

Preventing Hum and Noise Problems in Audio Amplifiers

An Antidote to
'Advanced Grounding Guruship'

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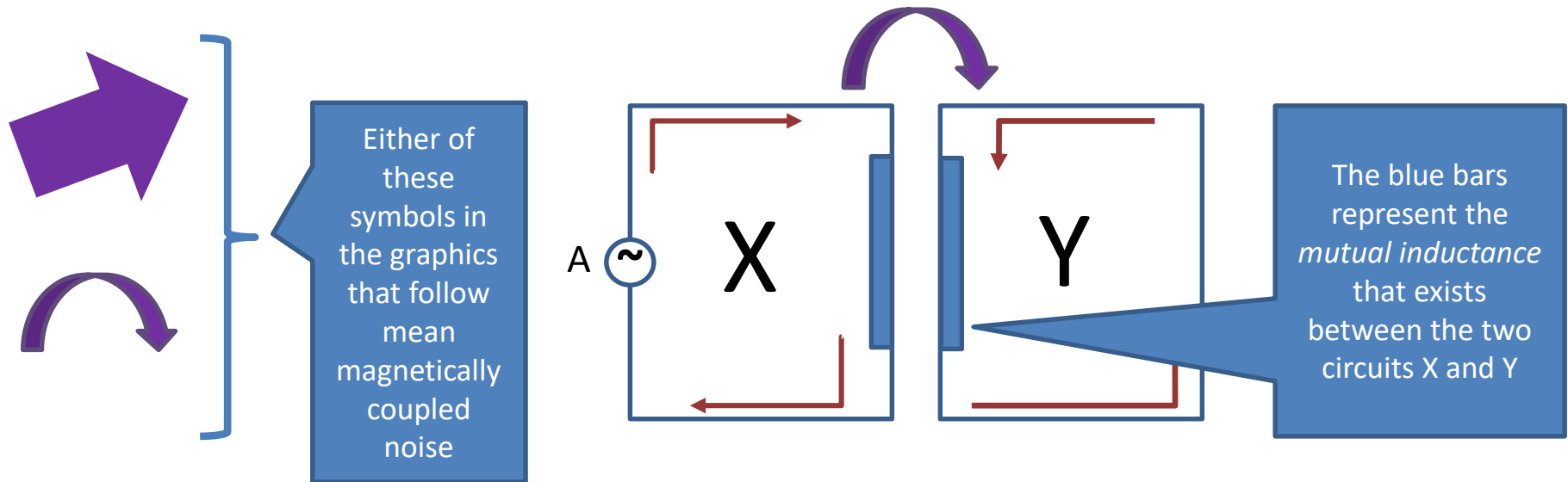
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Updated and new material added October 2017

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Magnetic Coupling - Basic Concept

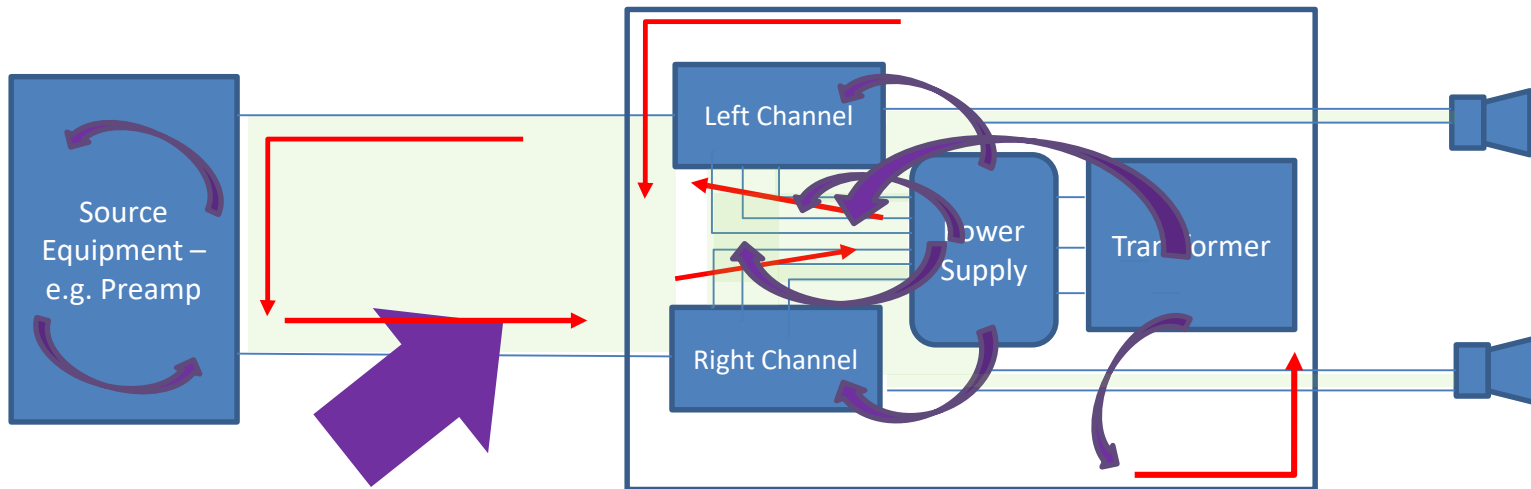


A signal **or noise voltage** source A causes an **electro-motive force** (EMF) that drives current flow around loop X. This will **induce** a current in loop Y that flows in the opposite direction through a physical process known as **magnetic induction**. The magnitude of the current flowing in Y is 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.

