How to Wire-up an Audio Amplifier

Preventing Hum and Noise Problems in Audio Amplifiers: An Antidote to ‘Advanced Grounding Guruship’

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Updated and new material added January 2019

What This Presentation Will Help you Accomplish

1. Understand the basics of *induction* and *capacitive coupling*, and why and how they cause hum and noise in audio amplifiers
2. The importance of *minimizing loop area*
3. How to use a *line diagram* to highlight loop areas that give rise to hum and noise and how to minimize loop area
4. Understand *common mode* noise and *series mode* noise
5. How to solve *ground loops* and *cross channel ground loops*
6. How to avoid *common impedance* coupling
7. How to *route and dress the wiring* inside an amplifier for minimum noise
8. Be able to wire up an amplifier every time and achieve better than -100dB noise performance wrt to 1 Watt output into 8 Ohms
9. At the end of the presentation, a simple methodology is provided to help you identify which noise mechanism (ground loop, cross channel ground loop) is causing you problems

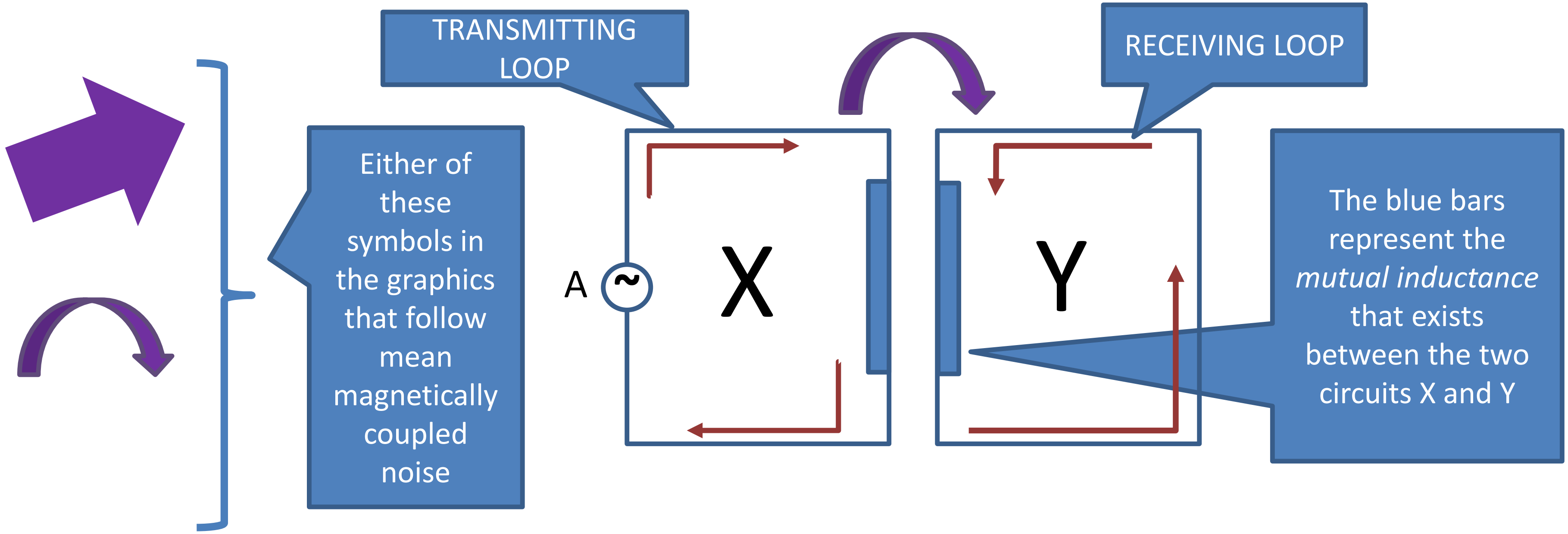
How to Wire-up an Audio Amplifier - Contents

- Basic Concepts
  - magnetic and capacitive coupling
  - common mode and series mode coupling
  - Common impedance coupling
  - audio signal ground and safety earth [ground]* are not the same thing
  - differences in ground potential aren't the cause of hum
  - line diagrams
- Real-world noise mechanisms in audio amplifiers
- Classic AC ground/noise loops
- Cross channel ground loop
- Common impedance coupling
- Common mode conducted mains noise
- Radio Frequency Interference (RFI)
- The Practical Stuff Basic rules for wiring an amplifier for zero noise problems
  - How to wire up an amplifier – practical examples
  - Headphone trick for noise debugging
  - Debugging - some ideas to get you going
  - How to hook-up equipment for minimum noise
- Acknowledgments and references

* UK/Australia/NZ = safety earth and USA = safety ground

We will refer to the safety earth as earth[ground] throughout this presentation to mean safety earth and safety ground

Magnetic Coupling - Basic Concept

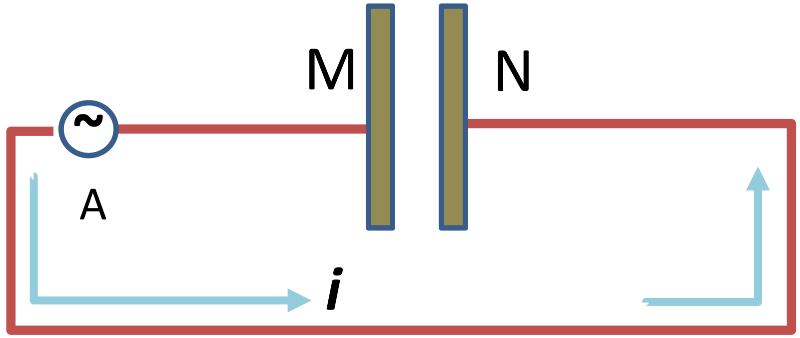


A signal ***or noise voltage*** source A causes an ***electro-motive force*** (EMF) that drives current flow around loop X. This will ***induce*** a current in loop Y that flows in the opposite direction through a physical process known as ***magnetic induction***. The magnitude of the current flowing 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, source A causes and *electric field* across M and N (i.e. the capacitance that exists between two parts of a circuit) that drives a *displacement current **i*** that flows around the circuit. When M is positive with respect to N, electrons flow around the circuit to N. When M is negative with respect to N, electrons are repelled and flow away from N towards the source.

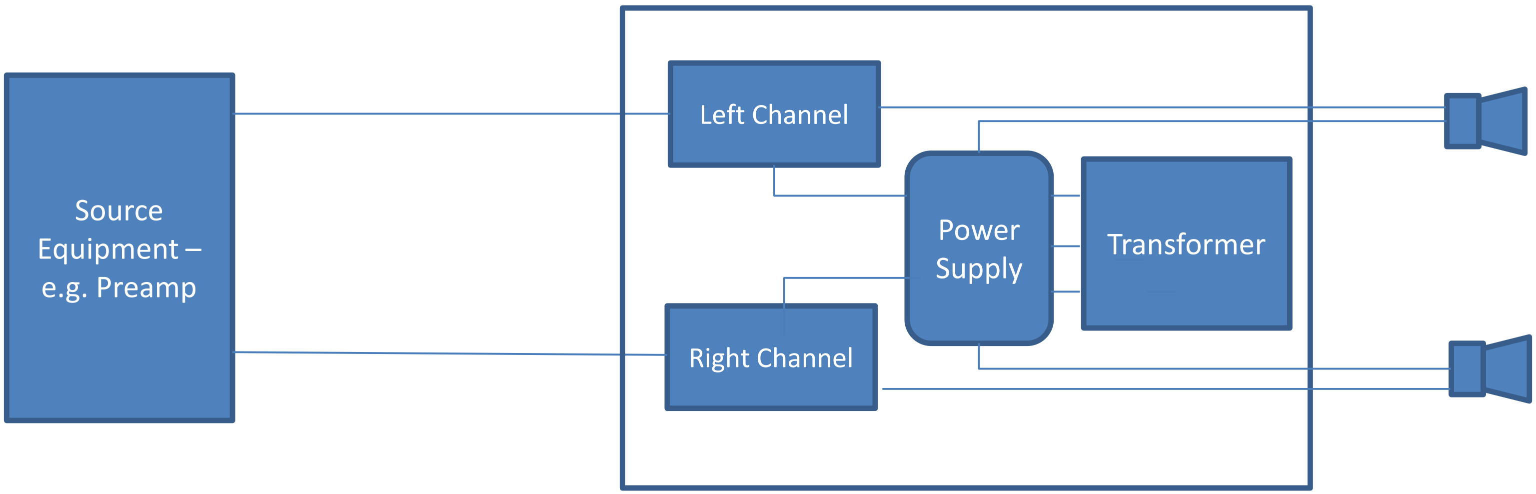
The magnitude of current ***i*** is proportional to the source voltage A, the size of the capacitance appearing between M and N and the frequency of source A. In general, the higher the frequency, the greater the coupling.

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).

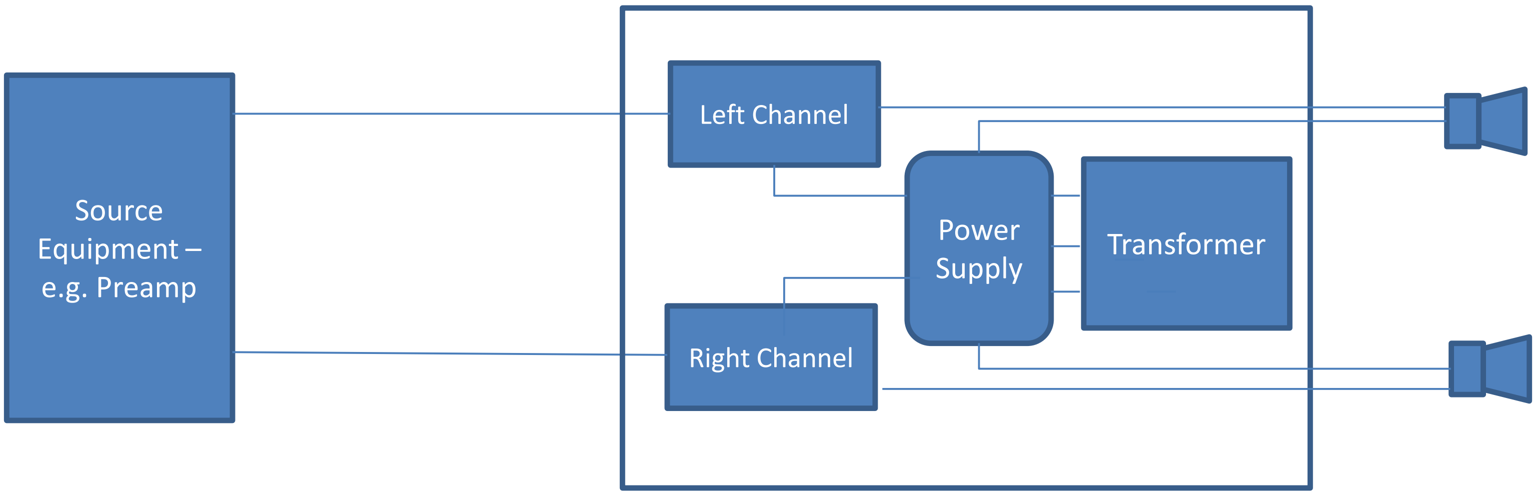
How to Use a Line Diagram to Highlight Loop Areas



In a line diagram, the power supply 0V, safety earth[ground], signal returns and speaker return connections are drawn as single lines so that the *total area bounded by all these 0V and Ground connections etc* is highlighted. This quickly identifies the total area available for magnetic induction coupling – i.e. for the formation of ground and noise loops. In any amplifier (or electronic gear), to minimise noise you have to minimize the total loop area bounded by the power supply 0V, signal return and mains safety earth – this is a critically important point.

Further, the objective of ground or noise loop mitigation is to prevent these types of noise currents flowing in the interconnect signal return or in other words, ensure that the signal return only carries the audio signal and nothing else.

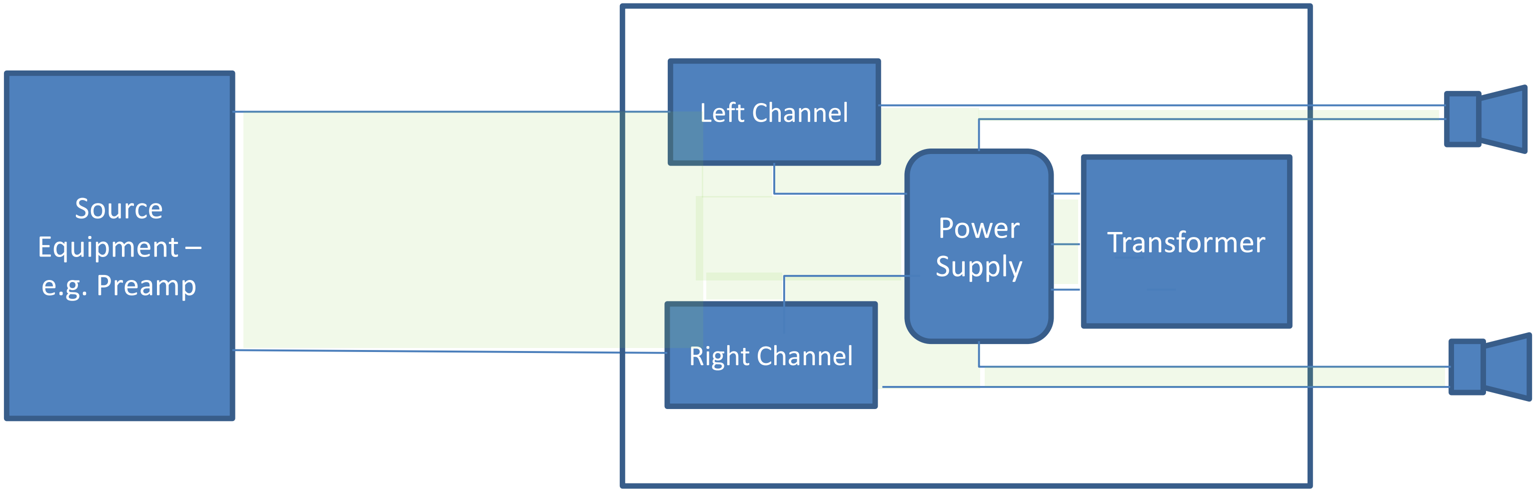
We Start With a Basic Audio Set-up . . .



A source on the left provides inputs to an amplifier on the right. For clarity, the interconnections are simply shown as single lines (this is why we call it a *line diagram*) – they would in reality consist of a signal and a return (normally the cable shield). Inside the amplifier we have the left and right power amplifiers themselves, and a power supply – usually a bank of reservoir capacitors and associated rectifiers and a transformer.

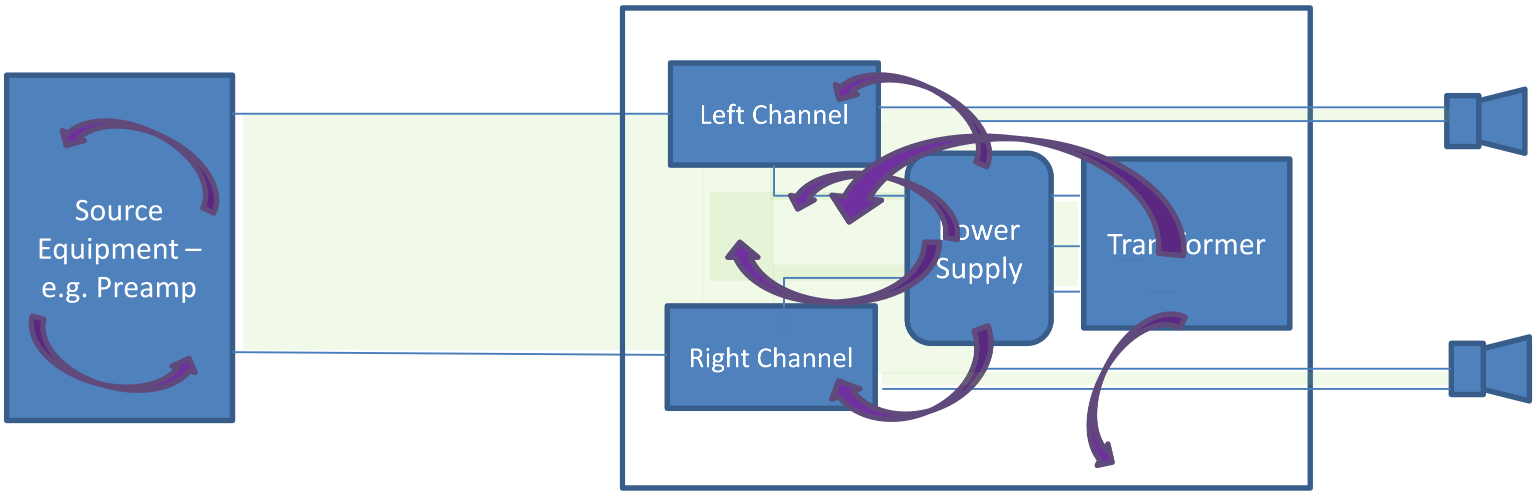
Next, we highlight the loop areas in green . . .

Loop Areas Prone to Hum/noise Pickup Highlighted in Green



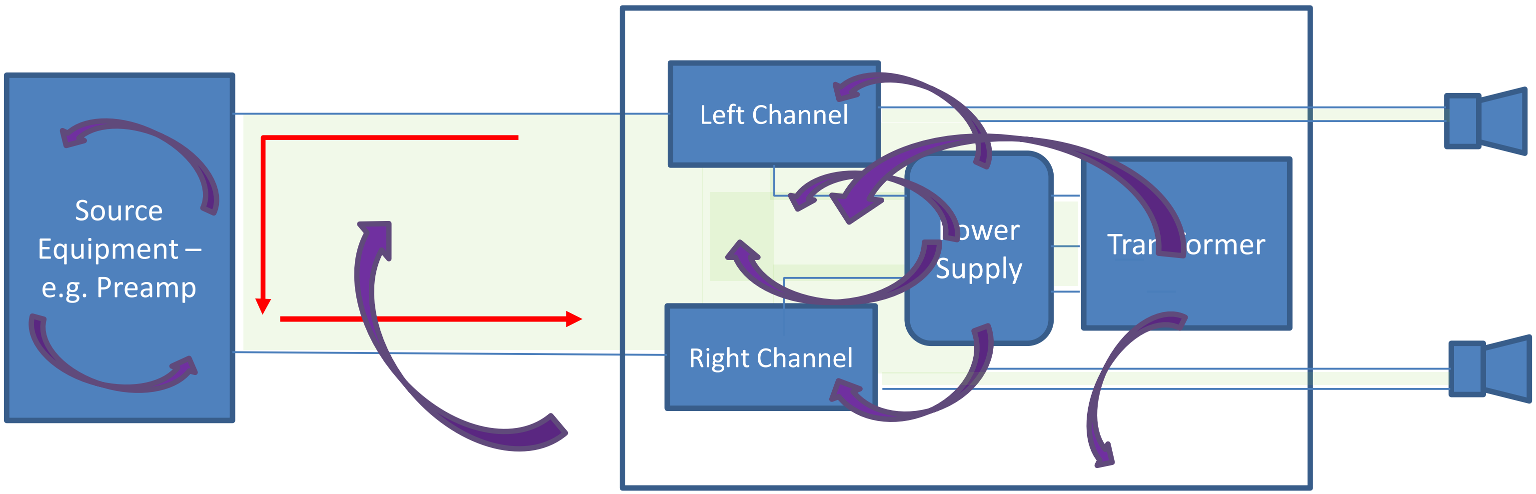
Highlighted in this example is the total loop area. Note that it extends out between the equipment, and between the internal signal interconnects, power supply wiring and to the speakers

Magnetic Coupling – The Concept and Importance of Loop Area



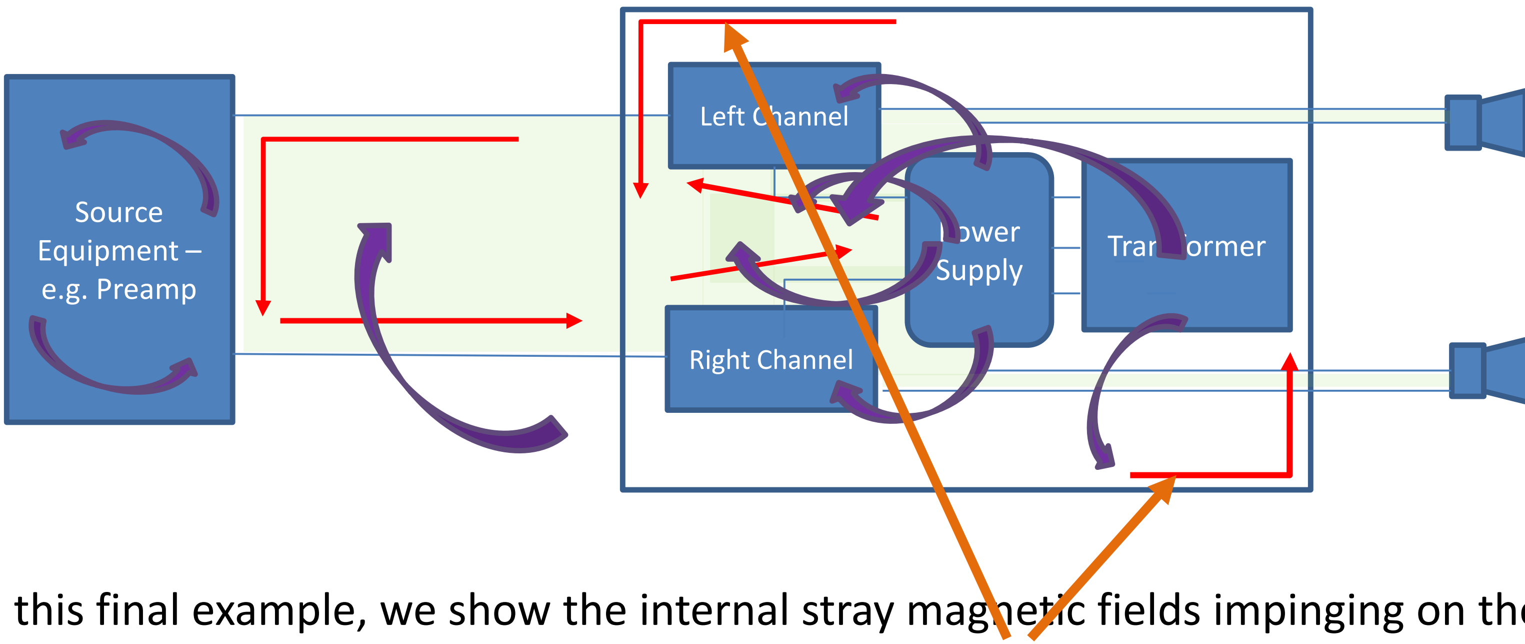
Stray magnetic fields arise from external sources, and from within the equipment itself. For example, on a large reservoir capacitor bank, 20 or 30 Amp ***mains frequency related*** current pulses flow through the transformer secondary, the rectifier and into the capacitors. These currents generate large magnetic fields, which if not managed carefully, can couple into nearby wiring. Between the reservoir capacitors, the amplifier modules and the loudspeakers, large ***signal frequency related*** currents flow, radiating magnetic fields at the associated audio frequencies.

Magnetic Coupling Causes Loop Currents *Between* the External Interconnects



Stray magnetic fields intersecting the green shaded loop areas will cause a loop current to flow. These loop currents, flowing for example through the interconnect and shield resistances will give rise to a small voltage drop that will *appear in series with the source signal*, and thus degrade the signal to noise ratio. This scenario is repeated in the other loops that exist within the amplifier and any source equipment. On professional and commercial audio dear, the reason why RCA receptacles are always co-located on the rear of equipment and why the interconnect cable left and right channels are bonded together: it dramatically ***reduces the loop area*** and hence minimizes the opportunity for noise ingress.

