THE LIBRARY OF GROUNDING PROBLEMS

Introduction

The human ear is a marvel of sensitivity. Just a nano-watt[1], that's 1 billionth of a Watt, is at the threshold of audibility if your put your ear up to a speaker. Now, most of us are at least a meter away from our speakers when we listen, and both our rooms and recordings have enough noise to mask this nano-watt. Still, we will use this as a benchmark for a "blameless" noise level.[2] In round numbers, this is 100 µV into an 8 Ohm speaker.

Our plan is to investigate the causes and cures of a library of ground loops. We'll start with the more obvious, and work our way to the subtle.

Supply Ripple Ground Loop

Figure 1 demonstrates the supply ripple ground loop. We're using an op-amp to represent the essence of the amplifier.
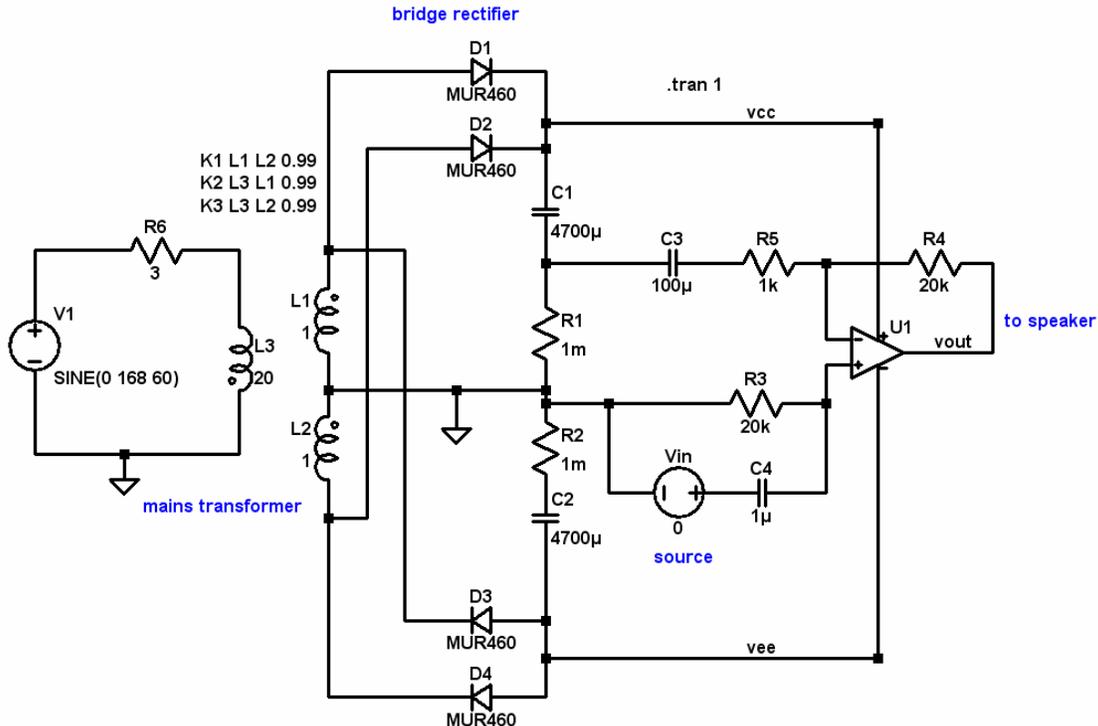
Figure 1 – supply ripple ground loop

Figure 1 has the mains transformer, bridge rectifier, and reservoir capacitors C1 and C2. Pulses of charging current flow through C1, C2, R1 and R2 120 times per second. R1 and R2 represent the resistance of the bit of wiring used to connect C1 and C2 to ground. 1 milliohm is the resistance of about 2 inches of 18 gauge hook-up wire.

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[1] A sensitive speaker produces 90 dB SPL at 1 meter with 1 Watt of input. Thus it produces 0 dB SPL, defined as the threshold of hearing, at 1 meter with 1 nano-watt of input. If we move closer than 1 meter, we assume that the SPL rises enough to counteract the ear's losses at low frequencies where hum resides.
[2] With a tip of the hat to the master of the blameless amplifier, Douglas Self.

The problem here is that the negative ("grounded") side of the source connects to a different place than the left side of C3. This makes the ripple voltage developed across the 1 milliohm wiring resistance of R1 part of the input signal. A simulation of Figure 1 shows 2.52 mV RMS of hum at vout[3]. That's 20 times the 100 µV maximum that we'd like to see.