Magnetic Coupling - examples

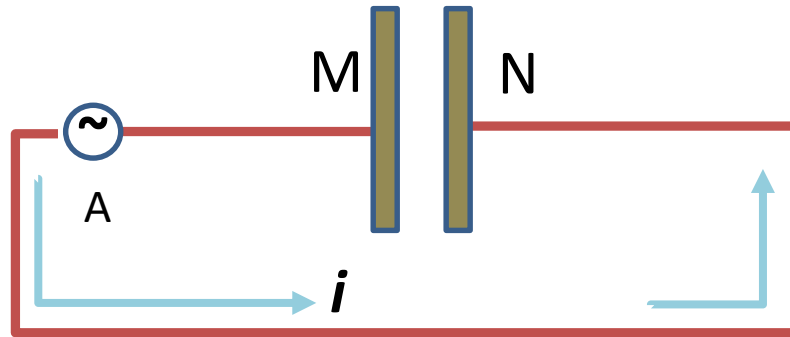


Stray magnetic fields impinging on the green shaded areas shown above drive signal currents (i.e. noise) at the source frequency, or associated harmonics, that create loop currents that corrupt the information (the music) signal resulting in degraded signal to noise ratios and increased distortion. In the following pages we will learn how to mitigate these problems so that, even in conventional unbalanced interconnected systems, outstanding noise performance can be attained.

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

Capacitive Coupling - Basic Concept



In *capacitive* (also termed *electrostatic*) coupling, source A causes an *electric field* across plates M and N 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. 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).

Important Basic Concept: Audio Signal Ground and Safety Ground Are Different

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

This perception 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 ground (earth)** is there to provide a path to ground (earth) in the event either the live (hot) or neutral accidentally come into contact with any exposed metal parts of the chassis or any part of the audio circuit. This ground (earth) makes zero contribution to minimizing hum in a system. It is there for safety and is a legal requirement in all countries.

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

Safety issues aside, if you do find connecting your audio signal ground to the safety ground (earth) reduces noise, it is a sure indication that you have an ground loop or some related problem – the alarm bells should therefore begin to ring.

Basic concept: Differences in 'Ground Voltages' 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*.

This understanding and the proposed cure is WRONG.

It is the magnetic field lines from transformers and power cables intersecting loop connections inside the equipment, and the interconnects between the equipment, that result in noise. Nothing to do with differences in ground potential!

These loop currents flow from the source - i.e. where the magnetic lines of flux are coupling into the loop - through interconnect and cable resistances and return to the source. In so doing, developing noise voltages across the interconnect and wiring resistances that appear in series with the signal voltage and are then amplified along with the signal (i.e. music).

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

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. Common mode mains conducted noise – usually at HF (100's of kHz)
4. Radio Frequency Interference (RFI) – 100's of kHz to MHz