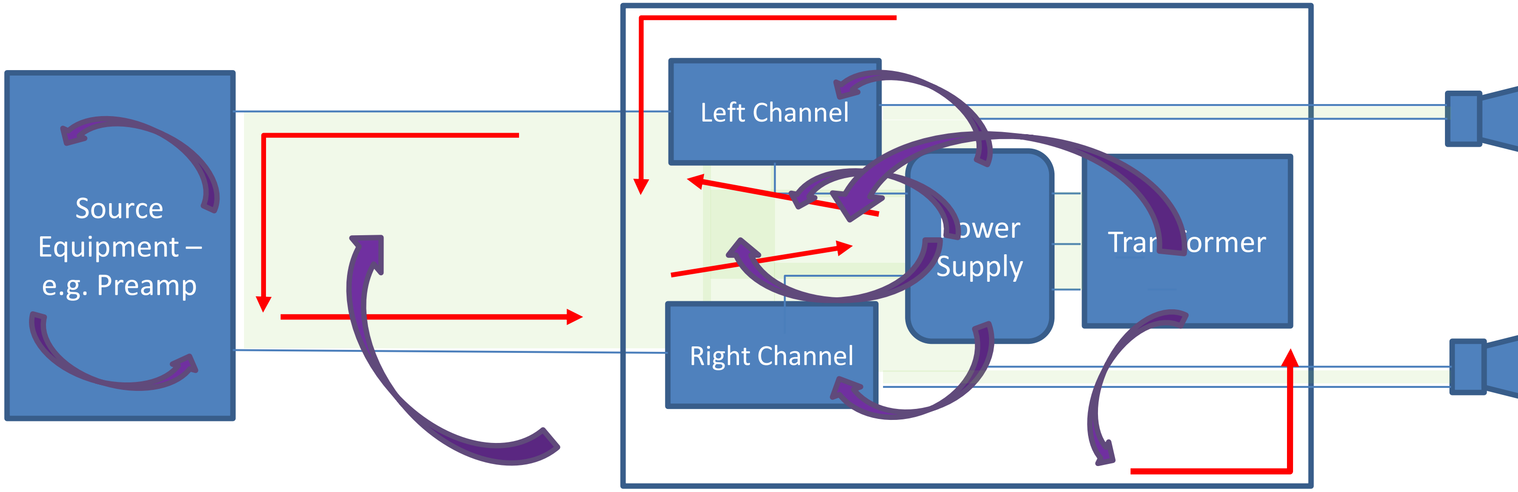
Loop Currents Flow in the Housing Metalwork



In this final example, we show the internal stray magnetic fields impinging on the metal housing of the amplifier, causing noise currents to flow in the metalwork. For this reason there should only ever be ***one and only one connection between the electronics 0V and the housing*** – if you have more than one connection, you run the risk of creating a loop and injecting unwanted noise into your circuit.

We will cover the safety aspects of the ground a little later as well.

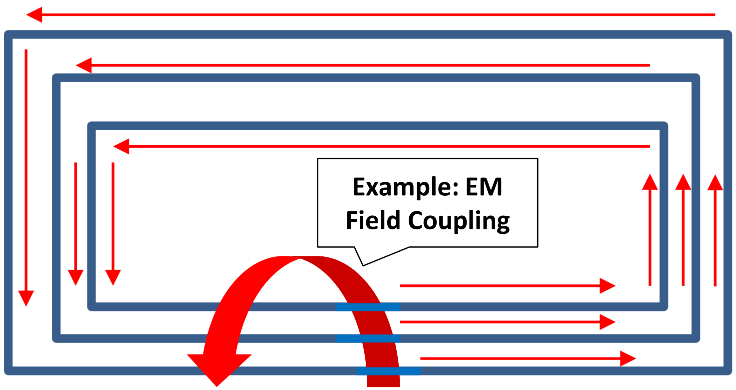
Magnetic Coupling and Loop Area - Summary

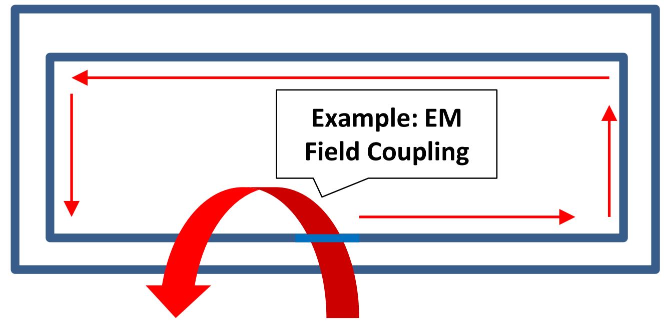


Stray magnetic fields impinging on the green shaded areas shown above drive signal currents (i.e. noise) at the source frequency. These create loop currents that degrade signal to noise ratios if they are allowed to combine with the signal. There are many potential loops and stray (unwanted) magnetic fields in an amplifier – we have touched on only a few here.

- Noise (and any electrical signal for that matter) always flows out from the source, through the circuit and returns to the source again.
- *All* cables in close proximity possess mutual inductance – i.e. are magnetically coupled
- Noise or hum pickup is proportional to current magnitude and loop areas
- The path the loop current takes is highly dependent upon the frequency of the magnetic field

Basic Concept: CM and SM Coupling



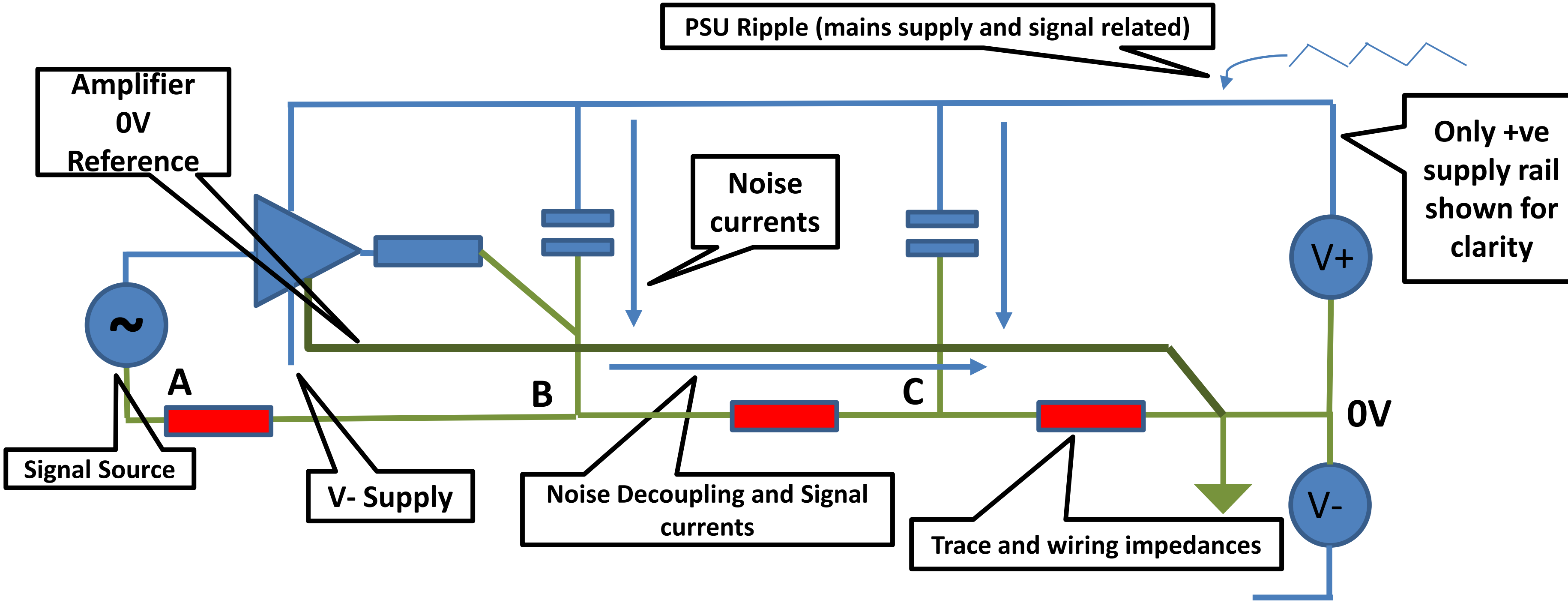


Common Mode: All three of the conductors are cut by the EM field simultaneously, driving an associated loop current around all three loops. Usually arises through magnetic field coupling. The exact route the current flow takes in practical cases if ***highly frequency dependent.*** Example: the EM field couples to both the central signal conductor and the shield

Series Mode: Only one conductor in a signal and its return pair couples to the noise source. It usually arises through common impedance coupling or magnetic field coupling where the signal and return wire loop area is not minimized. The exact route the induced current flow takes is ***highly frequency dependent.*** Example: EM field couples between the central signal conductor and its associated signal return conductor

Magnetic field coupling covers LF through to 100's of KHz typically. C***apacitive coupling***, usually 100's of kHz and higher as the *parasitic capacitances* within an amplifier are not more than 1-2nF maximum and more like 50-100pF in most cases. RFI couples through the EM field, and is almost always common mode. Common impedance coupling usually gives rise to series mode noise signals covering DC to 100's of kHz.

Basic Concept: Common Impedance Coupling



In amplifiers, the supply rails contain ***power supply ripple voltages and large amounts signal related ripple currents and voltages***. In ***common impedance coupling***, the signal ground reference (A) is mixed with the decoupling return paths (B) and (C). This places the volt drops across the **RED** PCB trace and cabling impedances in series with the signal. The load return currents also develop voltage drops across these impedances. If the design suffers from common impedance coupling issues, high levels of supply noise and high levels of distortion arise because they end up effectively as additional (unwanted) voltage sources in ***series with the signal voltage***. We will show how to avoid all of these problems later in the presentation

Basic concept: ‘Differences in Ground Potential’ Between Equipment are NOT the Cause of Hum

The solution, it is often said, is therefore is to ensure the two pieces of equipment are *solidly connected to Earth* ([Safety Ground] in the USA), or are *bonded together and bonded to the safety earth [ground]*.

<u>This understanding and the proposed cure is WRONG.</u>

The only time a difference in ‘ground potential’ between two pieces of equipment will arise will be when there is a fault resulting in large currents flowing in the safety earth [ground] cable and that will immediately trip the RCD in the mains distribution box.

It is the magnetic field lines from transformers and power cables intersecting loop connections inside the equipment, the interconnects and the mains power and safety earth[ground] cabling that result in noise. This happens because the magnetic fields induce a current into the loops inside and between the equipment. <u>Nothing to do with differences in ground potential!</u>

These loop currents flow from the source - i.e. where the magnetic lines of flux are coupling into the loop - through earth [ground] connections, through the PSU 0V safety bond to the chassis, then the interconnect and cable resistances and return to the source. In so doing, the loop current develops noise voltages across the interconnect and wiring resistances that appear <u>in series with the signal voltage</u> and are then amplified along with the signal (i.e. music). So, the prime focus in noise reduction is in minimizing loop areas and cable dressing i.e. placement, to avoid stray magnetic fields and reducing interconnect resistances and, in reducing interconnect resistances – especially the interconnect cables.

The techniques to overcome these problems will be presented in the pages that follow.

Important Basic Concept: Audio Signal Ground and Safety Ground Are Not the Same Thing

Often, the role of the audio ground and the safety ground (earth) are confused. There is a perception that without a safety earth(ground) a hi-fi system will hum – so a good solid connection to the mains safety earth [ground] will help reduce hum or completely stop it.

This perception and the proposed cure is WRONG.

The **audio signal ground** is required simply to complete the path from the generating source to the receiving equipment or circuit – i.e. it provides the return path for the audio signal. As will be made clearer in the following pages, this audio signal ground, or return path, should be coupled tightly (twisted together with) the audio signal wire from the source to the load or receiving circuit to minimize the loop area. On double layer PCB's we can lay the audio signal connection and the audio signal return ground connection on opposing sides of the board, or adjacent to one another if the PCB is single sided in order to minimize the loop area. Still better, is the use of a ground plane in multilayer PCBs.

The **safety earth(ground**) is there to provide a path to earth (ground) in the event either the live (hot) or neutral accidently come into contact with any exposed metal parts of the chassis or any part of the audio circuit. This earth[ground] makes zero contribution to minimizing hum in a system (but can contribute to causing hum if the overall system is not wired correctly). It is there for safety and is a legal requirement in all countries. On a LIVE (HOT) or NEUTRAL short to EARTH (GROUND) the RCD at the mains distribution box will detect an imbalance in the supply and return currents, and the RCD/GFCI will trip.

In non-double insulated equipment we connect the main audio ground which is at the junction of the filter capacitors in a split supply system to the chassis simply for safety reasons. This has nothing to do with trying to reduce hum.

Summary

Important basic concepts we have covered:-

- Magnetic Induction
- Capacitive Coupling
- How to use a line diagram to identify loop area(s)
- The importance of minimizing loop area to prevent/reduce hum
- Common mode (CM) coupling
- Series Mode (SM) Coupling
- Common impedance coupling
- The exact current flow in a noise (ground) loop is highly frequency dependent
- Audio Ground and Safety Earth[Ground] have different purposes

We now go on to consider practical aspects of noise reduction in audio amplifiers

Ground/Noise Loops

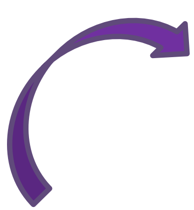
Noise arising through magnetic field coupling

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

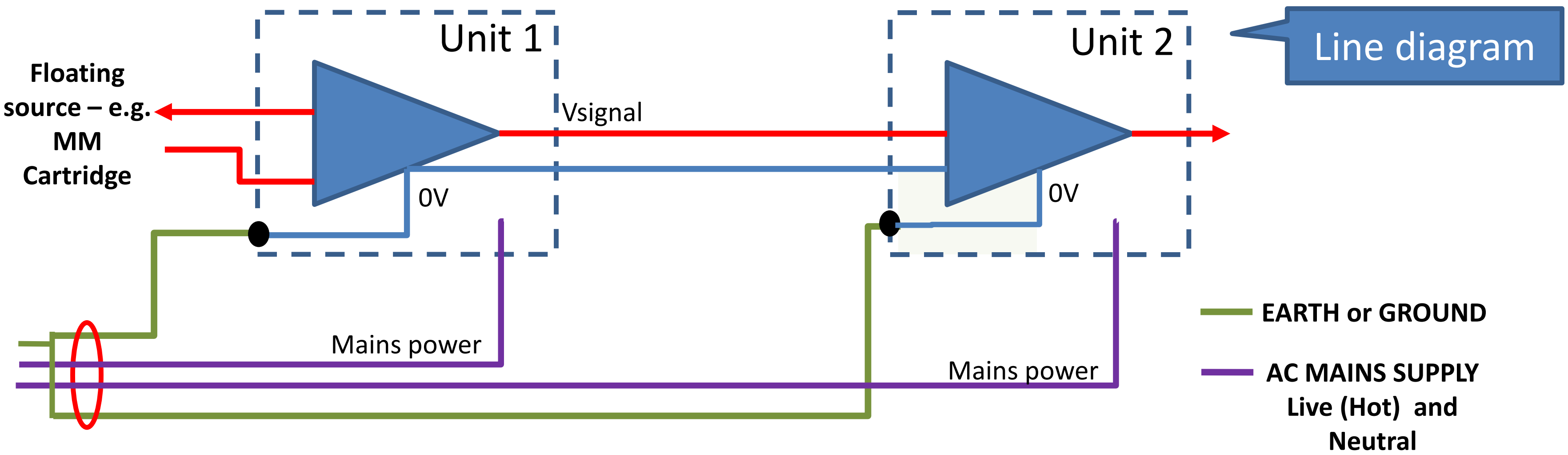
1st Line Remedy

- Keep LOOP AREAS as small as practicable and especially those carrying significant current by twisting together ground and signal wiring, and 0V supply wires with the + and – supply to modules. Keep sensitive circuits away from high current circuits. Use good quality interconnects (braided shield) with low interconnect resistance and high contact force connectors
- Specify your transformer with a flux band
- Specify an inter-winding screen on transformers – especially toroidal transformers



Remember, this symbol in the graphics that follow mean **magnetically coupled** noise

Classic AC Ground Loop – Typical Set-Up

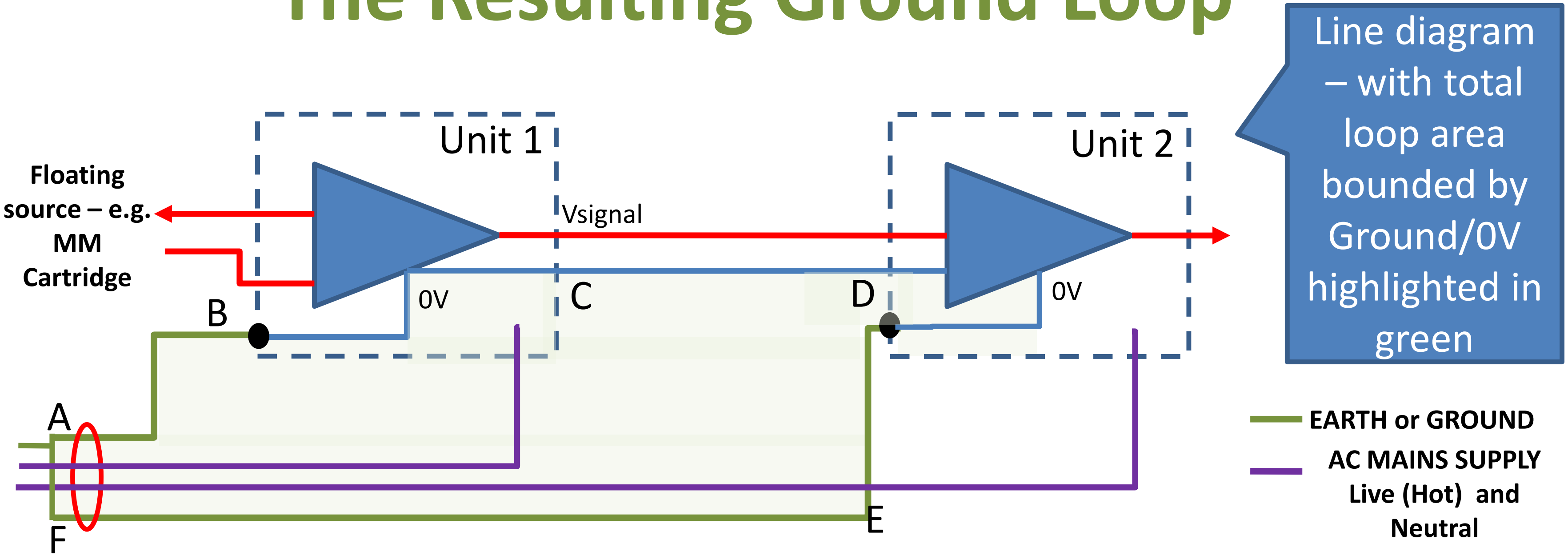


Both metal chassis' must be SAFETY EARTHED (GROUNDED) which is a legal safety requirement in most countries

The signal return is bonded to the chassis through a single connection from the power supply 0V to the metal chassis

The equipment interconnect signal wire is shown as RED while the signal return is shown as BLUE

The Resulting Ground Loop



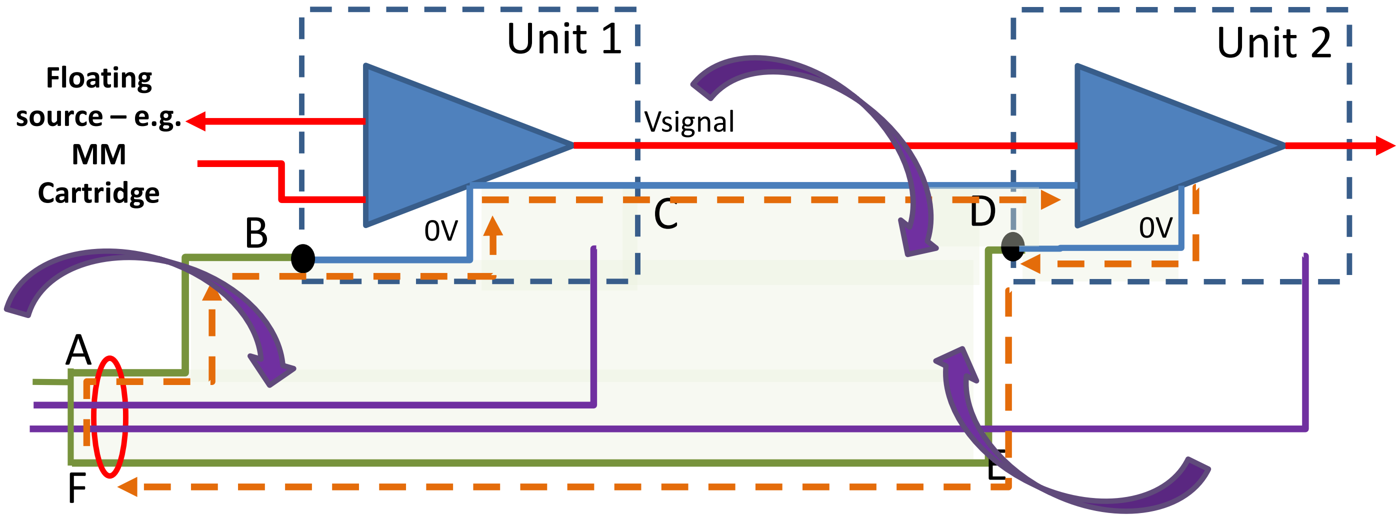
In this line diagram, the electromagnetic loop is the TOTAL AREA prescribed by A>B>C>D>E>F>A shown in light green. It is important to note that the loop is bounded by the signal return connection (C to D) between the two pieces of equipment and the safety earth [ground] which is the GREEN wire.

Again, remember to think about the all-important LOOP AREA when looking at this problem – it is in effect a very large pickup coil or loop antenna.

Tip #1: In all the diagrams that follow, keeping the GREEN shaded area as small as possible will minimize the loop area and the susceptibility to noise pickup through magnetic induction

Tip #2: The whole thrust of ground loop mitigation is to prevent noise currents flowing through the signal cable shield or any signal return wiring – if they are, you will have a noise problem.

