Grounding Techniques

by Tamara Schmitz, Principal Applications Engineer, Intersil Corporation

Ground is taken for granted. We stand on it, we dig into it, we make mud pies out of it. The ground isn't supposed to move. We don't have to think about it; it just is. When it comes to grounding a circuit, we assume that our connections are as solid as the turf below our scuffed shoes. Many times, this is a reasonable assumption – but not always. How do we know when there is a problem with a circuit's ground? What practices will ensure we construct a good ground?

No longer to be taken for granted, we define ground in ideal and real situations. Ground configurations and printed circuit board (PCB) examples are presented.

Ground Terminology

Many nodes are called *ground*. There are floating grounds, virtual grounds, ac grounds and earth grounds. For clarity, let's look at the difference:

- Floating grounds are reference points within an isolated system. They are a reference point and only equal to 0 V through luck
- Virtual grounds exist in a negative feedback circuit at the inverting terminal of an op amp. When the noninverting input is held at 0 V, the feedback (in a stable circuit) will cause the inverting terminal to match. The value is only held by feedback and is not a stable return for other circuit currents
- Ac grounds are nodes with low impedance dc values. That dc voltage is stable with small circuit perturbations. Since the node has a dc value, it is not useful as a proper ground. However, since it is stable, it is useful as a reference point. Ac (or small-signal) analysis considers these points to be unchanging, thus like a ground
- Earth ground is exactly what the words suggest. Every house has a copper pole sunk into the ground to deplete surplus currents. Without the presence of a buried battery, the top layer of turf is fairly homogenous. A house down the street from yours might have a difference in ground voltage of a hundred microvolts. This is the type of ground we are going to discuss.

Ground Terminology	Definition	Connected to earth ground	Example
Floating Ground	Local reference potential	NO	Medical systems to protect patient
Virtual Ground	Node held at or near ground potential by feedback	NO	Negative input terminal on Inverting Op Amp
Ac Ground	Node held at a constant dc potential	NO	Vsupply, Bias voltage, Bandgap voltage
Reference/ Earth Ground	System ground	YES	DIRECT CONNECTION to earth ground

Table 1: Comparison of Various Types of Electrical Grounds

What is Ground?

I asked a handful of fellow engineers to define “ground”. A chorus of answers responded “Zero volts” or “Zero reference.” A more extensive definition can be found on Wikipedia, “a large conducting body (as the earth) used as a common return for an electric current and as an arbitrary zero of potential.” This definition is particularly helpful because it refers to the role of ground in terms of voltage AND current.

To explore this dual role, let’s look at an extremely simple circuit, Fig. 1(a). This circuit could represent a plethora of different systems: a flashlight, a coffee maker, or even an iPod. Fig. 1(b) represents those circuits just as well. Of course, we don’t typically think of ungrounding a circuit to turn it off, we think of disconnecting the power. The truth is, they are equally effective. The load and the switch are in series, so the order is irrelevant. An open switch stops the flow of current; zero current through the load means zero power in the load. (In practice, the circuit in Fig. 1(a) is more common than Fig. 1(b) for a practical reason: it is more likely that the system could accidentally become connected to ground (a loose wire to the chassis, for instance) causing unwanted power in the load than to accidentally become connected to the power supply. The principle, however, is useful.