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 Loops

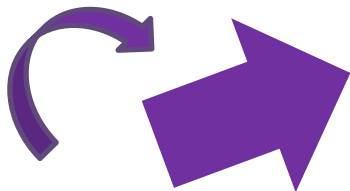
Causes

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



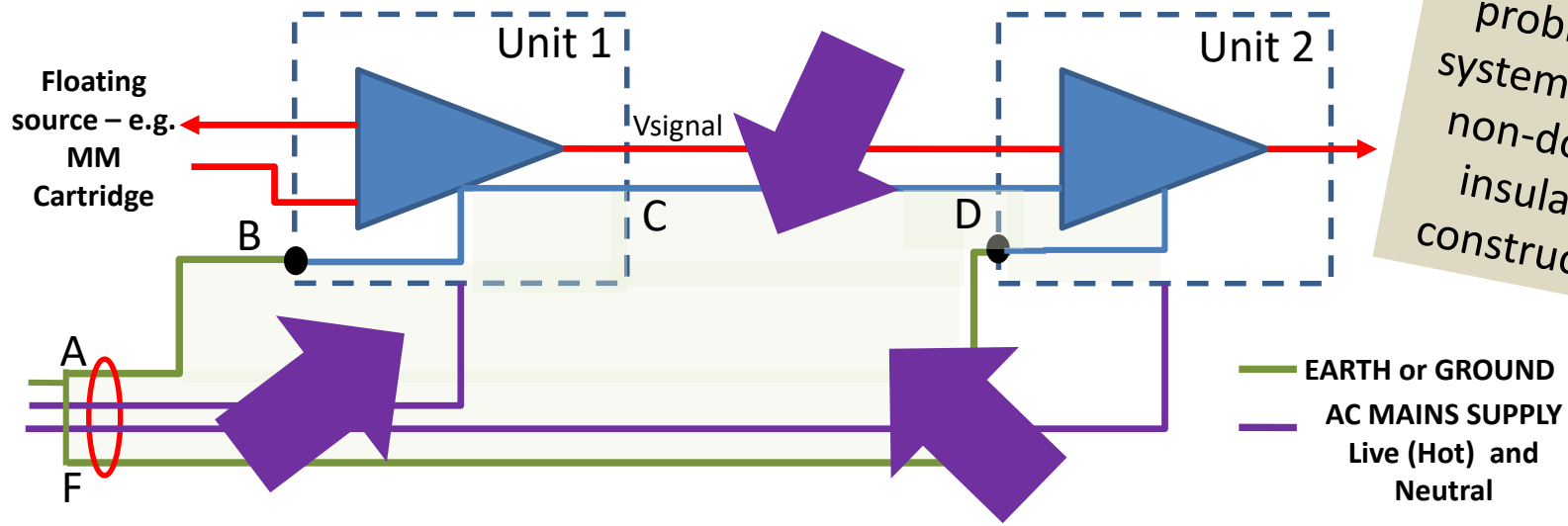
1st Line Remedy

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



Remember, these symbols 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

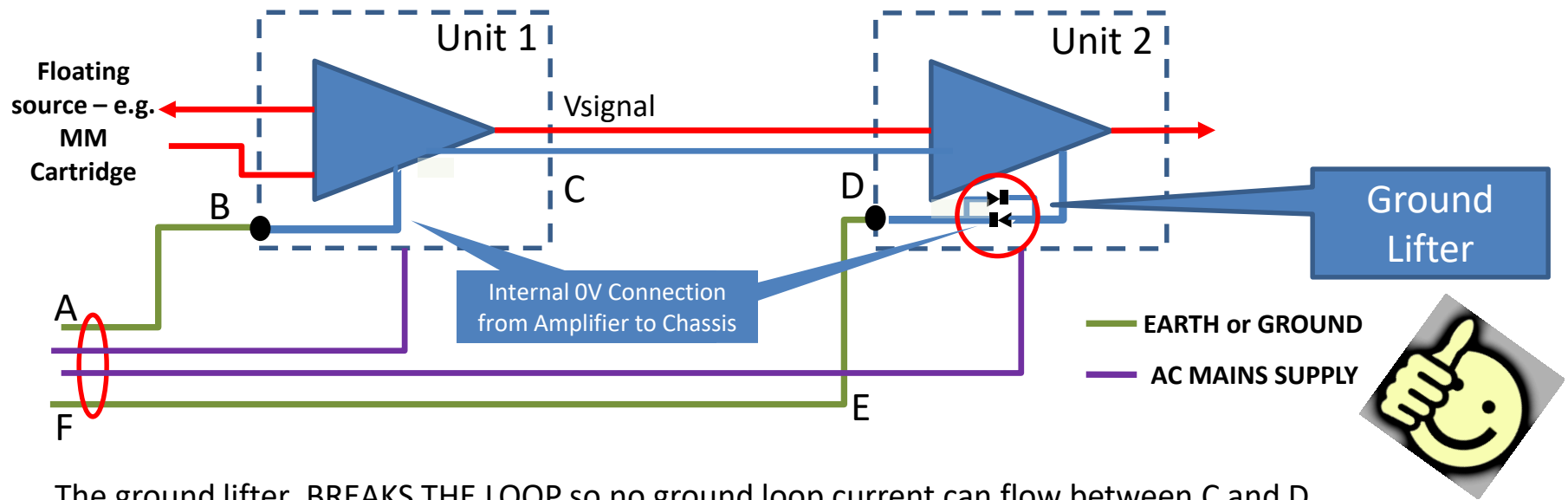
An electromagnetic loop is the TOTAL AREA prescribed by $A > B > C > D > E > F > A$ shown in light green in the diagram above

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

The generated voltages are usually small in the order of 10's to 100's μV and the associated loop currents in the 10's of μA 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 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 V_{be} – i.e. $\pm 0.6V$ 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 $\pm 1.2V$

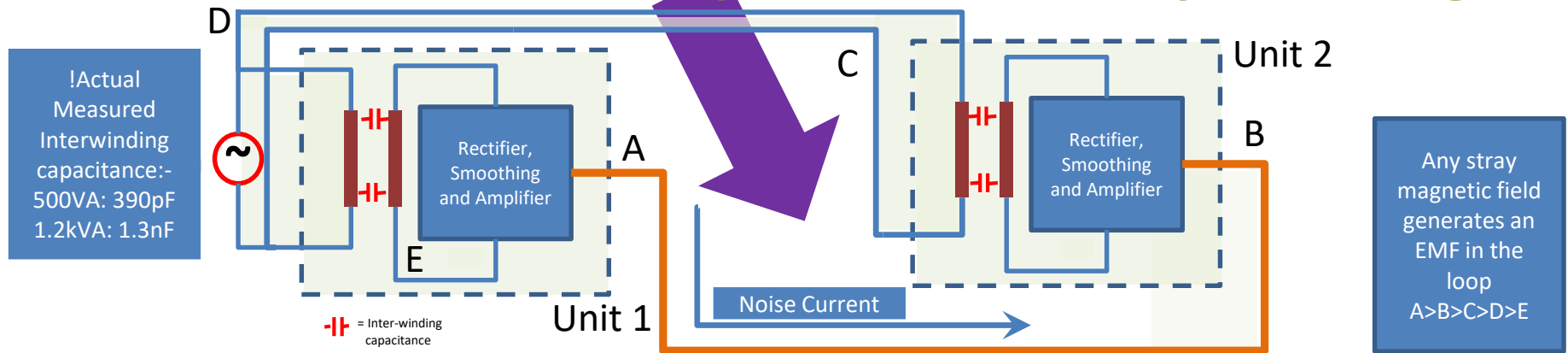
It is IMPORTANT that a HIGH POWER bridge rectifier is used – use a chassis mount 25-35A device with a surge rating of >200 Amps

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/RCB (Residual Current Breaker/Residual Current Detector) 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.