So we see that missing the correct ground points by just 2" leads to too much hum. Figure 2 remedies that situation. Note that Vin (the source) and the left side of C3 (the input side of the feedback loop) are now grounded together on a wire that doesn't carry the bumps of charging current. That one small change completely eliminates the hum from this circuit.
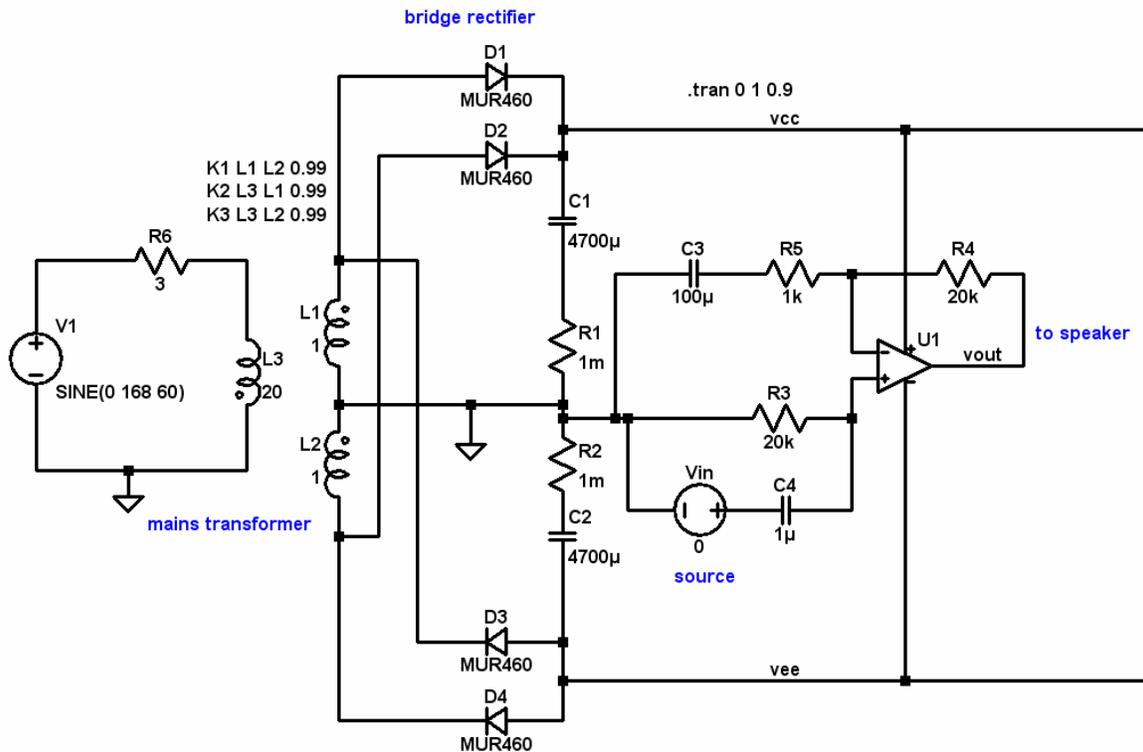
Figure 2 – grounding Vin and C3 on a wire free of ripple current eliminates hum

AC Mains Ground Loop

Every device in your system (preamp, power amp, CD player, tuner) has a power transformer. Each power transformer has a common connection at the AC mains. Each power transformer also has parasitic capacitance from the mains to the low voltage windings. That capacitance can force currents through the grounds of the connections between devices. That current creates a voltage in the ground of the cables, a voltage that appears in series with, thus adding to the signals. Since the currents come from the 60 Hz mains, we hear them (and their harmonics) as hum. You may have observed this if

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[3] In this simulation, we made the power amp U1 take about 100 mA of quiescent current.

