Preventing Hum and Noise Problem in Audio Amplifiers

An Antidote to 'Advanced Grounding Guruship'

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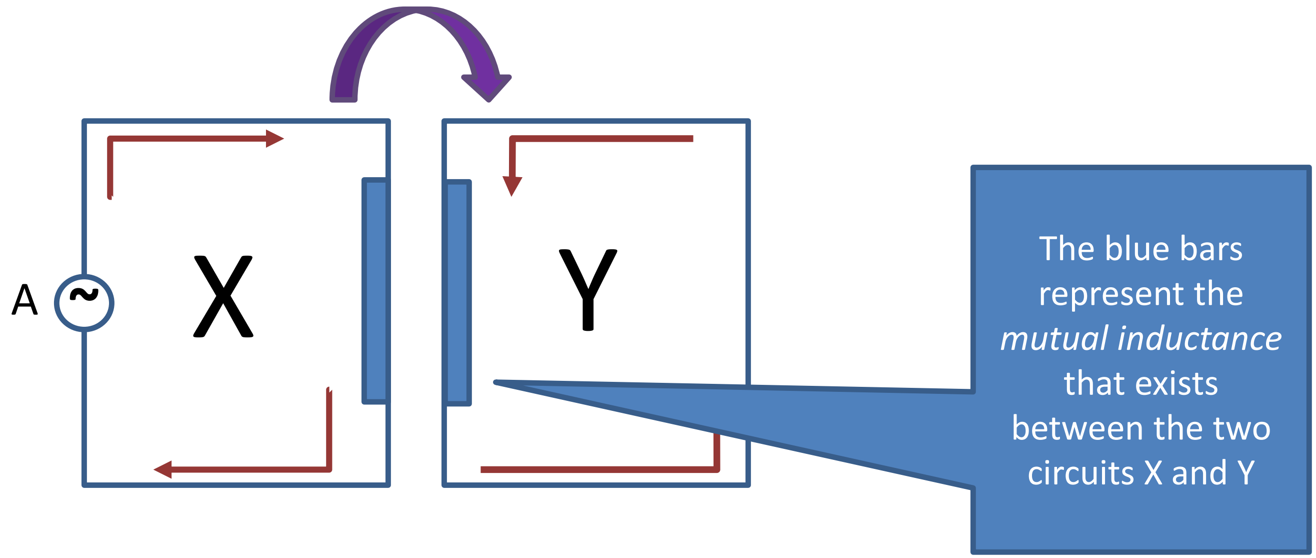
Magnetic Coupling - Basic Concept

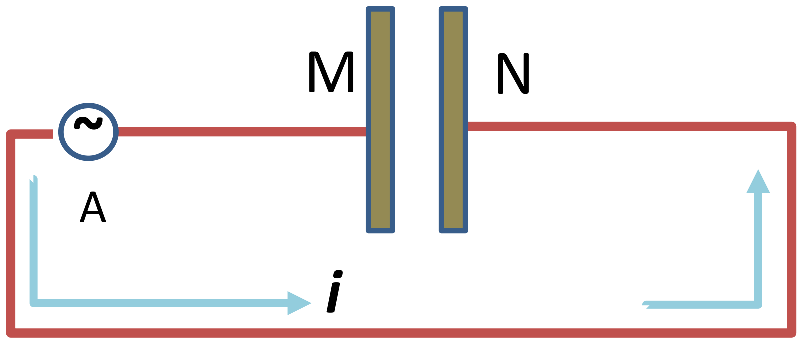


A signal ***or noise voltage*** source A causes an ***electro-motive force*** (EMF) that drives current flow around loop X. This will ***induce*** a current in loop Y that flows in the opposite direction through a physical process known as ***magnetic induction***. The magnitude of the current flowing in Y is proportional the magnitude of the current flowing in X, the coupling constant ('k') that exists between the two loops and critically, the area of the loops X and Y. The larger the loop areas, the greater the coupling.

For A in the example above, the source current will exit out the top travel around the loop and return in the bottom. The loop current induced in Y will exit out the bottom and return to the top.

The majority of the loop current ALWAYS flows via the lowest *impedance* return path to its source. Hence, the current return path is frequency dependent.

Capacitive Coupling - Basic Concept



In capacitive coupling, AC source A causes and *electric field* across plates M and N that drives a displacement current ***i*** that flows around the circuit.

The magnitude of current ***i*** is proportional to the source voltage A, the size of the capacitance appearing between M and N and the frequency of source A. The higher the frequency, the greater the coupling.

For A in the example above, current ***i*** will exit out the LHS, travel around the loop to N, across the capacitor to M and return to the RHS of A.

As with magnetic induction, the majority of the loop current ***i*** ALWAYS flows via the lowest *impedance* return path to its source. Hence, the current return path is frequency dependent.

Parasitic capacitance, or **stray capacitance** is the unwanted capacitance that exists between the parts of an electronic component or circuit due to their proximity to each. Practical examples would be the interwinding capacitance in a transformer, or the capacitive coupling of HF noise by unshielded wires running in close proximity to a Switch Mode Power Supply (SMPS).

Major Noise Mechanisms in Audio Amplifiers

(excluding thermal noise)

1. Ground loops – Mainly AC mains and Cross Channel

2. Common impedance coupling – Power supply and signal wiring giving rise to noise and/or distortion

3. Radio Frequency Interference (RFI)

Electrical equipment can produce noise (transmitter) and can be susceptible to noise (receiver). Further, within a piece of equipment, like an amplifier for example, some parts of the circuit may produce noise, whilst other parts are susceptible to that noise.

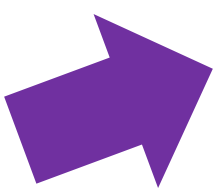
AC Ground/Noise Loops

Causes

- Stray magnetic fields from transformers/power supplies (transmitter) induce an EMF into more sensitive parts of the amplifier circuit (receiver) via inductive coupling
- Capacitive coupling across mains transformer primary<>secondary winding at low frequencies
- At HF, main coupling mechanism is capacitive

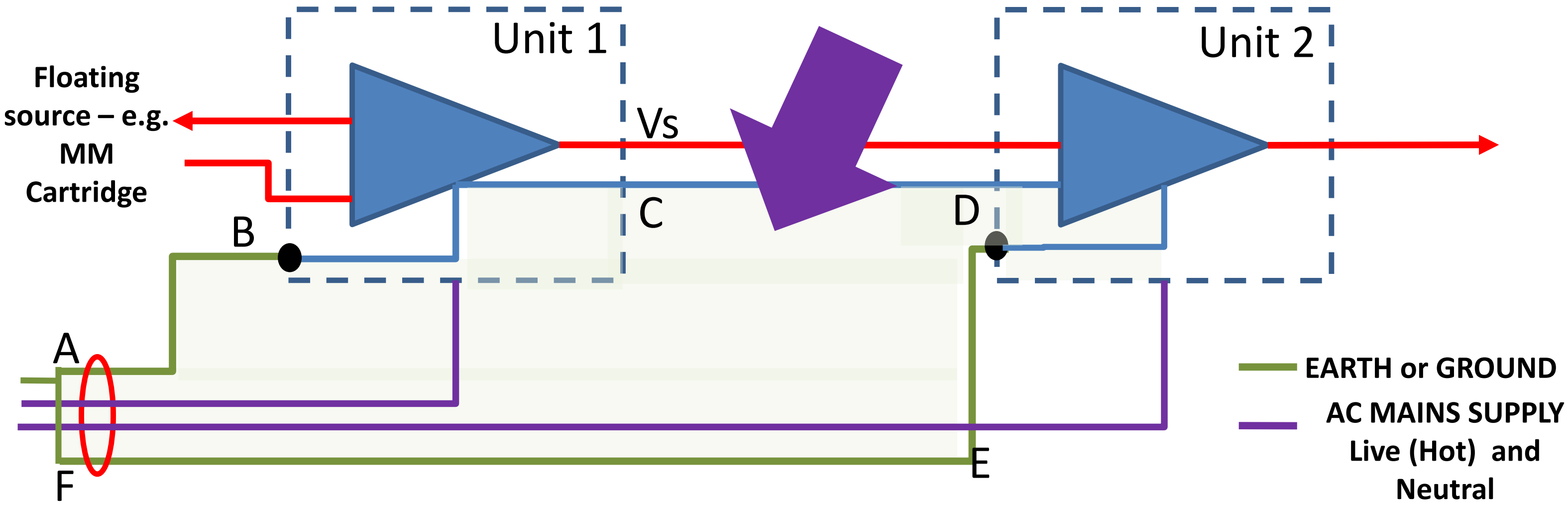
1^{st} Line Remedy

- Keep LOOP AREAS as small as practicable and especially those carrying significant current. Keep sensitive circuits away from high current circuits
- Specify your transformer with a flux band
- Specify an inter-winding screen on transformers – especially toroidal transformers