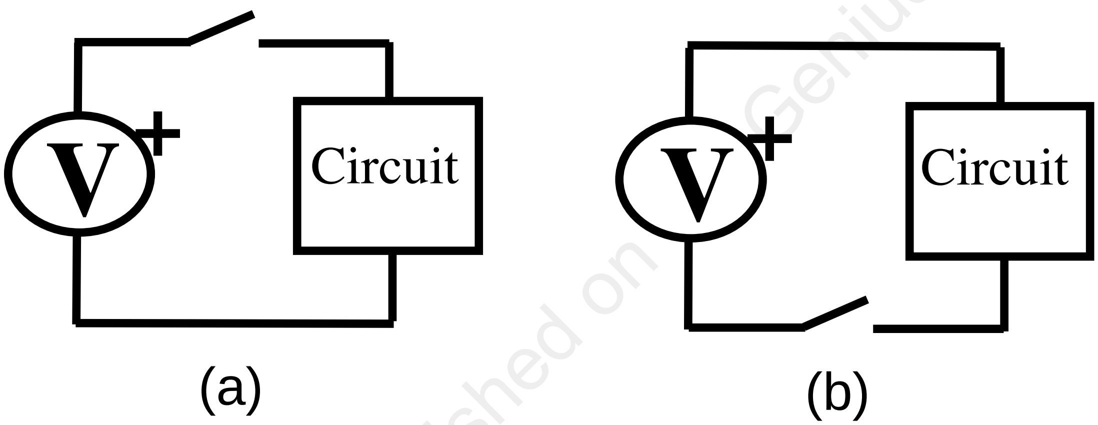

Fig. 1: Simple Circuit: Switch Can stop Flow of Current to Circuit OR Away

Those lines representing the connection between the source and load could be of a wide variety of lengths. They could be a few inches long, as in a household appliance, or they could be miles long, as in the power grid. In small systems, the assumption of a lossless wire is reasonable. As system sizes increase, the connections (wires, board traces, and interfaces) can no longer be considered lossless. An extreme example is the lines from the power company. Between the repeaters, the power is transmitted with high voltage (hundreds of kilovolts) and minimal current to negate losses caused by series resistance.

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Ground Configurations

Acknowledging that both the current through the return path and the voltage level are important, prepares us to discuss the common topologies used in grounding a system. Fig. 2 shows the most popular configurations.

An example of a floating ground system is any battery-operated toy or gadget. A second example is the patient side of transformer-isolated medical equipment. There is no reference zero volts connected to an eight-foot copper pipe hammered into the ground. The lowest potential actually floats, while the battery causes a potential difference between this point and the supply node. This isolation also ensures that any stray ground currents cannot couple directly into the floating (and isolated) system.

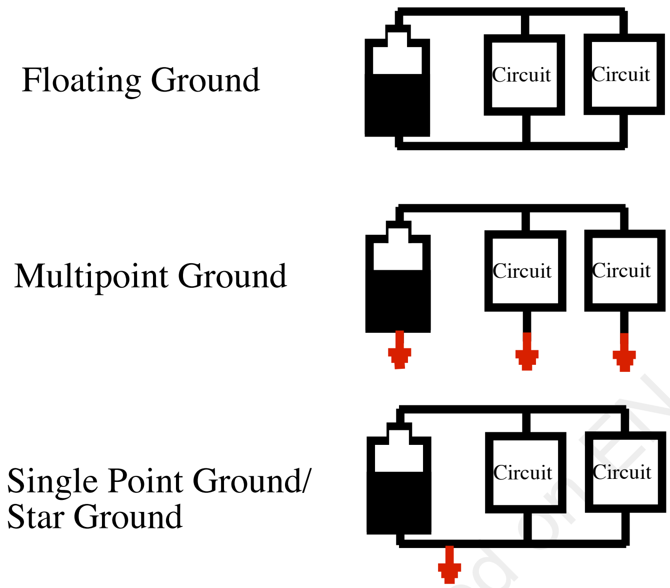

Fig. 2: Grounding Topologies

A multipoint ground system uses local ground points or planes. Every sub-circuit is connected to the closest ground. The most common example is the use of a separate analog and digital ground plane in mixed-signal systems. Multipoint ground systems assume each ground connection is 0.00 V. In return, this technique minimizes impedance by placing multiple ground paths in parallel. Unfortunately, this can also allow ground currents to form alternate loops, called ground loops. (If one of the ground terminals is at a voltage higher than zero, charge from that terminal is drawn to each of the other ground terminals. This can wreak havoc on systems and the poor engineers trying to debug them.)

If you are a student, realize that the protoboard where you plug in various components to quickly prototype a circuit is an example of a multipoint ground system. If substantial ground currents exist, the ground will not be at a uniform potential. One of your debugging steps should include a systematic check of the ground. Measure the potential with a digital multimeter at multiple points to look for any variations. (Use an oscilloscope to probe if you suspect ac interference.) Any significant dc or ac signal on the ground node flags the nearby circuit. It may need a lower resistance connection to ground, relocation closer to the power supply, shielding, bypassing, or other isolation.