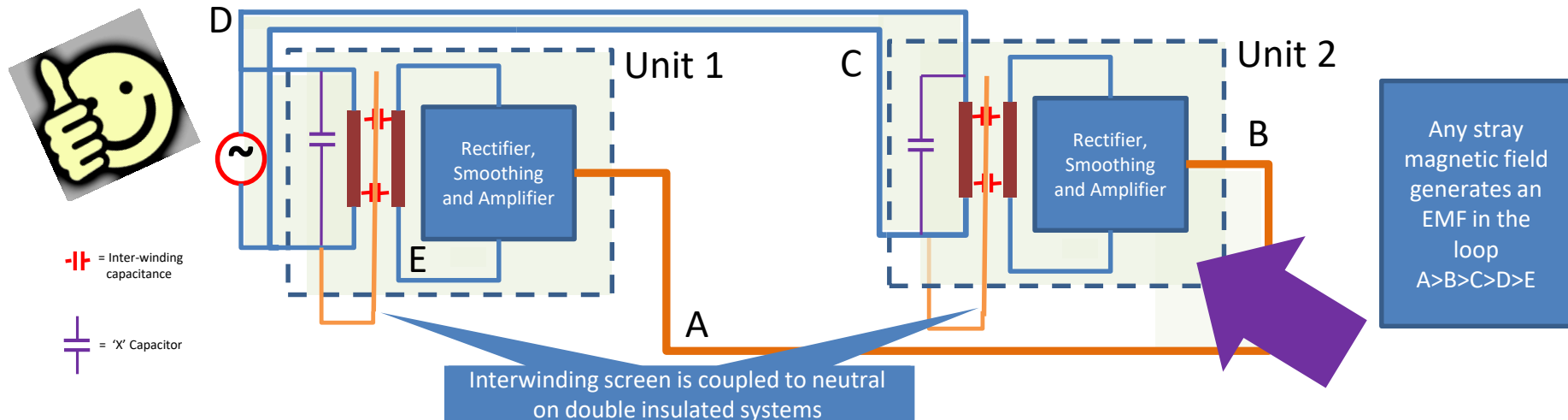
AC Ground Loop via Capacitive Coupling Across Transformer Primary and Secondary Winding



In this example, Unit 1 and Unit 2 are double insulated devices. No Safety Earth is used in Double Insulated equipment

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>A. 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 more readily. 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. 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.

Cure for Ground Loop via Capacitive Coupling Across Transformer Primary and Secondary Windings

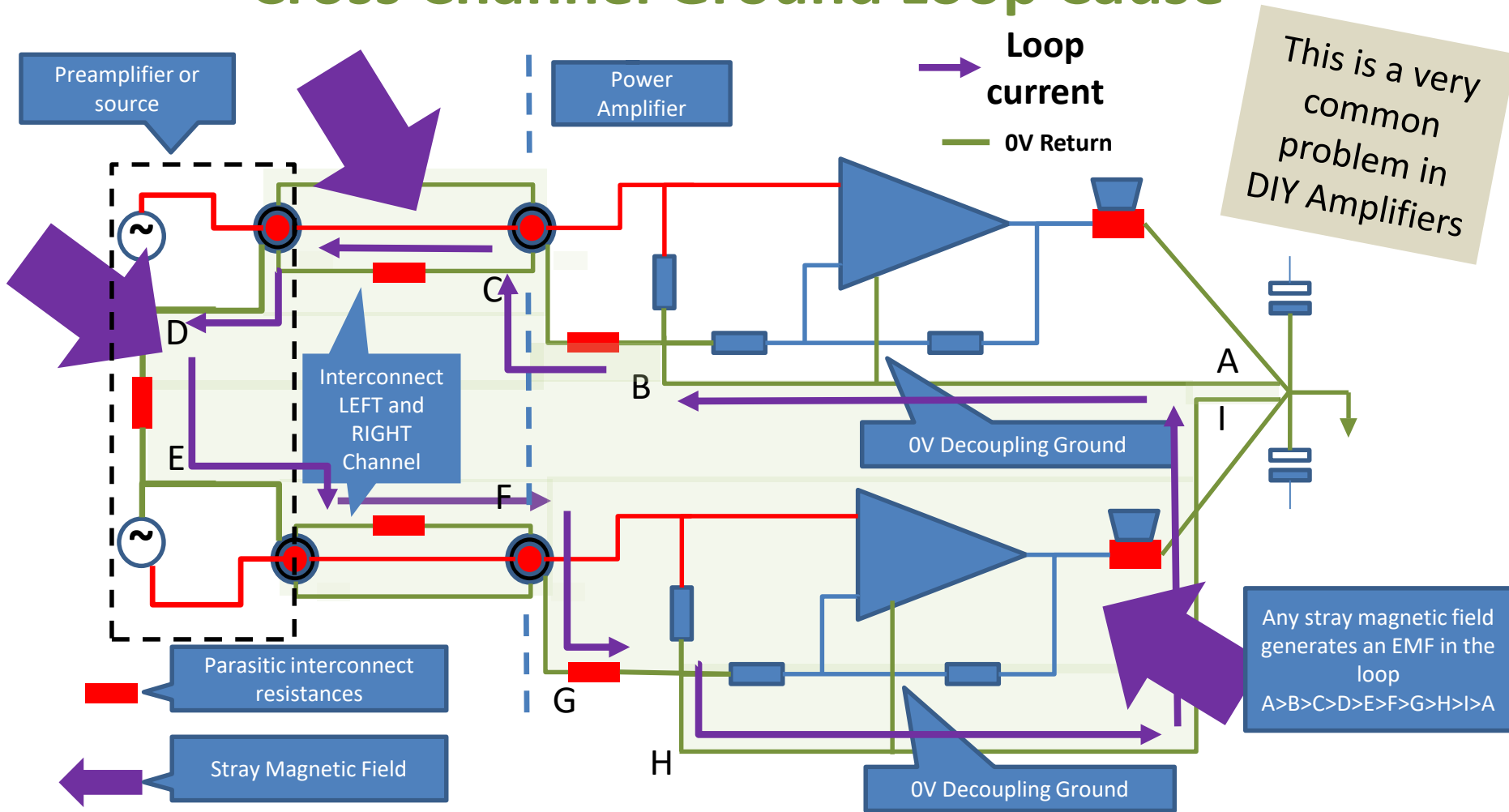


The cure for this type of AC noise loop is to specify a transformer with an **interwinding screen**, and **shunt the screen directly to the chassis with a low value cap of 1-5 nF right at the input connector (see slide 25 on how to do this)**. In modern SMPSU based (e.g. CD players, DAC's) systems, the interwinding screen is usually connected to neutral and thus shunts the inter-winding capacitance to the incoming mains *in conjunction with an X-cap*, whose value is orders of magnitude higher than the transformer interwinding capacitance. In non-double insulated systems that have a SAFETY EARTH (SAFETY GROUND), the interwinding screen is usually connected directly to EARTH (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. See later slides for a discussion on clamp-on Ferrites.