This symbol in the graphics that follow means magnetically coupled noise

Classic AC Ground Loop



Both metal chassis' must be EARTHED (legal safety requirement)

Both units 0V are connected to the chassis internally

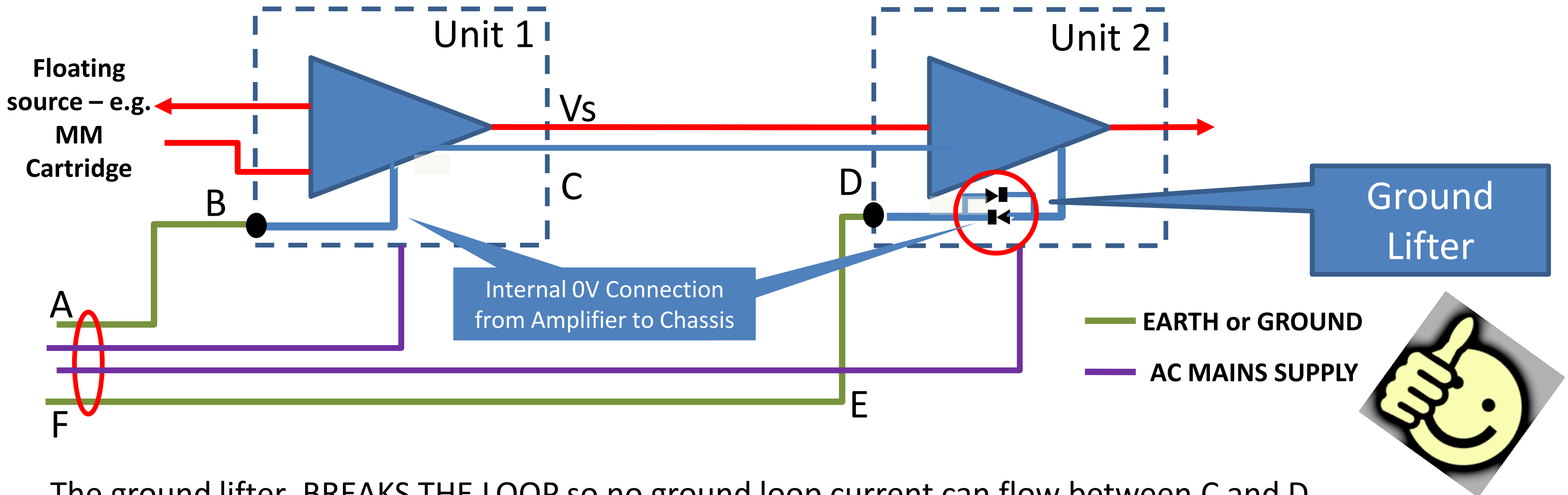
An electromagnetic loop is the TOTAL AREA prescribed by A>B>C>D>E>F>A shown in light green in the diagram above

Any magnetic field impinging on this loop (the green area) will generate an EMF and cause a current to flow around the loop i.e. an EARTH LOOP CURENT

The generating voltages are usually small in the order of 10's to 100's uV and the associated loop currents in the 10's of uA range (<u>magnitude very installation dependent</u>)

The result is a NOISE VOLTAGE between C and D caused by the loop current flowing through the shield and interconnect resistances that appears in series with the signal voltage. The higher the earth loop current and the interconnecting ground resistances, the bigger the noise voltage

Classic AC Ground Loop and Ground Lifter Cure



The ground lifter BREAKS THE LOOP so no ground loop current can flow between C and D

For any ground loop current to flow, the ground loop generating voltages would have to be in excess of the diode Vbe – i.e. +-0.6V and highly unlikely. A bridge rectifier is usually used, since this is convenient to mount and high current versions are cheaply available in which case the protection is +-1.2V

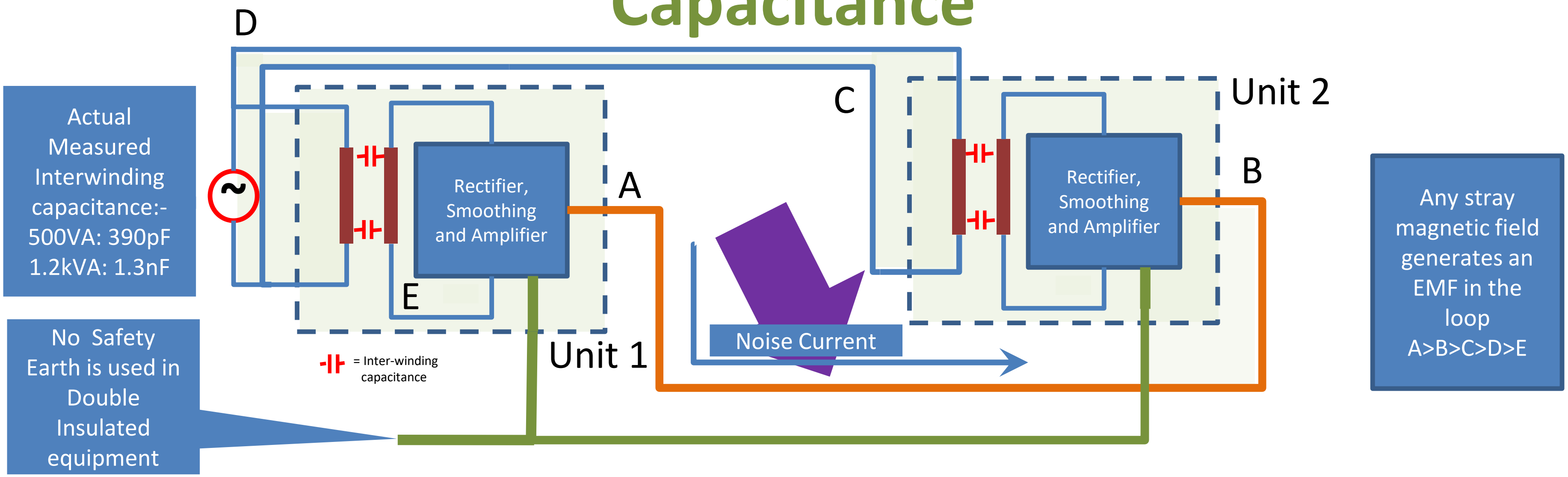
It is IMPORTANT that a HIGH POWER bridge rectifier is used – use a chassis mount 25-35A device with a surge rating of >200 Amps

If a serious fault occurs inside either unit – eg LIVE wire touches the amplifier PCB or Speaker return wire for example - the rectifier must take the FULL FAULT CURRENT until the RCB at the mains distribution panel trips. This is typically 20-30 milli-seconds

1. UNDER NO CIRCUMSTANCES can you use this technique in equipment that will be powered off old style fused mains distribution panels that do not feature RCB/RCD (Residual Current Breaker/Residual Current Detector) systems. If in doubt: <u>DON'T USE THIS TECHNIQUE</u>

