Chapter 4L

Lab 4: Bipolar Transistors I

Contents

Time: Total time: 2:40 (2 hrs, 40 min)

REV 2[1]; October 30, 2014.

4L.1 Transistor Preliminaries: look at devices out of circuit

4L.1.1 Transistor Junctions are Diodes

Time: 10 min

Here is a method for spot-checking a suspected bad transistor: the transistor must look like a pair of diodes when you test each junction separately. But, *caution:* do not take this as a description of the transistor's

[1] Revisions: respond to Paul's notes, change subscripts to lower-case (8/14); add headerfile (6/14); add index (2013?); amend text ref re Beta; add many answers to questions posed in lab; double base drive of switch (9/13); add index (7/12).

mechanism when it is operating: it does *not* behave like two back-to-back diodes when operating (the circuits of fig. 1, if made with a pair of ordinary diodes, would be a flop, indeed:)

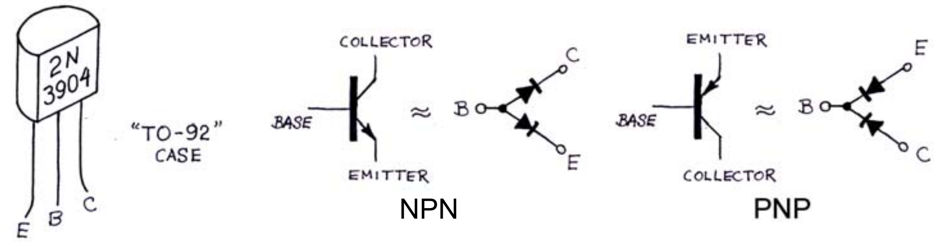

Figure 1: Transistor junctions: (for testing, not to describe transistor operation)

4L.1.1.1 A Game: discover transistor type and pinout, on desert island

See if you can determine the *type* (NPN or PNP) and *pinout* (base, emitter, collector leads) of a 2N3904 transistor by *experiment*. (On a desert island with DVM and a box of unknown transistors, you could sort and label the transistors; thus you could start the process of building a radio transmitter to summon your rescuers.) You can settle both *type* and *pinout* questions by flipping to the pinout section at the back of this book, of course.

But try using a DVM, instead, employing its *diode test* function. (Most meters use a diode symbol to indicate this function.) The diode test applies a small current (a few milliamps: current flows from Red to Black lead), and the meter reads the junction voltage. Using the diode-test function, you can determine the directions in which pairs of leads conduct. That will let you answer the *NPN vs PNP* question. You can also distinguish *BC from BE* junction this way: the BC junction is the larger of the two junctions, and the lower current density across that *larger junction* is revealed by a slightly *lower voltage drop*.

4L.1.2 'Decouple' Power Supplies: Fuzz Warning

This is the first lab in which you may see high-frequency oscillations on your circuit outputs. At a modest sweep rate, this fuzz will look like a thickening of the trace; at a high sweep rate it may reveal itself to be a more-or-less sinusoidal waveform in the range between a few hundred kilohertz and 100MHz. If you see such noise, you need to quiet your circuit with *decoupling* capacitors. See the note that follows these lab exercises, below (§ 4L.6 on page 9).

4L.2 Emitter Follower

Time: 15 min

Wire up an NPN transistor as an emitter follower, as shown below. Drive the follower with a sine wave that is symmetrical about zero volts (be sure the dc"offset" of the function generator is set to zero), and look with a scope at the poor replica that comes out. Why does this happen?[2]

If you turn up the waveform amplitude you will begin to see bumps *below* ground. How do you explain these?[3]

[2]This is pretty simple: when V_{in} falls below about +0.6V we are violating one of our transistor "ground rules:" we are failing to permit forward-biasing of the V_{BE} junction. I_{C} and I_{E} fall to zero.

[3]Powerful hint: the data sheet for the 2N3904 shows V_{BE} breakdown can occur—for a *reverse* bias across the BE diode—at a voltage as low as 6V.

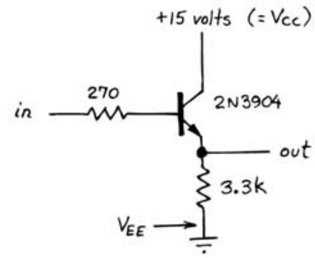

Figure 2: Emitter follower. The small base resistor is often necessary to prevent oscillation

Now try connecting the emitter return (the point marked V_{EE}) to -15V instead of ground, and look at the output. Explain the improvement.