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you've ever tried turning over the mains plugs of your equipment to try to minimize hum. Figure 3 shows this phenomenon.
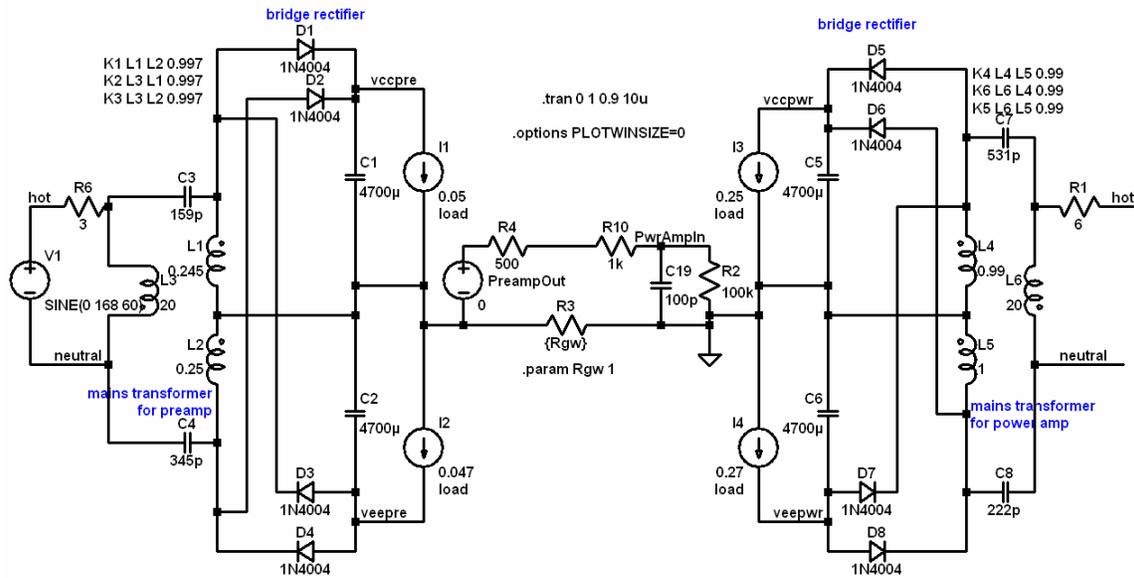

Figure 3 – Current from the AC mains flows through R3, by way of C3, C4, C7 and C8, causing a noise voltage that appears at PwrAmpIn.

In Figure 3, the noise voltage is developed across R3, having a resistance of Rgw. Figure 3 has about 6.5 uA of ground loop current at 60 Hz. With Rgw=1 Ohm, that makes for 6.5 uV at PwrAmpIn, and 21 times that amount, or 136.5 uV at the amplifier's output.

If you have a sensitive micro-ammeter, you could connect the preamp output ground to the power amp input ground and read the current that flows. If you multiply that current times the resistance of the ground wire in your connector cable, this translates to the noise input voltage at the amplifier.

Another way to diagnose the amount of ground loop current would be to deliberately place 10 or 100 Ohms in the ground path between the preamp out and the power amp input, e.g. in series with Rgw in Figure 3. If there is ground loop current, that would certainly make its effect worse, and perhaps large enough to easily measure in the form of hum at the power amplifier's output[4].

Finally, note that in this situation, the lower the resistance of your cable, the less the ground loop current gets to add to the noise.

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[4] Just so there's no confusion, this is a diagnostic technique only.

Cross Channel Ground Loop

This one is pretty subtle. Consider a power amplifier. They have large power transformers with large external magnetic fields at the 60 Hz power frequency, and harmonics thereof. Even relatively short pieces of wire, if oriented just right, can develop a hundred microvolts of hum.
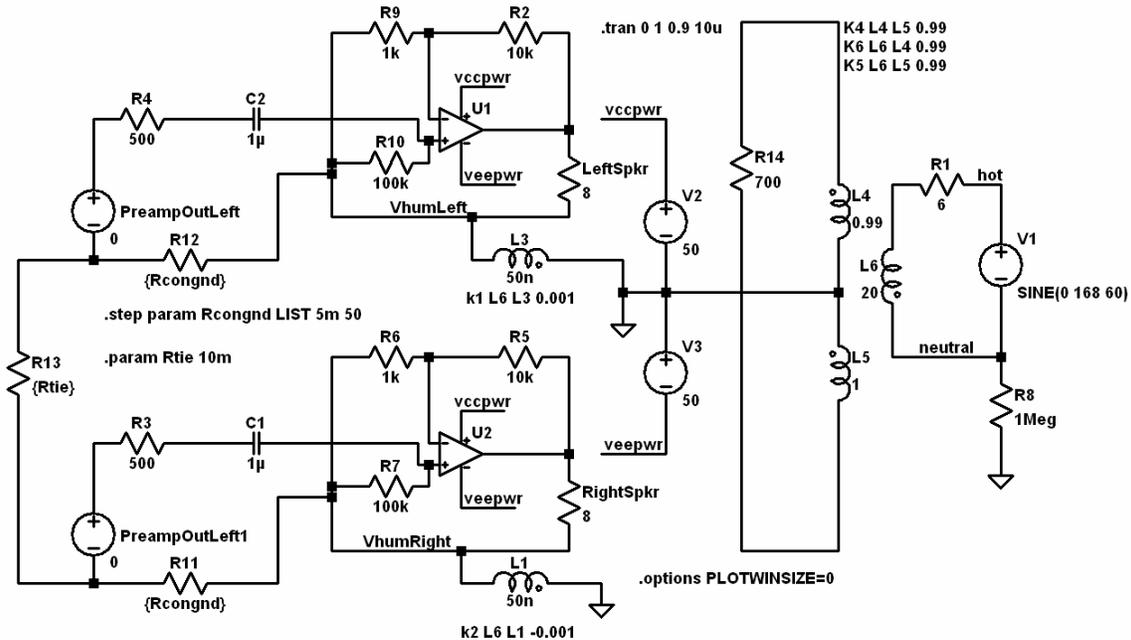

