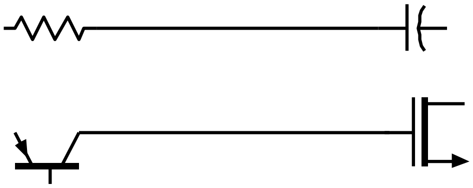
Lab Hints

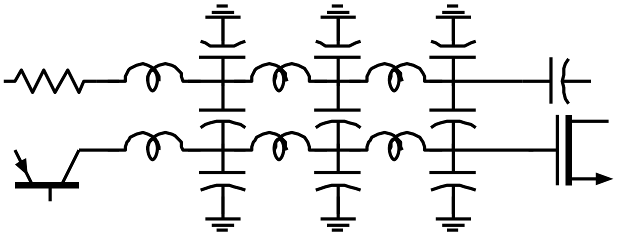
How to reduce the degree of effort in testing lab assignments

General Wiring parasitics

On a circuit diagram, wires appear as simple lines, like so



The voltages are equal at 2 wire ends, and the current entering on one end equals the current leaving on the other. This ignores the electromagnetic nature of the wires, and is approximately true only if the wires are very short. ECE144A gives a full treatment of this problem, and 145ab covers transistor circuit design including the effect. What follows below is approximate.



Real wires (above) have inductance per unit length (both self-inductance and mutual inductance between nearby wires) and capacitance per unit length (both to ground and to nearby wires.

How big is the effect ? A typical wire has ~50 pF/meter capacitance to ground and ~500 nH/meter series inductance. At 300 MHz, the current-gain cutoff frequency of an extremely cheap discrete bipolar transistor, a one meter length wire has ~100 Ohms of parallel shunt capacitive reactance to ground and ~900 Ohms series impedance.

Given the difference between the 2 above figures, there are 3 design alternatives

1) Use long wires, yet ignore their electromagnetic nature. This will result in designs which don't work properly, the usual problem being unexpected oscillation--an output signal appearing spontaneously without a corresponding input being applied. Oscillations tend to be present in 50-75% of undergraduate design projects, and cause difficulties with unexpected shifts in bias conditions, excessive device dissipation, and reduced overload margins.

2) Use moderately long wires when necessary, but model their effect carefully. This is called RF/microwave circuit design, and is the subject of 145ab.

3) Keep the wires sufficiently short that wiring parasitics are reduced to negligible levels.

I recommend alternative (3) for 137ab lab projects.

Oscillation

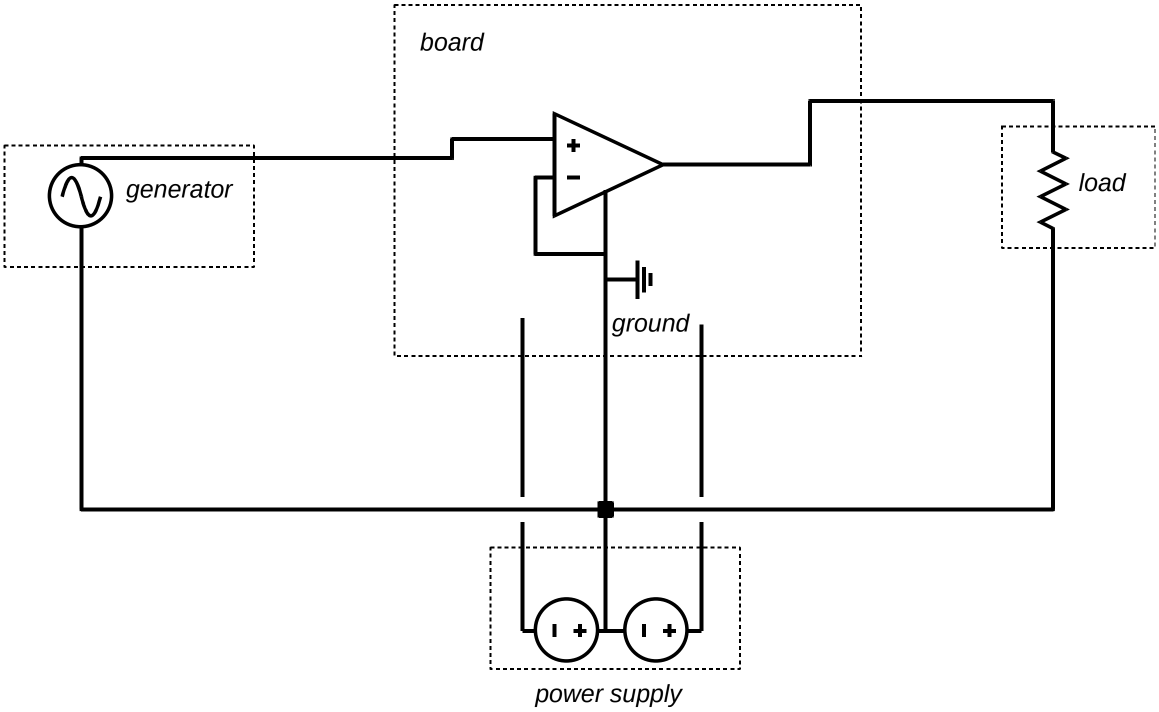
An output with no input present. Commonly caused by accidental feedback from an amplifier output back to its input, a familiar example being placement of a microphone in front of a speaker in a Public address system, and the resulting acoustic howl.