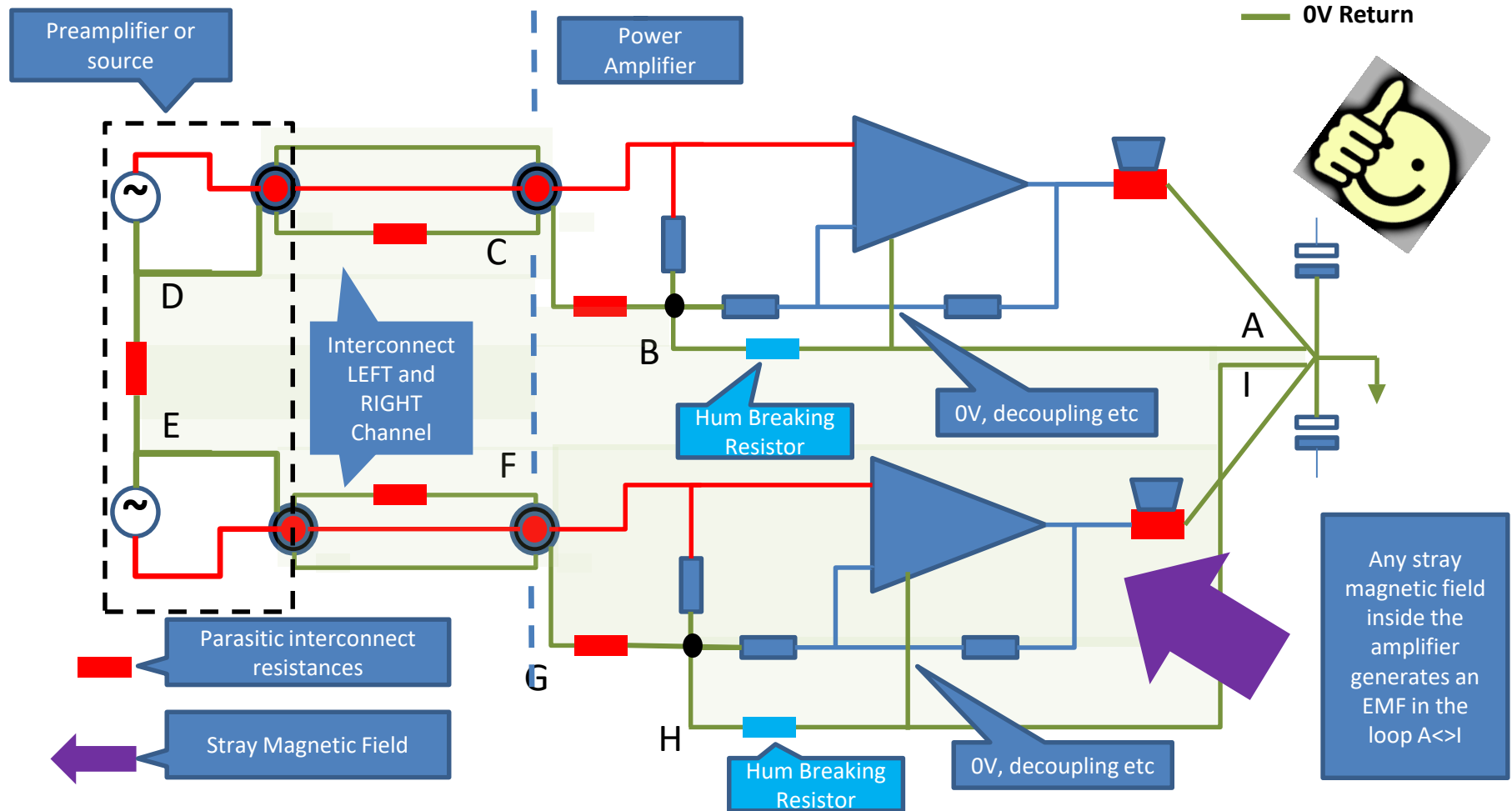
If the mains filter route is used to solve your noise problem, it is highly recommended for safety reasons that an off the shelf solution is used. Good suppliers of these types of filter are [Schaffner](#) and [Schurter](#) readily available from Mouser, Digikey and RS Components