Figure 4 – Cross channel ground loop

L1 and L3 represent short pieces of wire in the grounding system. Note that each channel is done about as well as can be done. The input termination, feedback, and load all tie to single points; the top of L1 for the right channel, and the top of L3 for the left channel. We'll assume that each of L1 and L3 have lengths of 2", and partial self inductances of 50 nH. The k values chosen represent the partial mutual inductances between L1, L3 and the turns of L6.

The small hum voltages induced across L1 and L3 (shown anti-phase in Figure 4) cause current to flow through R13, causing hum voltages across R11 and R12 that appear in series with the input. Typically, R11, R12, and R13 have similar resistances. Thus a significant fraction of the hum adds to the input, being developed across R11 and R12. In contrast, If R13 is perhaps 1 Ohm, and R11 and R12 are small, e.g. 10 milli-Ohms, then the hum is greatly attenuated.

## The Cross Channel Ground Loop Remedy
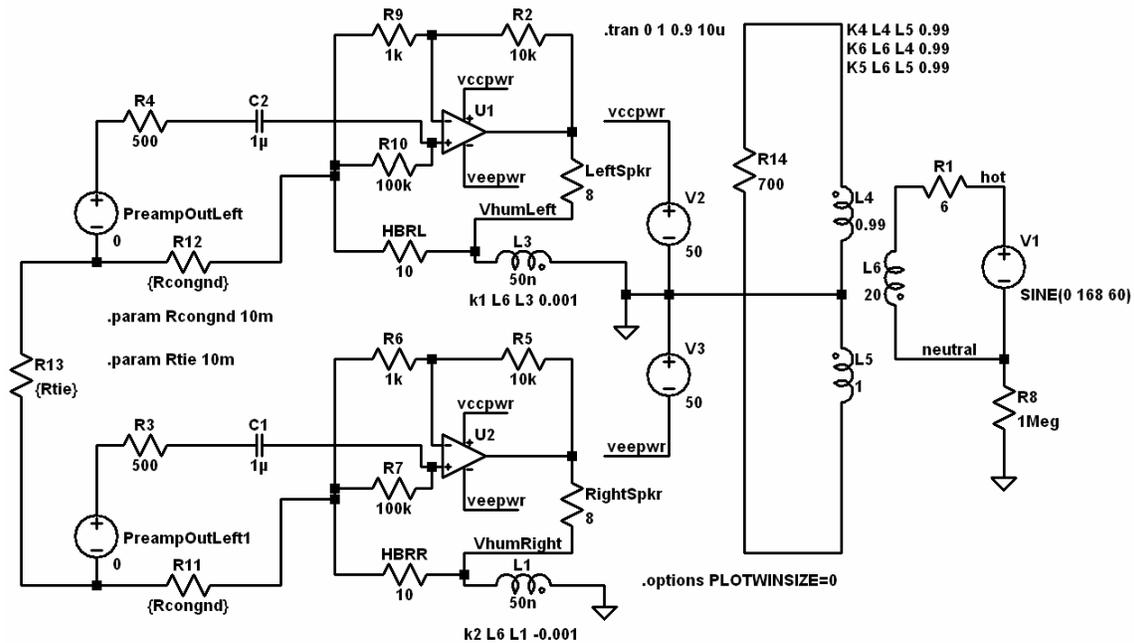
Figure 5 – remedy for cross-channel ground loop

Figure 5 provides a remedy for the cross-channel ground loop. HBRL and HBRR (Hum breaking resistors right and left) dramatically decrease the current that flows through the ground resistance of the connector cables (R11 and R12). This dramatically decreases the hum voltage developed across either resistor, and hence the hum voltage that appears in series with the input. Removing hum voltages that appear in series with the input is particularly powerful, since now the amplifier gain doesn't multiply the hum. This method of remedying the cross-channel ground loop doesn't compromise performance in the face of our earlier nemesis, the AC mains ground loop.