Such feedback can arise from
--coupling between the input and output wires of the amplifier
--coupling through the power supply. The supply is assumed to be an AC ground, but will only be so if adequately bypassed on the circuit board by AC power supply bypass capacitors
--coupling through the ground system.

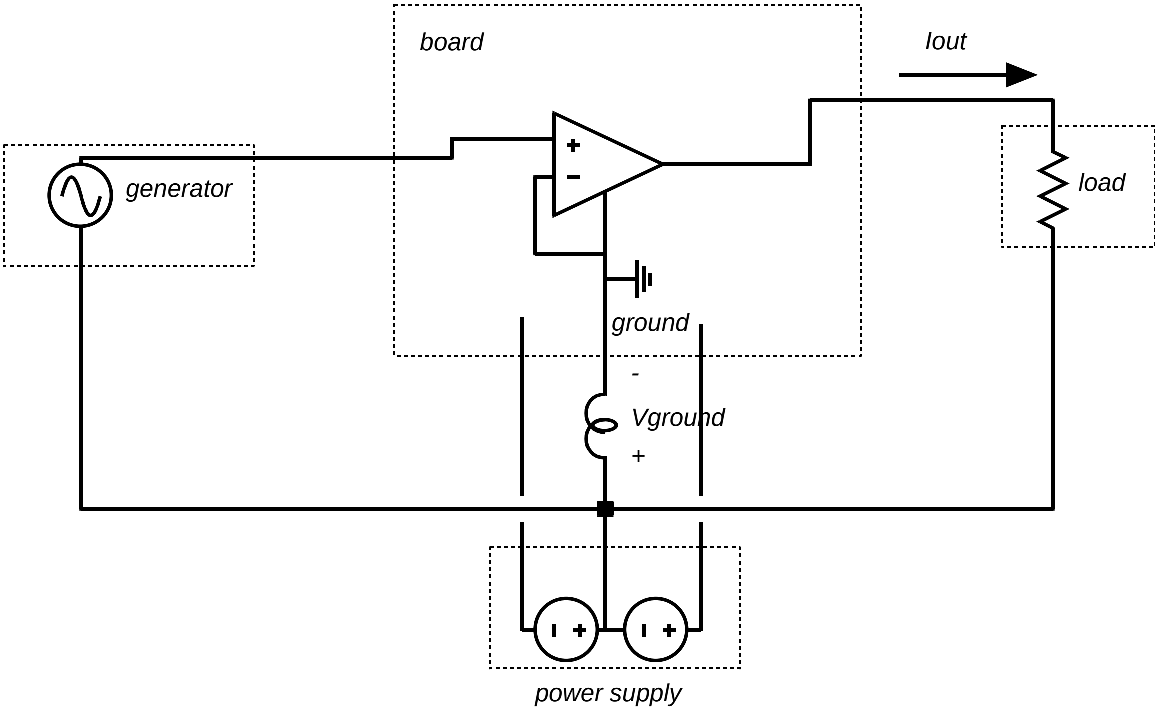
It is important to note that the oscillation can arise at any frequency within the transistor bandwidth. Even the most inexpensive transistors have cutoff frequencies of a few hundred MHz, so the circuit construction must be sufficiently careful that the wiring capacitive susceptance $j\omega C_{wire}$ and inductive reactance $j\omega L_{wire}$ are negligible at the transistor cutoff frequency, even if the circuit intended operational frequency is much lower.