4L.2.1 Input and Output Impedance of Follower

Time: 45 min

Measure Z_{in} and Z_{out} for the follower below.[4]

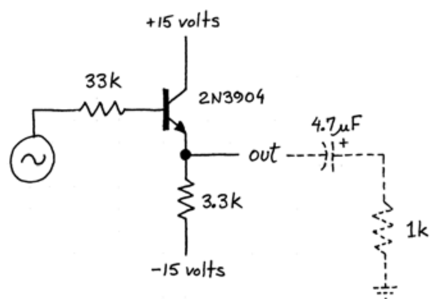

Figure 3: Follower: circuit for measuring Z_{in} and Z_{out}

4L.2.1.1 Measure Z_{in}

In the circuit of fig. 2 on the facing page replace the small base resistor with progressively-larger resistors, in order to simulate a signal source of moderately high impedance, i.e., low current capability.

Start with 33k, as shown in fig. 3; you are likely to see attenuation of only 5% to 10%, With such small attenuation, it is possible but tedious to infer β.

If you install larger resistors in place of this 33k, eventually you will see attenuation of about 50%, and then your observation (and your arithmetic) will become easy. You'll know, if you get to 50% attenuation, that your installed R is about equal to R_{IN}. Use this data to make your inference of β.

Caution: Make sure that it is R_{IN} that you are observing, and not an effect of C_{IN} or C_{probe} that you are seeing. To make sure of this, adjust the input frequency until no appreciable phase-shift appears between the original signal and what you see at the transistor's base.

With 1k "load" *detached*, measure Z_{in} for the circuit. In this case, that is the impedance looking into the transistor's base (the 33k series resistor, or the larger value you may have installed, is *not* a part of the follower. It is included to model a signal source with mediocre R_{out}). You can discover Z_{in} by using the

[4] We are calling this "Z," but what interests us here is really R; we want to avoid effects that are frequency dependent. Particularly, we don't want to find ourselves studying attenuations caused by stray capacitance.

scope's two channels to look at both sides of the base resistor. For this measurement the 3.3k emitter resistor is treated as the follower's"load". Use a small signal—less than a volt in amplitude.

The attenuation that you see may be *slight*, at least at first, and therefore hard to measure. If you are using a digital scope you can be lazy, using its amplitude-measurement functions. If you are using an analog scope, you need to work harder. The best way to measure a small attenuation, using an analog scope, is to take advantage of the *percent* markings on the scope screen.

Suggestions for Measurement of Z_IN (analog scope)

- center the two waveforms on the 0% mark–these are the waveforms that appear on the two sides of the base resistor: let's call the waveforms"source" and"input";
- *AC couple* the signals to the scope, to ensure centering;
- adjust the function-generator's amplitude to make the *source* peak just hit 100%;
- now read the *input* waveform's amplitude in percent.

Does your result make sense? Is the follower transforming the impedance"seen through it," as promised? Once you have measured a value of Z_{IN} you can infer the transistor's β (or"h_{FE}"). (See AoE §2.1.1). Make a note of this calculated β; in a few minutes you will want to compare it to the β you infer from your measurement of Z_{out}.

4L.2.1.2 Measure Z_{out}

Replace any other base resistor you may have installed, *returning to the value of 33k shown in fig. 3 on the preceding page*.[5]

Now measure Z_{out}, the output impedance of the follower, by connecting a 1k load to the output and observing the drop in output signal amplitude; again use a small input signal, less than a volt.

The procedure for measuring Z_{out} is slightly different from the one used to measure Z_{in}.

In order to measure Z_{out}, you need a two-step process:

- with *no load* attached, measure the amplitude of V_{out}
- then attach the 1k "load," and note the resulting attenuation;
- infer Z_{out}: you recall that you have built a voltage divider, where the upper "resistor" is the circuit's Z_{out} and the lower "resistor" in the divider is the load. The value of the *base resistor* is critical to your calculation, of course; this is the "source resistance" that the follower reduces by the factor β. So make note of what base resistor you are working with.

Infer β once again: in principle it should match the β you inferred from your measured Z_{in}.

[5] Larger R values make your work harder, not permitting you to ignore the effect of R_E, whose value strictly parallels the path through the transistor. This exercise is hard enough without that complication.