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One note for mixed-signal systems: it is an excellent idea to separate analog and digital grounds. The digital grounds will have much higher noise and currents flowing through them because of the rail-to-rail signals. The analog side, on the other hand, will need a quiet ground for references and precision. These two systems should be separated, and then joined at a single point which serves as the system ground.

A single-point ground system doesn't allow any local ground nodes, only one centralized point. Since many nodes will need to reach this centralized point, it follows that some of those connections will be longer in this topology. Fortunately, traces carrying high frequencies can be isolated with choke or ferrite bead if space allows. Longer traces or wires create extra parasitic series resistance.

Each of the ground topologies trades off the ability to eliminate ground loops and to hold the ground potential at zero volts. The simplest way to intuitively understand is a parallel-series comparison. The multipoint ground system puts many connections in parallel. Parallel systems favor the shared voltage, but create opportunities for ground loops. Single-point grounding forces each of the ground nodes to travel through one point to the ground return. The long connections of each subsystem and shared connections to ground will create resistance in series, creating offsets but eliminating ground loops.

Shielding and Antennas

Another important use of ground is shielding. Shielding is commonly used around the power supplies in a computer or around every subsystem in a cellular phone. Thin conductive housings are connected to ground and protect signals from entering or exiting the protected area.

Why do the areas need protection? Every trace, lead, package and circuit can act as an antenna. Signals can be received from an adjacent circuit or from a local radio station. Since these unwanted signals can disrupt the power, ground and signal path, it is important to minimize the length of every connection. In the lab, this means grabbing a foot-long cable instead of one that is three feet-long, or longer. On the power and ground traces from the power supply, twist the wires to minimize circular antenna loops. On sensitive signals, use coax cable with suitable connectors (like BNC or SMA) instead of an unshielded piece of wire. On a multilayer printed circuit board, an internal trace will be shielded by the power/ground planes compared to a surface trace. (Remember, though, that the vias needed to reach the internal layers will affect high-frequency operation as will the extra capacitance from the power planes.)

PCB Examples

A dual op amp is chosen as the layout example. For clarity, a single layer of copper is used for all routing (this is not the best choice for speed, isolation, coupling, etc). Fig. 3 shows the complete schematic used for each of the PCB examples. Capacitors C1 and C2 are included to bypass the supply for the dual op amp package. Resistors R1, R4, R5, and R8 are matching resistors for terminating cables, assuming we are operating in a 50 Ω environment. Resistors R2, R3, R6, and R7 set the amplifiers in a non-inverting configuration with a gain of 2. And, lastly, because a single layer is used and a bit of wire-jumping is necessary, a few zero ohm resistors (R9 - R12) have also been included.

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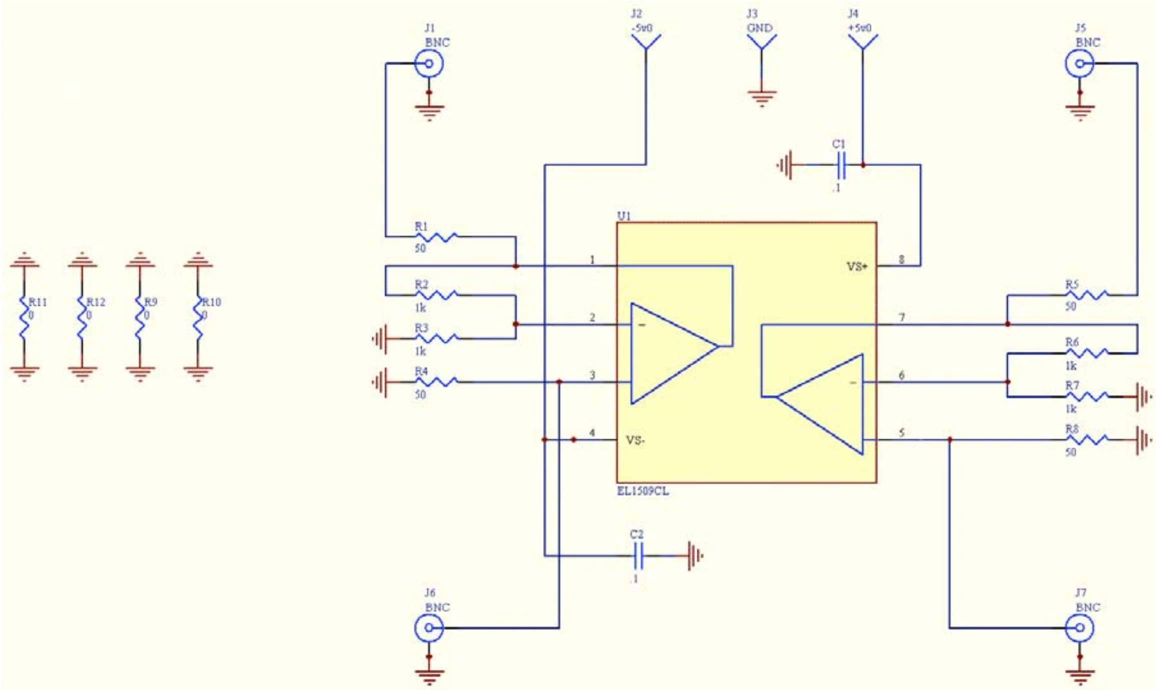

