IN PURSUIT OF GLITCHES

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How to banish elusive problems that haunt your circuits

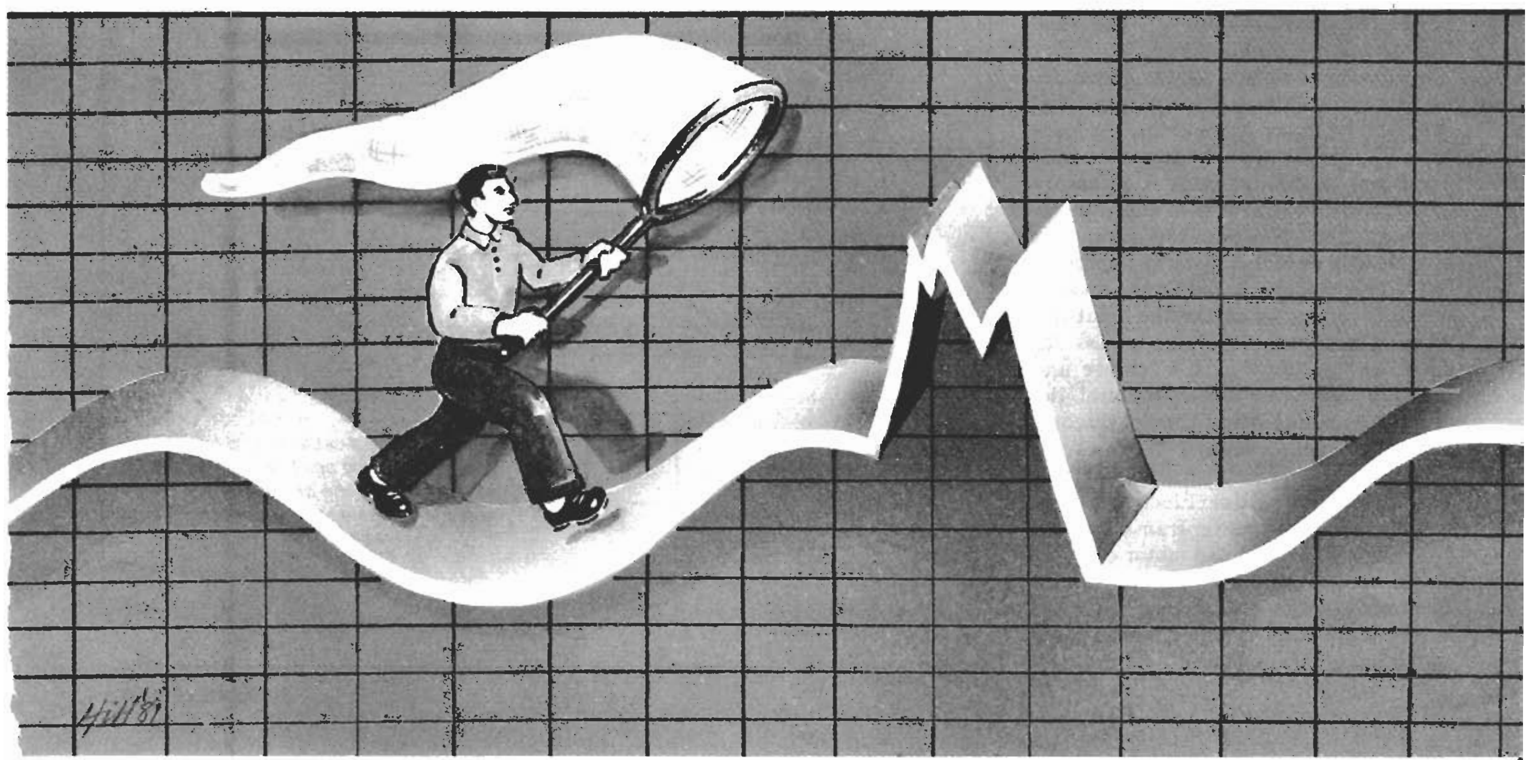
BUILDING projects from schematic diagrams can be a hit-or-miss proposition. Working without benefit of wiring diagrams or written instructions, you may build a circuit that appears perfectly reasonable on paper and find that it breaks into oscillation, suffers from hum, or exhibits lower-than-designed gain or sensitivity for some unfathomable reason. In most cases, the fault doesn't lie in the design of the circuit; rather, it's how you wired and/or laid out the components. The solutions for such problems lie in using a little common sense and care in assembly.

