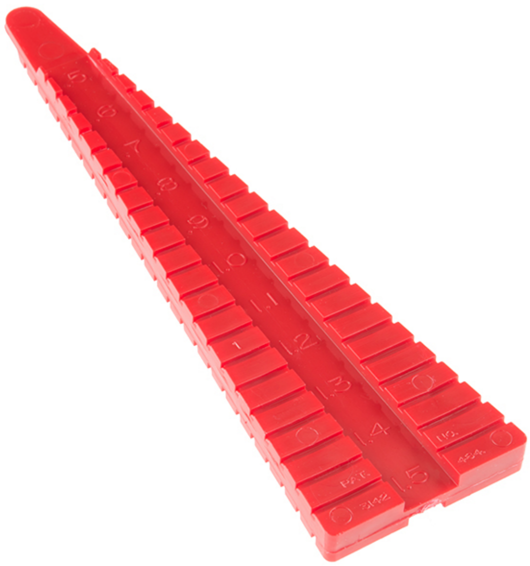

Figure 7: Lead-bending tool in 0.1″ increments, for through-hole axial components such as resistors.

Breadboard connections work best when made with solid-core 22AWG wire. The jumper wires shown below, made from a single piece of solid 22AWG wire accurately cut and folded, are the best choice for neat and reliable breadboard experiments.

Figure 8: Good breadboard jumper wires.

[3]If you have a 3D printer, try `https://www.thingiverse.com/thing:6703` for a similar DIY alternative.

The short, uninsulated one in the photo above is 0.1″ long (1 breadboard unit) and the brown one at the top is 1.0″ long (10 breadboard units). All the increments in between are colour-coded in 0.1″ units, just like the resistor colour code, so you know that if you need to hop seven spaces on the breadboard, you reach for the purple wires in the kit. In Figure 4 above, we can see that two orange wires are used to bridge the 0.3″ gap.

This also works well for Veroboard or similar "prototyping PCB" systems with 0.1″ grid pitch, or with bespoke PCBs, since 1/4W resistors are usually laid out on a PCB with the same 0.4″ footprint, and many other components follow a 0.1″ grid spacing.

Bulk rolls of 22AWG solid-core wire, such as Adafruit `1311`, are also handy if you need a longer jumper and you want to cut a piece that is exactly the right length. If component A connects to component B, plug them into the same breadboard node where ever possible. Don't add a jumper wire if you don't need one.

Don't be afraid to make a component value slightly "inaccurate". Suppose, for example, we calculate that in theory a particular resistor should be 5.0 kΩ. We could put 4.7 kΩ in series with a 330 Ω resistor, or a 4.7 kΩ in series with two 150 Ω resistors, for example. But usually you should just use a single 4.7 kΩ resistor.

Working in the lab on a breadboard, using three resistors in series instead of one resistor means you have six breadboard connections that may be loose or intermittent causing frustrating problems, instead of two. Adding three resistors to a circuit adds cost both in the bill of materials and in the manufacturing cost (e.g. solder), and it takes up more PCB area. Adding more components to a circuit makes debugging harder and makes repair harder. It increases the number of potential points of failure, such as the number of potentially faulty solder joints.

Like most practical engineering, it's all about knowing where to make certain tradeoffs, and when you can't. A well-designed circuit is relatively insensitive to the values of most passive components such as resistors. This obviously has some exceptions, such as voltage feedback networks or bias networks where the resistor values are important - but there's no point trying to pick component values stacked together to get a tolerance better than the tolerance of the claimed values of the components that you're using. 5% tolerance resistors are cheapest, and most common. The E12 series (1.0, 1.2, 1.5, 1.8, 2.2, 3.3, 3.9, 4.7, 5.6, 6.8, 8.2, 9.1) are most commonly used, the most commonly stocked, and are the best choice where possible. A reel of 5.1 kΩ, 5% resistors cost AUD$10.05, and a reel of 4.99 kΩ, 1% resistors cost AUD$12.99, and a reel of 5.0 k Ω, 0.1% resistors cost AUD$231.00 - an enormous difference.[4]

Now, back to that circuit in Figure 4 - a long-tailed pair. The two 2N3906 transistors at left form a current mirror, which sets the collector current into the differential pair made up of the two 2N3904 transistors at right. The emitters of both the 2N3906 transistors in the current mirror are connected to V_{CC} (column 1) via 470 Ω resistors, and the two 2N3906 bases are tied together with an 0.3″ jumper.