Resultant AC Ground Loop Currents



This is the most common 'hum' problem in systems using non-double insulated construction

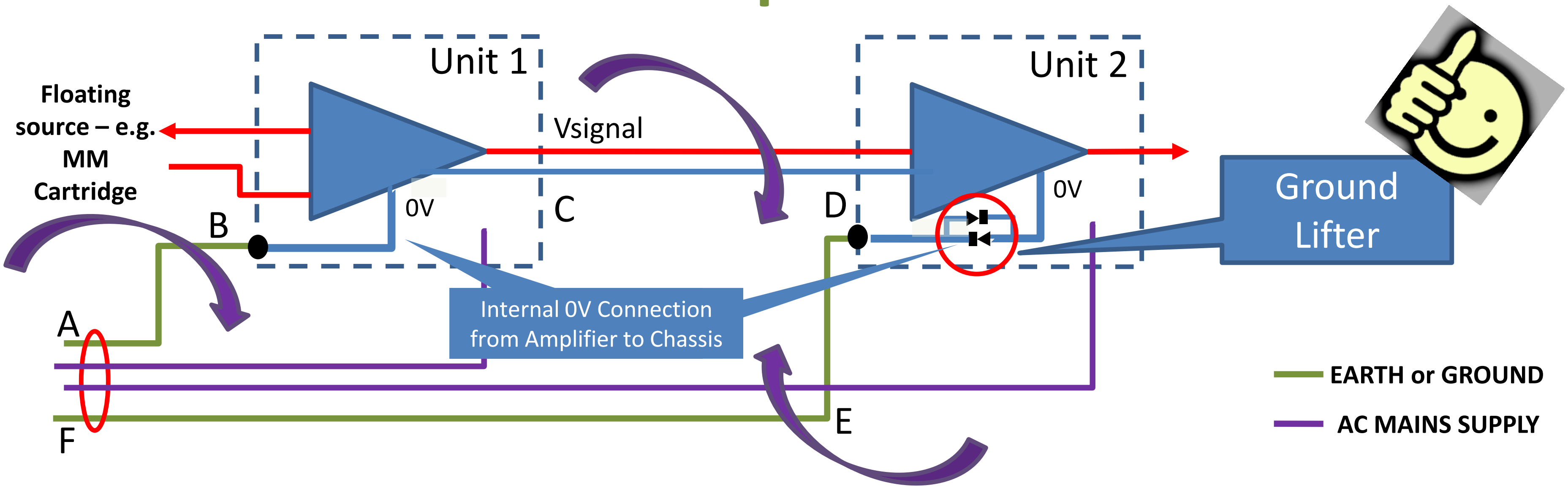
Any magnetic field impinging on this loop (the green area) will generate an EMF and cause a **current to flow around the loop** A>B>C>D>E>F>A i.e. an EARTH [GROUND] LOOP CURENT

The frequency of the loop current is that of the impinging magnetic field – usually 50/60 Hz and related harmonics arising from the rectification process. However, higher frequencies up to 100's of kHz are also a problem – these usually arise from computer, TV and DVD player switchmode power supplies, LED lamps and so forth

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

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 [ground] loop current and the interconnecting ground resistances, the bigger the noise voltage

Classic AC Ground Loop and Ground Lifter Cure



The ground lifter consists of two diodes placed in ‘anti-parallel’ between the amplifier power supply 0V and the chassis (WHICH MUST BE EARTHED/GROUNDED) and BREAKS THE GROUND LOOP so no ground loop current can flow between C and D

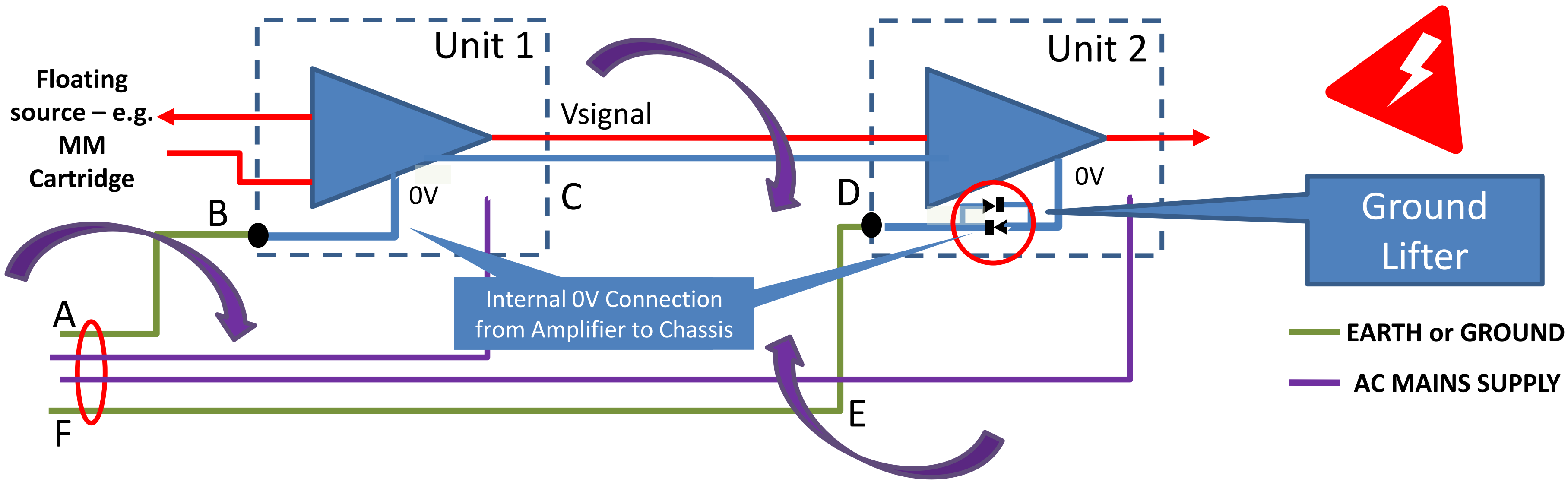
For any ground loop current to flow, the ground loop generating voltages would have to be in excess of the diode Vbe – i.e. +-0.6V and highly unlikely.

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

Note carefully, that the equipment chassis are still bonded to the safety earth [ground] in this set-up

Important Safety Information follows . . .

Important Safety Points WRT Ground Lifters



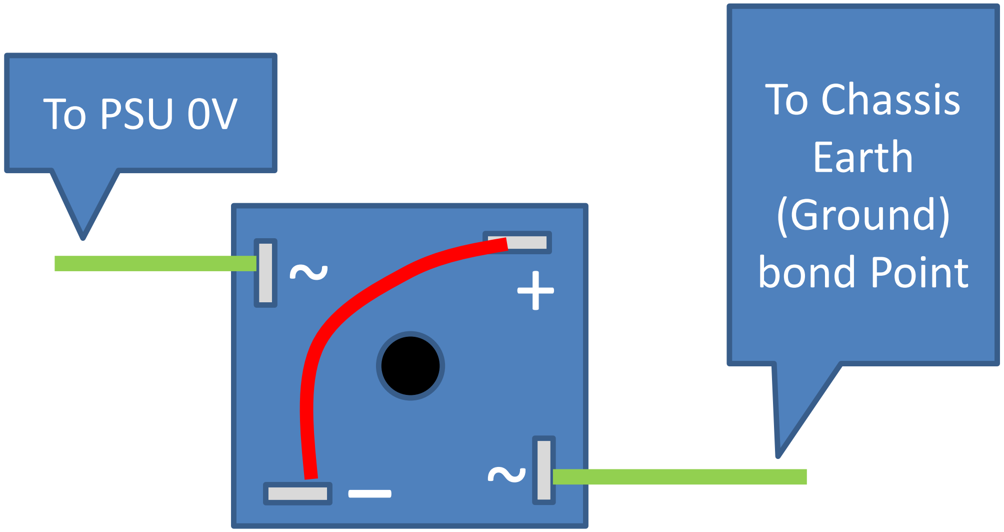
It is IMPORTANT that HIGH POWER rectifiers are used – use a chassis mount 25-35A device with a surge rating of >200 Amps

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 RCD (GFCI) at the mains distribution panel trips. This is typically 20-40 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 RCD/GFCI systems. If in doubt: DON'T USE THIS TECHNIQUE

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.

How to Wire a Bridge Rectifier as a Ground Lifter

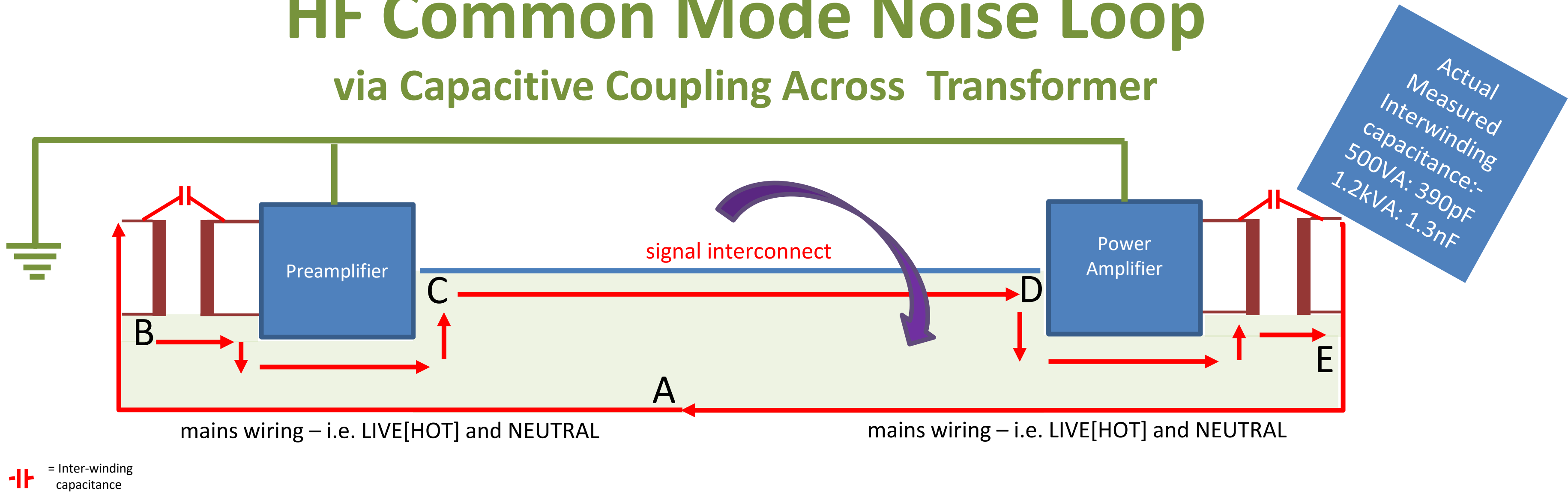


35A 400V or higher voltage Bridge Rectifier e.g. [KBPC3504]
This must conduct the FULL fault current until the RCD/GFCI trips at the mains distribution box. The currents can range from 10 to 150A for at least 1 mains cycle, but can be 2-3 mains cycles. The peak single cycle surge current capability of this particular bridge rectifier is 400 Amps

- Use a 35A 400V (or higher voltage) chassis mount Bridge Rectifier
- Wires to and from the rectifier must be at least 2.5mm^2, as should be the RED wire that connects + to –
- Keep all wires as short as practicable
- Bolt the bridge rectifier directly to the chassis

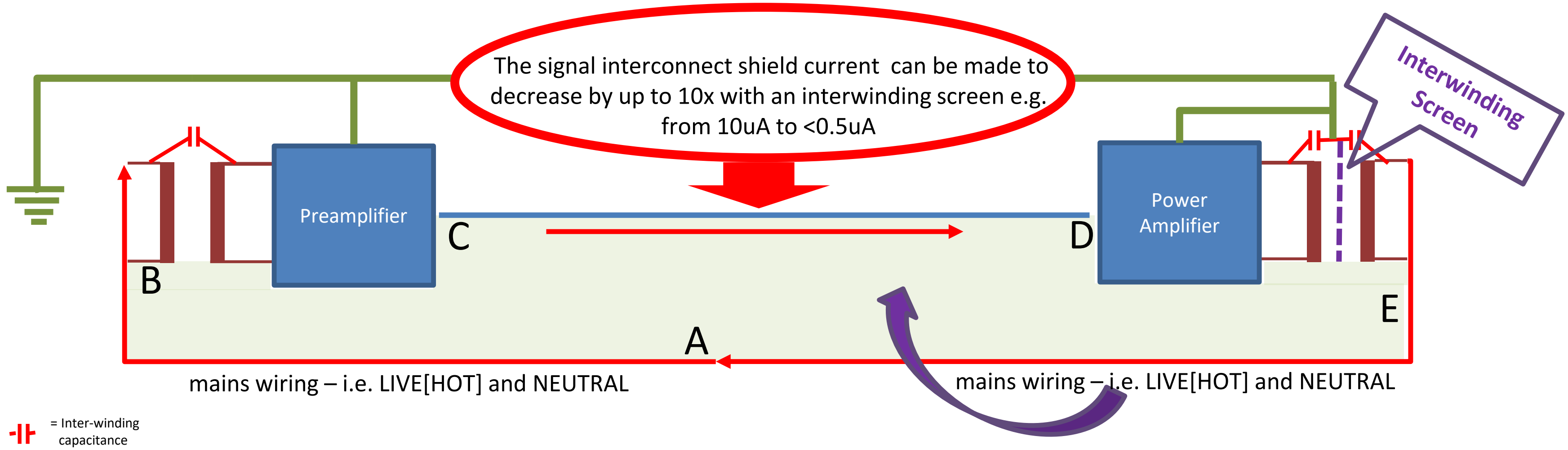
HF Common Mode Noise Loop

via Capacitive Coupling Across Transformer



Any stray high frequency (HF) magnetic field impinging on **GREEN** area will generate an EMF that will cause a current to flow around the path A>B>C>D>E via the transformer interwinding capacitances and the mains cabling. Like the classic AC ground loop discussed earlier, 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 noise loop is susceptible to HF coupling, since the transformer stray capacitances are relatively low and they therefore pass HF more readily than mains frequencies. Examples of HF noise sources would be SMPS, 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 and through the mains LIVE[HOT] and NEUTRAL as a common mode signal. Ground lifters usually don't work with HF noise coupling of this type.

Inter-winding Screen Cure for AC Common Mode Noise



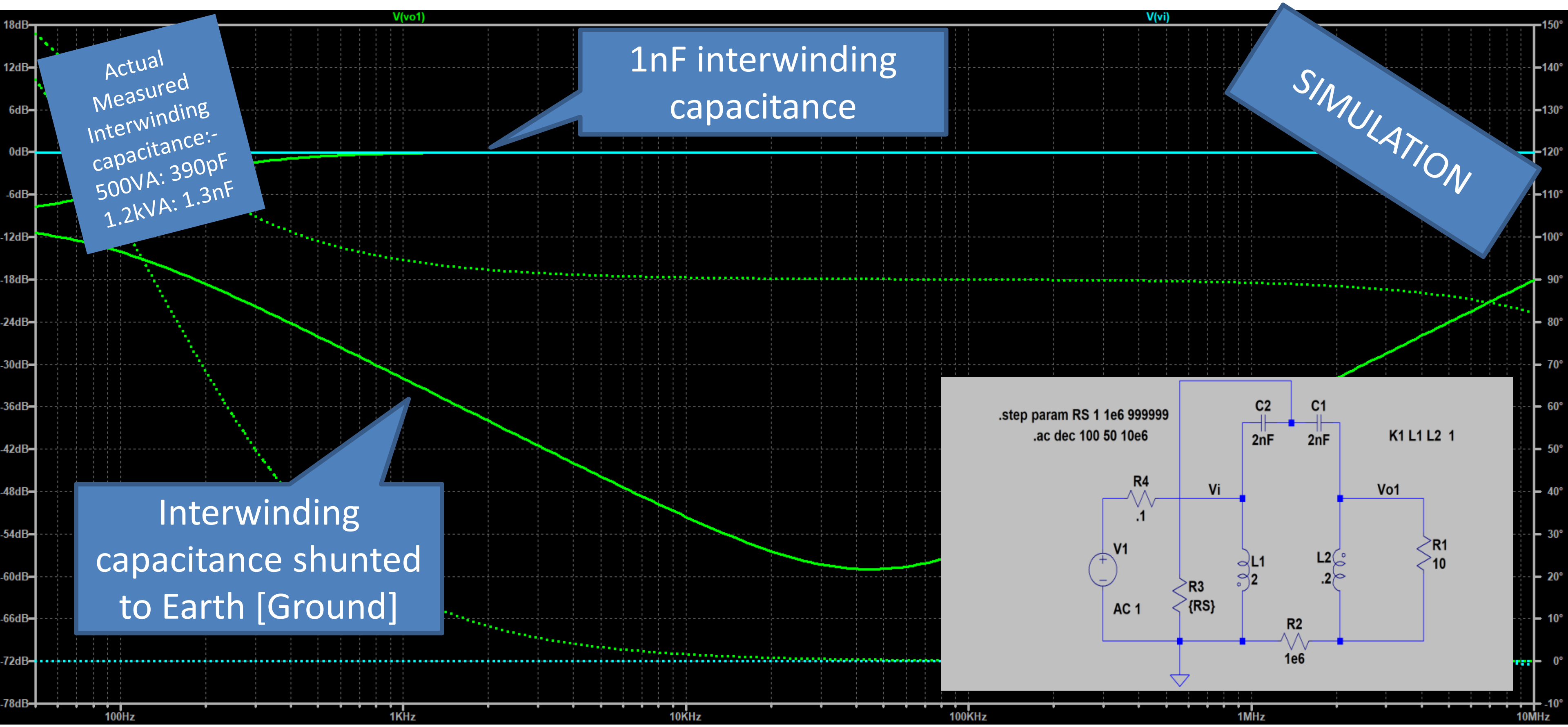
By specifying an **interwinding screen** between the primary and secondary, and connecting the screen to earth[ground], the loop impedance is dramatically increased, lowering the loop current and thus the associated noise. The grounded screen on a 1.2KVA reduced the interwinding capacitance from 1.3nF to 100pF i.e. > 10x. The screen *may* also help to reduce differential mode noise coming in from the mains line. With an interwinding screen, any residual loop current will likely flow through the safety earth[ground] wire and *away* from the interconnect shield.

The use of 'Y' capacitors can also help alleviate these types of noise problems by providing a lower impedance path for any induction noise problems to safety earth [ground], but the interwinding screen is the most elegant. Note also, that 'Y' capacitors have their own set of problems, amongst them equipment that 'tingles' when touched.

In modern double insulated consumer equipment that uses SMPS, [special winding techniques]are used to reduce interwinding capacitance and to reduce the common mode noise generated in the power transformer.

The best location for the interwinding screen is in the power amplifier transformer where the interwinding capacitance is highest.

Effectiveness of Reducing Inter-winding Capacitance

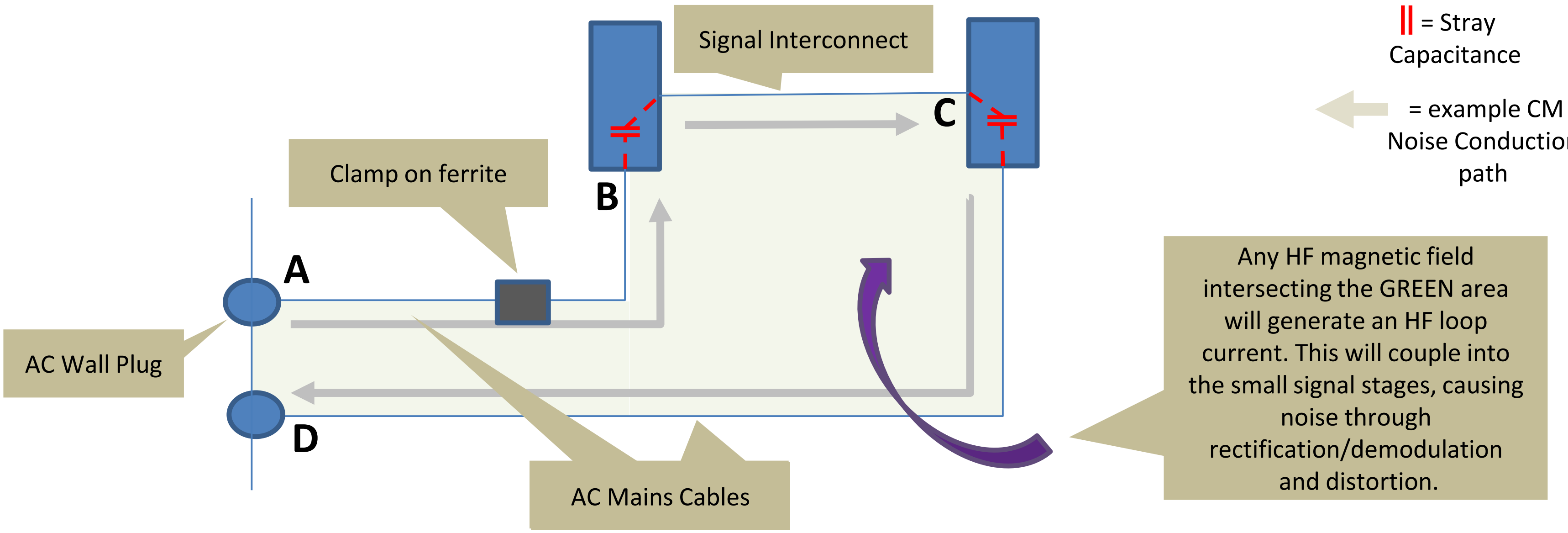


The Y axis in the above plot is attenuation

This LTspice simulation demonstrates how reducing the interwinding capacitance on a mains transformer attenuates HF noise. In this example, above 1 kHz, >30 dB attenuation is provided, while at 50 kHz it approaches 60 dB. This is a simulation – in practice the performance is not quite as good. On a large toroid (1.2 kVA), *the measured differential mode -3 dB bandwidth is 60 kHz* while the *measured common mode bandwidth through interwinding capacitance is many 10's of MHz.*

Take away: Toroidal transformers are very wide bandwidth transducers in both differential and common mode

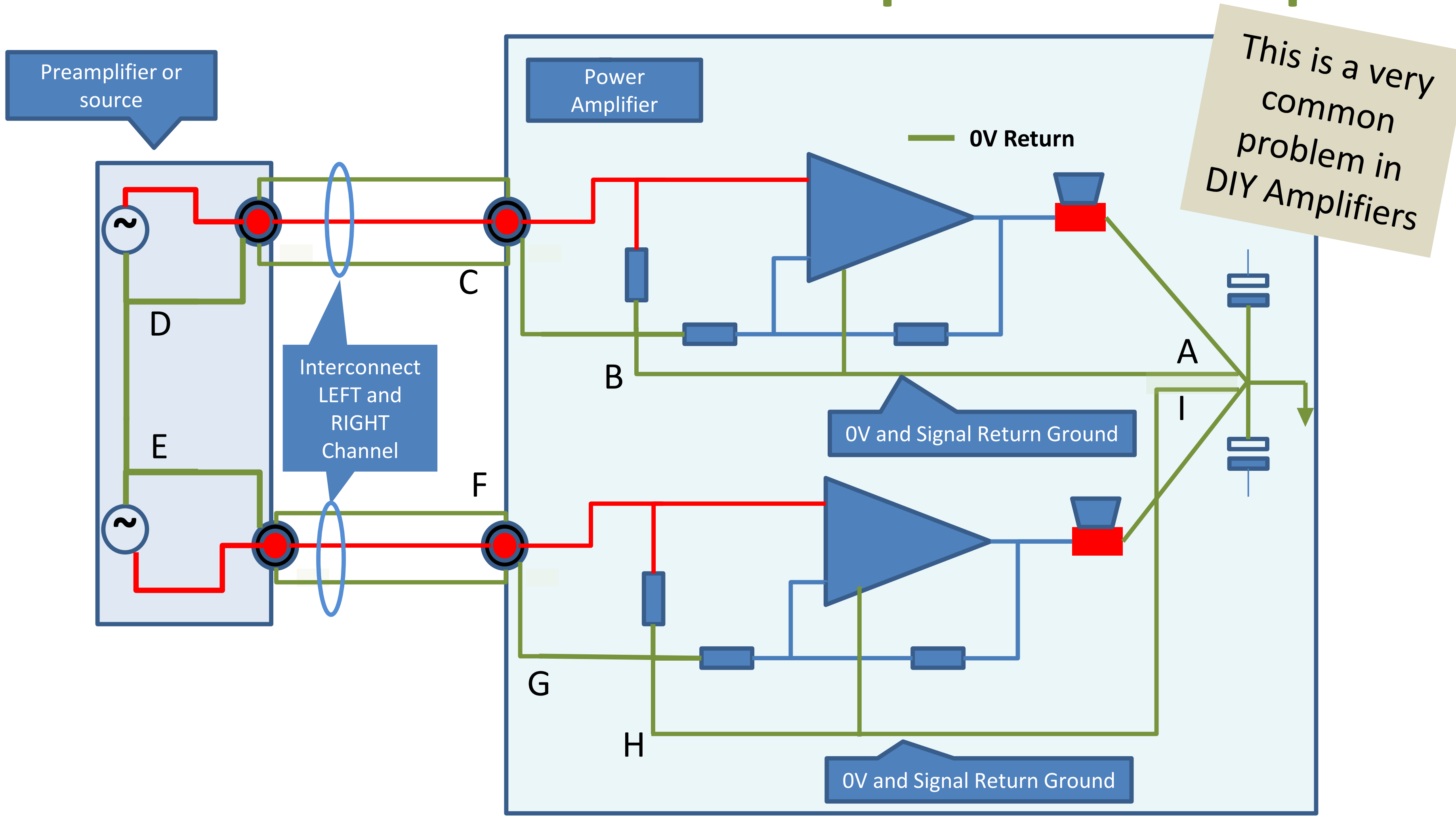
HF Common Mode Noise and Ferrite Clamps



A solution where there is HF common mode noise and no safety earth [ground] as in double insulated systems is to place ferrite clamps around mains supply cables - you often see this on laptop power adaptors where they may be required in order for the power supply to meet regulatory emissions standards. However, the technique is also very useful for audio work as well. The ferrite works by attenuating the HF because it dramatically ***increases the impedance*** of the loop A>B>C>D at HF. Furthermore, since the ferrite is formulated to be ‘lossy’ it converts any HF energy into harmless heat energy. Since there is no connection to Earth (Safety Ground) in double insulated systems to shunt HF energy away from the loop using ‘Y’ caps, this type of common mode filter is particularly effective in these cases.