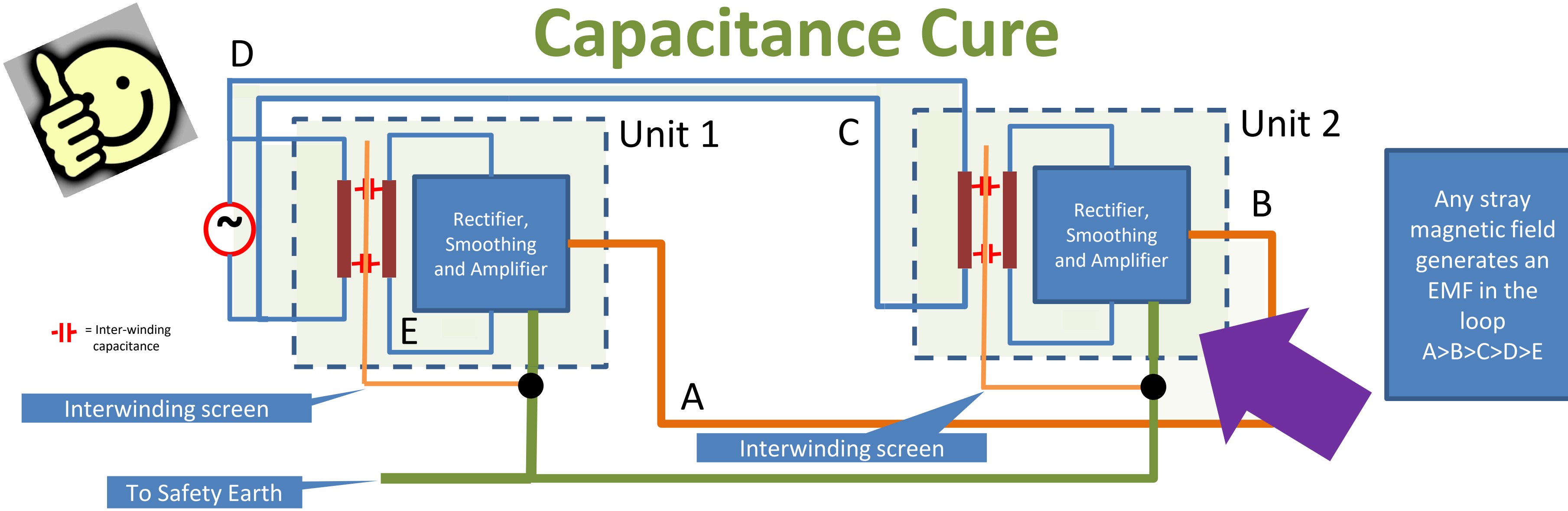
2. NEVER use devices like 'ground lifter plugs' that break the Earth (Ground) connection in order to break the ground loop. These are dangerous and in most countries illegal.

AC Ground Loop Via Transformer Inter-winding Capacitance



Any stray magnetic field impinging on the interconnect screen (*across A and B*) will generate an EMF that will cause a current to flow around the path A>B>C>D>E. This type of noise loop is particularly prevalent in double insulated consumer equipment where there are no safety earth connections. Like the classic AC ground loop discussed previously, any extraneous current flowing through the interconnect shield will cause small voltage drops across the shield and interconnect resistances. These error voltages will be in series with the main music signal, amplified and output to the speaker. This type of ground loop is particularly susceptible to HF coupling, since the transformer stray capacitances are relatively low and they therefore pass HF easily. Examples of HF noise sources would be SMPS, Modern LED and CFL lamps. It should be noted that the EMF will find any available path to close the loop – the specific route shown above highlights the problem when it flows through the interconnect shield. In modern consumer equipment that uses SMPS, special winding techniques are used to reduce interwinding capacitance of the transformer to help minimize this type of ground loop noise.

AC Ground Loop Via Transformer Inter-winding Capacitance Cure

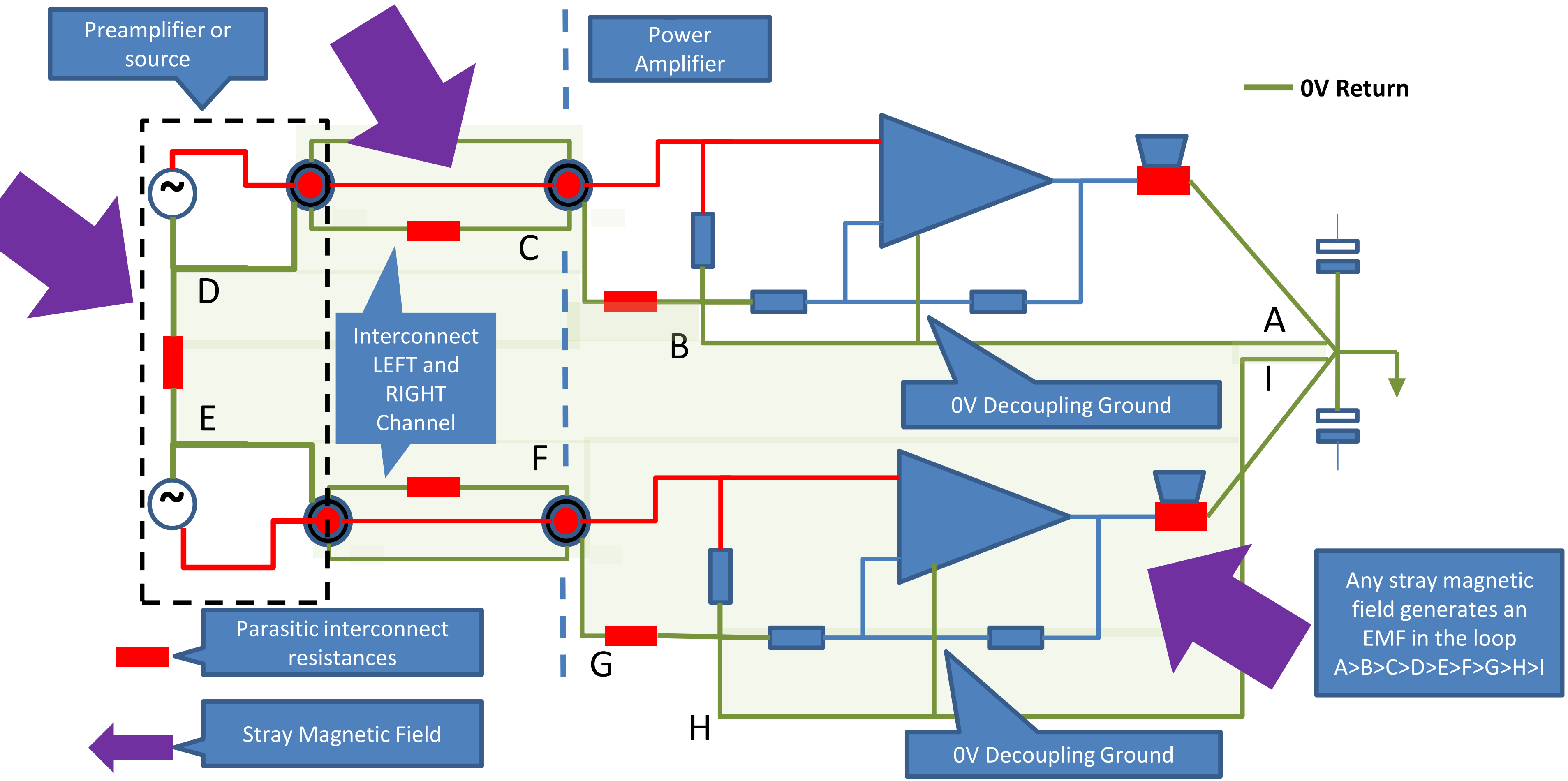


The cure for this type of AC noise loop is to specify a transformer with an **interwinding screen**. The interwinding capacitance is shunted to SAFETY EARTH (SAFETY GROUND). The loop is then flows through the Earth (Ground) wiring and away from the interconnect shield where it is most troublesome.

Other techniques that may alleviate this are ‘Y’ capacitors that connect from LIVE (HOT) and NEUTRAL to the Safety Earth (Safety Ground). These provide a path for the loop via the ground. In double insulated systems where there is no safety ground, this type of noise problem can be particularly difficult to solve. Interconnect cable routing and low interconnect resistances then become an important part of the solution, while in particularly severe cases, isolating transformers are required.