Fig. 3: Test Circuit Used in Layouts (Figs. 4 – 6)

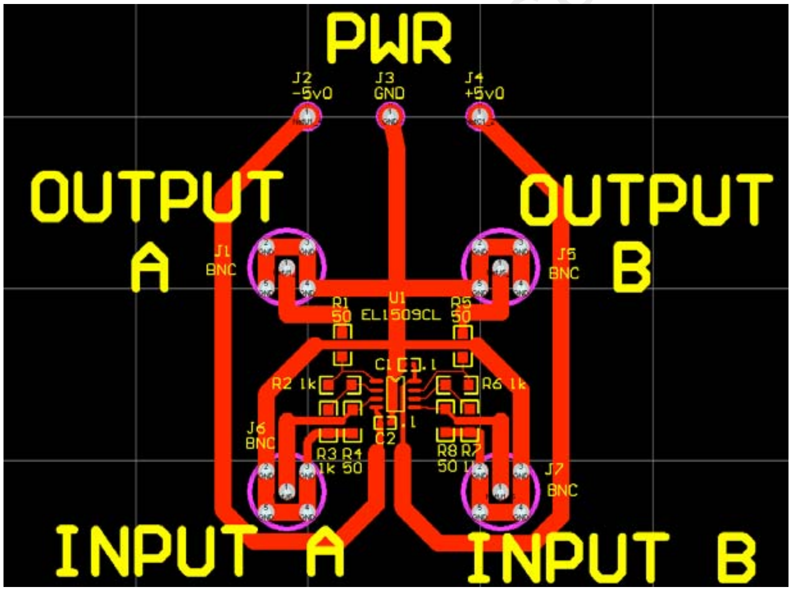

Fig. 4: Wired Ground Layout

Fig. 4 shows the first attempt to layout our circuit. The ground connection travels right down the center, providing a spine to our bilaterally symmetric creation. Sadly, though, both the positive and negative supplies travel in a large loop around both sides of the device. It's great that the layout is symmetric; it's not so great that the power lines loop around the board. These long, thin traces will act as antennas, picking up as much of the local RF noise as they can. In addition, the traces may have measurable I_R drop in them, another downside.

The next attempt at layout is shown in Fig. 5. In a single-layer board, this is a close approximation to having a *ground plane*. This time the ground loops around the outside of the board. A connection to ground is made every time it is needed. This could be considered a multi-point ground. Instead of a thin trace, though, the ground connection is wide (considerably lower impedance). However, any noise that couples into either power supply will still be radiated from the area of the loop created by the power trace and the ground connection.