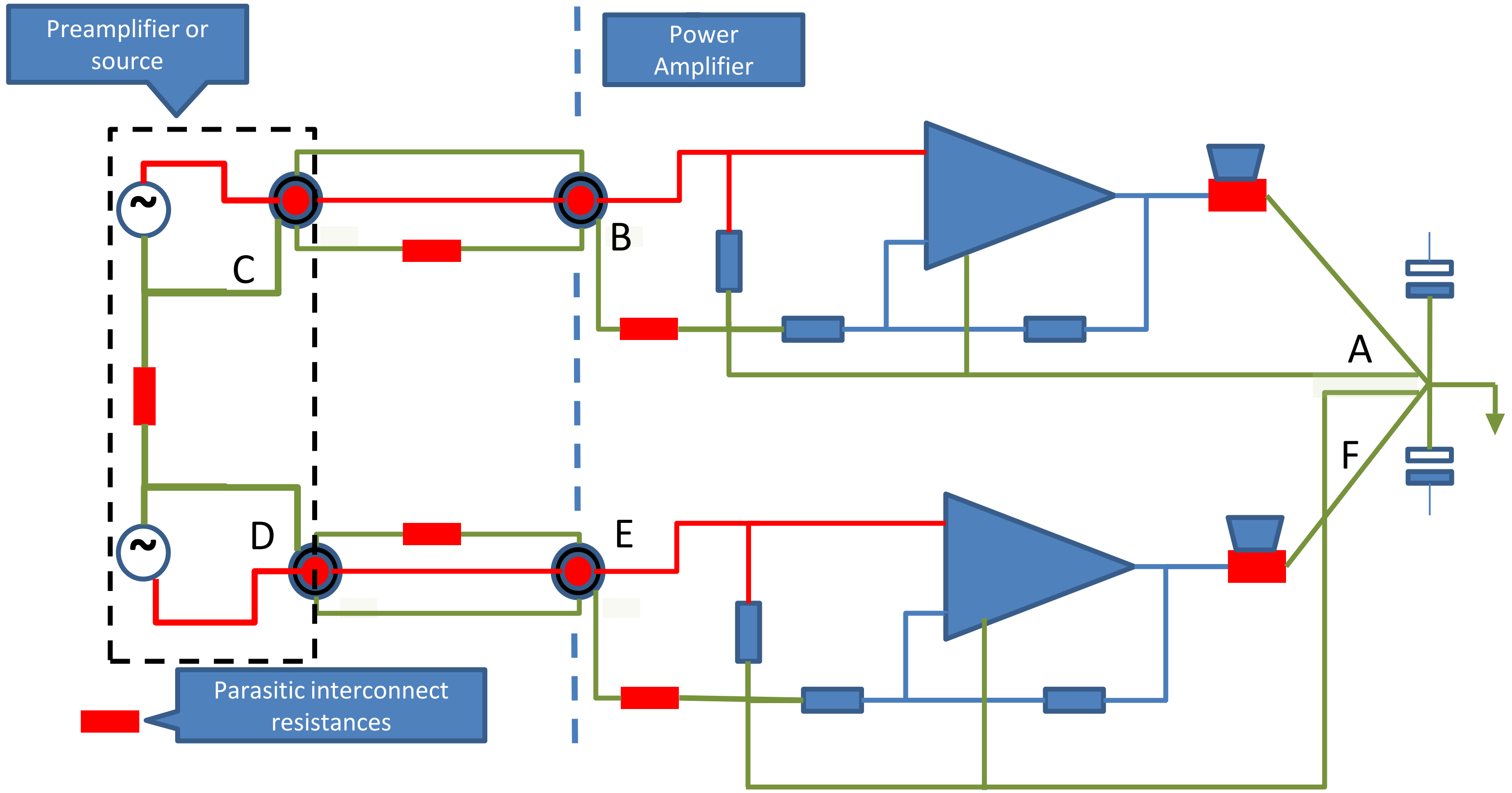
In double insulated systems, you can theoretically put the clamp anywhere in the loop. Most audiophiles would of course object to having it in the signal interconnects (you would have to put the ferrite clamp over *both left and right interconnects together* for it to be effective). Rest assured however, it would not affect the audio signal integrity one iota.

Cross Channel Ground Loop – Basic Set-up



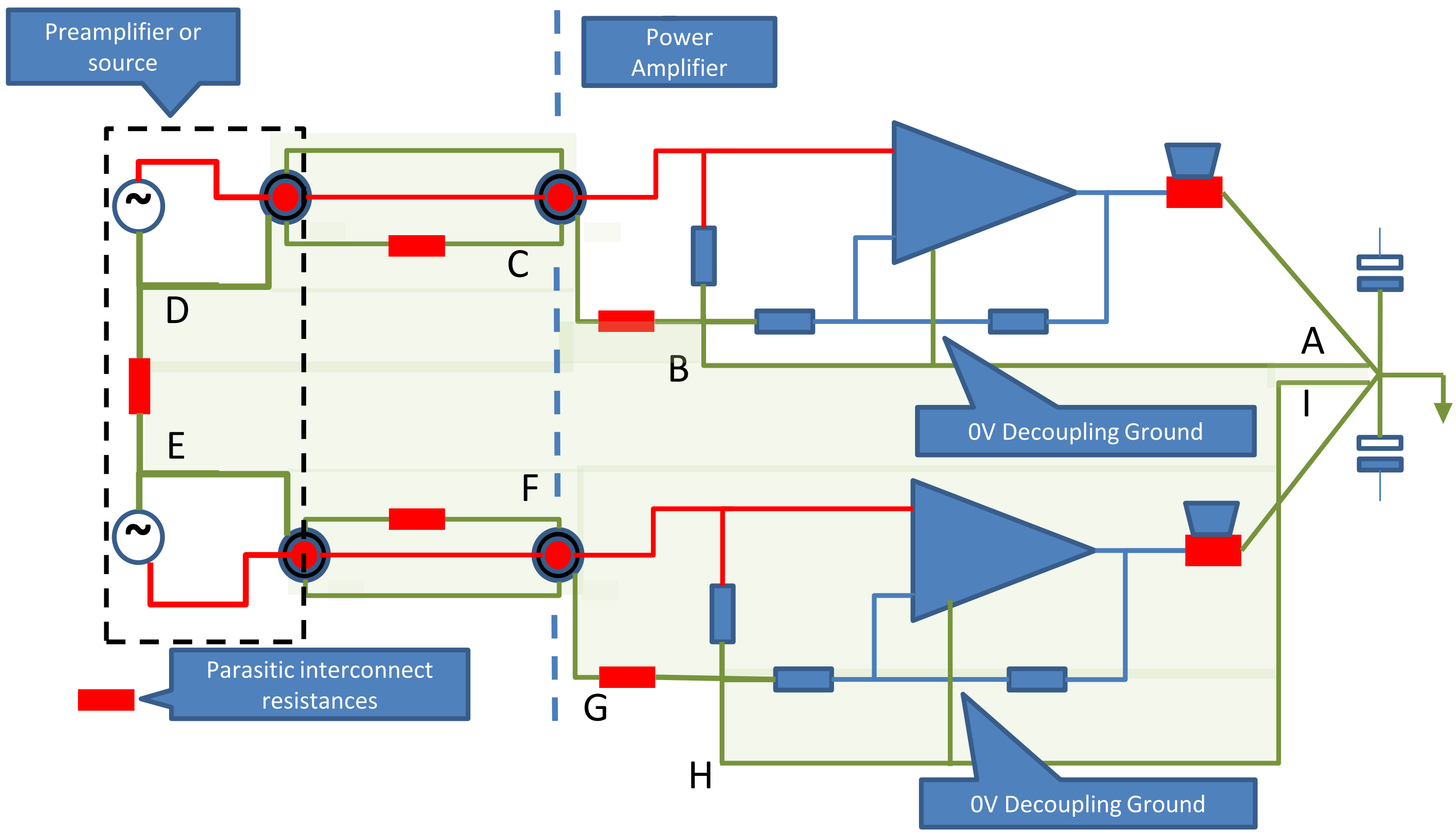
We start with a typical pre-amplifier to amplifier set-up. The preamp on the left, shaded blue, feeds a power amp on the right shaded aqua via two shielded interconnects (left and right). Without the preamp connected, the power amp is completely quiet – there is no hum whatsoever emanating from the speakers even with the volume turned up full – on a positive note, a sure sign that there are no internal common impedance wiring errors in the power amplifier. With one channel connected, the amplifier is still silent. However, connect the second channel, and there is hum and/or buzz from the speakers.

Next, We Show the Interconnect Resistances in the System



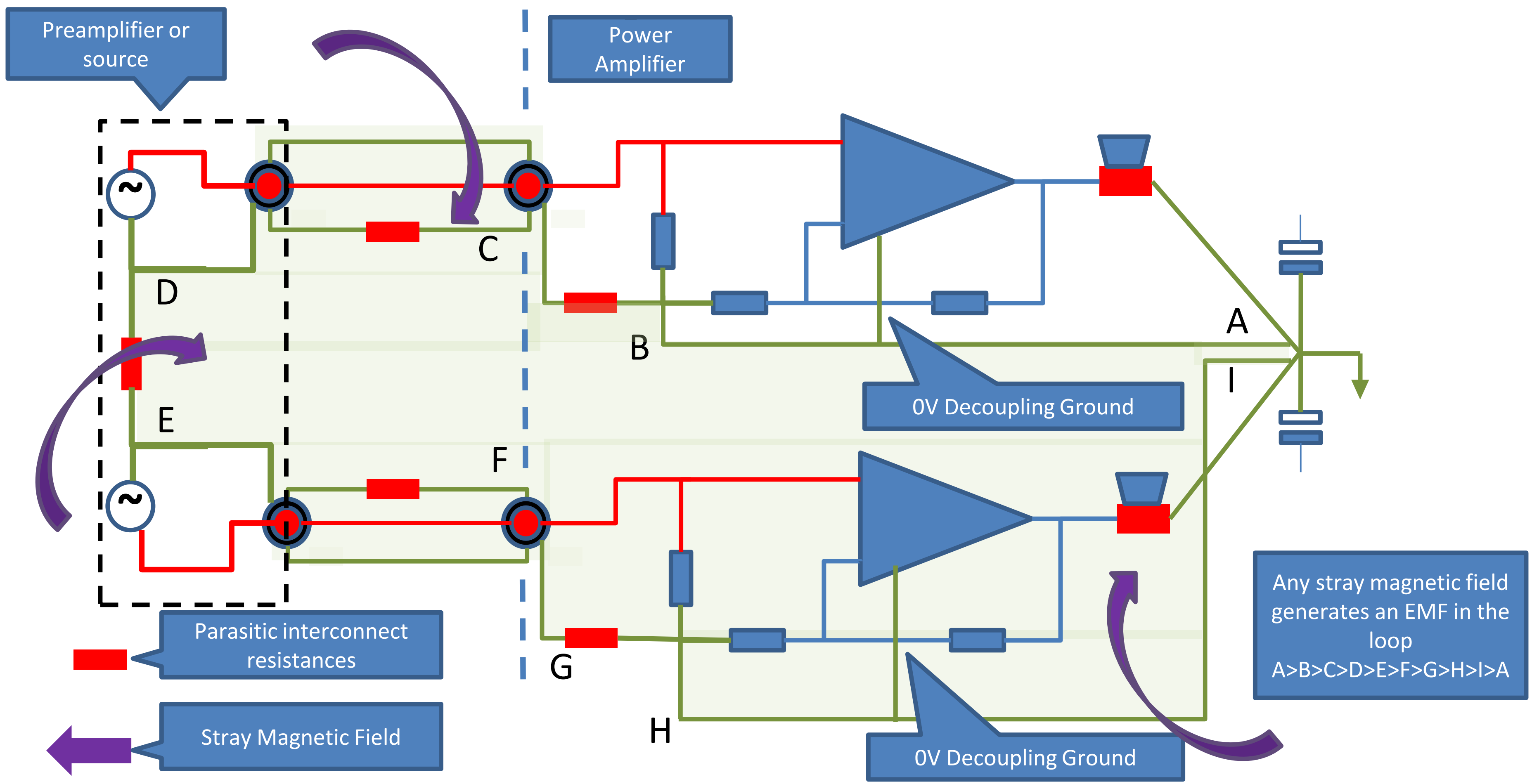
Here we add the (unwanted) interconnect resistances in **RED**. In a system with good quality low resistance interconnects (braided shield cable, high contact force connectors) you can expect 50 ~ 100 milli-Ohms resistance from A to C or D (so total loop resistance is approximately twice that, or 100 ~ 200 milli-Ohms. On a bad set-up using cheap cables, low quality RCA plugs/receptacles and sub-par internal wiring, it could be as high as a 1 Ohm. Good quality cables have a braided shield (=low resistance/impedance) and high contact force connectors. Internal ground wires in an amplifier must be at least 2.5mm square or larger.

Total Loop Area Available for Magnetic Coupling



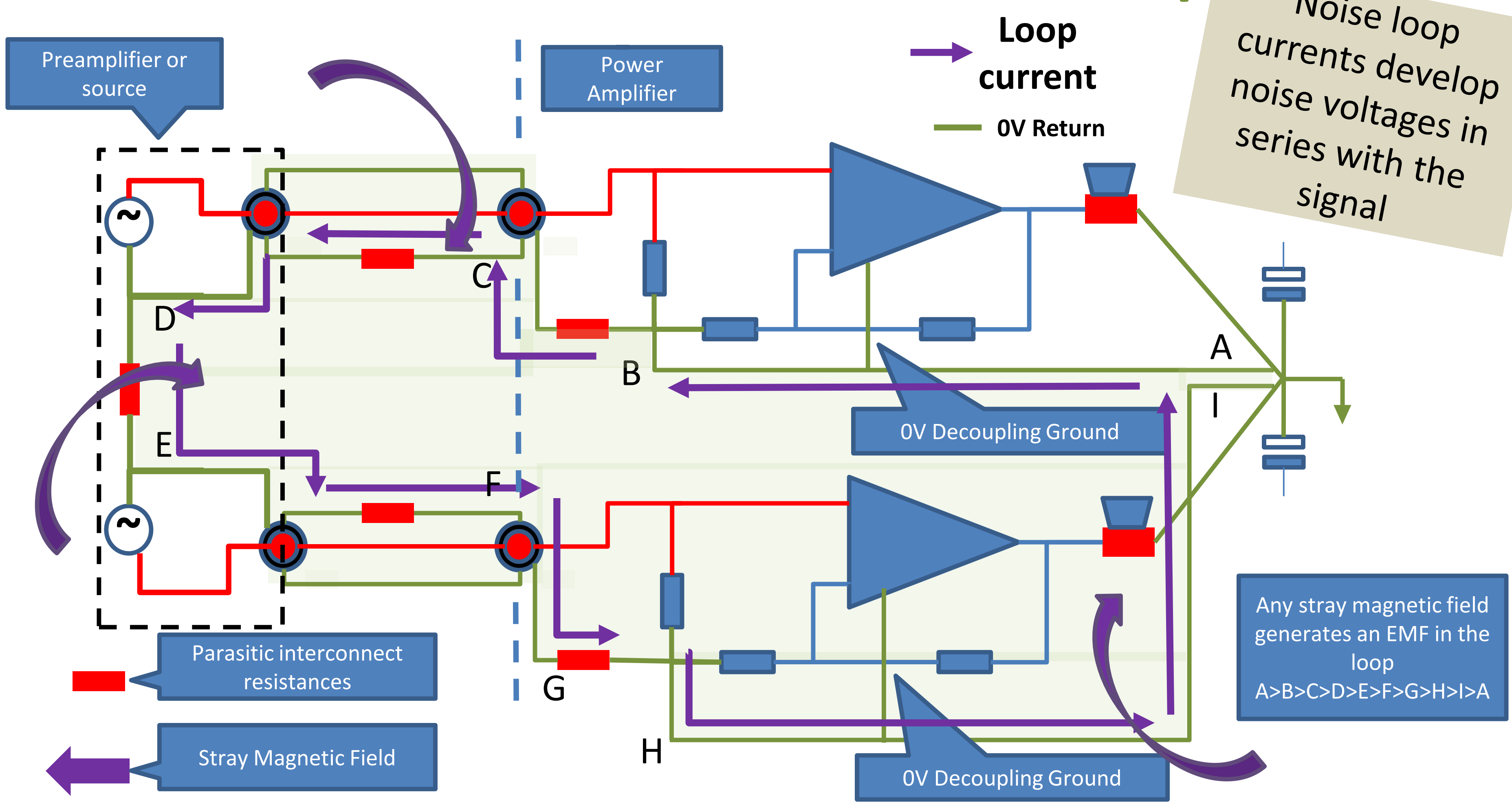
The shaded **GREEN** areas represent the total loop area between the two pieces of equipment wrt the cross channel ground loop. *Note carefully that the loop area includes the areas inside the preamplifier and power amplifier*. Next, we will consider what happens in the presence of magnetic fields . . .

Cross Channel Ground Loop - Magnetic Fields



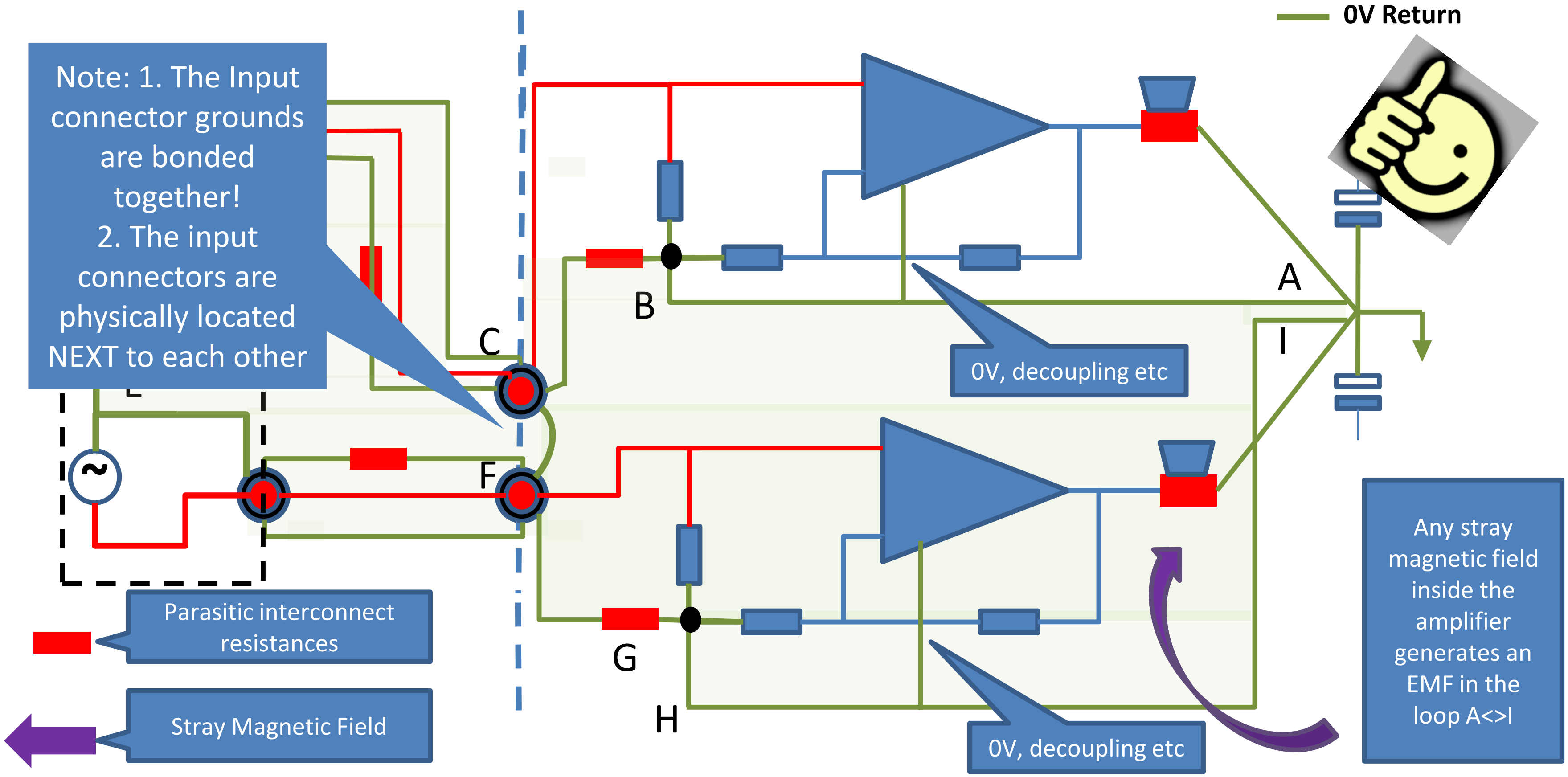
Stray (parasitic) magnetic fields are denoted by the large **PURPLE** arrows. These arise both INSIDE the preamplifier and the power amplifier from their power transformers, or in some cases switchmode PSU's. EXTERNAL interference can come about if the interconnect cables are routed near other equipment that may be radiating electromagnetic fields – like a TV, LED lamps and so forth. You can also see from this depiction why keeping the left and right channel interconnects close to each other – as in a bonded two channel cable – helps to reduce the total loop are and thus susceptibility to external interference pickup. It is also very important to keep the area ABGHI inside the amplifier as small as possible.