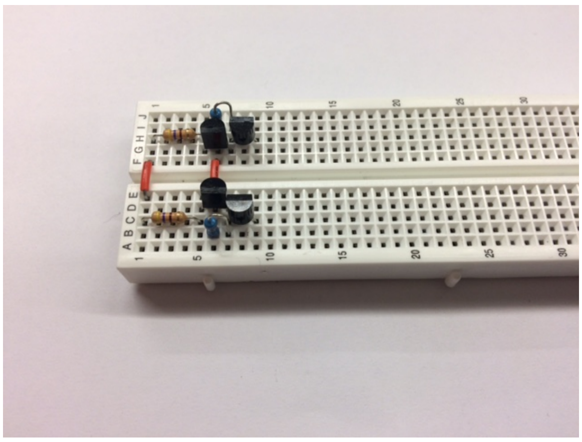

Figure 9: Step-by-step, compact, neat circuit layout on a breadboard.

[4]In small volumes, that is. These are the current Digi-Key Australian site prices for a single reel of 5000 Yageo 0603 chip resistors.

The collectors of the two 2N3904 transistors are connected directly to the collectors of the 2N3906 transistors, so they're simply put right next to each other and the 2N3904 transistors are facing the other way, so the collectors are joined together at column 7, and everything is neat and tidy.

Some resistors are placed between the base and the collector of the current mirror BJTs. To make this as neat and compact as possible, the resistor lead can be folded around a small screwdriver, pen or something with a diameter of about 2.54 mm, and then the resistor leads cut off at about 8 mm long.

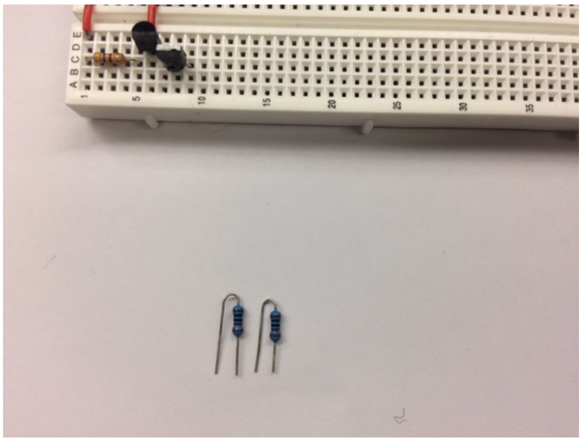

Figure 10: Resistors folded with 0.1″ lead spacing.

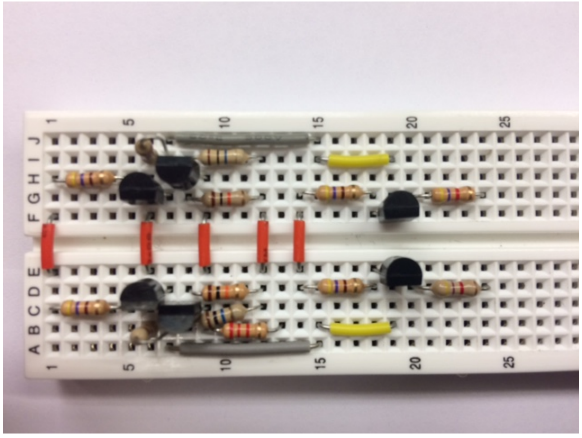

Figure 11: An almost complete circuit.

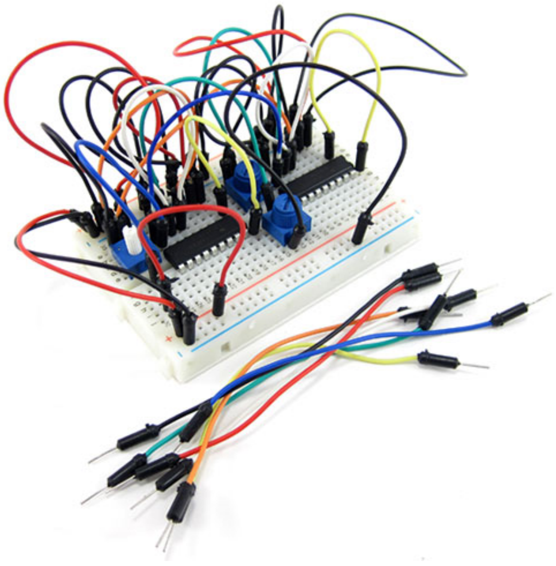

Figure 12: Here all the jumper wires are long. You can see how rapidly the circuit becomes a confusing mess.