Coupling & oscillation due to sloppy wiring on the bench

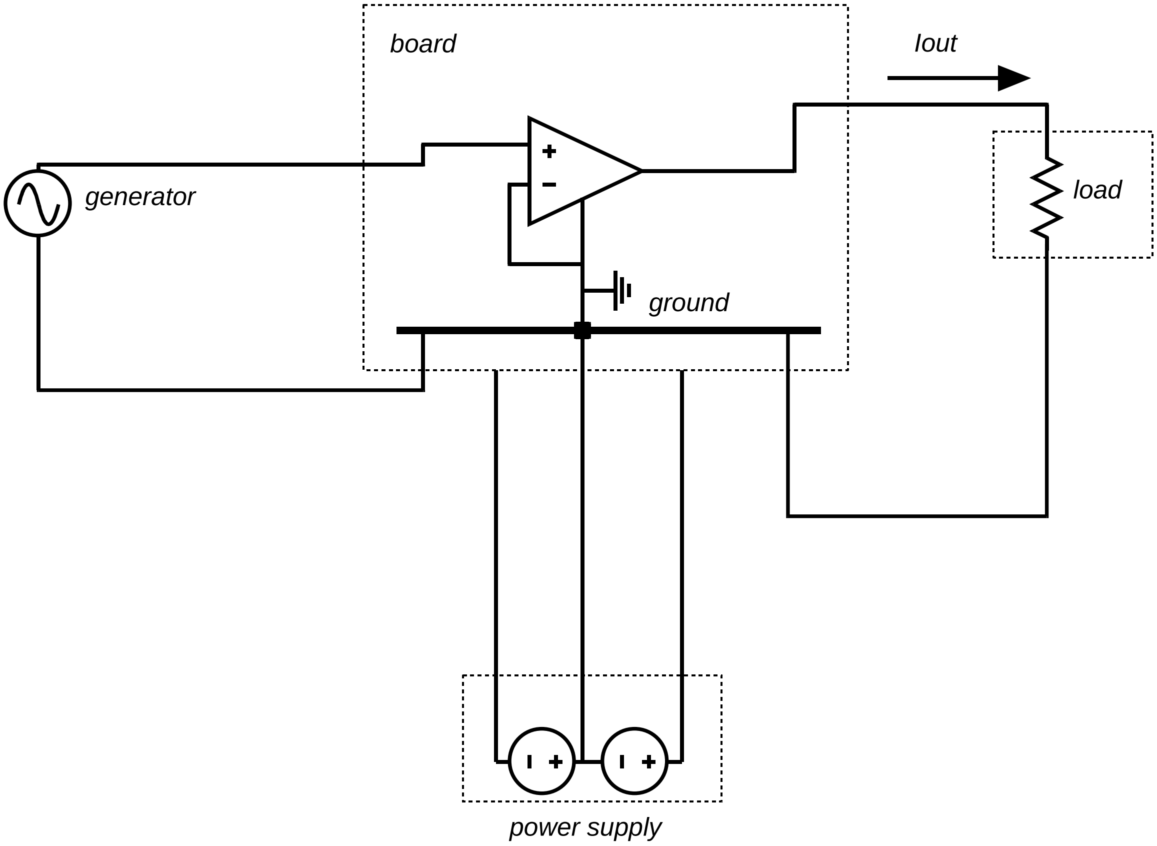
<u>Sharing of ground connections on the bench</u>



Here a well-constructed amplifier is connected on the bench. A single wire is used to connect the amplifier to the grounds of the supply, the load, the generator, and perhaps the oscilloscope. The wire is long, perhaps 1-2 feet.