The Blocking Capacitor used in measurement of Z_{out}

Why do we suggest that you use a blocking capacitor as you measure Z_{out}? The answer is rather subtle, in this case, because here you could get away with omitting the blocking cap; but in many other cases you could not get away with that.

We include the blocking capacitor so as to avoid disturbing *DC* levels in the circuit, while we watch what happens to time-varying (or *AC*) *signals*. In this case, the DC level at the emitter is approximately one volt negative; this is close enough to ground so that omitting the blocking cap would do no harm. Omitting the cap would alter that level only slightly. But in many other cases, where the emitter's DC voltage happened to be well away from ground, attaching a 1k *DC* "load" to ground would alter the DC or "bias" level appreciably. We do not want to do that; we mean only to see what the load does to *signal* amplitude (and we assume the signal is a voltage *wiggle*).

It's too bad that the cap in this case doesn't provide a more striking benefit. But we are trying to teach you a good habit: if you're interested in AC behavior, measure that behavior without disturbing DC conditions.

4L.3 Current Source

Time: 20 min

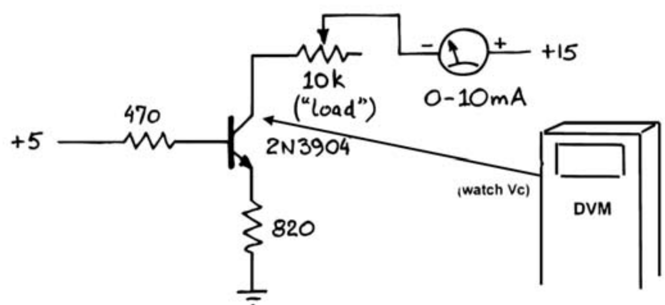

Figure 4: Transistor current source

Construct the current source shown above (sometimes called, more exactly, a current "sink").

Slowly vary the 10k variable load, and look for changes in current measured by the VOM. What happens at maximum resistance? Can you explain, in terms of *voltage compliance* of the current source ("compliance" is jargon for "range in which the circuit works properly)?[6]

Even within the compliance range, there are detectable variations in output current as the load is varied. What causes these variations?[7]

4L.4 Common Emitter Amplifier

e: 20 min

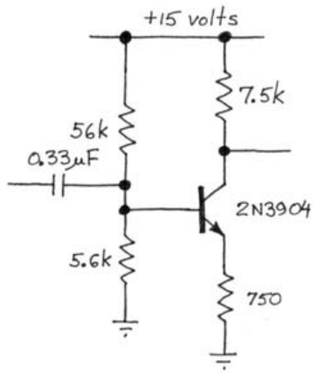

Figure 5: Common-emitter amplifier

Wire up the common emitter amplifier shown above. What should its voltage gain be? Check it out. Is the signal's phase inverted?

Is the collector *quiescent* operating point right (that is, its resting voltage)?[8] How about the amplifier's low frequency 3dB point?[9] What should the output impedance be?[10] Check it by connecting a resistive load—let's say *7.5*k—using a blocking capacitor. (The blocking cap, again, lets you test impedance at signal frequencies without messing up the biasing scheme.)

4L.4.1 Maximizing gain: sneak preview of Ebers-Moll at Work!

20 min.

Now let's try a case that our first, simple view of the common-emitter amplifier does not describe accurately: let's watch what happens if we parallel the emitter resistor with a big capacitor, so that at "signal frequencies" $R_{\rm E}$ is shorted out

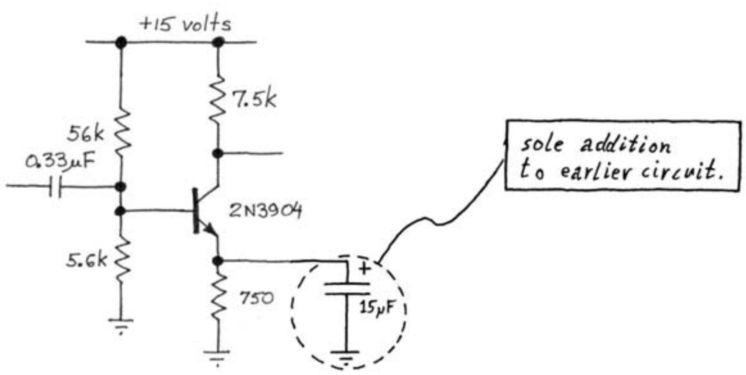

Figure 6: Grounded emitter amplifier

Modify your common-emitter amp, so as to make the amplifier shown above (similar to Classnotes 5, fig. 17).