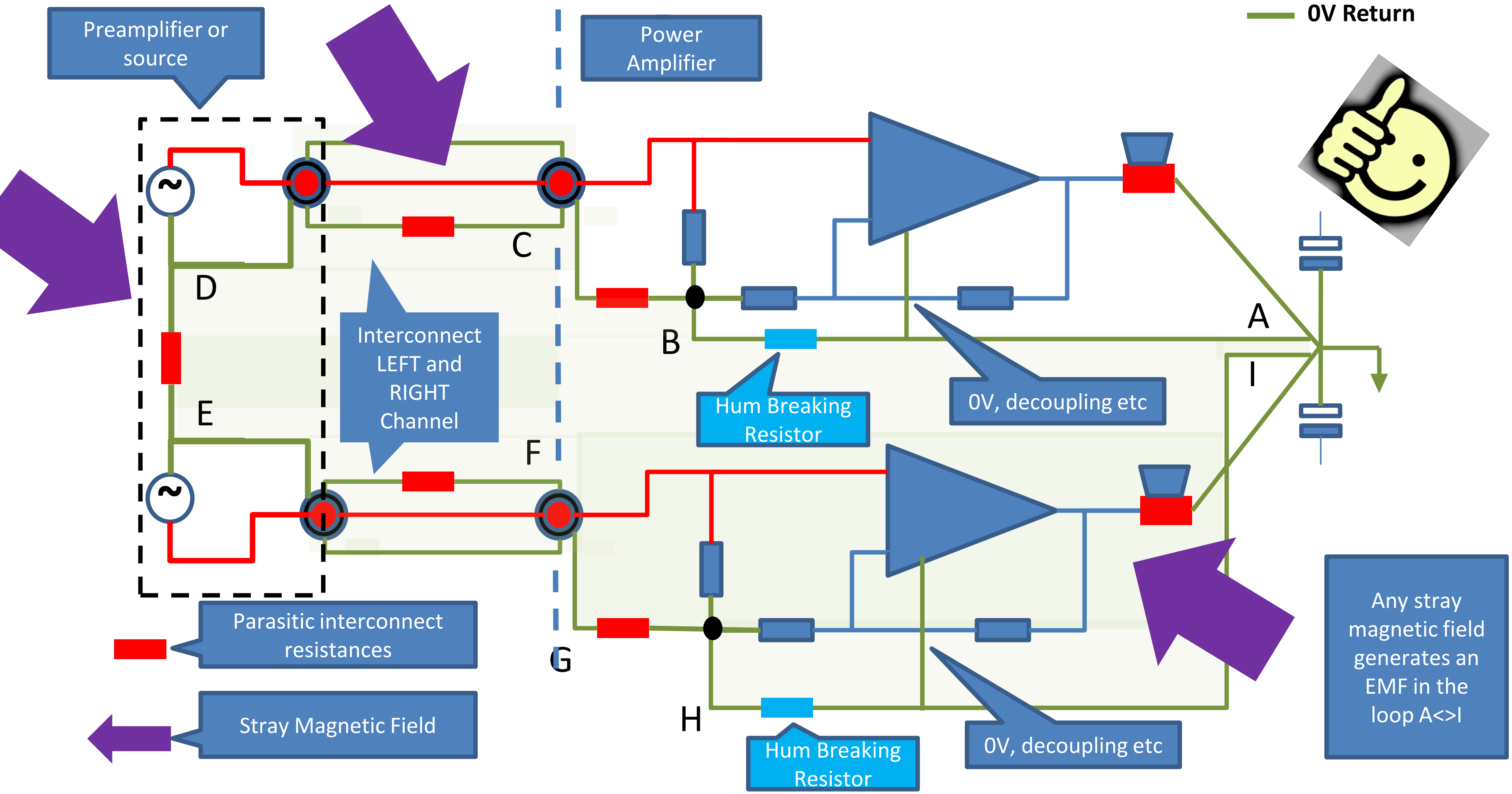
If the mains filter route is used to solve your noise problem, it is highly recommended for safety reasons that an off the shelf solution is used. Good suppliers of these types of filter are Schaffner and Schurter readily available from Mouser, Digikey and RS Components

Cross Channel Ground Loop Cause



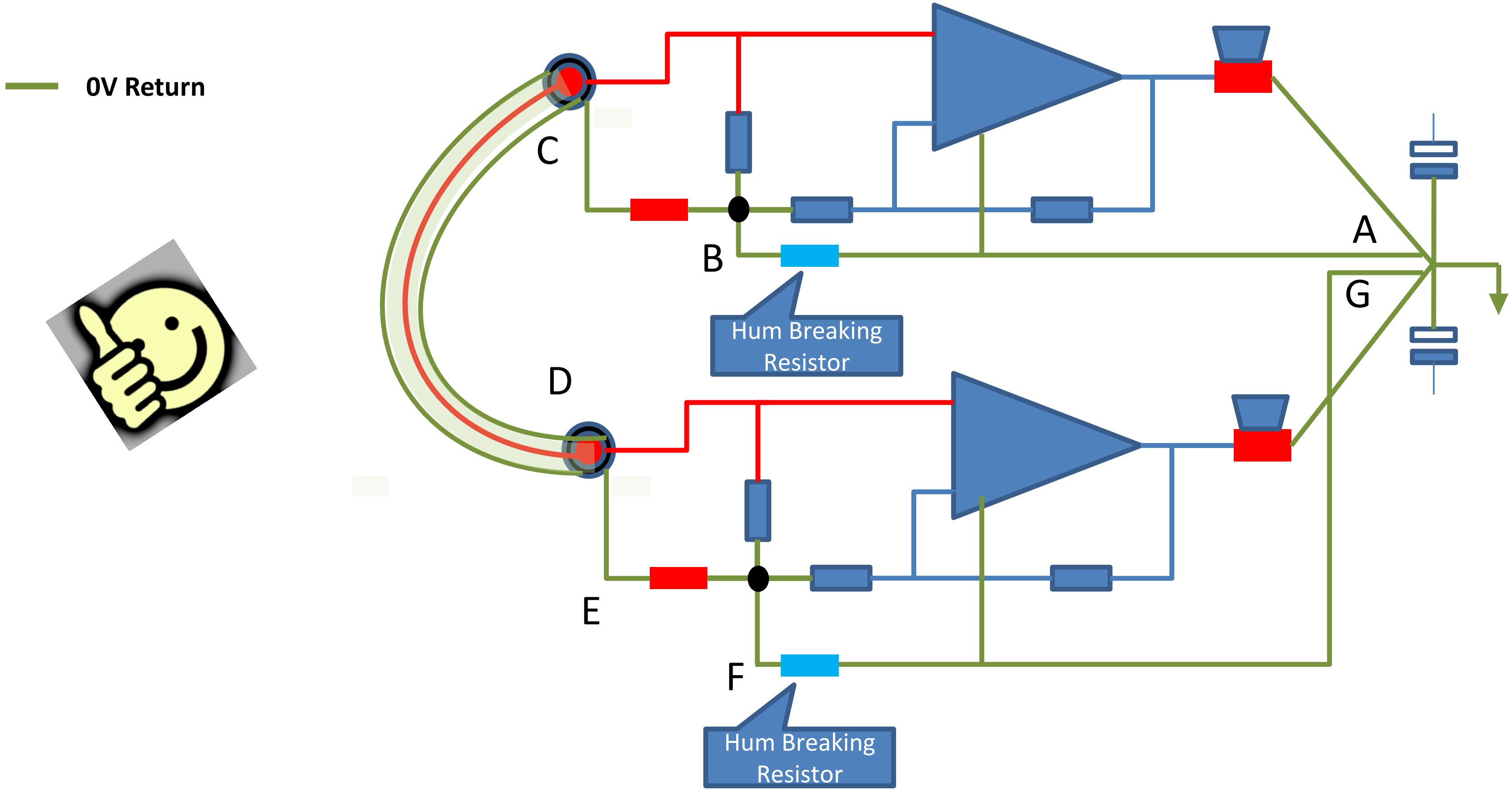
In a cross channel ground loop, an EMF is generated around the electromagnetic loop area shown in green prescribed by A>B>C>D>E>F>G>H>I. The resultant EMF loop current gives rise to noise voltages across the parasitic resistances (shown as RED) that appear in series with the signal (~) and thus amplified along with it. These parasitic interconnect resistances are between 0.1 to 1 ohm, but may be higher than this in bad systems. The loop currents range from low 10's of uA to 100's of uA – very system specific and highly dependent on the amplifier wiring and layout.