You'll note that VhumLeft and VhumRight still appear in the speaker. However, without the gain of the amplifier acting on the hum, it will likely be inaudible.

The cross-channel ground loop hum source doesn't have to be in the power amp. Figure 6 shows it from a similar cause, but in the preamp. As before, the power transformer inductively couples a bit of hum voltage onto a conductor separating the left and right grounds of the preamp outputs. To concentrate on this phenomenon, we've removed the power transformer from the power amp, showing only the power transformer in the preamp. It couples hum into the inductance L4, representing a wire that connects the grounds of the two preamp output connectors. Note that Rtie is typically close to zero.

HBRL and HBRR are once again powerful tools in the fight against ground loop hum.
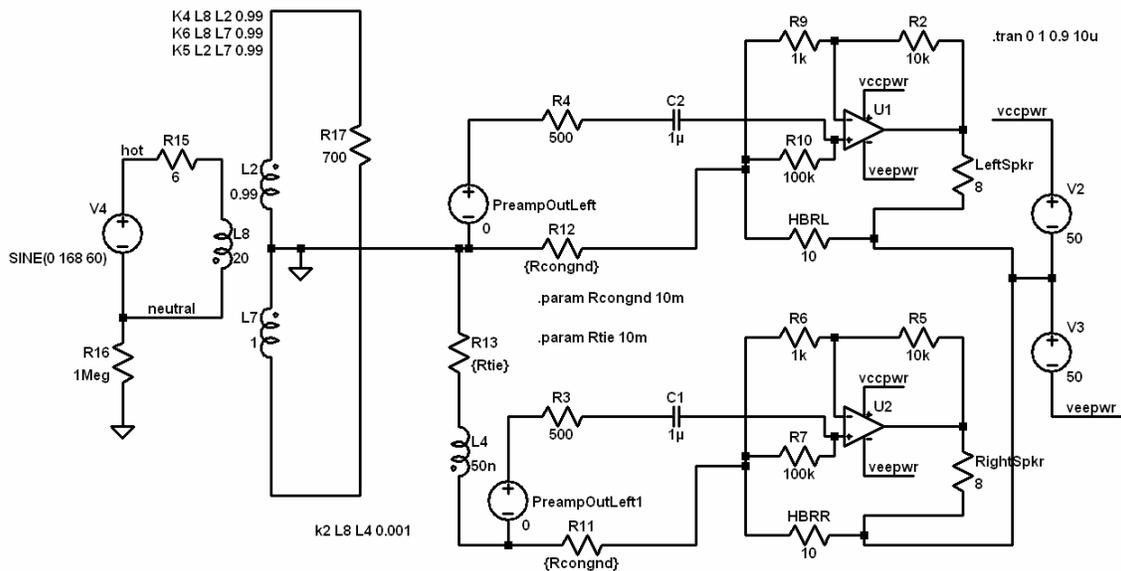
Figure 6 – cross channel hum can originate in the preamp (L4)

Other Hum Remedies

The methods outlined here, applied carefully, can dramatically reduce the hum within equipment, and with interconnected equipment. While there are other causes and cures for hum, we have to stop writing at some time. We'll only list them for now, without further comment or explanation:

- Electrostatic shields on transformers
- Belly (flux) bands on transformers
- Toroidal transformers
- Shielded cable or twisted pairs
- Mu metal shielding

If you really need the minimum of hum in your interconnections, then balanced I/O, carefully implemented, can be a great help. Nothing however is free. As Self points out, without careful design, the balanced input can easily be much noisier than an unbalanced input.

References

[1] "Audio Power Amplifier Design Handbook", Douglas Self, focal press, © 2009

[2] "Small Signal Audio Design", Douglas Self, focal press, © 2010

[3] "Partial Inductance", Clayton R. Paul, IEEE, © 2010

[4] "Electromagnetic Compatibility Engineering", Henry W. Ott, John Wiley, © 2009