Cross Channel Noise Current Loop



The **thin purple arrows** depict the resultant LOOP CURRENTS that flow when a magnetic field impinges upon the green shaded loop area. The frequency of the loop current is that of the magnetic field: 50/60 Hz and harmonics, but if the interference is from a switch mode PSU, it can be 10’s or 100’s of KHz and higher. The loop current is 10’s (typical) to 100’s of uA (bad case) and causes voltage drops to appear across the loop resistances (shown in **RED**). These voltage drops are in series with the signal and cause the cross channel hum

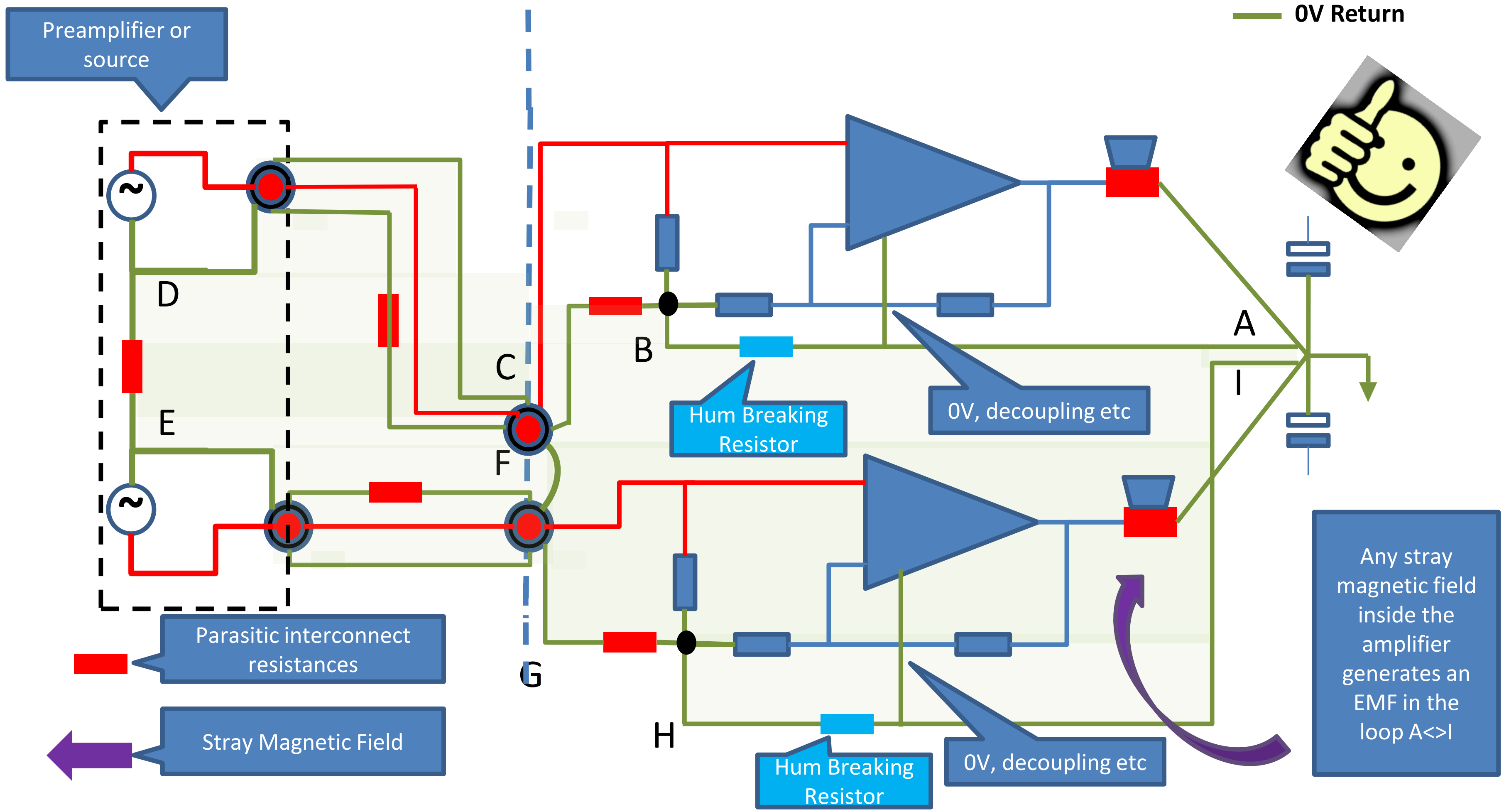
Cross Channel Ground Loop Cure #1: Minimize Loop Area!



Keep the areas shaded GREEN both *inside the equipment* and externally between the interconnect cables as small as possible to minimize the total loop area! Bond the Left and right input signal grounds together; mount the input connectors NEXT TO EACH OTHER.

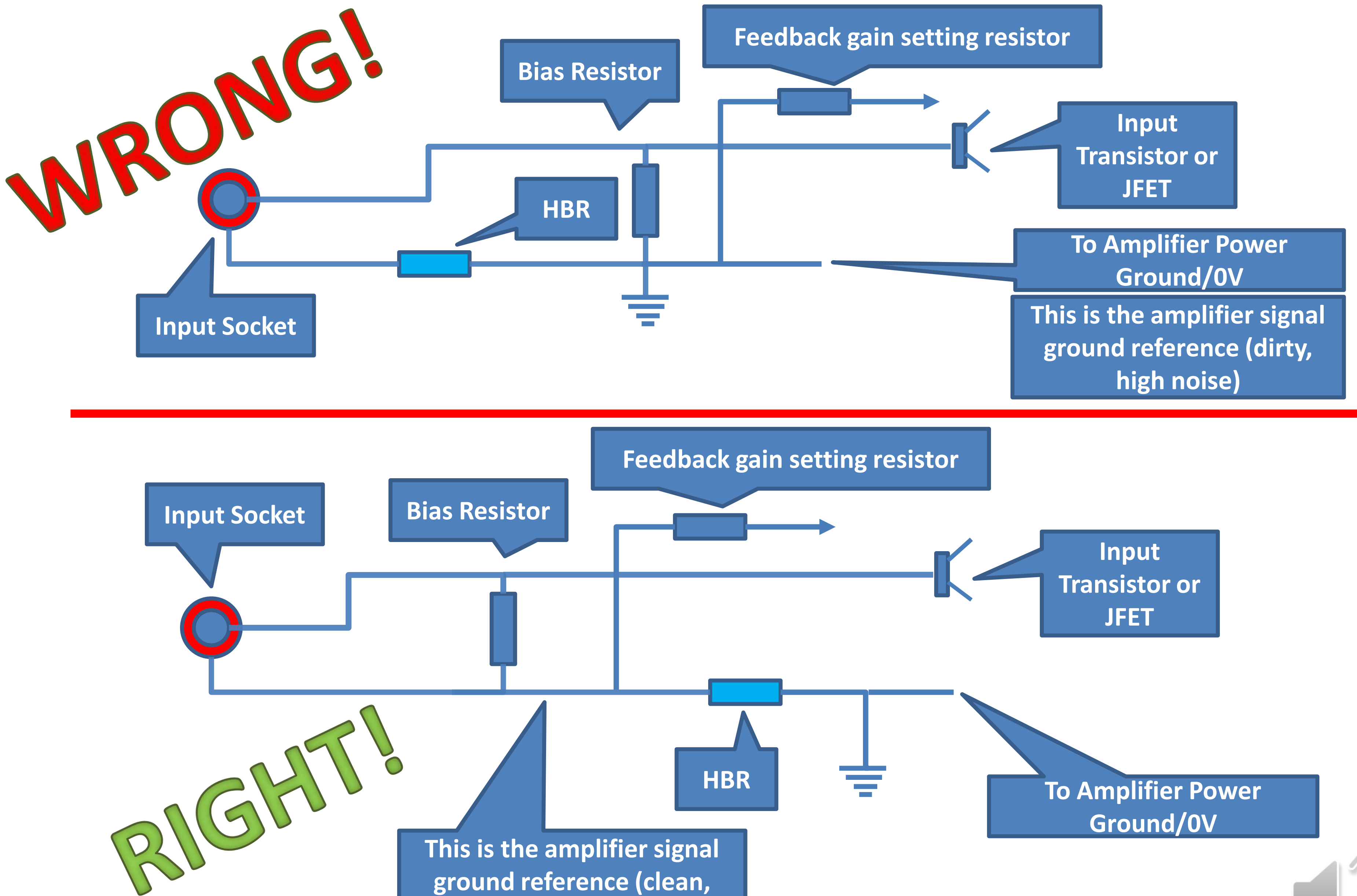
Next, we will show how Hum Breaking Resistors (HBR) help

Cross Channel Ground Loop Cure #2: Use HBR's

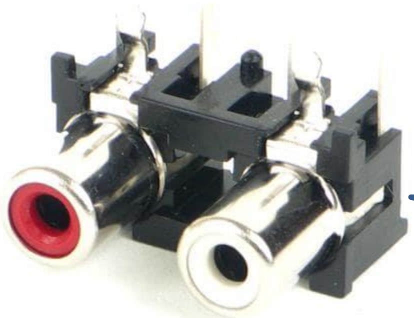


To reduce the error voltages appearing across the parasitic interconnect and ground resistances, the loop current must be reduced. This is accomplished using **'Hum Breaking Resistors'** (HBR). This *reduces the loop current* and forms a *voltage divider* with the parasitic resistors. For example, if 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.

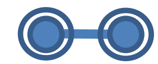
Hum Breaking Resistor Location: Note Carefully!



Bond the phono input socket signal grounds together to trap cross channel ground loops within the amplifier



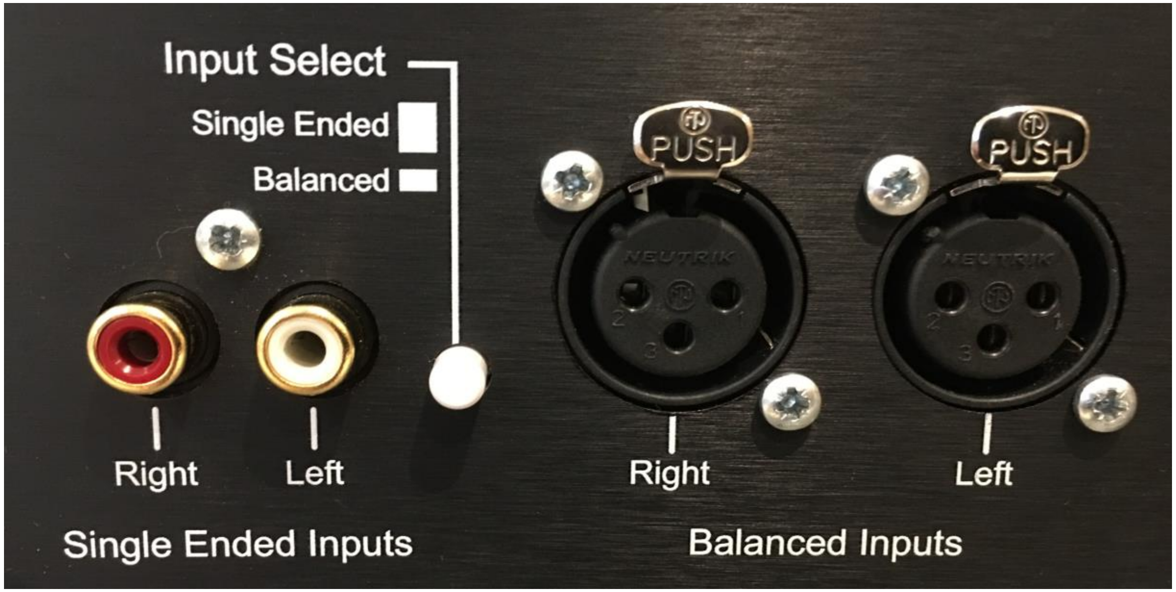
Example of recommended dual RCA phono socket – Kobicon or Switchcraft



Bond the Input Phono socket Signal Grounds together electrically

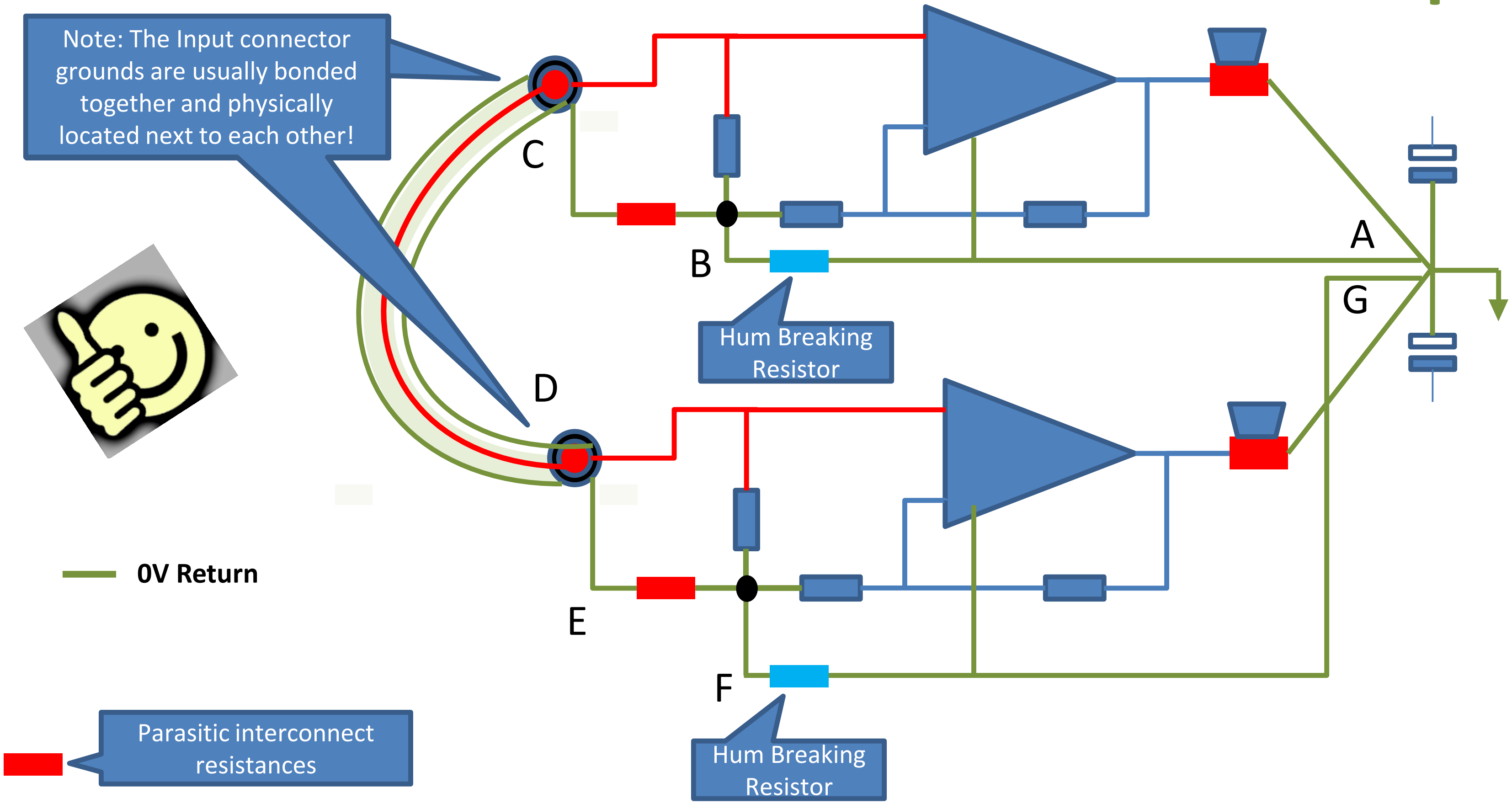
- If you bond the input signal grounds together at the input sockets, the total cross channel loop area is split into two smaller loops: external loop meeting at the input connector signal ground and internal loop meeting at the input connector signal ground. The total area taken together remains the same. Any loop currents intersecting either of the loops will still give rise to their associated loop currents
- However, the benefit of bonding the phono sockets signal grounds together at the amplifier (same for preamplifiers as well) inputs is that loop currents arising ***internally in the amplifier*** do not flow out through the interconnect shield to the source and back again to the other channel input, but ***remain trapped within the amplifier***.
- This reduces noise voltages arising across the interconnect shield (unwanted) resistances and therefore improves the amplifier noise performance.
- Same rationale applied to preamplifier outputs: keep them next to each other and bond them together at the output.
- Remember that the Hum Breaking Resistor inside the amplifier will act to reduce the loop currents and divide any internally arising noise voltage down – so always make sure this is fitted.

Good quality Interconnect Cables and Connectors



1. A good interconnect cable will consist of a central multi-strand conductor of at least 1mm^2 covered by an insulation layer over which a ***low resistance braided shield*** is woven followed by another insulation layer. The RCA plugs either end will use ***high contact force*** connectors. Connectors do not have to be gold plated (it will wear through after a few dozen insertions anyway) – nickel is a better practical choice. The left and right channel cables will be ***physically bonded*** as shown above to ensure minimal inter-channel loop area between the equipment. This also lowers the interconnect loop inductance and ensures the signal return path is via the shield and NEVER via any other route e.g. safety ground in non-double insulated systems
2. The left and right RCA receptacles on the source and receiving equipment will be ***mounted next to each other*** – again, in the interests of minimizing the inter-channel loop area. The signal grounds of the RCA input sockets are BONDED TOGETHER. The sockets are insulated from the chassis to prevent an internal ground loop.

How to Test for a Cross Channel Ground Loop



Without the cable connecting the left and right channels, the amplifier must be quiet. If not, you have some other problem – most likely a common impedance coupling issue. Next, connect the Left and Right inputs together using an RCA interconnect cable as shown. If the amplifier suffers from a cross channel ground loop, it will hum (see 'Headphone Trick' later on) . The HBR resistor is typically between 15 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.* Of course, if you have located the input sockets together and bonded them electrically together and used an HBR, you should detect no change when the cable is plugged in as directed.

Cross Channel Ground Loop Cure - Summary

1. ***Keep loop areas inside the amplifier and preamplifier small*** – power wiring to and from modules and speaker wires from the modules to the output connectors; note carefully the points about input wiring
2. ALWAYS include a **'hum breaking resistor'** in your amplifiers located as shown previously – a good value is 15 to 22 Ohms
3. Ensure interconnects are low resistance (braided shield and 1mm square signal wire) and that the connector plugs make a high force, low resistance contact with the receptacles
4. Use a dual channel bonded interconnect cable to keep the interconnect loop area as small as possible
5. Place the left and right channel connectors on the preamplifier and power amplifier close to each other – separating them in the interests of 'preserving channel separation' does nothing of the sort – it only invites problems. All well designed equipment places the left and right channel connectors close to each other (balanced XLR and/or RCA Phono types)
6. Make sure the signal grounds of the input RCA sockets are BONDED TOGETHER right at the input on the rear panel of the amplifier
7. (5)+(6) above ensures the cross channel ground loop current remains trapped within the amplifier.
8. Ensure all internal wiring in the preamplifier and power amplifier is good quality and low resistance

Common Impedance Coupling

This is the most prevalent 'beginner' constructor problem

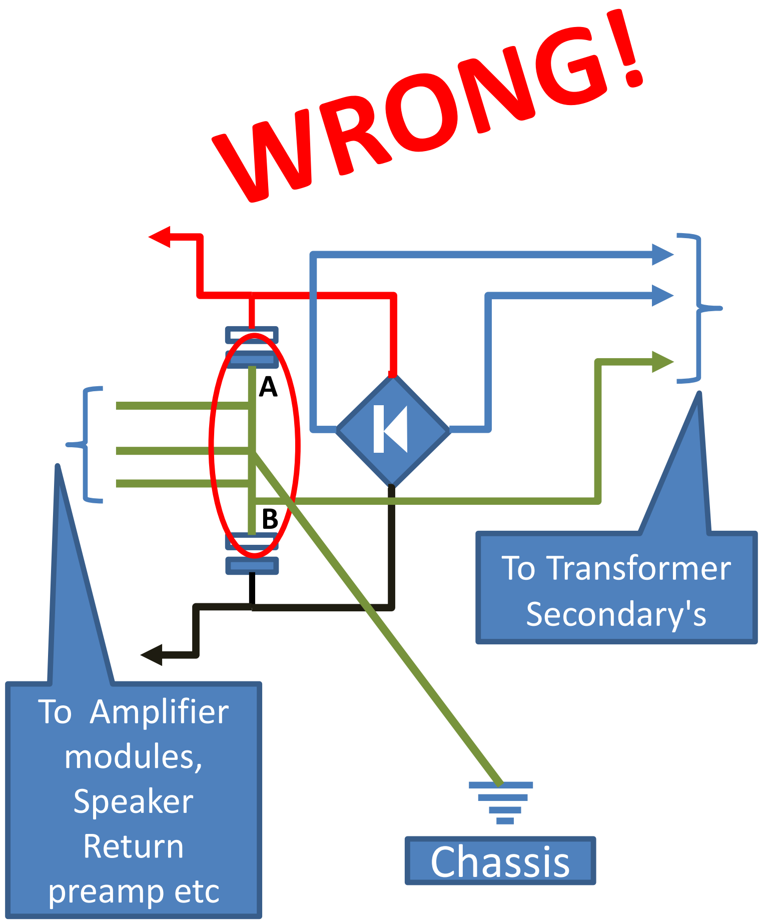
Causes

- 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

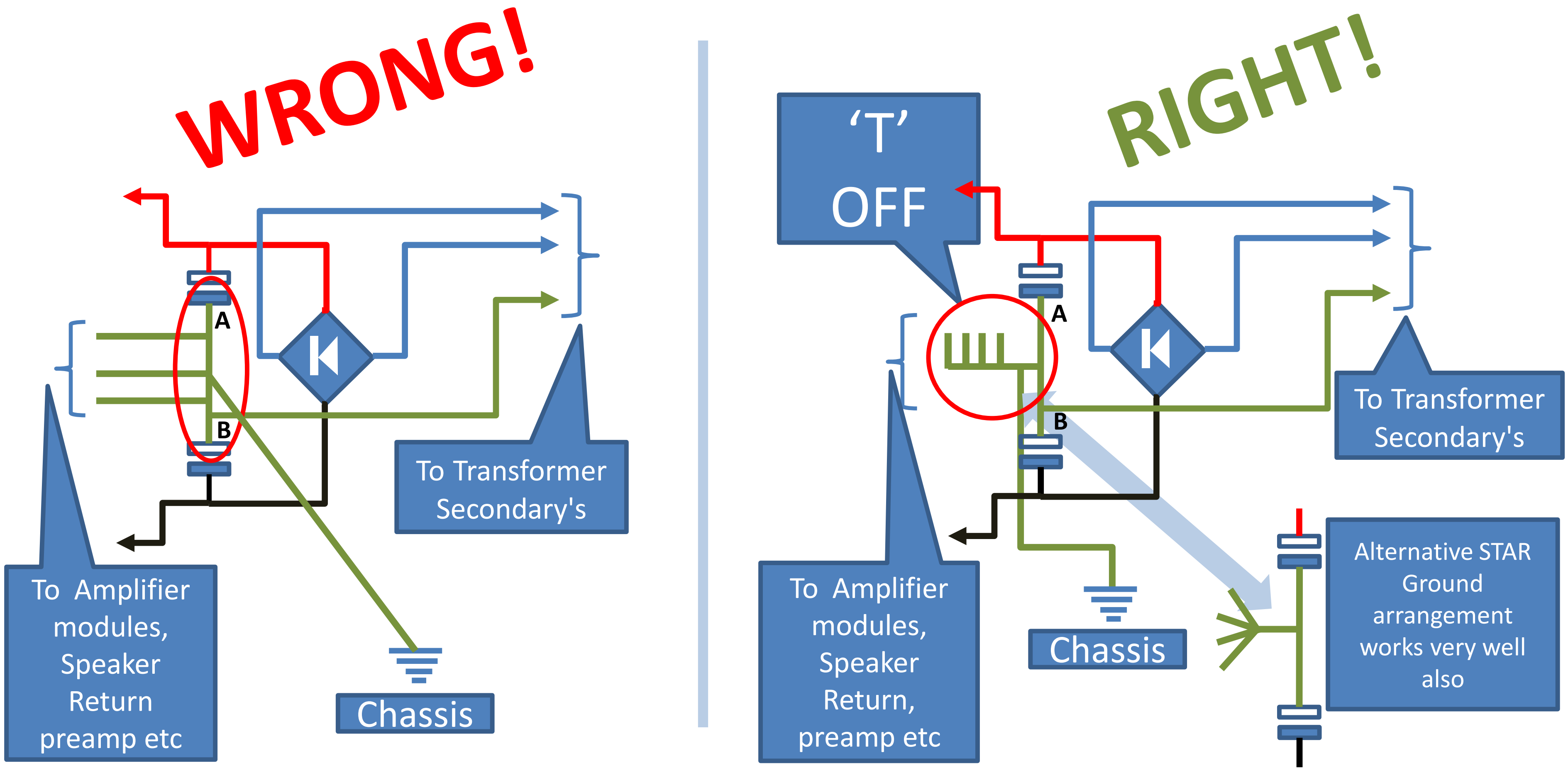
- Keep signal and ground returns separate and only connect them together at a single place on the PCB – namely the star ground or the 'T'
- Do not make any direct connections to the common ground point where the reservoir capacitors are connected together – ALWAYS 'T' off; use a STAR or 'T' grounding system
- Keep all ground traces and interconnections as thick/large as practicable

Common Impedance Coupling



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 across the (low) resistances in the connection betwwen the reservoir capacitors. These voltage drops then appear BETWEEN the signal returns. These can add in series with the audio signal, introducing noise *and distortion*. Similarly, signal grounds should not be mixed up with decoupling grounds on amplifier module PCB's where the same mechanism can occur

Common Impedance Coupling - Wiring

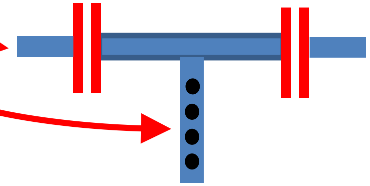


On the right hand side we see how to do it correctly. 'T' off from the 0V junction where the two reservoir capacitors are connected. Then make the connection to the chassis, and after this the connections to the amplifier modules and small signal circuits. How these latter connections are ordered can also impact noise and distortion – we'll look at this next . . .