The amplifier oscillates. The above diagram shows why. Inductance in the long shared ground lead leads to a coupled ground voltage of $V_{ground} = L_{ground} \bullet j\omega I_{out} = L_{ground} \bullet j\omega V_{out} / R_{load}$. The input voltage applied to the amplifier is the sum of the generator voltage and the ground voltage. A feedback path from output to input is present.



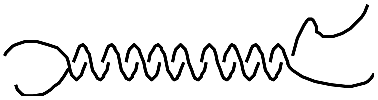
The solution, as shown above, is to provide a separate ground connection between each instrument / load / supply / etc and the board under test. The ground system on the board in turn must then have low inductance. This is discussed later.

Coupling between input and output though disorganized wiring

If there is a tangle of wiring on the bench, capacitive coupling between wires connected to input and output can also cause feedback. So,

1) Keep the wires on the bench short, tidy, and keep input and output connections away from each other

2) Wrapping e.g. + and - wires together in pairs (for the load or for the power supply connections) reduces both capacitive and inductive coupling. Like so:



4) While it is convenient to measure amplifier gain by using channels 1 and 2 of the oscilloscope to measure amplifier input and output simultaneously, coupling between the scope probes can cause oscillation. It is better to use 1 probe and to connect the scope alternately to input and output.

Oscillation due to capacitive loads

Certain circuits, emitter/source followers particularly, are prone to oscillation when driving heavily capacitive loads. The scope probes used in the 137ab lab have ~100 pF/meter shunt capacitance, and are ~ 1meter long. This is sufficient to cause difficulties. If probing such a circuit, place a 50 Ohm resistor between the amplifier output and the oscilloscope probe. Better remedies for this difficulty will be covered in lab1 of 137b.

Oscillation due to circuit construction.

Ground system inductance

Oscillation due to finite ground system inductance on the test bench was discussed above. Similar effects often arise within the circuit board layout itself. The most easily-implemented solution for the circuit board ground impedance difficulty is to minimize the ground system inductance on the circuit board. Ground connections are provided not by long, thin (highly inductive) wires, but by a short and wide (low inductance) ground plane on the circuit board.

Power supply bypass capacitors

Coupling from the amplifier output stages back to the amplifier input stages can arise through the power supply, insofar as it can support a signal voltage. This would result in the case of non-zero power supply voltage. While the power supply on the lab bench has a low output impedance, it is connected to the circuit under test by several feet of wire. The wire impedance at a few hundred MHz is several hundred ohms, and the power supply impedance seen by the amplifier can thus be very large.

The power supply must therefore be AC grounded on the circuit board using bypass capacitors on the circuit board. I suggest a parallel combination of an electrolytic capacitor in the 10-100 microfarad range with smaller ceramic capacitors in the 0.1 uF range.

For future reference, please note that the wiring inductance and the bypass capacitance will form a parallel LC resonator, and we have thus not entirely solved the problem. For ECE137ab we will ignore this subtlety. Note, however, that if you should later be involved with RF/wireless IC or system design, that bypass capacitors often must be accompanied by a small series resistance whose function is to damp and thereby suppress this resonance.

Wiring parasitics on the board

Later classes (145abc) will cover the design of transistor oscillators, implemented either using explicit external feedback, or (fundamentally but not obviously equivalent) by adding appropriate inductances and capacitances to a single-transistor amplifier stage.

Common oscillator designs:
Emitter/Source follower with inductance in the base lead and a capacitive load.
Common base/gate with inductance in the base lead and a capacitive source.
Common emitter/source with inductive generator and load (harder).

Wiring parasitics on the circuit board (or IC) can easily produce such configurations by accident. Keep the wires short.