Cross Channel Ground Loop Cause



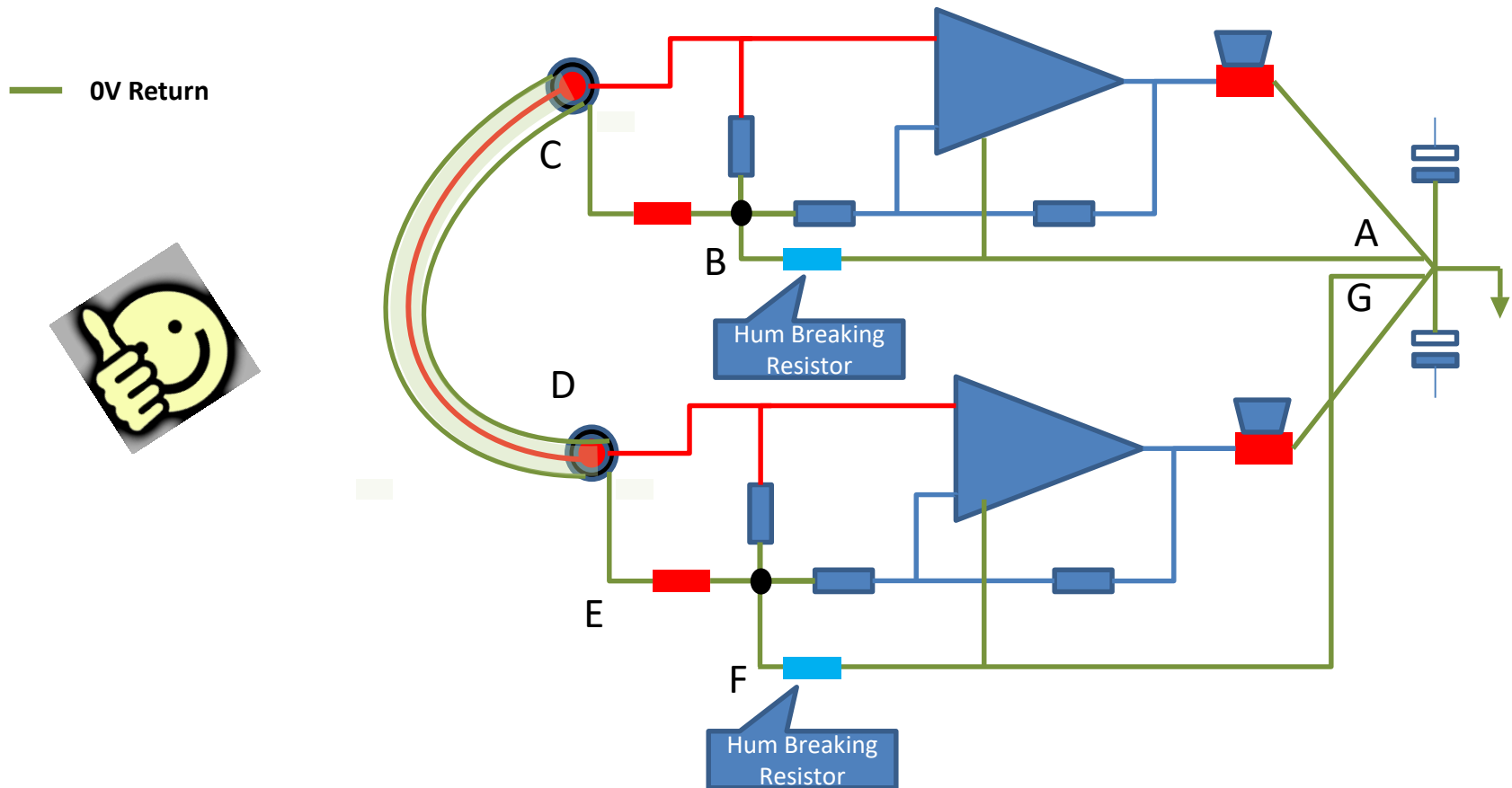
In a cross channel ground loop, an EMF is generated around the electromagnetic loop area shown in green prescribed by A>B>C>D>E>F>G>H>I>A. The resultant EMF loop current gives rise to noise voltages across the parasitic resistances (shown as RED) that appear in series with the signal (~) and thus amplified 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 34 '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