The ‘T’: How to Avoid Common Impedance Coupling

- Note carefully the order to the ‘T’ section

  1. Reservoir capacitors junction is across the top part of the ‘T’ with NO other connections between the two
  2. On the ‘T’ upright in THIS ORDER FROM TOP TO BOTTOM
     - Take off point to chassis earth [ground] 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)



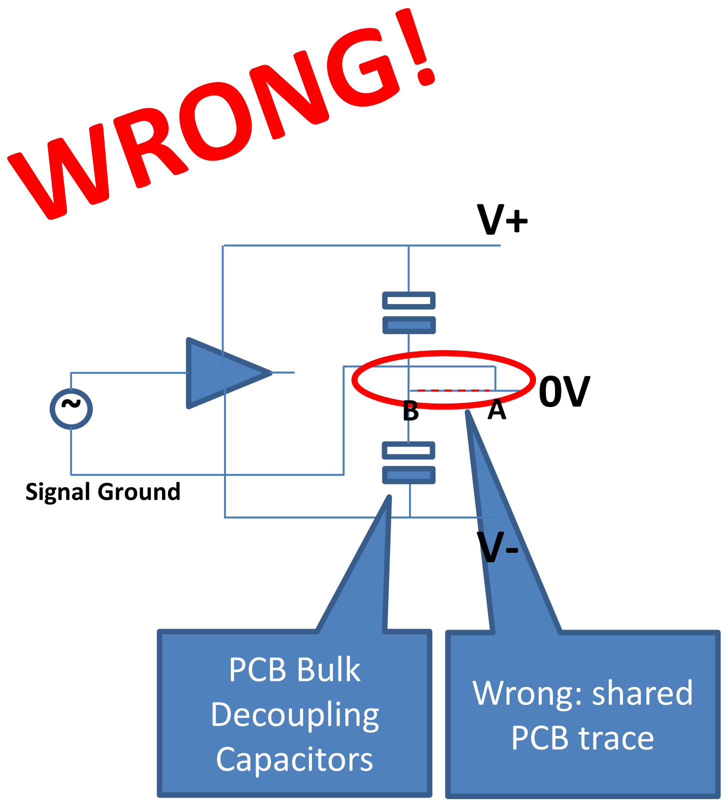
- The total length of the ‘I’ in the ‘T’ need not be longer 1-2 cm and you can even ‘stack’ the 0V connections on top of each other. The whole idea with the central 0V here is to avoid common impedance coupling errors which could lead to noise and distortion

- 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 in the cross bar in the ‘T’ in single rectifier dual rail systems. In split, separately rectified secondary PSU’s, large low frequency audio signal related currents flow between the reservoir capacitors along the cross bar of the ‘T’

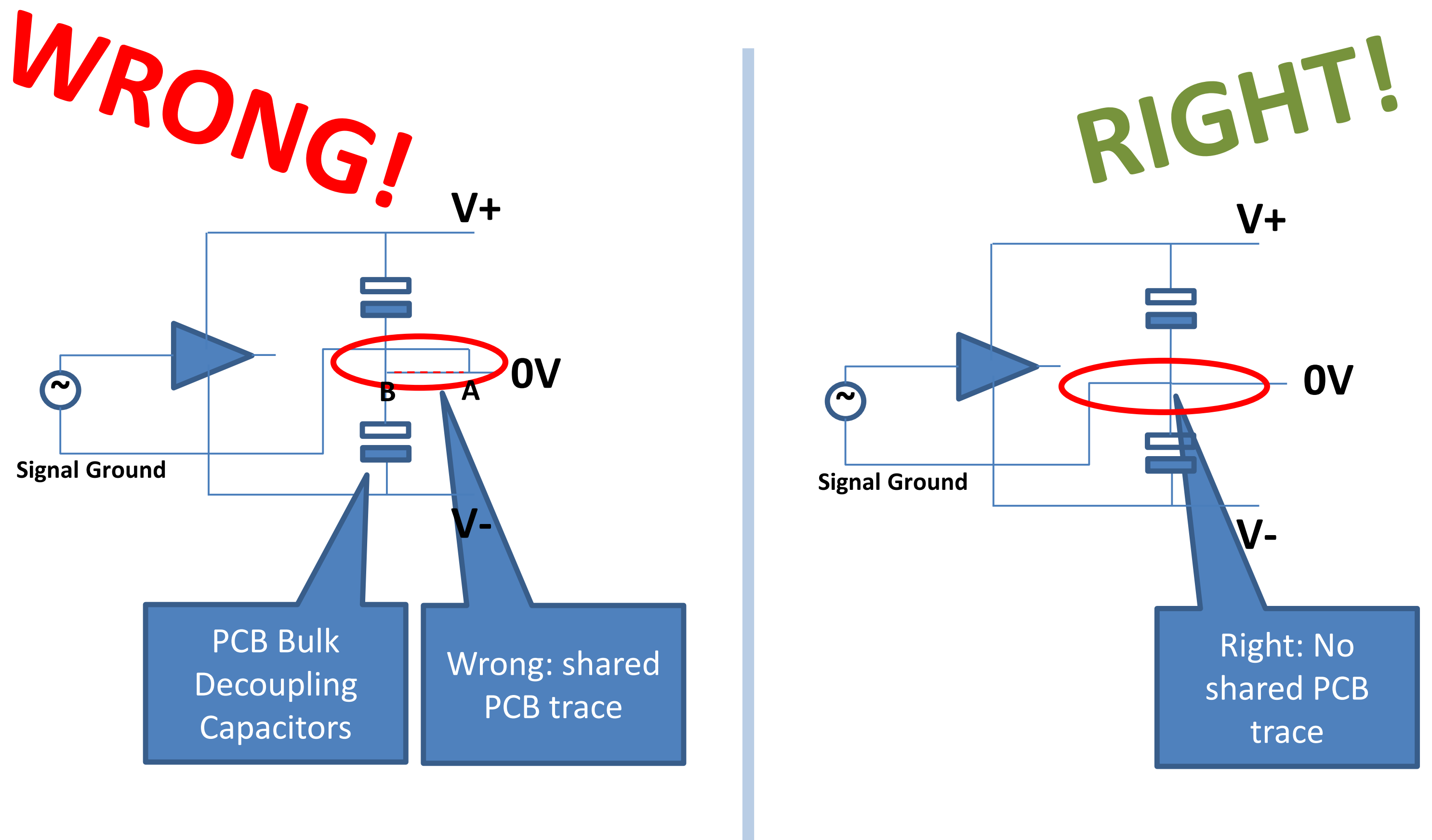
- Always take the 0V connection to the chassis off at the ‘T’ upright or STAR ground and *never* on the connection between the filter capacitors

Common Impedance Coupling – PCB

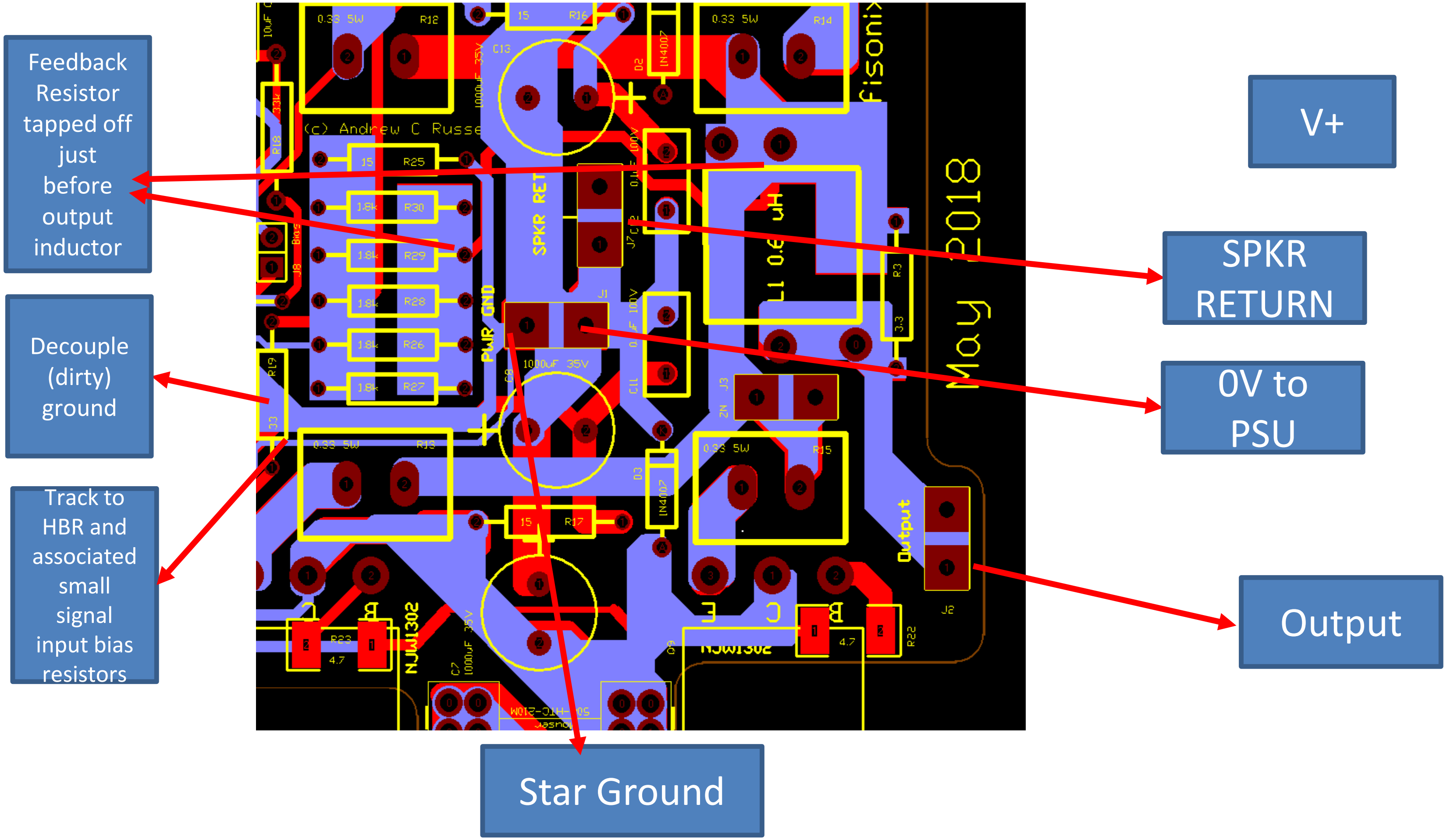


This diagram shows the common impedance problem but applied to a PCB. Current flowing between A and B (dashed RED/BLUE line) creates a voltage drop that appears in series with the signal source ~. Since the decoupling capacitors will be passing mains harmonics and music half wave harmonics, this type of problem can lead to significant increases in distortion and noise. This is another very common problem amplifier designers run into – a great amplifier design ends up as a completely mediocre final product simply because of lack of attention to this simple issue

Common Impedance Coupling – PCB



On the RHS, you see how to do it correctly. 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. There is thus no error voltage placed in series with the input source as in the left hand panel example and the result is very low noise. As a practical example, I had an amplifier producing 60ppm distortion at 1 kHz. After resolving a problem like the one above, the distortion dropped to 10ppm – a 15.5 dB improvement.



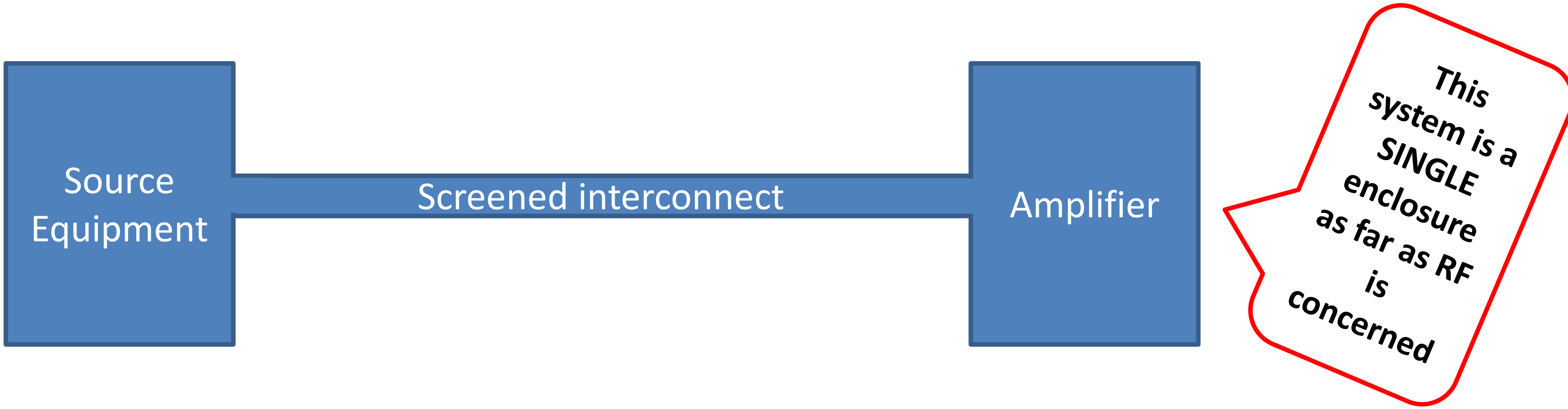
Here is a close up of the connections around the STAR GROUND on the PCB. The small signal ground connects directly to the 0V terminal and the decouple grounds connect at that point as well. The speaker return joins at the 0V and there are no other connections between it and the 0V terminal. ***<u>The STAR ground on the PCB is the ground reference point for the whole amplifier</u>***

Radio Frequency Interference (RFI)

How does RFI manifest?

- You may hear a local AM station coming from your speakers
- Intermittent buzzing or clicking sound from the speakers, especially when the volume is turned up
- ‘Chirping’ when you use your mobile phone nearby
- Clicking sounds when mains switches are operated, or refrigerator compressors kick-in
- Hissing or ‘shhhh’ sound (not to be confused with Johnson thermal noise or HF amplifier oscillation)
- The radio interference comes and goes – worse at specific times of the day, or worse under certain weather conditions
- In sub-optimally designed equipment, may lead to DC offsets (triggering protection circuits in some cases), audible distortion and or ‘harsh’ or fuzzy sounding systems

Radio Frequency Interference (RFI)



The shielded interconnect works extremely well at RF because the shield works to block the RF EM field and in doing so effectively makes the source equipment, the amplifier and the shielded cable one enclosure – and this is one of the keys to ensuring RFI immunity.

Note, the shielded interconnect cable offers NO protection against differential magnetically coupled LF noise between the signal connection and the shield return connection: minimizing the loop area between the central hot conductor and the shield does!

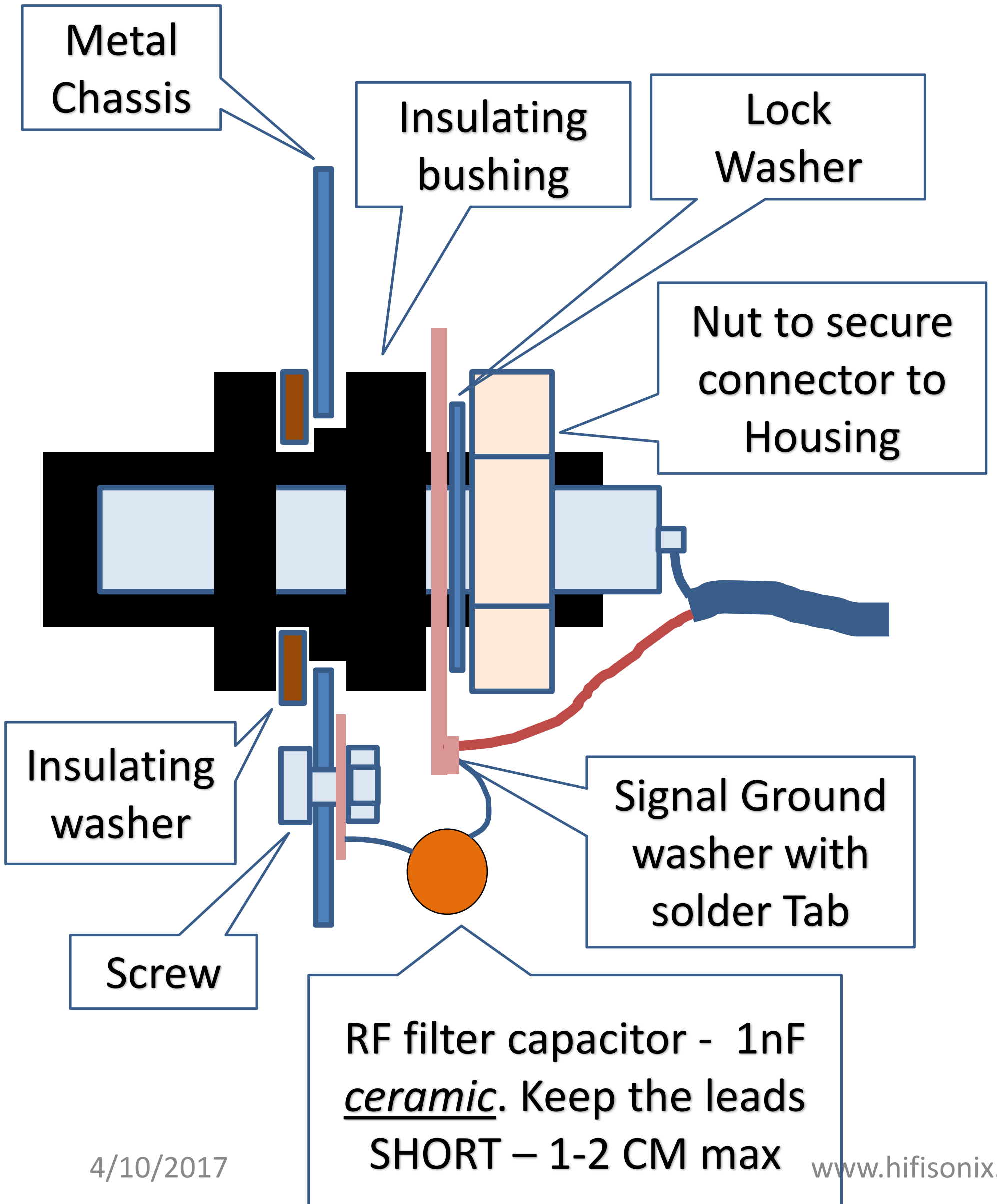
There are a number of techniques for terminating the interconnect screen between the source and amplifier. Some approaches physically bond the connector receptacles to the equipment metal housing at exit/entry points, while others (which we will use), bond the connector ground on the receptacles to the chassis at the point of entry/exit with a small ceramic capacitor. At RF this is a short, so it is the equivalent of directly connecting the should to the metal chassis at the exit/entry points.

The reason why we don’t use the former approach, it that we want to avoid solving one problem (RFI) while introducing another (ground loops). The directly connected shield approach requires a different internal grounding and wiring technique – we will look at that approach in a future presentation.

Radio Frequency Interference (RFI) Cures

- Wire 1nF disc ceramic capacitor from the input socket ground to the chassis ***right at the entry point***. At RF this effectively makes the source equipment chassis, the screen and the receiving equipment chassis *a single enclosure*, maximizing RF Immunity through screening against the RF EM field
- Preamplifier Outputs: wire a 1nF disc ceramic capacitor from the signal return to the chassis right at the connector (only do this on unbalanced phono connector type outputs)
- Power Amplifiers: wire a 1nF disc ceramic capacitor from the speaker return to the chassis right where the connector is located on the chassis. Do not do this on bridged amplifiers
- In some designs, where you are using a ground lifter, 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 coming in through the input cables to the chassis
- 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

Input RFI Suppression Helps Reduce Problems With Both HF Common Mode Noise and RFI



- This is how to add an RFI/HF noise suppression capacitor a phono input connector, shown here in cross section.
- *The connector is insulated from the metal chassis!*
- The RF filter capacitor is located as close to the connector as possible and is connected directly to the chassis.
- A value of 1nF will usually be at least an order of magnitude higher than the interwinding capacitance of an HF SMPSU transformer and will thus shunt RFI noise (and a lot of HF noise) to the chassis and away from the amplifier inputs.
- Do not use film capacitors. The self-inductance will be too high.
- The amplifier inputs should also be fitted with an 'L' pad RC filter on the amplifier module PCB.
- PCB mounted Phono sockets [like this Kobiconn](#) for example, make filtering as shown here much easier as you can locate the RF capacitor on the PCB – typically you would use a 100V XR7 0805 or 1206 SMD device for best results.

OK, Enough Talking and Theory. Lets get down to the Practical Stuff

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.

- Safety Tip: ***you should not be able to touch or see ANY exposed mains wires or connectors inside your amplifier***. If using crimp connectors, use the fully insulated types. Always dress off mains wiring to switches and power inlet receptacles with good quality heat shrink.

- Transformer wires from each secondary to its associated bridge rectifier are tightly twisted together. Keep them as short as possible! Keep them away from signal wiring

- Wires from each bridge rectifier to their associated filter capacitor(s) are tightly twisted together. Keep them as short as possible!

- 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 on the pages that follow. Keep them as short as possible and well away from any signal wiring!