Cross Channel Ground Loop Cure



To reduce the error voltages appearing across the parasitic interconnect and ground resistances, the loop current must be reduced. This is accomplished using **'Hum Breaking Resistors'** (HBR). This *reduces the loop current* and forms a voltage divider with the parasitic resistors. For example, if the parasitic resistances total 1 Ohm and the HBR is 10 Ohms, the reduction in cross channel ground loop noise is in the order of 20 dB.

How to Test for a Cross Channel Ground Loop



Couple the Left and Right inputs together using an RCA interconnect cable. If the amplifier suffers from a cross channel ground loop, it will hum (see slide 24 ‘Headphone Trick’) . The HBR resistor is typically between 10 and 22 Ohms (I use 15 Ohms usually). *Always include the HBR on your amplifier module PCB layout. This will dramatically reduce any noise arising from a cross channel ground loop*

Common Impedance Coupling

Causes

- High Current return paths (e.g. decoupling or reservoir capacitor charging currents) are mixed in with signal ground returns

- Failure to separate Signal Ground from Power Ground

- High impedance/resistance ground connections exacerbate noise issues

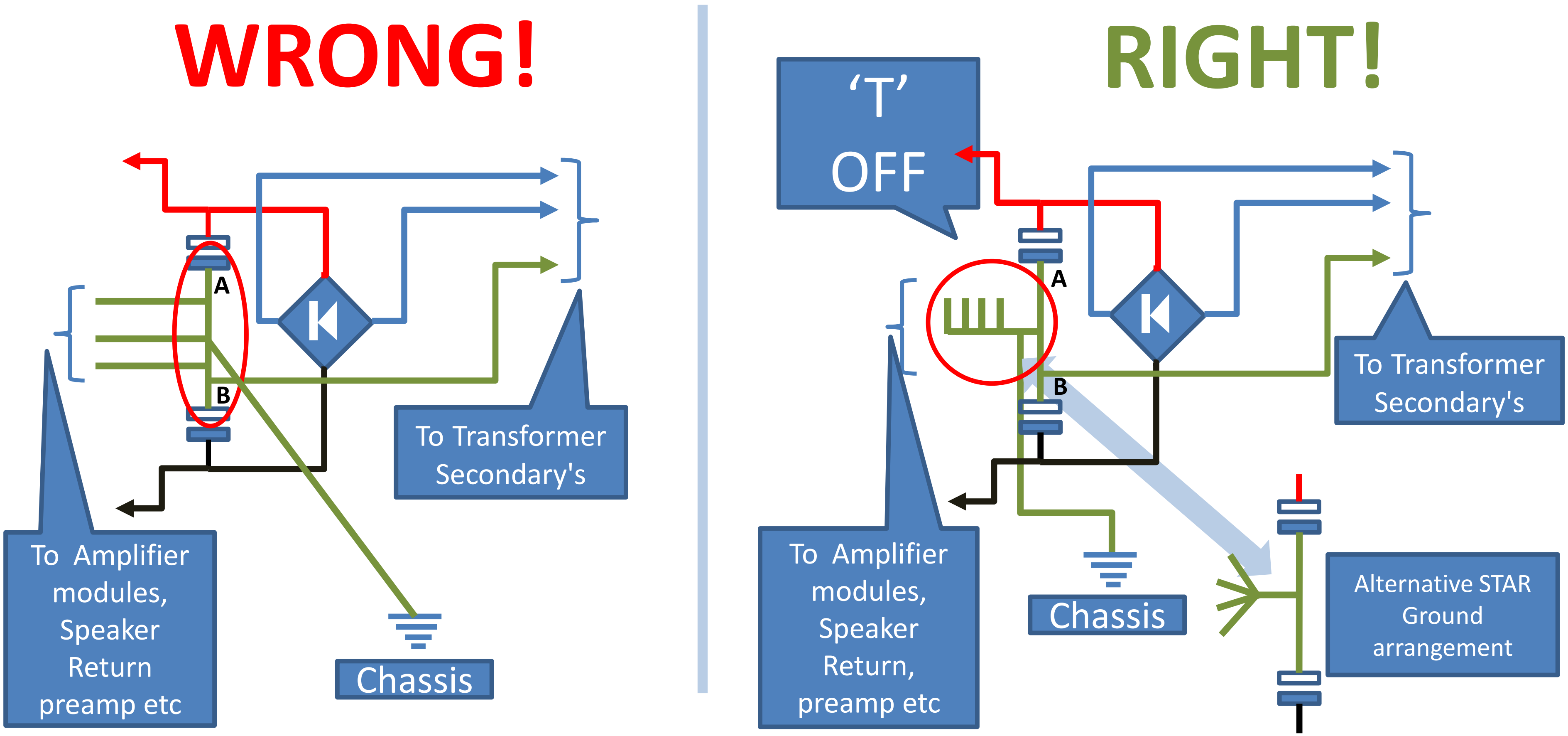
1st Line Remedy

- Keep signal and ground returns separate and only connect them together at a single place on the PCB – namely the star ground or the 'T'

- Do not make any direct connections to the common ground point where the reservoir capacitors are connected together – ALWAYS 'T' off; use a STAR or 'T' grounding system

- Keep all ground traces and interconnections as thick/large as practicable

Common Impedance Coupling - Wiring



This is the classic common impedance problem caused by connecting signal returns to the junction of the filter capacitors. High currents flow between the capacitors (**A** and **B**) giving rise to small voltage drops that then appear BETWEEN the signal returns. These can add in series with the audio signal, introducing noise. Similarly, signal grounds should not be mixed up with decoupling grounds on amplifier module PCB's where the same mechanism can occur

How to Avoid Common Impedance Coupling

- Note carefully the order to the 'T' section – from right to left on slide 14 and slides 20 ~ 24

   1. Reservoir capacitors junction is across the top part of the 'T' with NO other connections between the two
   2. On the 'T' upright
      - Take off point to earth bond connection
      - Any protection circuits or digital signal boards
      - Speaker returns – these are high current
      - Decoupling and small signal Amplifier module/PCB 0V
      - Any small signal analog board – e.g. preamplifier stage(s)

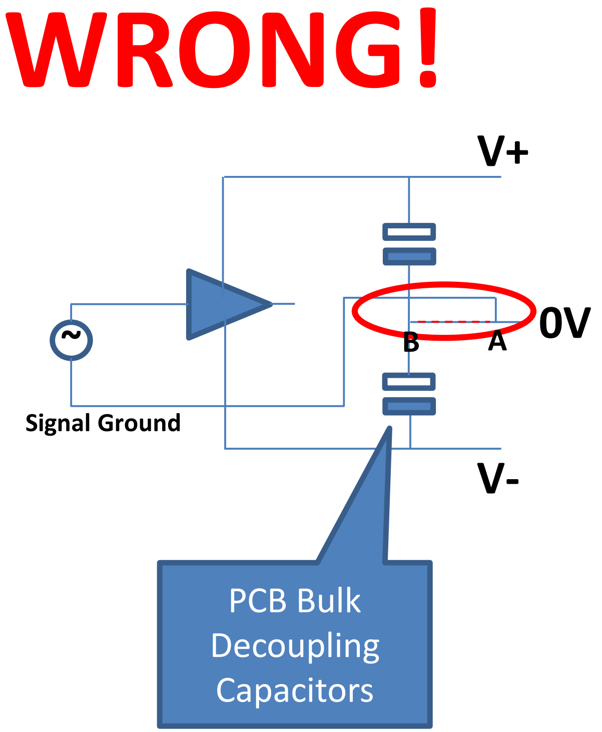
- The total length of the 'I' in the 'T' need not be longer 1-2 cm and you can even 'stack' the 0V connections on top of each other. The whole idea with the central 0V here is to avoid common impedance coupling errors which could lead to hum and noise