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

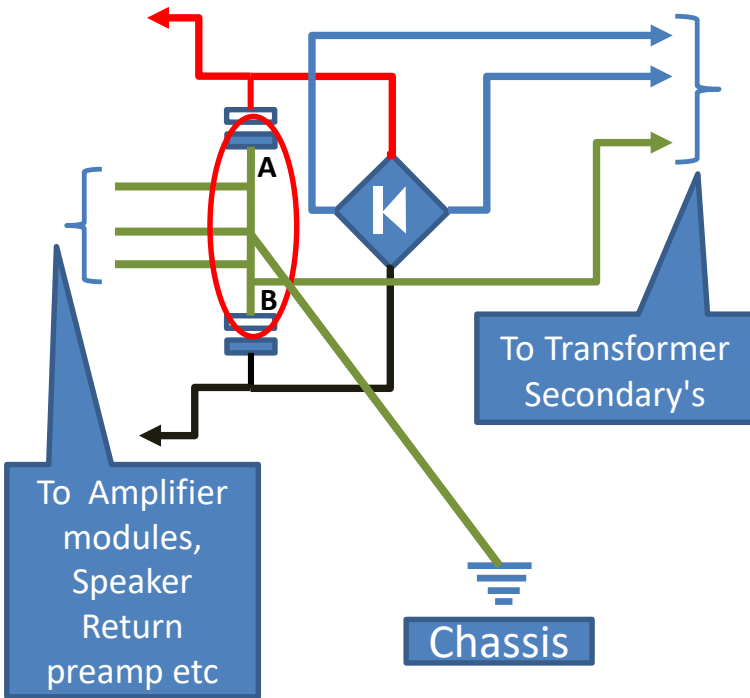


1st Line Remedy

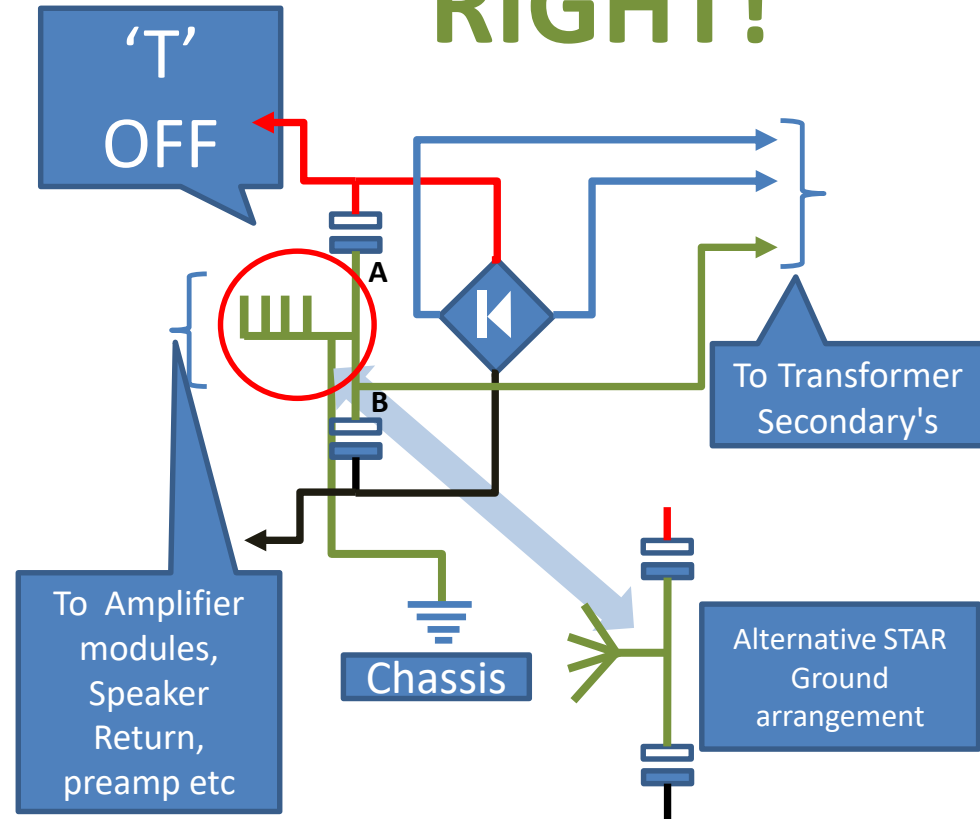
- Keep signal and ground returns separate and only connect them together at a single place on the PCB – namely the star ground or the 'T'
- Do not make any direct connections to the common ground point where the reservoir capacitors are connected together – ALWAYS 'T' off; use a STAR or 'T' grounding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

Common Impedance Coupling - Wiring

WRONG!



RIGHT!



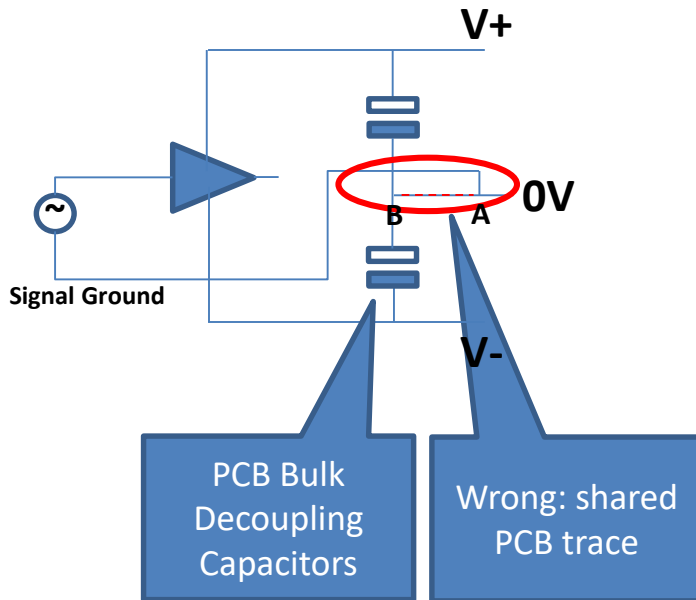
This is the classic common impedance problem caused by connecting signal returns to the junction of the filter capacitors. High currents flow between the capacitors (A and B) giving rise to small voltage drops that then appear BETWEEN the signal returns. These can add in series with the audio signal,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

The 'T': How to Avoid Common Impedance Coupling

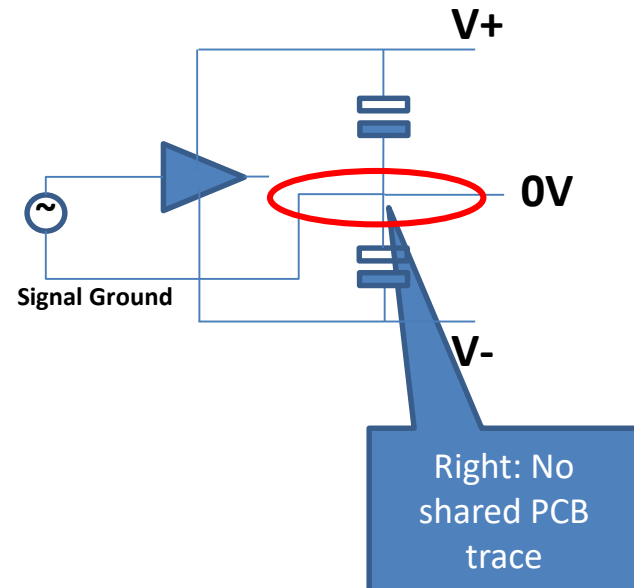
- Note carefully the order to the 'T' section – from right to left on slide 17 and slides 28 ~ 30
 1. Reservoir capacitors junction is across the top part of the 'T' with NO other connections between the two
 2. On the 'T' upright
 - Take off point to earth bond connection
 - Any protection circuits 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 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 chassis connection off at the 'T' or STAR ground and never on the connection between the filter capacitors

Common Impedance Coupling – PCB

WRONG!