- 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 [ground] loops. For SAFETY REASONS make sure it's a high quality connection – use a ring tab connector, 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.**

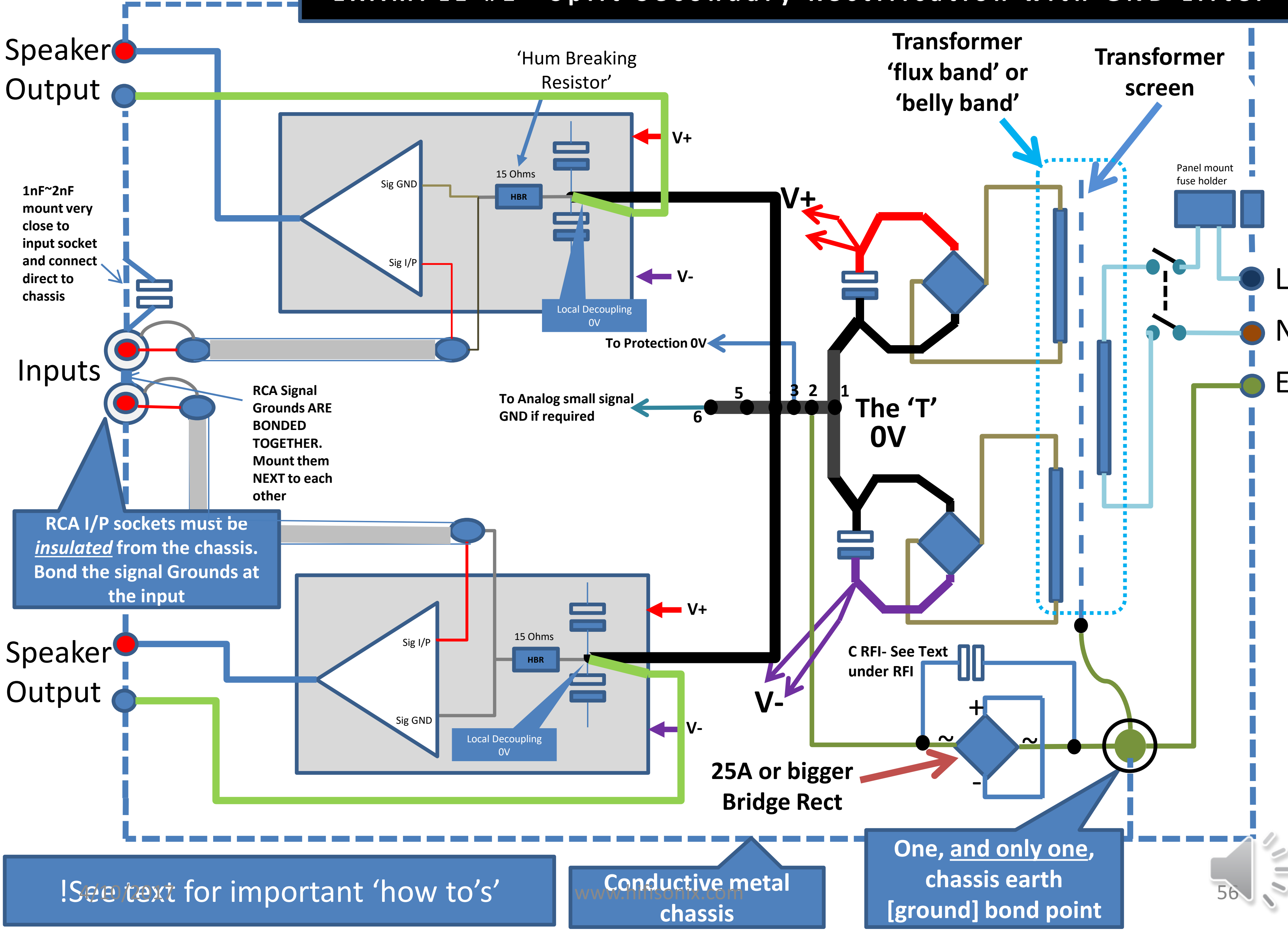
- Keep high current wires away from small signal wires

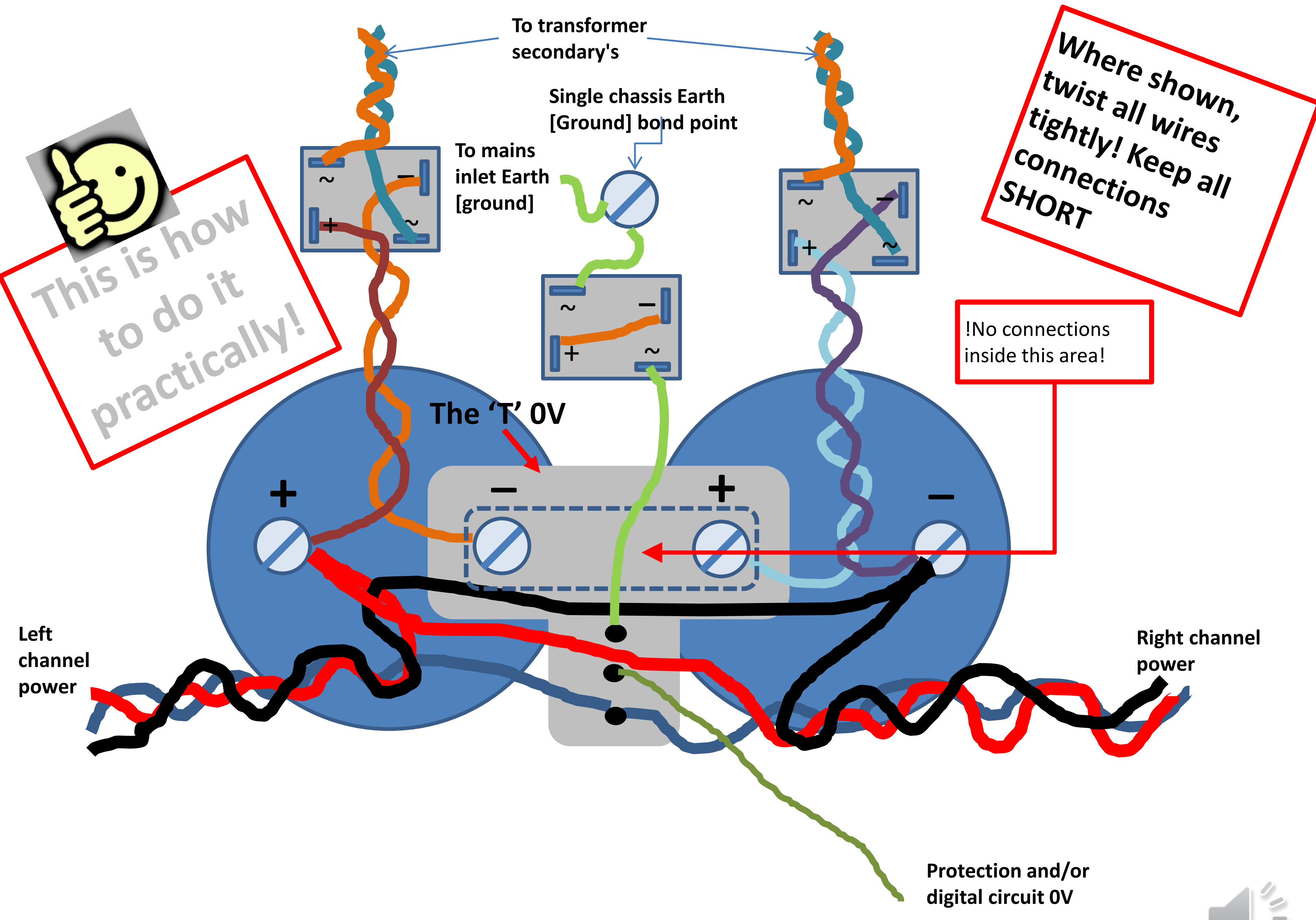
- The input and output sockets may NOT make any direct connection to the metal chassis. Make sure the inputs are mounted next to each other and the signal grounds are bonded together. If your amplifier modules are located apart from each other in the chassis, do not bond the speaker returns together.

- Use a 'HBR' resistor to prevent significant loop 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 [ground] loops and radiated noise (this will be at audio frequencies and associated harmonics). Keep the PCB layout compact. Be careful not to introduce any common impedance coupling - use a star ground on the PCB

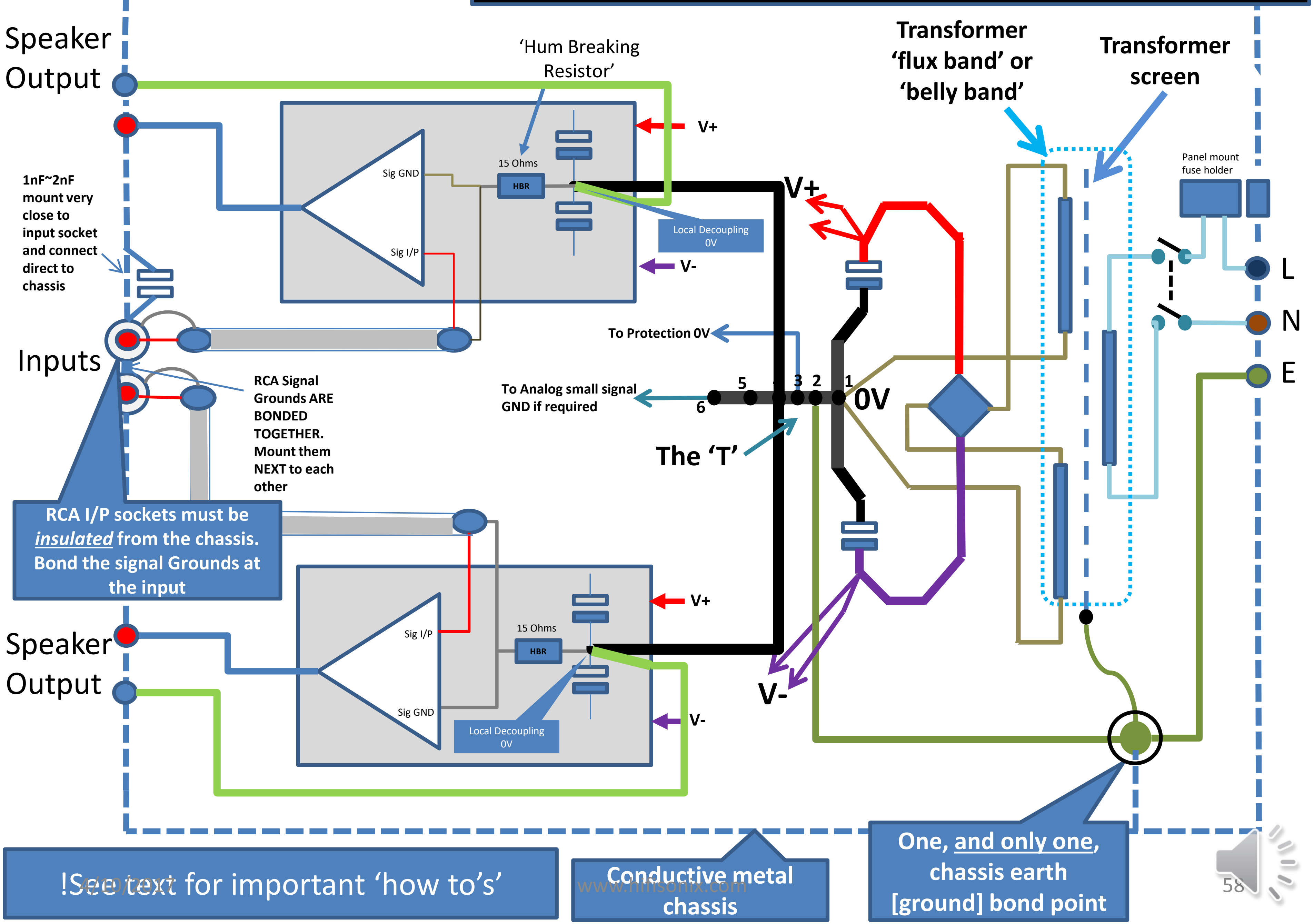
EXAMPLE #1 – Split Secondary Rectification with GND Lifter

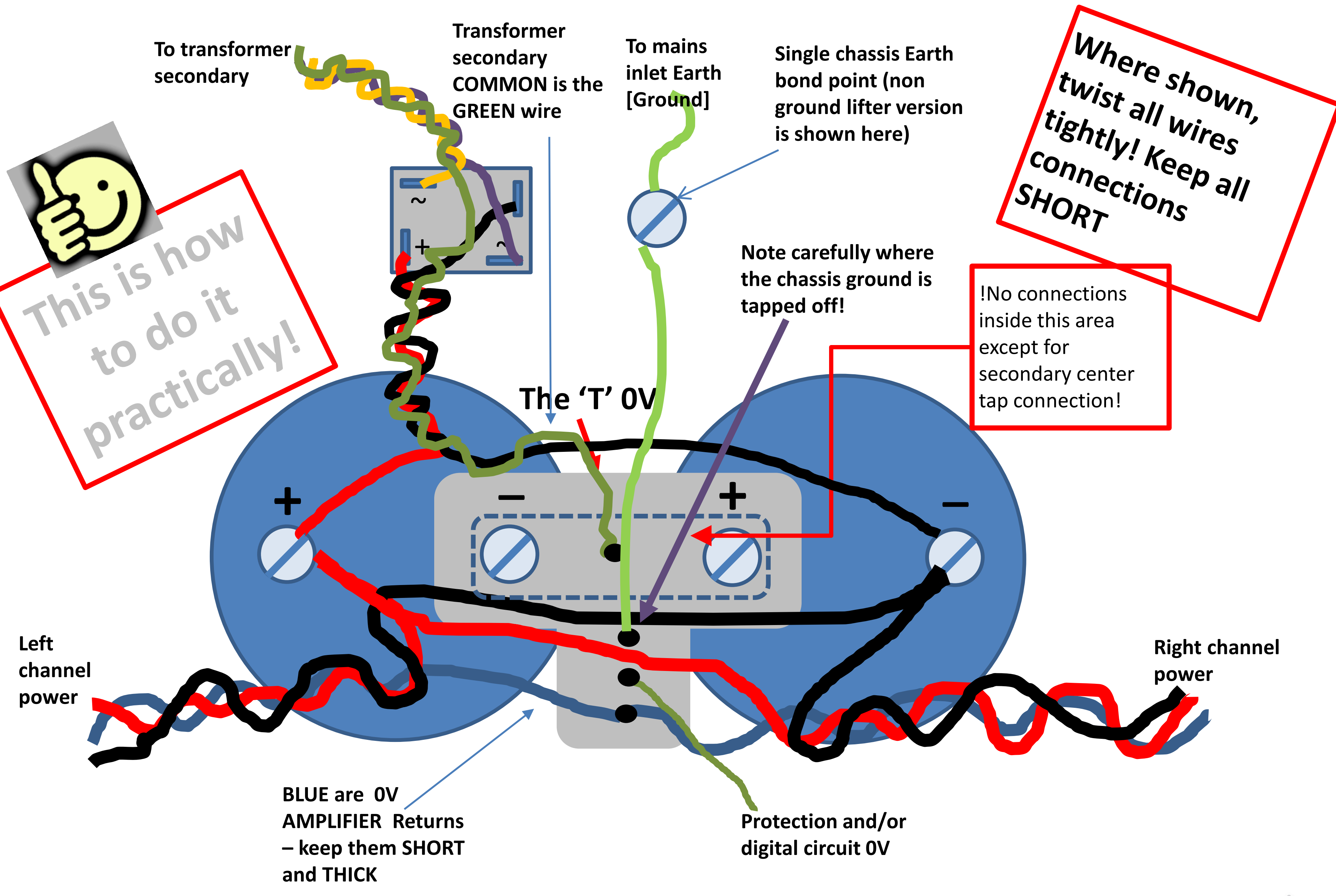




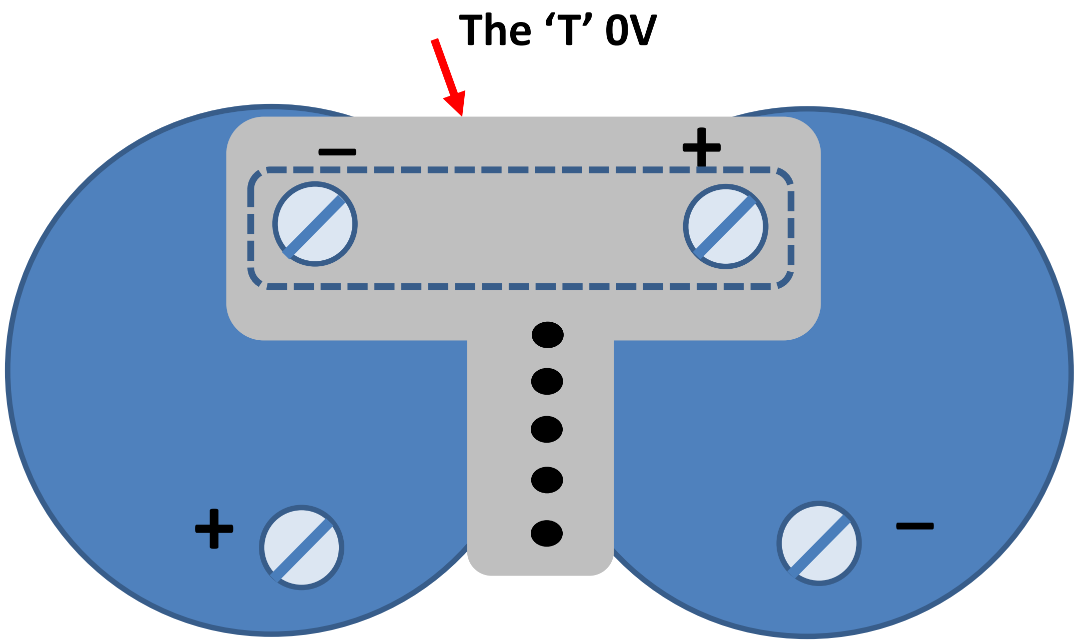
EXAMPLE #1 – Split Secondary Rectification How to do it Practically

EXAMPLE #1 –Single Bridge and NO GND Lifter





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

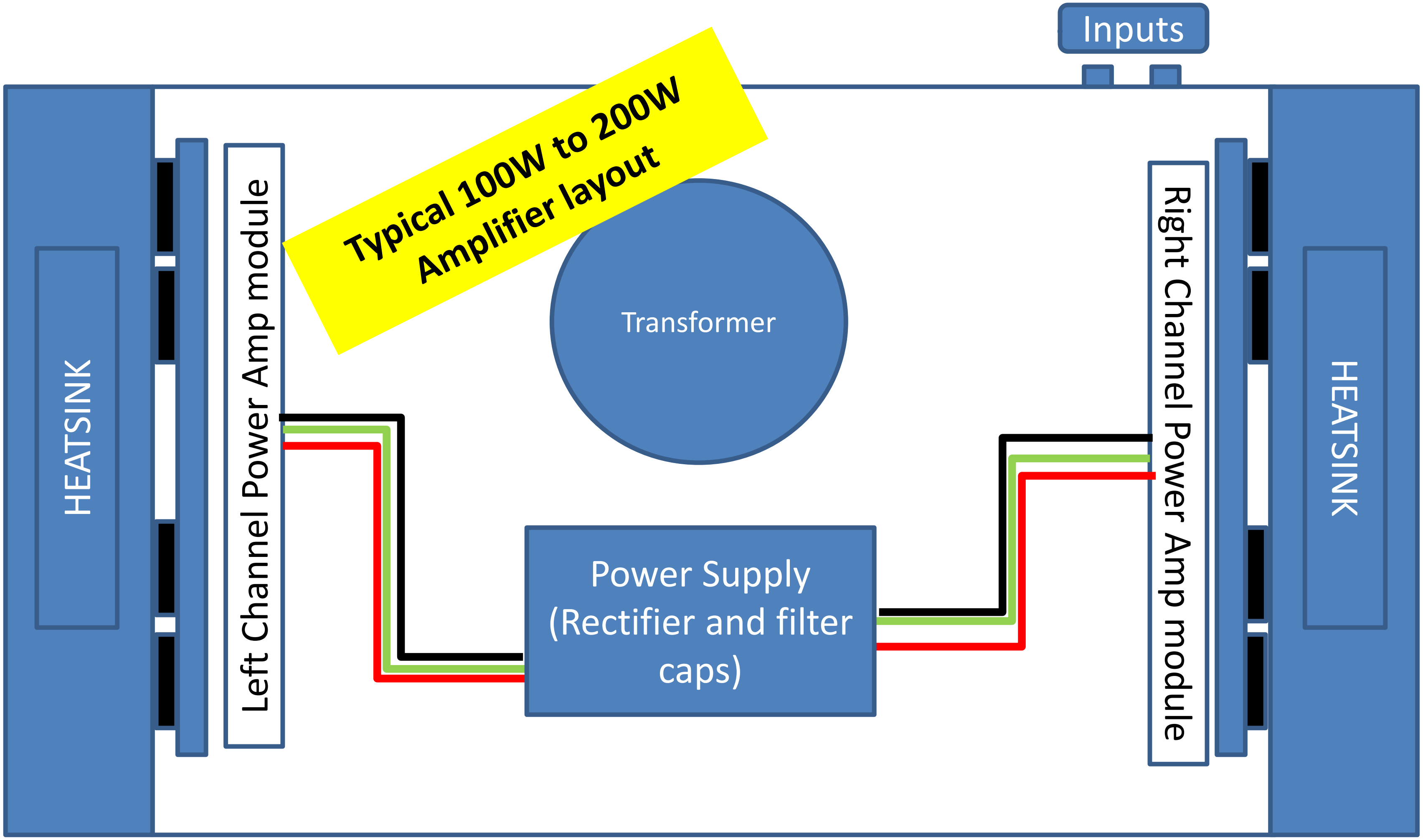


This drawing shows how you can minimize the loop area in the vicinity of the main reservoir caps by 'folding' the capacitors so that the + and – are closer than shown in the previous two diagrams. There are very large charging currents flowing into the reservoir capacitors, and they therefore radiate significant EM fields. Keep small signal wiring away from your reservoir capacitors. Make sure you keep the capacitors as close together as practically possible.

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.

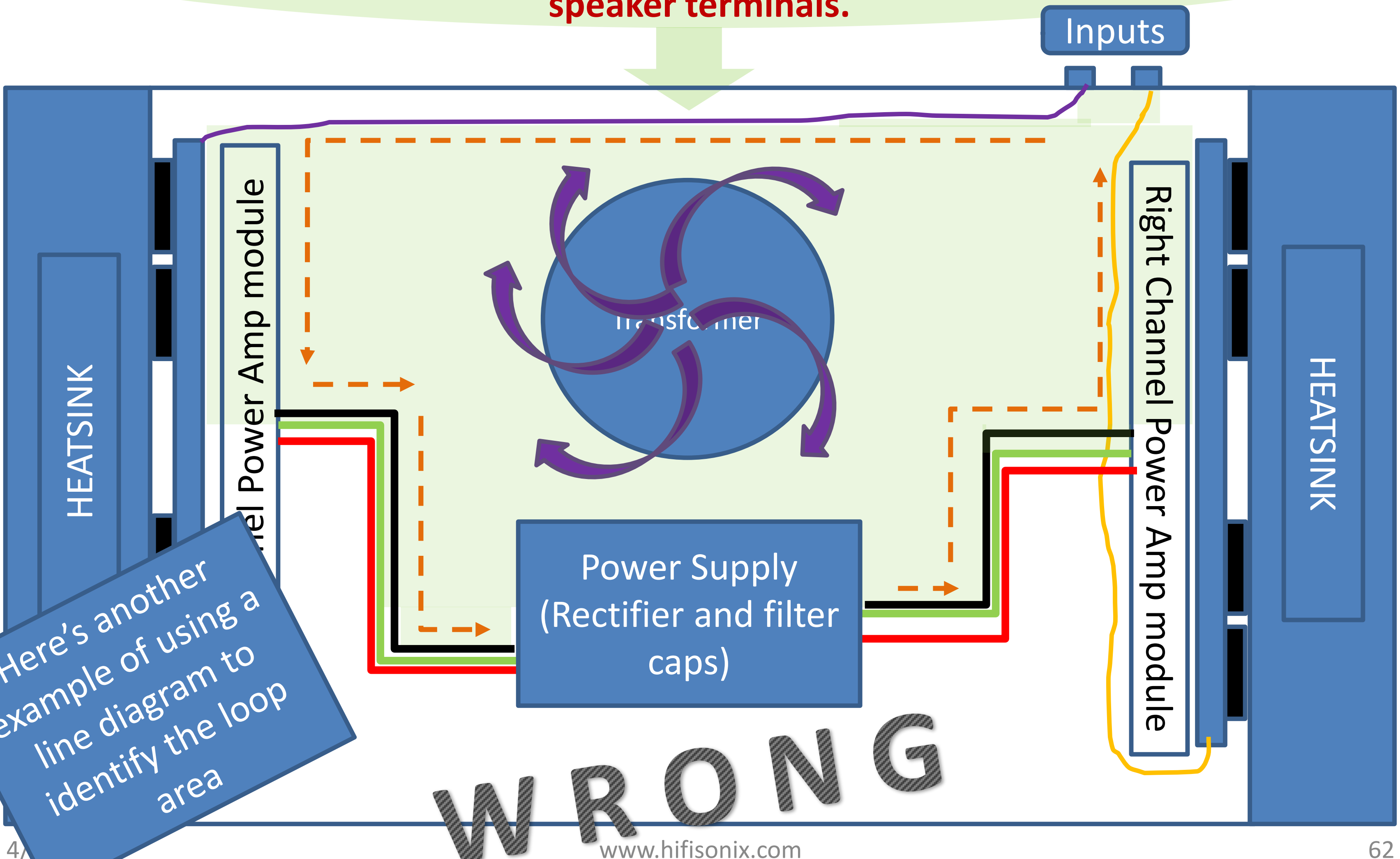
Routing Input connections in a power Amplifier (1)

How do you wire the input signal wires for least noise? Least noise will occur when the total input loop area is minimized.



Routing Input connections in a power Amplifier (2)

The shortest path is not always the best. The total loop area with this configuration is very large and is intersected by any stray magnetic fields from the transformer or mains wiring, and possible any high current signal wiring from the amp modules to the speaker terminals.