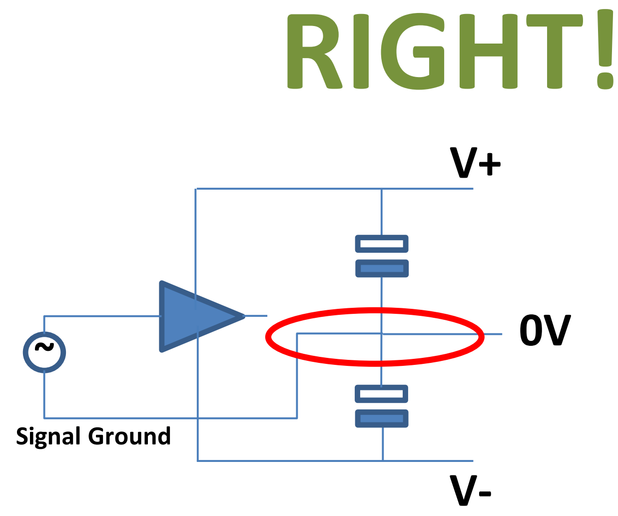
- Keep the top bar of the T as short as possible – to do this, mount the filter caps right next to each other

- Never make any connections between the two capacitors – i.e. along the top cross bar of the T other than the secondary windings of the transformer or where you couple separately rectified and smoothed secondaries. High charging currents flow across the cross bar in the 'T'.

- Always take the chassis connection off at the 'T' or STAR ground and never on the connection between the filter capacitors.

Common Impedance Coupling – PCB





This diagram shows the common impedance problem but applied to a PCB. Current flowing between A and B (dashed REDF/BLUE line) creates a voltage drop that appears in series with the signal source ~. Since the decoupling capacitors will be passing mains harmonics and music half wave harmonics, this type of problem can lead to significant increases in distortion and noise. Connect the decoupling ground (the junction of the PCB bulk decoupling capacitors) and the signal ground at one point only on the PCB as shown on the right hand side.

Follow These Basic Rules #1

- Mains wires to the fuse, switch and to the transformer primary: - use good quality 16 Amp SHEATHED mains cable for the mains side wiring. This ensures the live and neutral (hot and neutral) are close together and therefore minimize radiated magnetic fields. Being sheathed is also good for safety

- Transformer wires from each secondary to its associated bridge rectifier are tightly twisted together

- Wires from each bridge rectifier to their associated filter capacitor(s) are tightly twisted together

- The V+, V- and 0V to each of the amplifier boards are twisted tightly together. *These wires come directly off the filter capacitors* – note carefully how this is drawn in the diagrams

- Keep the speaker output wire from the amplifier board to the output terminal as short as practical

- Keep the speaker return wire from the speaker socket back to the 'T' as short as possible. Ideally, you should twist the speaker + and – cables together, but this may be difficult in practice due to layout limitations.

Follow These Basic Rules #2

- There is only ONE and only ONE chassis bond point in the amplifier – multiple bond points run the risk of creating earth loops. For SAFETY REASONS make sure it's a high quality connection – use serrated washers and lock nuts and ensure they are tight. Use a meter to check that all parts of the metal chassis connect to this bond point.

- Keep high current wires away from small signal wires

- The input and output sockets may NOT make any direct connection to the metal chassis

- Use a 'HBR' resistor to prevent significant ground currents flowing between the source device and receiving amplifier. The signal ground connects to the amplifier on-board ground through this resistor.

- PCB layout: If designing your own, keep the V+, 0V, V-, speaker output and speaker return connections as close as practically possible on the PCB to minimize earth loops and radiated noise (this will be at audio frequencies and associated harmonics). Keep the PCB layout compact. Always use STAR grounding on the PCB layout

Radio Frequency Interference (RFI)

- Wire 1nF ceramic capacitor from the input socket 0V to the chassis as close to the input socket as possible. At RF this effectively makes the source equipment chassis, the screen and the receiving equipment chassis *a single enclosure*, maximizing RF Immunity through screening

- In some designs, you *may* get better immunity by fitting a 1~2nF capacitor across the AC terminals of the ground lifter bridge rectifier. This shunts any residual RF on the chassis coming in through the input cables to earth

- You can test your amplifier immunity once fully assembled with all the panels screwed in by placing your mobile phone on top of your amplifier and then getting a friend to call you. There should be no buzzing or extraneous noises over your speakers

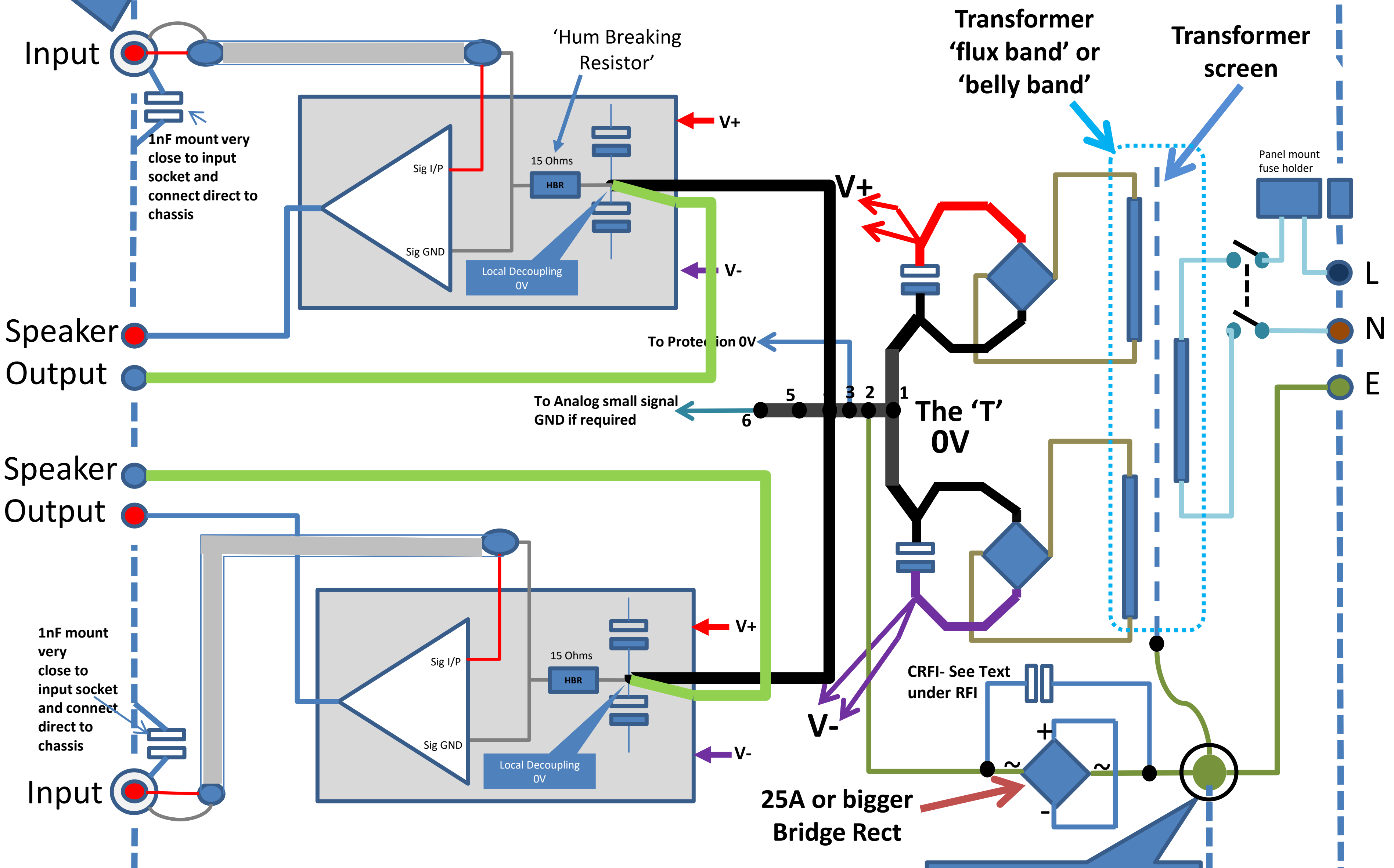
- Always ensure you have a band limiting filter on the input of your amplifier. 1k and 330pf is a good compromise. If you are worried about thermal noise, 220 Ohms and 1.5nF is also ok (f_c = 480 kHz). But, whatever you do, make sure you have the filter

- Good quality interconnects (tightly woven screen, high contact force connectors) also help prevent RFI problems and reduce interconnect resistance

How To Do It Practically . . .