A simple analysis of a schematic diagram won't always tell you what's supposed to happen in a circuit. Although schematics show all the components *intentionally* included in a circuit, additional "phantom" components and conductive paths often introduce "glitches" that can radically influence circuit operation, sometimes to the point where the circuit fails to operate at all. These phantom-component-induced glitches can all be eliminated *before* a circuit is translated from schematic to prototype. Once you're aware of where the problem situations can occur and how you can go about eliminating them, every soundly designed circuit can be made to work as well in fact as it does in theory.

Let's take a look at some of the most common problem areas you're likely to encounter and how to go about avoiding the pitfalls. In the process, you'll learn how to build glitch-free projects almost every time.

Phantom Resistors. Shown in Fig. 1A is a simple audio amplifier and power supply circuit. Each component that goes to ground in this schematic is shown with its own separate ground symbol, giving no specific information on how each ground is to be connected. If you were to assemble this circuit exactly as shown, without properly connecting the grounds, it would act more like an oscillator than an amplifier.

The same circuit, this time with a ground bus added and its resistance taken into account as *R1, R2, R3,* and *R4* is shown in Fig. 1B. Assume the speaker lead to ground to be a 2" length of No. 22 wire with a resistance, exclusive of soldered connections, of 2.5 milliohms. (Phantom resistors are almost always of very low ohmic value.) Applying power to this circuit causes current to flow through *R2* and the speaker to charge the output coupling capacitor, causing a voltage to be dropped across *R2*. Assume now that a short length of copper wire, represented by *R1*, connects the ground return (point A) of the input volume control to the same point used as the speaker ground. Under these conditions, the amplifier's input "sees" the unwanted voltage dropped across *R2* as an input signal.



Since the amplifier's input and output are in phase, a positive-feedback loop is created. Feedback in this circuit is pure ac, since the speaker coupling capacitor blocks dc. If the speaker were directly connected to the amplifier's output, both could be catastrophically damaged.

This situation can be avoided by connecting points A, B, and C together and then to point E, as shown in Fig. 1C, to keep all signal grounds at one common potential. Speaker line point D then independently connects to the filter capacitor's negative pole at point E. This done, the feedback path is removed from the circuit.

As a general rule, all ground returns should be made to the lowest-impedance point in the power supply, which is the negative side of the filter capacitor. Bear in mind that the filter capacitor absorbs large currents from the rectifiers, stores the dc charge, and then releases a flow of direct current to power the circuit. Current between the center tap of the transformer at point F and the negative side of the filter capacitor at point E consists of 120-Hz pulses with amplitude as high as five times the speaker current. This makes the current path from point E to F the noisiest part of the ground bus. It is best, therefore, to avoid using bare wire to make this connection or attaching any ground wires between these points.

Bipolar Power Supplies. A typical operational-amplifier audio circuit using a bipolar power supply is shown in Fig. 2. In this circuit, the $-V_{cc}$ (negative) dc line doesn't share the same line as the speaker return. This points up one of the great advantages of the bipolar power supply—isolation of the load from the power supply lines.

Audio input signals appear across *R1* and enter the op amp through the noninverting (+) input. In op amps, the feedback loop must supply at point C a voltage equal to that at point A to ensure that the differential sum of the voltages between these two points is zero. If a ground loop produces a voltage differential between points B and D, the op amp sees this voltage as part of the input signal and produces a voltage across *R2* equal to $V_{BD} + V_{AB}$. To remove any problem created by this differential, the grounds at points B and D must be combined into a single point.

Transformer Fields. Electromagnetic radiation from a power transformer or a tape-recorder or phono motor can also create problems with ground loops. Electromagnetic devices can produce large 60-Hz eddy currents whose associated magnetic fields can induce un-