[6] The current source fails when the transistor saturates. The DVM will let you measure $V_{\rm CE}$. Thus you can look for the relation between saturation and the fall of $I_{\rm out}$.

[7] Early Effect is the principal cause: varying $V_{\rm CE}$ slightly varies the effective base width. See Supplementary Note 5S2 on Current Mirrors and Early Effect.

[8] What level would be "right?" The voltage that permits the widest swing without "clipping"—hitting either upper or lower limit. Roughly, that quiescent point would be half the supply voltage. A perfectionist would say, "Better to put it midway between the lower limit of about 1V (V_E) and the supply. But with a 15V supply we don't mind the lazier answer, "half the supply voltage." This will be our usual answer, for single-supply circuits.

[9] To calculate this you'll need to decide what is the effective *resistance* that should be paired with the blocking capacitor. C and that R form a high-pass, as you know.

[10] Yes, just R_C. You've seen this point explained in today's classnotes.

What circuit properties does your addition of the *bypassing* capacitor affect? The answer is "Gain, because R_{E} disappears from the gain equation." Does the C alter the biasing of the output (which was designed to be centered roughly at half the supply voltage)?[11]

Now drive this new circuit with a small *triangle* wave at 10kHz, at an amplitude that almost produces clipping (you'll need to use plenty of attenuation—40dB or more—in the function generator). Does the output waveform look like the figure below (compare Classnotes 5, fig. 12)? Explain to yourself exactly why this "barn-roof" distortion occurs.

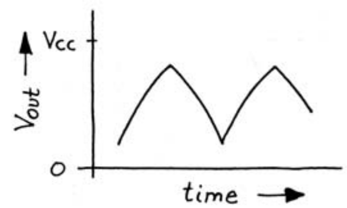

Figure 7: Large-swing output of grounded emitter amplifier when driven by a triangle wave

Installing the cap that bypasses R_{E} does *not* deliver infinite gain: sorry! In the next reading assignment you'll discover that we can predict the gain by adding to our transistor model a little resistor-like element in the emitter, a modelling device that we call ("affectionately") "little r_e." In the present circuit, where we're running a quiescent current of about 1mA, little r_e takes a value of about 25 ohms. See if your circuit's gain is consistent that value for r_e.

This measurement will be difficult. First, you will need to reduce the function generator output to a level close to the minimum possible. Then you will find the input is immeasurable small, viewed with a X10 probe. This, then, is one of the rare occasions when you need to revert to a X1 display: use a BNC rather than a X10 probe as you watch the *input* signal.

Typically, the gain you observe is around 250—lower than you predicted. Low I_{C} can help explain that; so can any curvature that remains in the output waveform: the gain revealed by such a waveform is sometimes higher than the quiescent value, sometimes lower, but the *net* effect of the curvature is to *reduce* gain.

4L.5 Transistor Switch

Time: 25 min

The circuit below differs from all the circuits you have built so far: the transistor, when ON, is *saturated*. In this regime you should not expect to see $I_C = \beta \times I_B$. Why not?[12] In addition, β for this big power transistor is much lower than what you have seen for the *small signal* transistor, 2N3904–at least at high currents. Minimum β for the MJE3055T is a mere *20*, at I_C= 4A (see plot, below in fig. 9 on the next page). But the transistor is big, and lives in a big package ("TO-220"), a package that can dissipate a lot of heat, especially if the metal package is thermally attached to a still bigger piece of metal (a "heat sink"). The large size of the transistor itself keeps current density down and saturation voltage low. You'll measure that $V_{\mathrm{CE(sat)}}$ in a few minutes.

[11] No. Biasing is a simple *DC* effect.