It can be tricky to make a reliable connection between the breadboard and a cable with a female receptacle (such as the test cable on the Analog Discovery 2). The best way to do this is with a strip of extra-long, double-ended 0.1″ header pins. A normal pin header strip intended for PCB use is only a couple of millimeters long at the bottom of the plastic spacer, and isn't suitable for this breadboard connection.

Some of these headers are supplied with the Analog Discovery 2, but if you need to buy more then Adafruit `400` or Sparkfun `PRT-12693` are suitable.

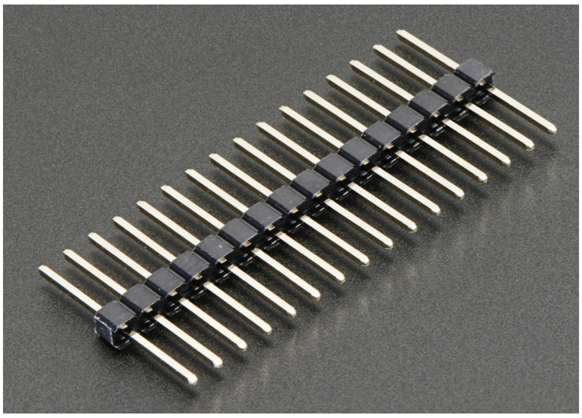

Figure 13: Double-length 0.1″ pin header strip.

Now, just keep going and carefully build up the circuit step by step, and try and keep each stage as neat as you can and arranged in a sensible place, checking that each connection and jumper wire is reliably connected.

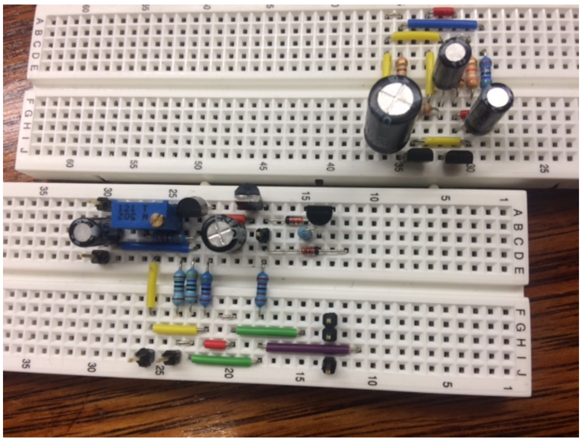

Figure 14: Here's another example of some circuits being laid out on a breadboard, in a compact and fairly neat way, with connections kept as short as possible.

Going back to practical component choices and design-for-manufacturability for a moment, specify the resistors or other components used to manufacture the design using the loosest tolerances you can. Specify a mandatory 1%, where it's needed, but leave it unspecified where it doesn't need to be better than 1%.

In practice, many things do get built using 1% resistors for everything today, since the price difference is negligible, and simplifying the bill of materials, and having less distinct line items to load into the pick-and-place machine, usually negates the cost. Call up your assembly factory right now, and they will almost certainly have reels of 4.7 kΩ already loaded on the machine - but probably not 4.99 kΩ.

(This is often largely irrelevant for a university lab, where you're provided with a "pre-cooked" and fairly limited set of components to choose from. But it's valuable to think about, since economics tends to be one of the most important factors in any system design in industry, especially for systems manufactured at scale.)

Some breadboards do have power rails, allowing neater, shorter connections to the power rails, since most circuits usually have many. You don't *need* to have such a breadboard, but it can help to make things neater in more complex circuit designs, and it makes it easy to plug a decoupling capacitor across V_{CC} and ground.

These jumper wires, with cheap generic clones of Amphenol FCI Mini-PV series $0.1''$ rectangular housings (formerly Dupont Connector Systems, hence the common reference to "Dupont connectors") are now ubiquitous. They're usable and quite handy - especially if you need to connect a breadboard to another external PCB which has $0.1''$ headers. They can also be used with a 2×15 housing, to make a custom interconnect cable that plugs into the Analog Discovery 2, using whatever connectors or interface you choose.

Figure 15: Jumper wires with generic $0.1''$ header-style rectangular connectors.