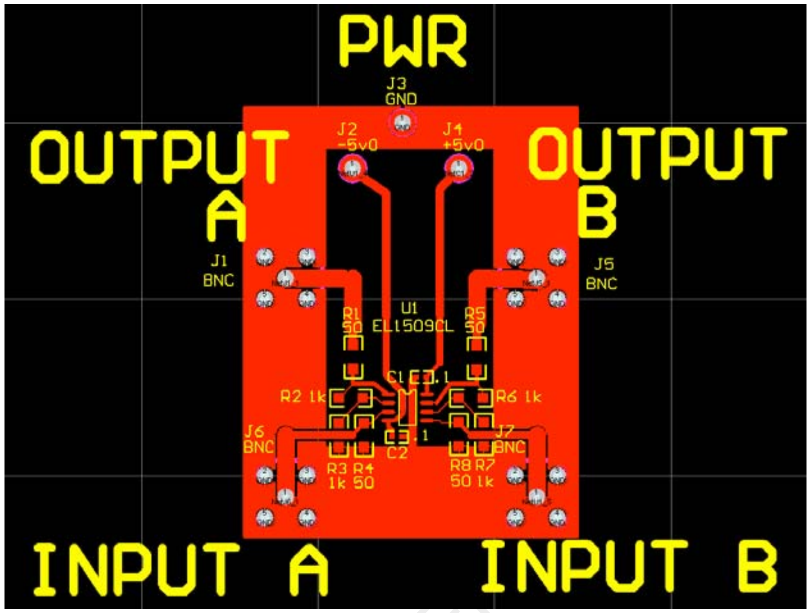

Fig. 5: Outer Ground Plane

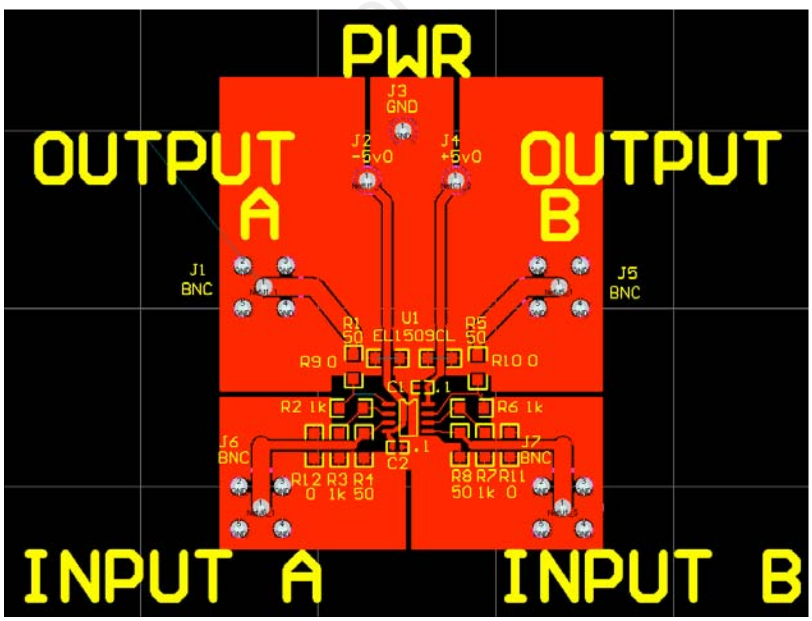

Fig. 6: Split/Star Ground Plane

Fig. 6 shows our best layout. Ground once again forms a plane around the device, but there are 5 slices keeping it from being continuous. Notice that each of the ground planes connects to the others, but only at one place. This is an example of a single-point or star ground. Currents cannot travel haphazardly throughout the ground plane, they are steered through specific paths we create and control. This type of set-up will minimize any antenna characteristics, both emitting and receiving.

These examples offer a bit of insight into the types of grounding schemes and how they appear on a printed circuit board. The best advice is to *follow the currents*:

- The longer a current has to travel, the more trouble it can cause. It is the best policy to keep wide, low-impedance ground connections as close to the devices as possible
- Multiple currents can interact. If multiple loops overlap, break up the ground connection to minimize coupling
- Don't forget the return currents! Every current leaving a node must return via some path. If the forward and return paths are very close (enclosed in a small area) the external fields cancel. If not, you have an antenna.

About The Author

Tamara grew up in the Midwest, finding her way West with an acceptance letter from Stanford University. After collecting 3 EE degrees (BS, MS, and PhD), she taught analog circuits and test development engineering as an assistant professor at San José State University. With 8 years of part-time experience in applications engineering, she joined industry full-time in August 2007 at Intersil Corporation as a principal applications engineer.

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