[12] One way to explain this is just to note that achieving a current as high as that would require either a smaller resistance on the collector or a larger power supply. When the transistor is saturated, the current is limited not by the transistor but by the *load*,

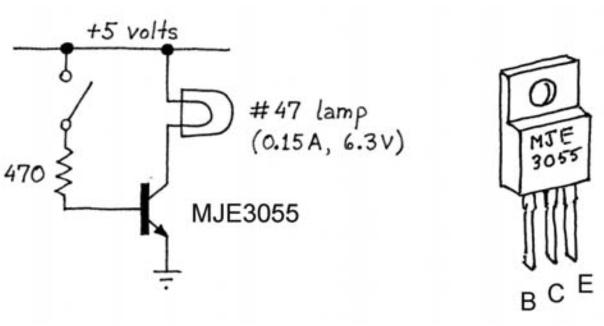

Figure 8: Transistor switch: twist each transistor lead 90°, so that each fits easily into the breadboard's slots

Turn the base current on and off by flipping the toggle switch—or, if you're too lazy to wire a switch, by pulling one end of the resistor out of the breadboard and touching it either to +5 or to ground. What is $I_{\rm B}$, roughly? What is the minimum required β?[13]

4L.5.1 Saturation or "On" voltage: $V_{\rm CE(sat)}$

Now let's make the transistor work harder. Replace the lamp with a 10Ω *power* resistor (not an ordinary 1/4-Watt resistor; how much power will the resistor have to dissipate? $V^2/R = 25/10 = 2.5W$). A 1/4-watt resistor would cook, in this circuit.

Measure the saturation voltage, $V_{\rm CE(sat)}$, with DVM or scope. Then parallel the base resistor with 150 ohms, and note the improved $V_{\rm CE(sat)}$. Compare your results with the results promised by the data set out below. Note that the curves assume heavy base drive: $I_B = I_C/10$, not I_C/β.

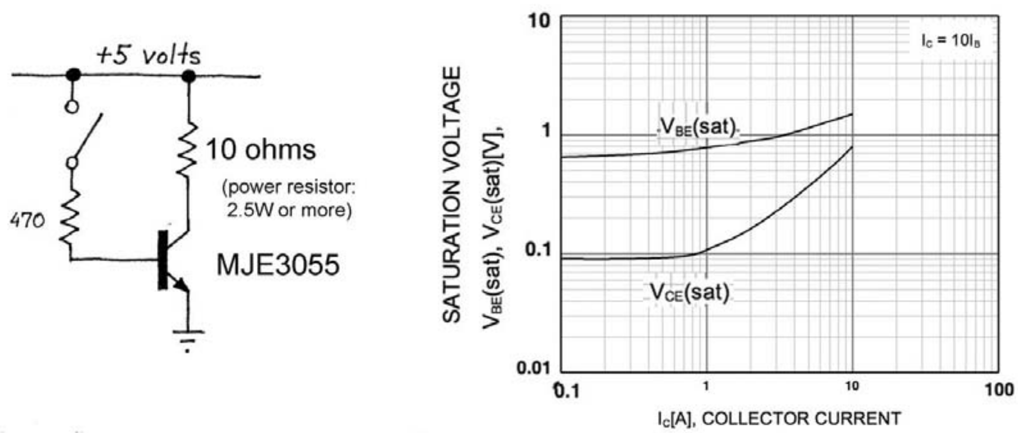

Figure 9: Switch saturation: a heavier load current asks more of the switch, here (data courtesy of ON Semiconductor)

We will return to transistor switches in a later lab (Lab 11), when we'll meet the leading competitor for the tasks a '3055 can do: a big power field-effect transistor ("MOSFET"). At that time, we'll set up a competition between a '3055 and a MOSFET and see which does a better job of delivering power to the load.

[13]You'll notice that we are *overdriving* the base, here, as is usual in a switch. Since base current here is about 10mA, even at the specified minimum *beta* of 20, the transistor could pass more current than the load will permit. That's good: the switch will be well saturated, and its $V_{\rm CE}$ will therefore be low.

4L.5.2 Switch an inductive load (more exciting!)

Now replace the resistor at the collector with a 10mH *inductor*. Replace the 5V supply with 1.5V from a single AA cell (we don't want to overheat the inductor—and the low cell voltage makes all the more impressive the voltage spike that soon will appear.) Drive the 470-ohm base resistor with a square wave from the function generator's "TTL" or "Sync" terminal (this is a "logic level" waveform: a square wave switching between ground and four or five volts).