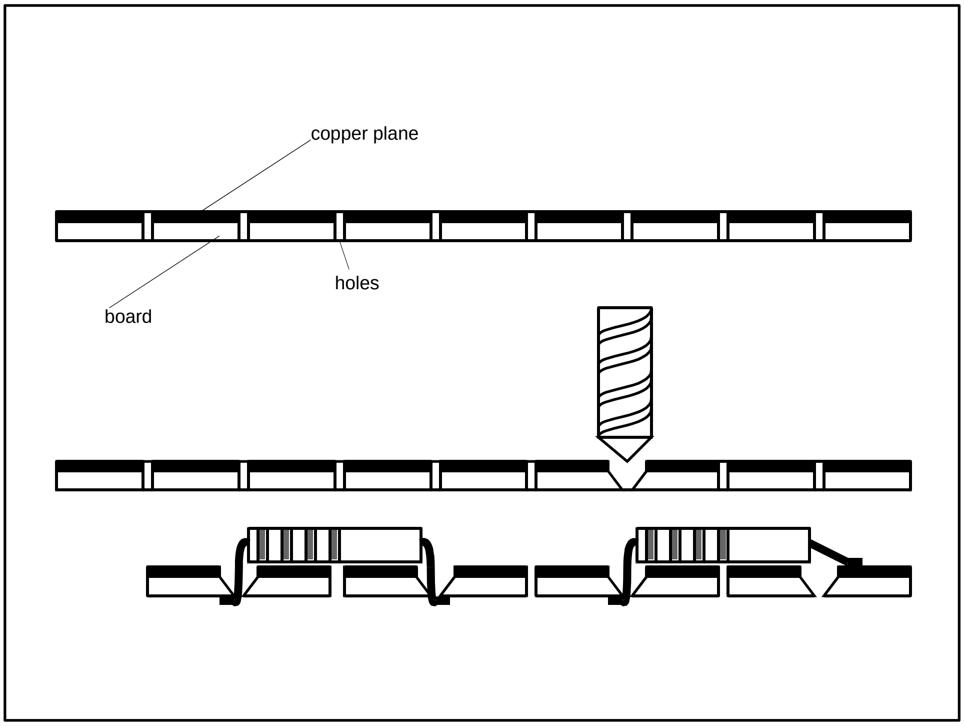
Circuit Construction

From the above, the circuit should be made physically small

Copper-clad ground-plane circuit board

This material is stocked by the shop. All ground connections on the board are made by soldering the ground lead of relevant components directly to the copper ground plane. The plane is wide, hence ground system inductance is made small.

Copper-plated "perfboard" is a board with a pre-drilled array of holes at 0.1" spacing, coated one side with copper. Components leads are passed through the board…they will inadvertently short to the ground plane. To avoid this, grab a small drill bit in your fingers, and use it to bevel the holes, as shown. Wires to ground are soldered directly to the ground plane. Wiring between components can be done by running wires and soldering them to parts. Or, you can run wiring traces on the board using thin strips of sticky copper tape…the shop usually stocks this. The glue on the tape does not conduct, so joints between copper tape strips must be soldered.



Not Copper-clad ground-plane circuit board
If this seems too hard, use the usual unclad board. But, make a ground plane on it by using a WIDE strip of sticky copper tape. Use this for all your ground connections.