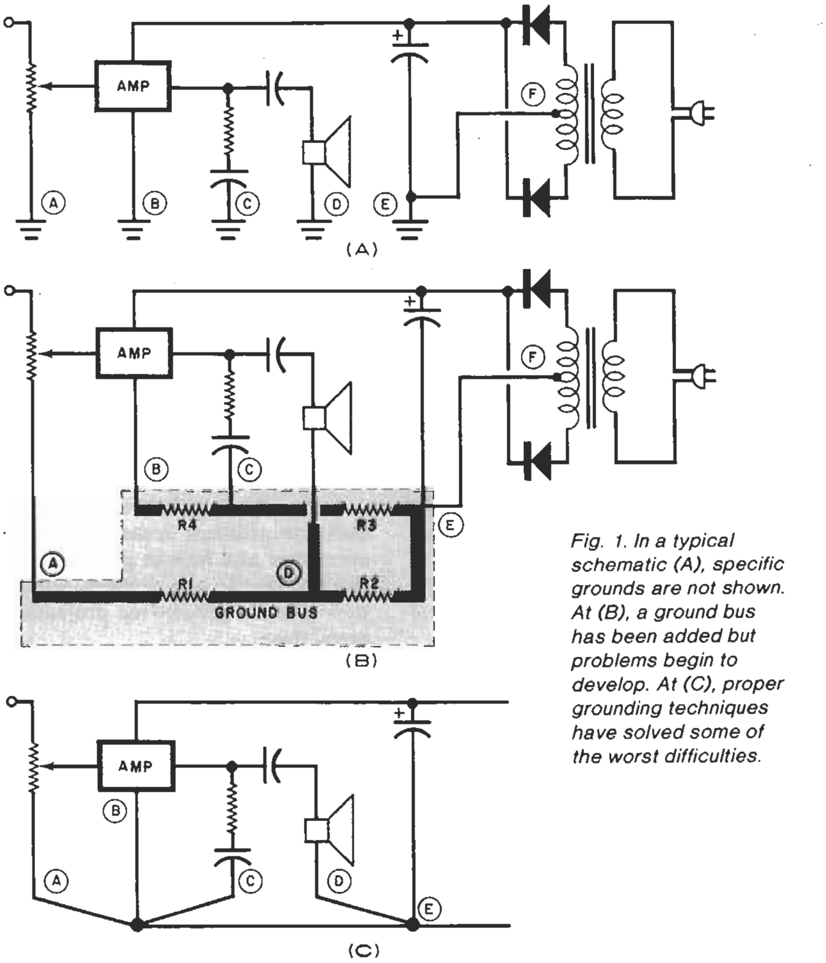


Fig. 1. In a typical schematic (A), specific grounds are not shown. At (B), a ground bus has been added but problems begin to develop. At (C), proper grounding techniques have solved some of the worst difficulties.

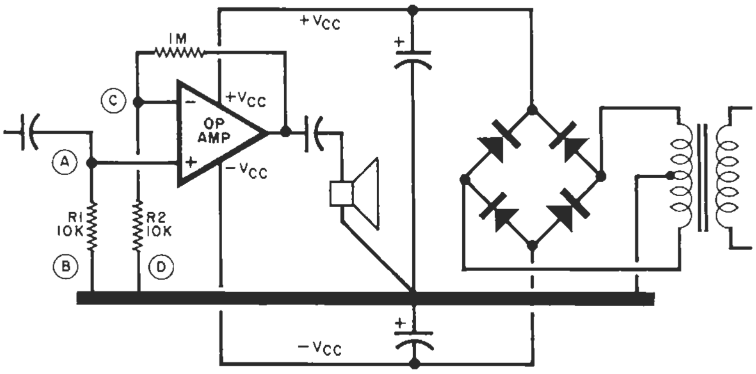


Fig. 2. An op-amp audio circuit using a bipolar power supply to isolate audio grounds from supply lines.

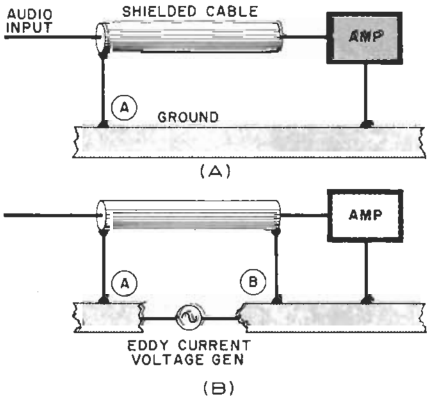


Fig. 3. Shielded cable should be grounded at only one point (A). Grounds at both ends of the cable (B) may result in hum due to an eddy-current loop.

wanted voltages in any nearby conductor. Being metal, a ground bus will pick up these eddy currents. Therefore, care must be taken to keep these induced currents from being combined with the signal. The obvious precaution is to locate electromagnetic devices as far as possible from sensitive circuits.