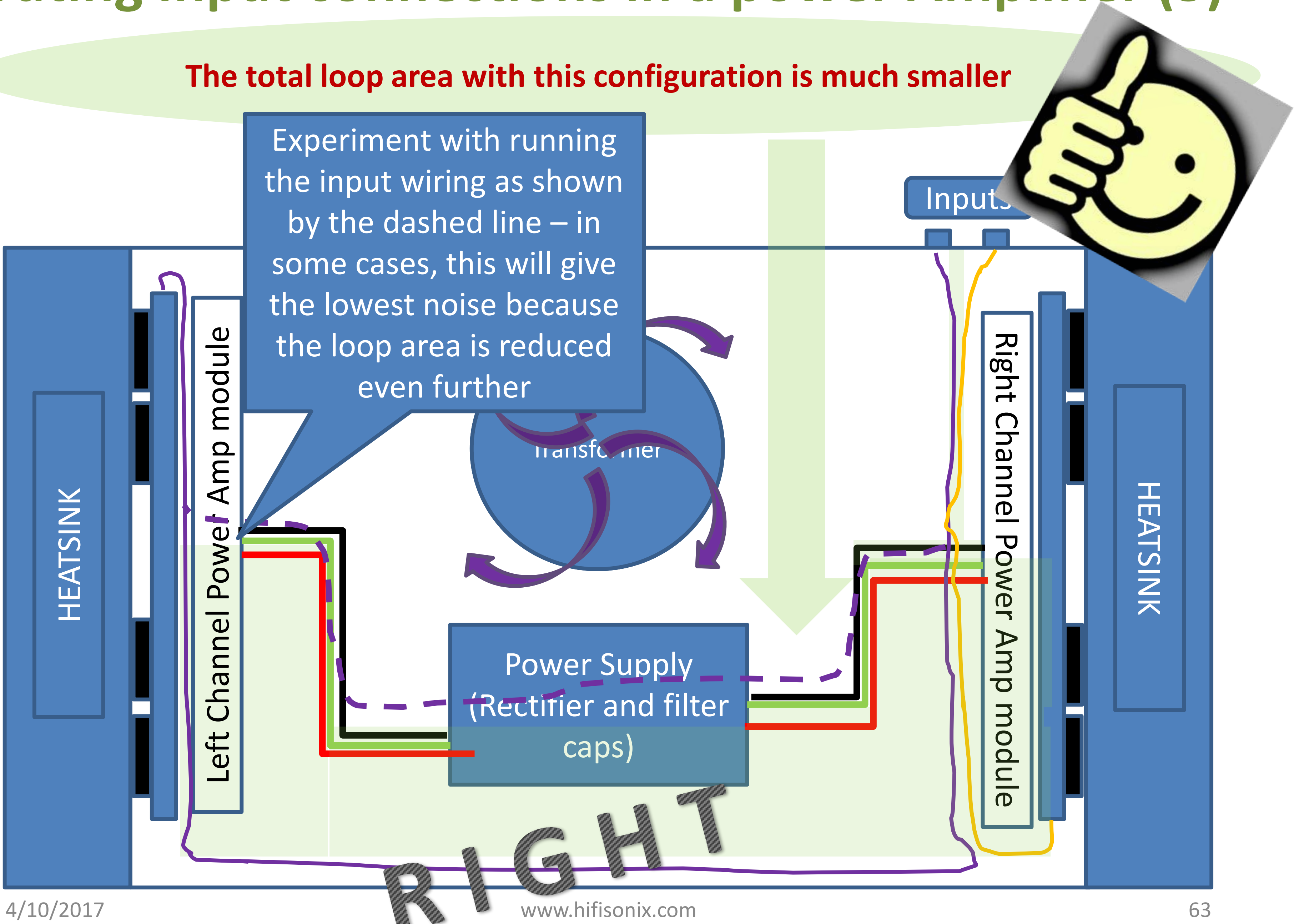


Here's another example of using a line diagram to identify the loop area

Routing Input connections in a power Amplifier (3)

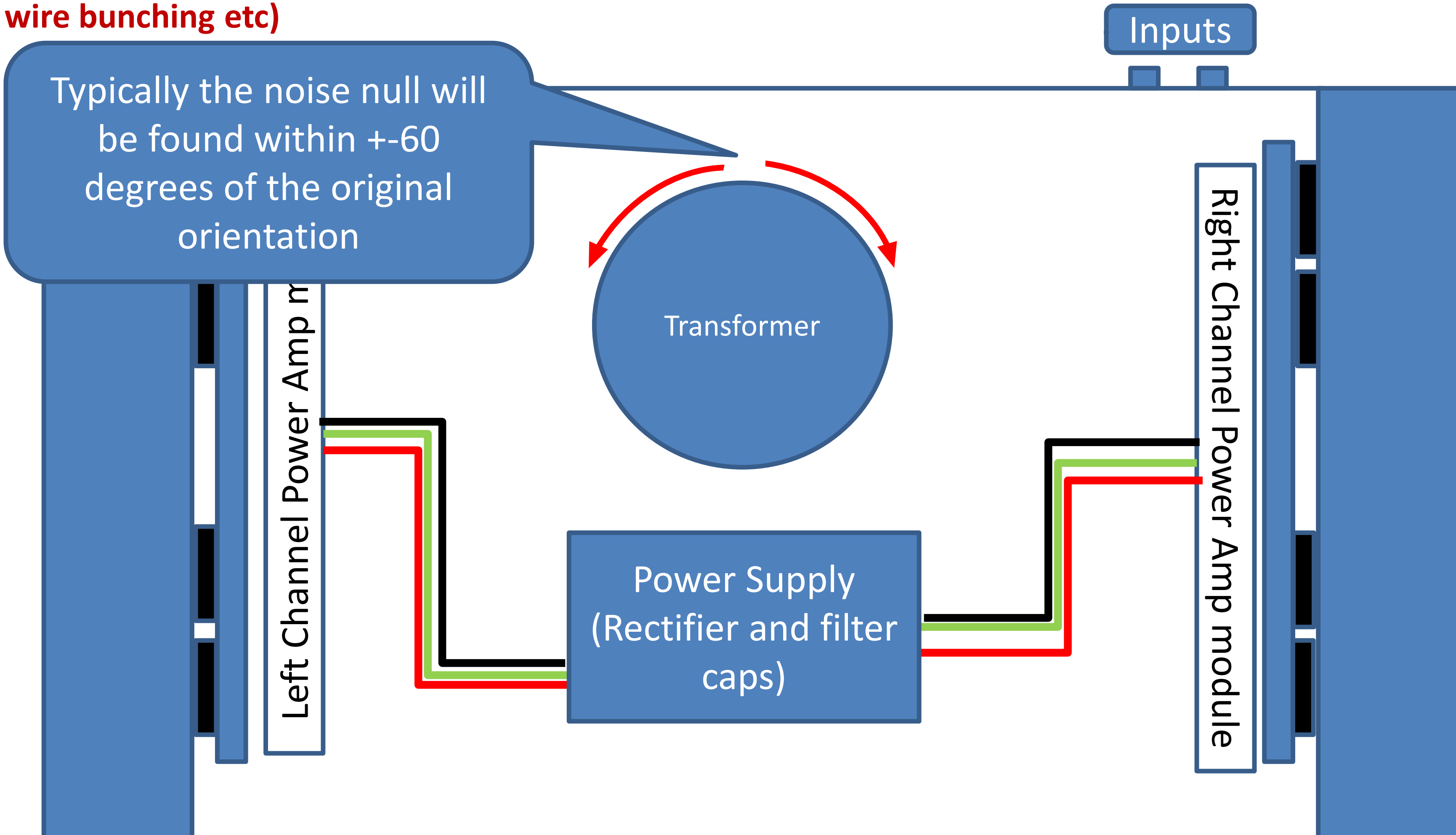
The total loop area with this configuration is much smaller

Experiment with running the input wiring as shown by the dashed line – in some cases, this will give the lowest noise because the loop area is reduced even further



Quick Tip About Toroidal Transformers and Noise!

Once installed and wired up, try rotating the transformer clockwise and then counter-clockwise while listening to any noise through your headphones. You will fund a null point where the noise will be 8-10 dB lower. Once done tighten the mounting bolts to secure the transformer. This happens because the radiated fields from a toroid are not uniform (depends on winding geometry, wire bunching etc)



‘Headphone Scope’ Trick – Quick and Easy Hum/Noise Debugging (1)

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 measurement preamplifier.

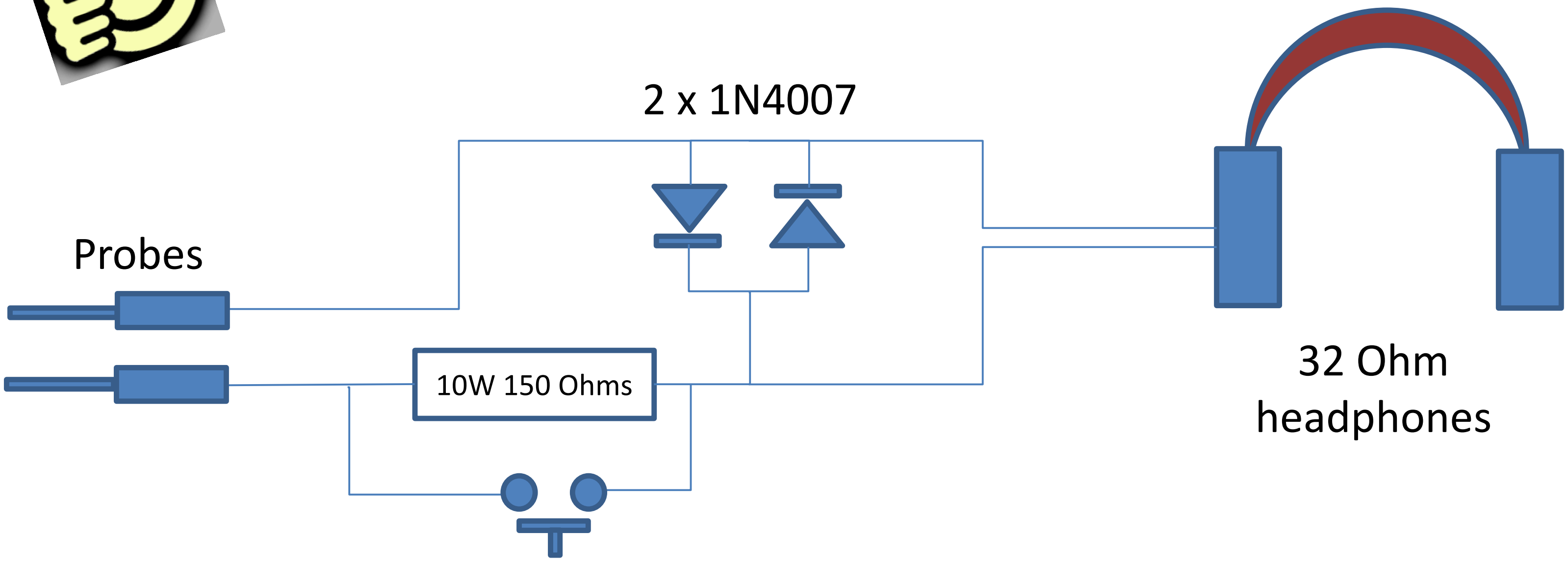
Connect a pair of headphones directly to the output of your amplifier **<u>(do this AFTER it has been switched on and the outputs have settled)</u>** and without any input source connected. Make sure your amp does not have any DC offsets

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

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

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.

Headphone Trick – Protecting your headphone from overload (2)



Connect the headphone probe across the amplifier output terminals.

Here is a simple way to protect your headphones when using the headphone to probe cable dressing and layout in your amplifier and it will also protect your ears of you happen to probe in the wrong place. You can fit a pushbutton switch across the 150 Ohm resistor – if you hear nothing or little noise, depress the switch to momentarily improve the sensitivity.

Do not connect the headphone probe across DC!

A few practical tips for isolating the root cause(s) of your noise problems

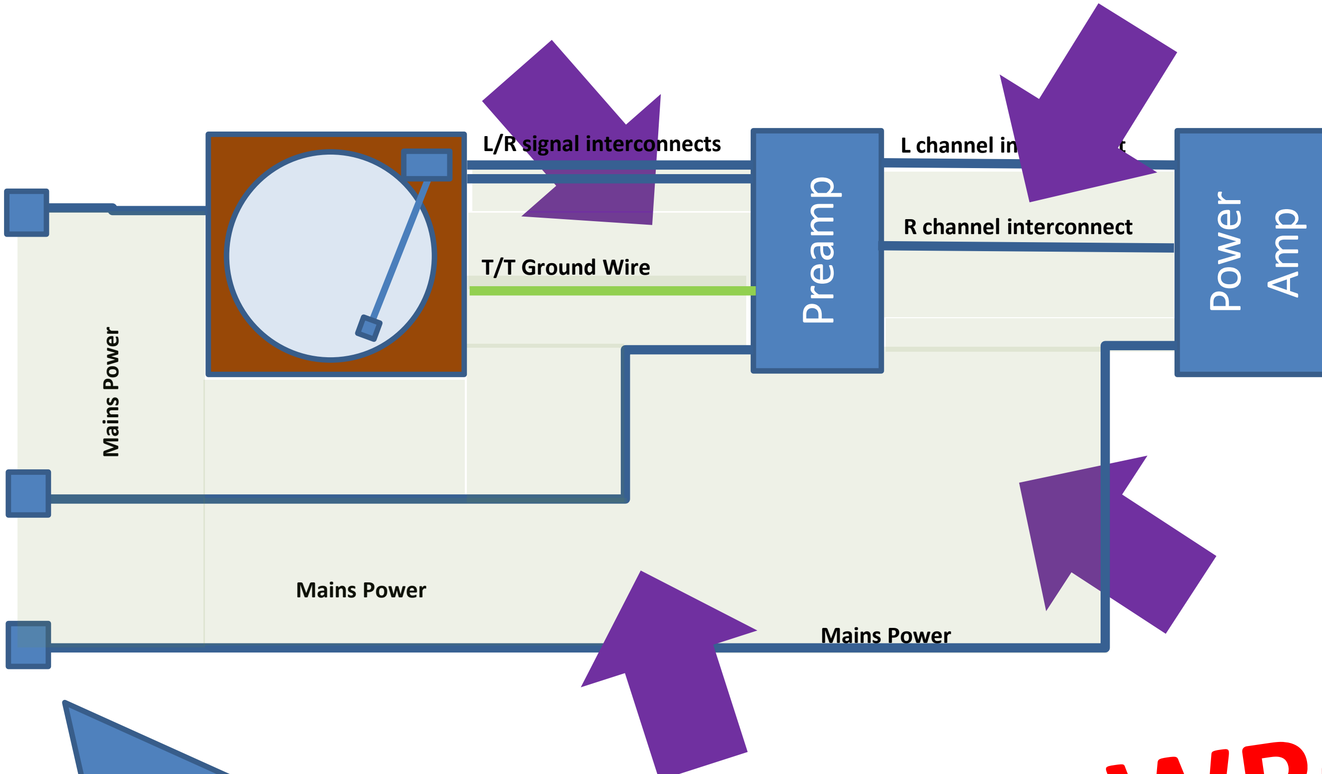
Debugging Audio Amplifier Noise (1)

1. Powered up and with ***no inputs plugged in*** does it hum or buzz? If YES, then you most likely have a common impedance wiring problem inside your amplifier. Remember this problem can arise in the PSU wiring and/or on the amplifier PCB module – *both have to be wired correctly* to get rid of noise. You may also have one or both of your input connecters making direct contact with the chassis – this will cause problems. Assuming all is ok, move to the next step.
2. ***Connect the left and right channels together with an interconnect cable***. If you now hear hum, you most likely have a cross channel ground loop arising inside your amplifier. Make sure the loop areas inside your amplifier are small. You must also fit a **Hum Breaking Resistor (HBR).** *Note very carefully how this is wired into the amplifier – it is NOT simply in series with the input screen/ground wire!* Check cable dressing - use the 'headphone scope' trick to make improvements. Did you bond the input connectors together? Are the input connectors mounted right next to each other?
3. If everything is ok, the next step is to make sure you don't have any noise problems coming from your source equipment (I recently experienced a cross channel ground loop in a $5000 CD player at a show . . .)
4. ***UNPLUG your SOURCE equipment from the mains*** e.g. a preamplifier (just switching it off is not good enough)
5. ***Connect one of the channels with an RCA cable*** (say 0.5 metres long) to your source. If it remains quiet with just the one channel connected, but starts humming as soon as you connect the second channel, you most likely have a cross channel ground loop that is arising OUTSIDE your amplifier. Check that this is not arising along the interconnect cables by moving them physically – does the noise level change significantly? If you move the source equipment, does the noise level change? In this manner you can quickly identify any external equipment that is causing the problem and move it, or re-route your interconnects to avoid the noise pickup. Once quiet, you can move to the next step.
6. ***Apply power to your source***. Does it now hum/buzz? If YES, you either have a cross channel ground loop arising INSIDE the source equipment, or a classic AC ground loop. Try plugging your amplifier and your source into the same outlet strip - this will minimize the loop area. If you move the mains cables or the input cables around, does the level of the hum change? If yes, you have a classic AC ground loop with a strong *external* EM field generating the loop. Check that you are not routing any signal or power cables near equipment that could be radiating EM energy.

Debugging Audio Amplifier Noise (2)

7. ***RFI*** If you are getting RFI ('shhh' sound, clicking, or you can actually hear radio stations from your speakers) make sure you have connected the input socket ground to the chassis with a 1nF value capacitor; use good quality interconnects with a braided screen
8. ***Potential HF common mode noise Loop***. If all is correct above but you are getting noise when you power up other equipment – especially stuff that uses a switch mode PSU – you can use a clamp on ferrite around the mains cable and the aforementioned 1nF RFI suppressor capacitors on the inputs. Remember to address the culprit piece of equipment as well.
9. ***Potential Amplifier Oscillation/Instability (this could also be due to (8) above).*** If you notice a reduction/change in hum when you touch the chassis or any other part of the amplifier (NOT OF COURSE NEAR ANY MAINS CIRCUITS, OR HIGH VOLTAGES), and assuming items 1-8 above are correct, there is a chance that your amplifier may be oscillating at HF.
   - Firstly, make sure ALL metal parts (including heatsinks) are bonded together and connected to safety Earth.
   - By Touching the amplifier you are changing the capacitive coupling to ground (even if all metal parts are well grounded – remember at HF circuit/wiring inductances play an important part) altering HF coupling into various parts of the amplifier which is then being rectified ('demodulated') by the semiconductor junctions – usually the input or VAS circuit.
   - The HF oscillation is invariably modulated by the power transformer magnetic field – once it is demodulated however, it manifests as mains hum/buzz on the speakers
   - Check that your amplifier compensation component values are correct.
   - Make sure you have a Zobel and output coil installed (all decent feedback amplifiers incorporate these)
10. ***Cable dressing and routing is critical!*** Finally, use the headphone scope trick to dress and bundle your wiring for lowest noise. Use cable ties and plastic cable clamps to hold wiring in position. You can also use small pieces of Gorilla tape or silicone sealant to position cabling.

How to Minimize Equipment Interconnect and Power Wiring Loop Areas (1)

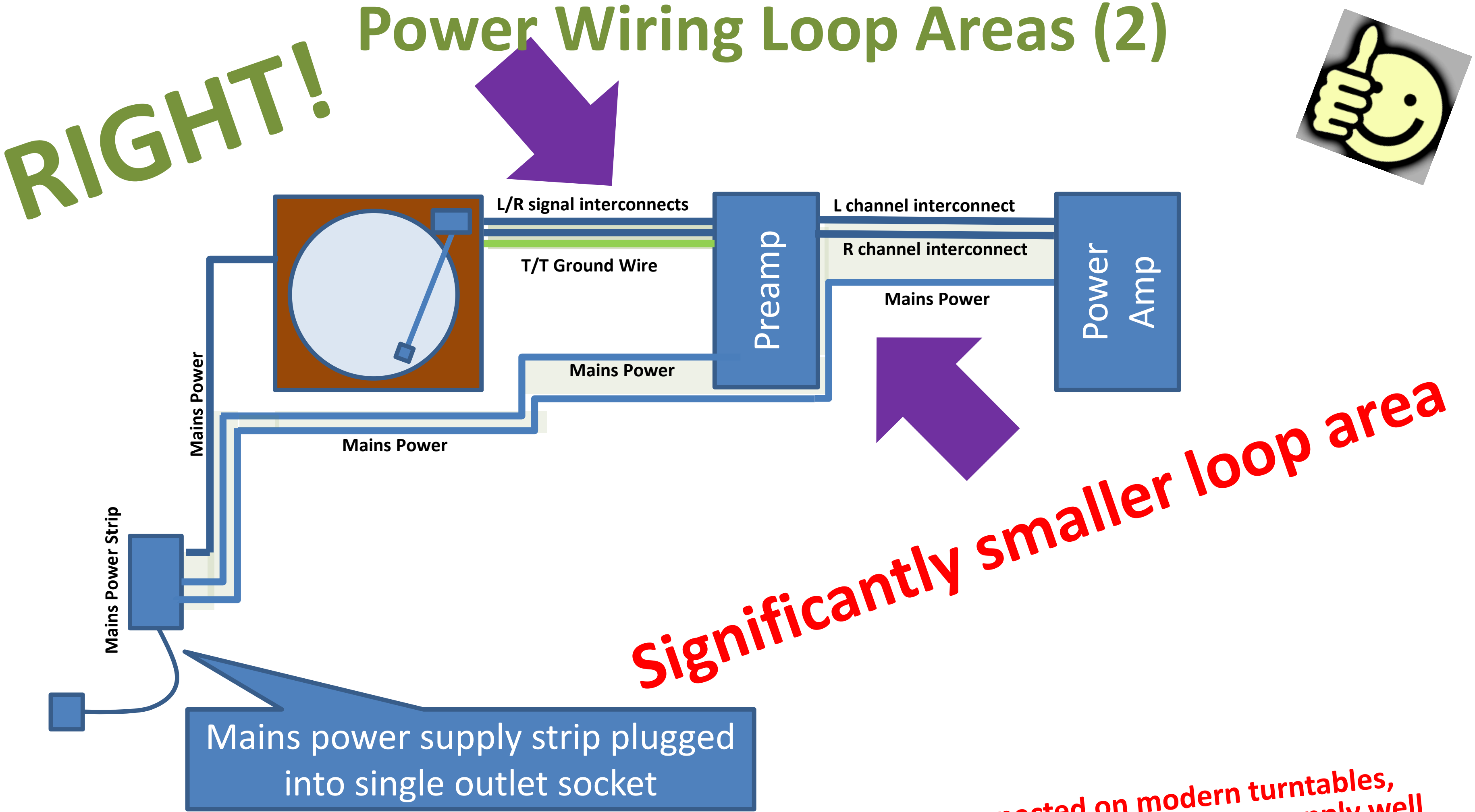


Mains supply plugged into individual wall sockets located apart

WRONG!

Large loop areas maximize induction pickup and therefore noise!

How to Minimize Equipment Interconnect and Power Wiring Loop Areas (2)



The cartridge ground wire and the motor ground are usually not connected on modern turntables, which in most cases use a separate low voltage AC or DC supply. Keep the turntable power supply well away from the interconnects. Importantly, keep T/T ground wire and signal wires tightly twisted. Keep the mains supply to the preamp and power amp bundled together.

This presentation has covered some of the major causes of hum and noise in DIY audio amplifiers. I hope you found it interesting and that will help you to solve any problems you may encounter.

If you have any questions, please feel free to post them up at www.hifisonix.com

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 discussion threads and private communications on DiyAudio.com
- Excellent overview of EMC by Keith Armstrong Understanding EMC
- Very Good article on balanced audio signals and ground loops
- EMC for Product Designers by Tim Williams (see Chapter 10)

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