EXAMPLE #1 –Split Secondary Rectification with GND Lifter

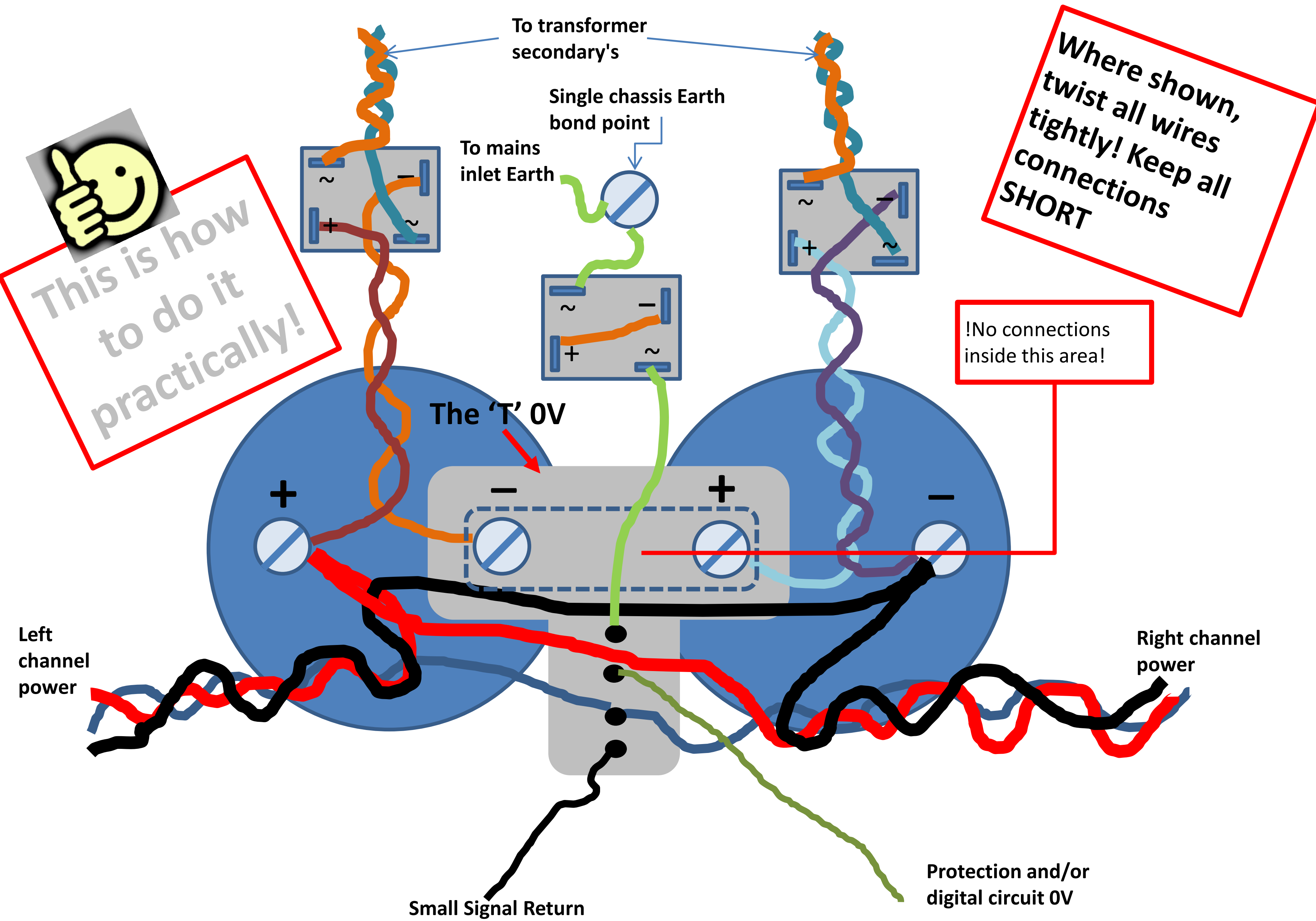
RCA I/P sockets must be insulated from the chassis



!See text for important 'how to's'