Shielded Cables. One of the most common causes of hum problems in audio amplifiers is shown in Fig. 3A. Here, a shielded cable feeds a signal from one point in the circuit to another. Good grounding practice calls for the shield to be grounded at only one place, point A. If hum appears in the signal, it more than likely is the result of the shield being grounded at both ends of the cable, as illustrated in Fig. 3B. In such a configuration, a few millivolts of 60-Hz signal can be induced into the ground path by eddy currents from a power transformer or coils of an ac motor. We assume in this circuit that both ends of the cable's shield are grounded at different points. Since the eddy-current loop has a very low source impedance, a rather large current can flow through the cable shield. As a consequence, the shield acts like the primary of a one-turn transformer and induces a 60-Hz voltage into the signal-carrying inner conductor of the shielded cable.

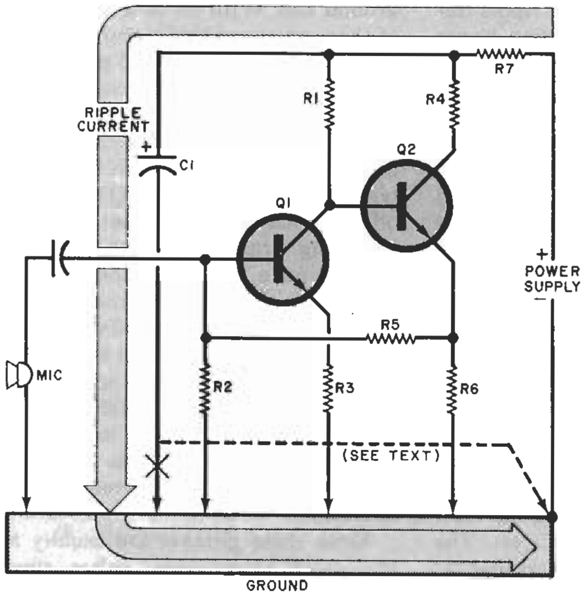


Fig. 4. To prevent hum caused by the ground loop through capacitor C1, the capacitor should be grounded as shown by the dotted line.

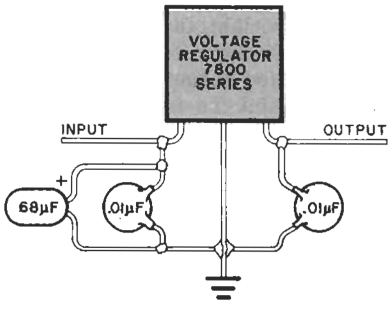


Fig. 5. Both input and output of a three-terminal voltage-regulator IC should be bypassed with capacitors connected as close to pins as possible.

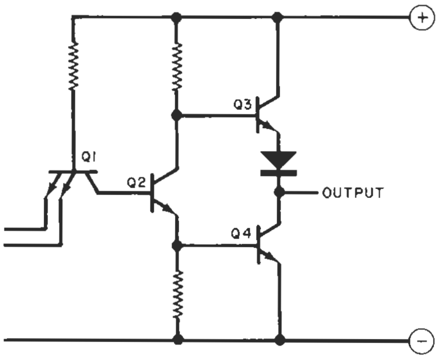


Fig. 6. In a standard TTL gate, both output transistors can be conducting briefly during switching, producing a high-current spike. Using a bypass capacitor is the solution.

Power Lines & Bypass. Op amps generally ignore ripple and low-frequency voltage variations in the power supply. However, IC amplifiers tend to oscillate if they see any appreciable inductance in their power-supply leads. Since even an inch or so of hook-up wire or pc-board trace may have enough inductance to cause problems, the best course is to bypass both the negative and the positive power-supply leads to ground through a 0.1-µF ceramic disc capacitor directly at the IC's power pins or the printed-circuit pads to which these pins are connected. In a bipolar supply, each power line must be independently bypassed to ground.

Motorboating. The "put-putting" sound that can sometimes be heard in an audio amplifier's speakers, called "motorboating," is a problem that results from poor power-supply regulation. When the amplifier connected to an inadequately regulated power supply draws current to charge its capacitors, a voltage drop appears across the power-supply lines. The result is that the amplifier turns itself off when the voltage drop occurs. Then, when the power supply recovers, the amplifier turns on again, immediately drawing current from the supply and causing a continuous repetition of the on/off cycle. It is this on/off cycle that produces the annoying put-put sound. The most efficacious cure for motorboating is heavy filtering of the amplifier at the power input to the output stage, or, if the amplifier is encapsulated, filtering directly at its power pins.

Keep in mind that ultrasonic or r-f oscillations can occur in an audio amplifier and cause it to draw large currents. Although large electrolytic capacitors with values of up to 50,000 µF may be effective against power supply ripple, power factor and internal inductance may make them inadequate bypasses at high frequencies. As a rule, then, all high-value electrolytic capacitors should be bypassed with a much lower value (say, 0.01-µF) capacitor to remove objectionable high-frequency signals. It isn't a case of how much capacitance to use here but of where to use it.