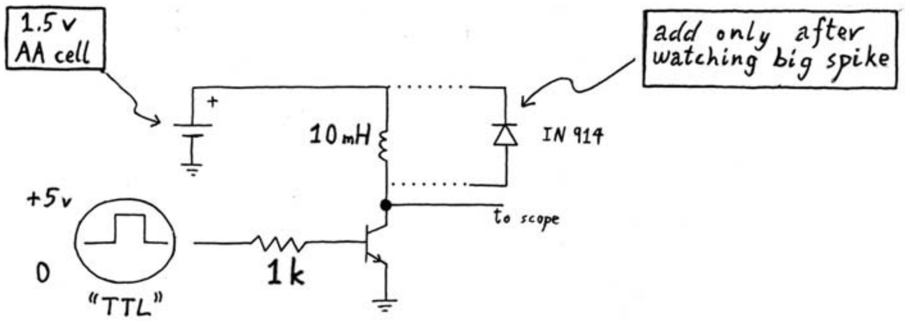

Figure 10: Transistor switch with inductive load

At the transistor's collector, you should find the inductor giving the transistor an alarming voltage spike (we saw about 100V). When the transistor tries to turn off, the inductor tries to keep the current flowing. Its method is to drive the collector voltage up, until the transistor "breaks down," permitting the inductor to have its way—keeping the current flowing despite the transistor's attempt to turn it off abruptly.

A diode from collector to V_+ tames this voltage spike; such a diode clamp is a standard protection in circuits that switch inductive loads. Most transistors don't like to break down (this time, we didn't mind, since our goal was to show you this spike). Incidentally, we'll see a circuit that makes good use of this voltage spike, when we look at "switching power supplies" later in the course (Lab 12).

4L.6 A Note on Power Supply Noise

You'll find a supplementary note named "Noise: Diagnosing Fuzz" later in this book (note 9S3). Here, we offer just a few pointers related to one form of noise.

Fig. 11 shows one of today's followers, swept rather slowly (at 20μs/division). The follower has been fed a sine of about 15kHz from the function generator. A strange *thickening* of the trace appears:

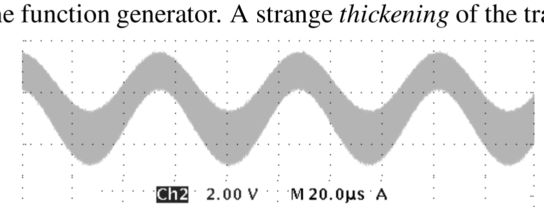

Figure 11: Thickening of scope trace indicates a nasty "parasitic" oscillation

Sweeping the scope faster (below, at 10ns/div) resolves the "thickening" into a very fast sinusoid—up in the *FM* radio broadcast range!:

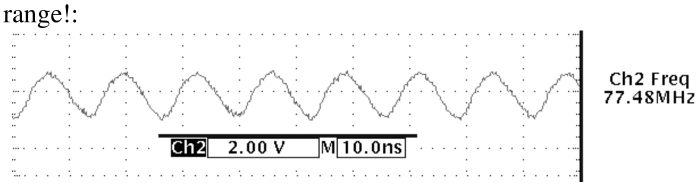

Figure 12: Fast scope sweep can resolve the "thickened" scope trace

Decoupling the power supplies should eliminate this problem (see below).

4L.6.0.1 Oscillations vs. radio pickup

If you see this fuzz, try turning off your breadboard power supply. If the fuzz disappears, your circuit is guilty: it was causing the fuzz, by running as an unintended *oscillator* (we'll look closely at the question how this can happen, in Lab 9). If the fuzz persists, your circuit is innocent and you're probably seeing radio-broadcast stuff picked up by your wiring. There's no quick way to eliminate that; you see it whenever your scope gain is very high and the point you look at does not show low impedance at those high frequencies.

Remedies

If your circuit is oscillating—not merely picking up radiated noise—there are three remedies you might try, in sequence:

1. make sure that you are watching the circuit output with a scope *probe*, not with a *BNC* cable. The 10X heavier capacitive load presented by the *BNC* cable often brings on oscillation.
2. try shortening the power and ground leads that feed your circuit. Six inches of wire can show substantial inductive reactance at Megahertz frequencies; shorter leads make the power supply and ground lines more nearly ideal—lower impedance—and harder for naughty circuits to wiggle.
3. if the oscillation persists after those two attempted repairs, then add a "decoupling" or "bypass" capacitor between each supply and ground. Use a *ceramic* capacitor of value 0.01 or 0.1μF; place it as close to your circuit as possible–again, inches can matter, at high frequencies.

   Incidentally, we have listed this option last not because there's anything wrong with decoupling the supplies; soon you will be putting decoupling caps in routinely. We placed this remedy last just because it *is* so effective: we wanted you to see, first, that the first two remedies also sometimes are sufficient.

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