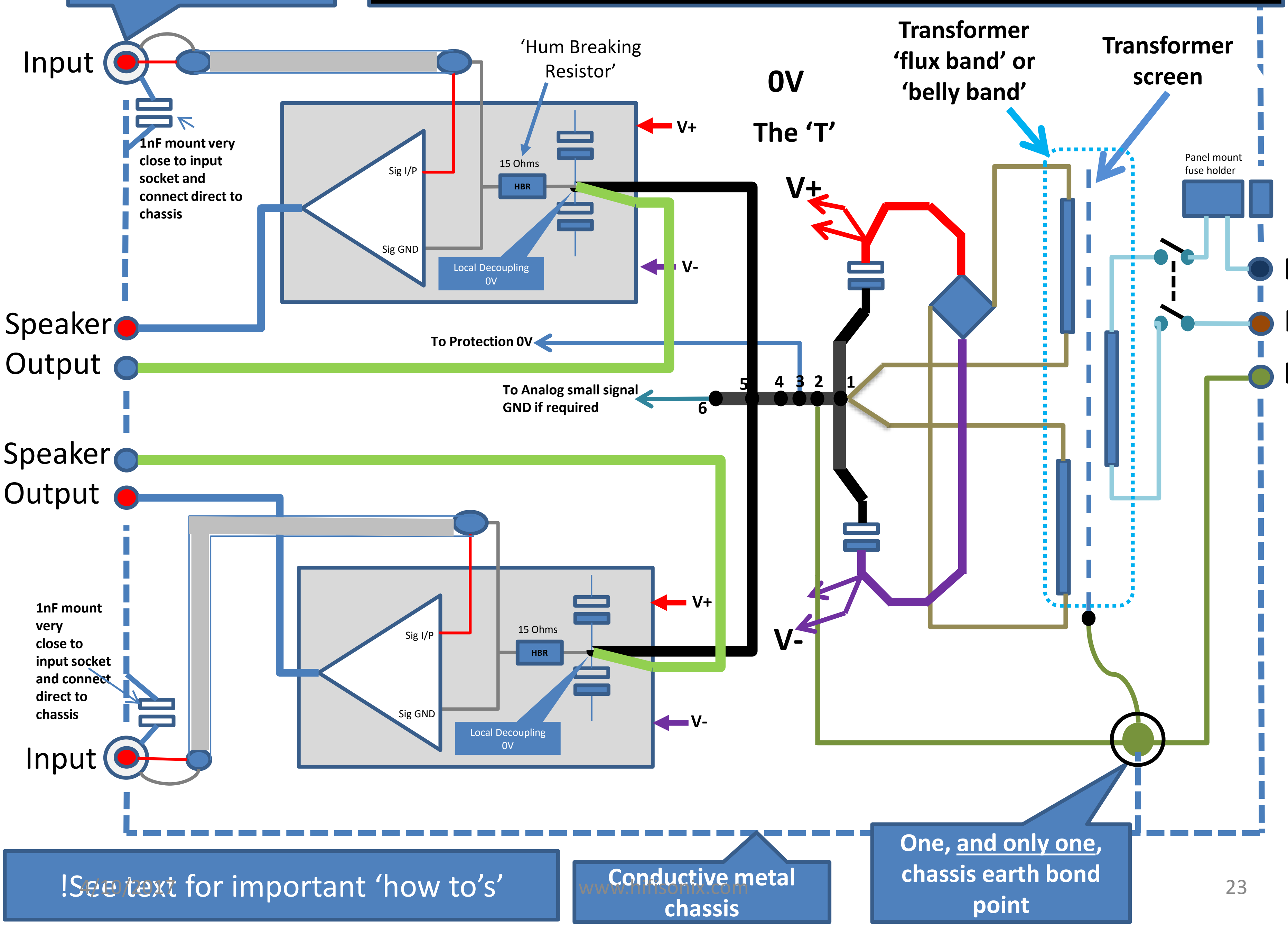
Conductive metal chassis

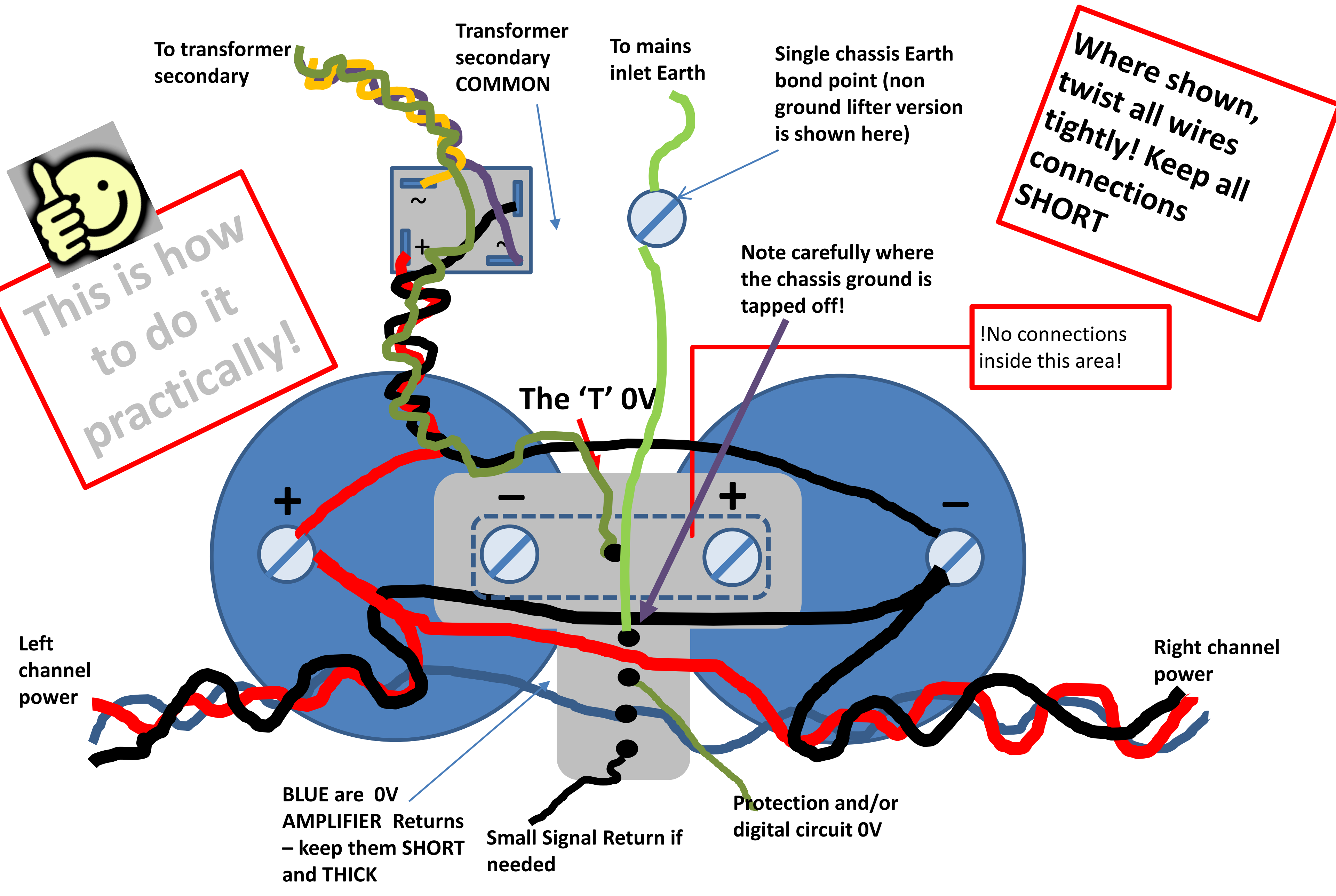
One, <u>and only one</u>, chassis earth bond point



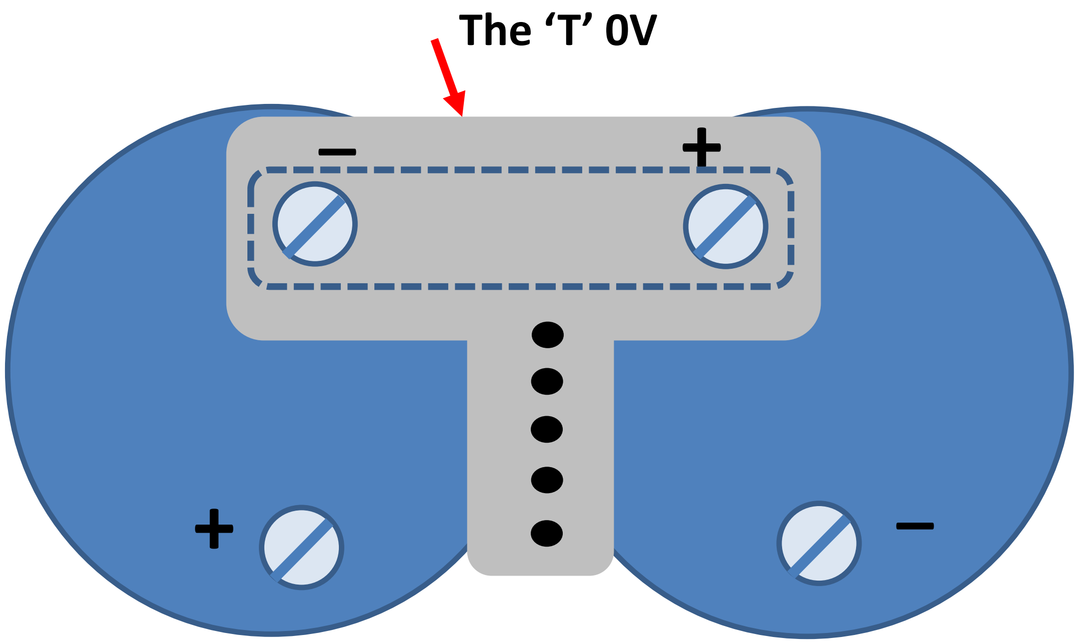
EXAMPLE #1 – Split Secondary Rectification How to do it Practically

EXAMPLE #2 – Single bridge and no GND Lifter





EXAMPLE #2 – Single bridge and no GND Lifter - How to do it Practically



This drawing shows how you can minimize the loop area in the vicinity of the main reservoir caps by 'folding' the capacitors so that the + and – are closer than shown in the previous two diagrams

Always strive to minimize the loop area between the source (the + and – in this case) and the return (the 0V). This principle also applies to the speaker output and the speaker return.

Headphone Trick – Quick and Easy Hum/Noise Debugging

A pair of 90 dB at 1mW headphones is about 1000 times more sensitive than a loudspeaker – a typical spec being 1 Watt for 90 dB SPL at 1 meter. Relatively speaking, that's of the same order as a good high gain, low noise preamplifier.

Connect a pair of headphones directly to the output of your amplifier **(do this AFTER it has been switched on and the outputs have settled)** and without any input source connected.

You can then experiment with cable dressing, transformer orientation etc to get the lowest noise on the 'phones.

On a *really good* layout and execution, you should struggle to hear any hum/buzz on the headphones. **Disconnect the headphones before powering down your amp.**

Once you are at this level, you can then use a sound card to do further debugging. A good, practical result will be -90 to -100 dBV as measured on a sound card.

Acknowledgements and References

- Henry Ott – Electromagnetic Compatibility Engineering
- Daniel Joffe - Library of Grounding Problems
- Jensen Transformers – Application Notes
- Bill Whitlock – Grounding and Noise Presentation
- Analog Devices – EMI, RFI and Shielding Concepts
- Dr. Tom Van Doren – Training Seminar attended by NXP Apps Engineers
- Various discussions, private communications on DIYAudio.com