Don't be afraid to use capacitors liberally; you can't have too many of them. A single 1-µF capacitor, for example, will never be as effective as twenty 0.05-μF capacitors judiciously scattered about a circuit.

Decoupling. In the discrete-component microphone amplifier circuit shown in Fig. 4, *C1* and *R7* form a decoupling network that's supposed to prevent noise and ripple in the power supply from entering the amplifier. When the grounds are connected exactly as shown and power is applied to the circuit, however, the amplifier will be plagued by hum. If you were to disconnect *C1*, the hum would diminish considerably. The hum is the result of *C1*'s low reactance of about 25 ohms at the 120-Hz ripple frequency of a full-wave rectifier power supply. Although it holds the dc voltage constant, *C1* presents a low resistance to the ripple current through the ground bus and back to the power supply. Therefore, connecting *C1* back into the circuit as shown creates a classical ground-loop situation. Also, since *R4* and *R7* make up the collector load for *Q2*, a feedback path from the output of *Q2*, through *R2*, to the base of *Q1* is created via the ground loop, thus forming an oscillator. To remedy this situation, simply move the ground side of *C1* closer to the power supply, using a separate wire if necessary.

Voltage Regulators. Three-terminal IC voltage regulators can bring their own special problems to a circuit. The 7800 series regulator, in particular, is prone to oscillation and must be carefully bypassed. In addition, these devices tend to oscillate at the onset of current limiting. It's important, therefore, never to operate a 7800 series regulator near its maximum rated output current and to properly heat sink the device.

Shown in Fig. 5 is a circuit for a typical 7800 series voltage regulator. In the interest of good circuit design, capacitors are connected as close as possible to the IC pins and a 68-μF tantalum capacitor is connected across the device's input. In some cases, a 0.001-μF capacitor may have to be connected in parallel with a 0.1-μF capacitor to arrive at a bypass combination that really works.

Diode Oscillation. If you have a circuit that's plagued by high-frequency signals and can't find the cause in the obvious locations, look to the rectifiers in the power supply. Silicon rectifiers require approximately 0.6 volt to begin conduction. If a clean power-line sine wave is applied to a rectifier, an almost square "notch" would appear in the waveform on each side of the zero-crossing point as a result of the 0.6-volt effect. This squared-off waveform is rich in harmonics, some at audible frequencies, that may sneak into the output of an audio amplifier. Ultrasonic harmonics can also change biasing and produce other undesirable effects. Bypassing each rectifier diode in the power supply with a low-value capacitor (say, 0.001 to 0.1 μF) will smooth the edges of the waveform and alleviate the problem.

Digital Circuits. While any given TTL gate may be required to sink only 1.6 mA of current, rarely is a TTL project operating with only one gate on. A typical TTL device may contain 30 or more gates connected to a common ground bus. With all or a large portion of these gates enabled simultaneously, a large current can flow and possibly produce unwanted signals through the power/ground system.

In the typical TTL gate shown in Fig. 6, the *Q3/Q4* output circuit forms a "totem pole" such that when *Q3* is on, *Q4* is off, and vice-versa. However, during the switching transition, both transistors conduct for a few nanoseconds, producing a high-current spike that can exist all along the power/ground system. Any gate (or other TTL device) connected to the power-bus system can see this spike as a legitimate signal and falsely trigger. In asynchronous circuits in which the logic doesn't switch at the same time, such glitches can be disastrous to circuit operation.

Since these glitches are usually narrow-width, high-current pulses, ringing can be caused across a broad spectrum of frequencies, making bypassing difficult. The only effective way to deal with the problem is to connect a bypass capacitor directly between the voltage pins and ground of *each* IC in the system, keeping capacitor leads as short as possible. In multiple-board printed-circuit systems, each pc board assembly should be heavily bypassed at the points where power and ground enter as well, to prevent glitches generated in one assembly from travelling to the others.

When analog and digital circuits are combined on a single pc board, it's best to use separate ground traces for each type of device and connect both together at the board's main filter capacitor.

Other Kinds of Glitches. The 10 problems and solutions we've presented here by no means exhaust the glitch-producing possibilities you're likely to encounter. Doubtless, you'll run across, or have already encountered, some that aren't covered in this article. However, the great majority fall into the categories we've discussed here, and the solutions we've presented may suggest fruitful courses of action in other cases. ◇