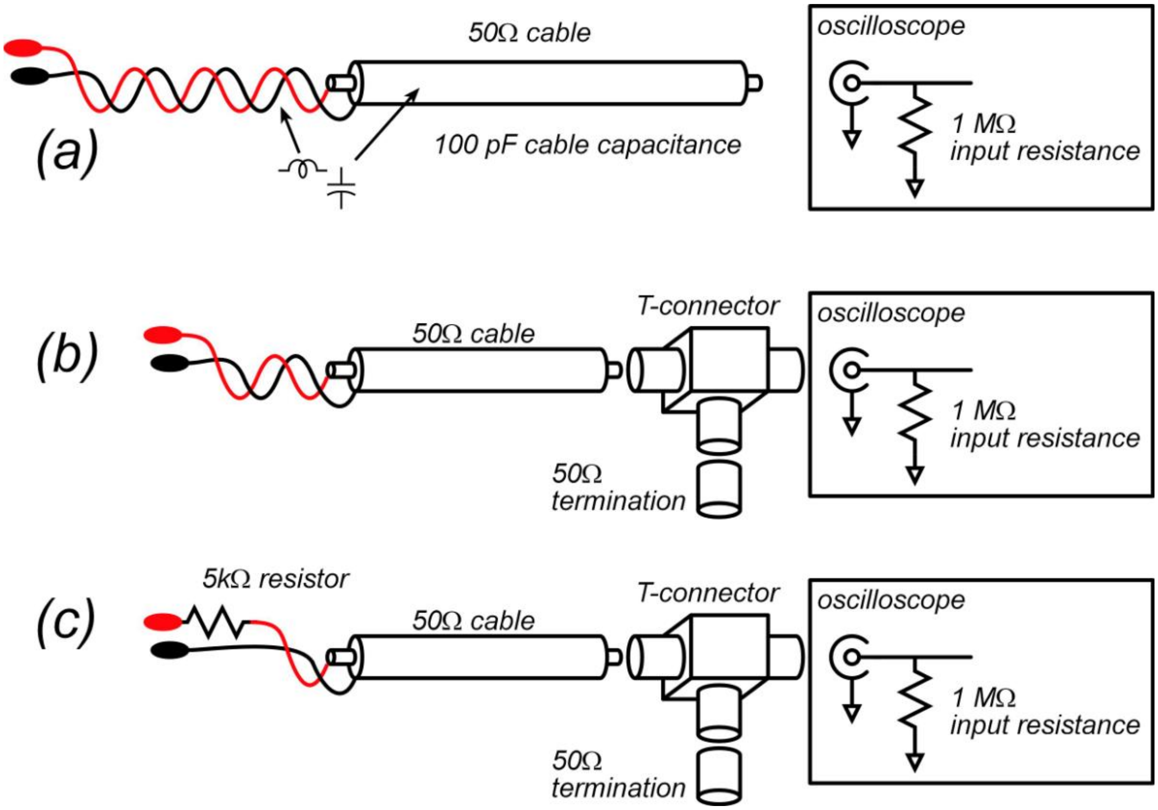
Proto-board

Initial design verification uses this. Keep the wires short. Cut component leads so that the device sits flush on the board, rather than 1-2 inches above it. Make the interconnecting wires short.

Generally

Use power supply bypass capacitors. Solder wires to the board to connect power. Wrap the +V/Ground/-V power wires together into a single twisted "rope".

Probing High-Frequency circuits



Probing high-speed circuits is a general challenge. Any connection between a circuit under test and an instrument will load the circuit in some fashion. Here are some suggestions on how to handle this.

In the top image (a), the circuit under test is probed with an oscilloscope, with the circuit and oscilloscope connected with a coaxial cable with alligator clip-leads. Unfortunately, the cable has c.a. 100pF/meter shunt capacitance: depending upon the impedance of the circuit node being probed, this may introduce a large RC time constant, and reduce the circuit bandwidth. Further, the inductance of the clip-lead wires may resonate with the cable capacitance to produce ringing.

In the central image (b) , the cable is loaded ("terminated") at the receiving end by a 50 Ohm termination. One can use a T-connector and a 50 Ohm terminator, or (better but more expensive) a 50 Ohm feed through termination. Some oscilloscopes allow you to select a 50 Ohm input impedance. If the cable is terminated in 50 Ohms, then (by transmission-line theory) the effect of the cable capacitance is eliminated. Using shorter clip-leads , the wiring inductance is also reduced. This is a good high-frequency connection, but the circuit is now loaded in 50 Ohms. Unless the circuit is designed for such loading, the gain and even the DC bias conditions can be upset.

A third alternative (c) eliminates this loading. Cut the signal lead connecting to the alligator clip, and solder in a 5 KOhm resistor. With a 50-Ohm-loaded cable, the effects of the cable capacitance is eliminated. The circuit is now loaded in 5KOHms, which is less likely to change the gain or DC bias conditions (but, you must check...). The 5kOhm resistor and the 50 Ohm termination form a 100:1 voltage divider, hence the signal measured on the oscilloscope is 1:100 of the circuit voltage.   You could use a 50kOhm resistor if you needed yet smaller circuit loading.