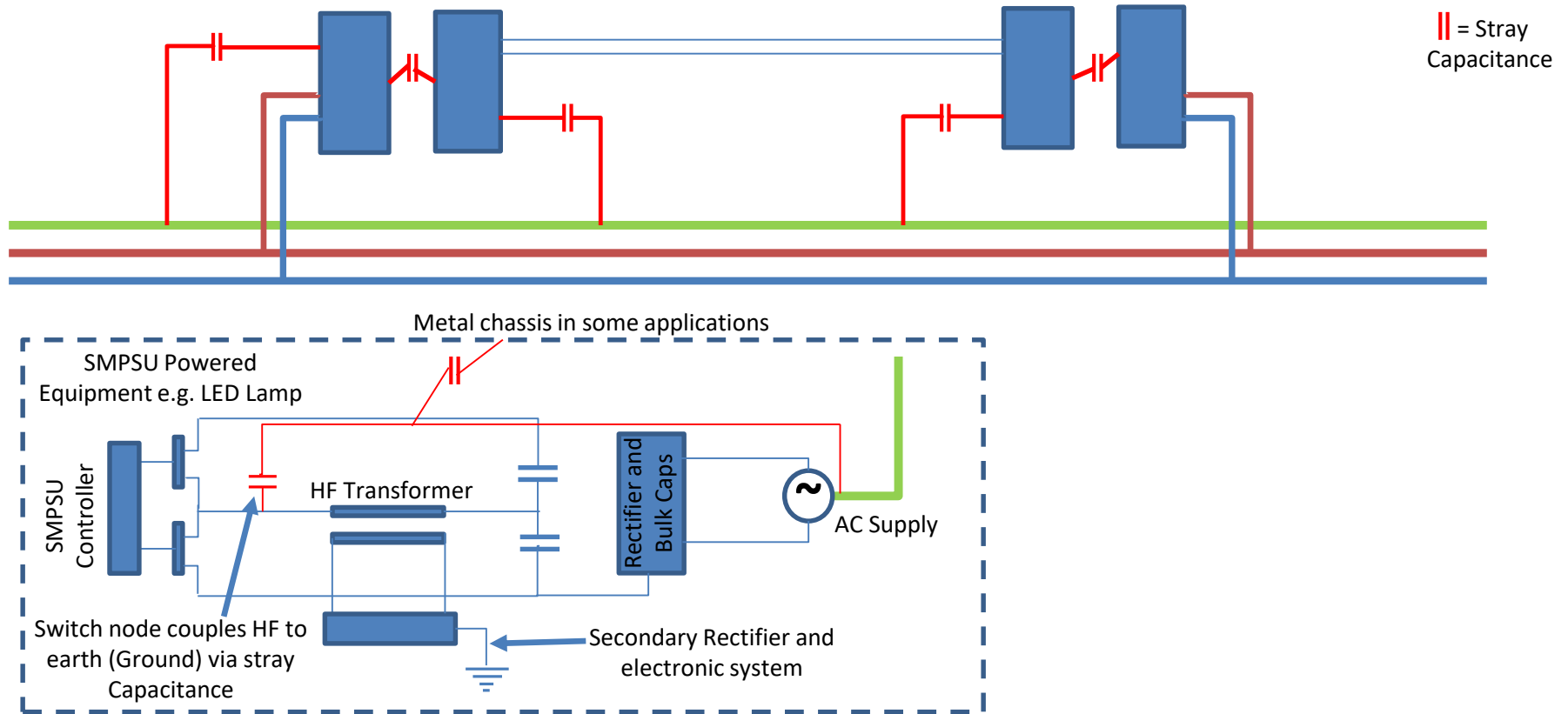


RIGHT!



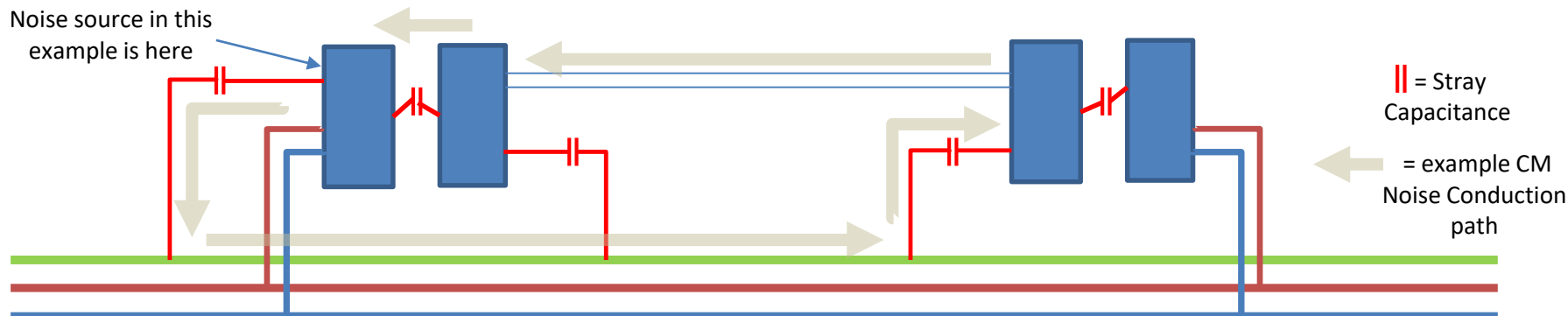
This diagram shows the common impedance problem but applied to a PCB. Current flowing between A and B (dashed RED/BLUE line) creates a voltage drop that appears in series with the signal source ~. Since the decoupling capacitors will be passing mains harmonics and music half wave harmonics, this type of problem can lead to significant increases in distortion and noise. 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

HF Conducted Mains Noise



This diagram shows a typical system where HF conducted noise may arise - most noise problems of this type arise at high frequencies - 100's of kHz. A common source of the problem is the PSU switch node which can be swinging hundreds of volts in a matter of 10's or 100's of nano-seconds, coupling electrostatically to ground/earth and live/neutral (hot/neutral). This HF noise then flows around the connections, through the equipment interconnecting cables, small signal circuitry and back to the source. The exact path taken will depend upon the source frequency, the stray capacitance and wiring inductances.

HF Conducted Mains Noise Cures

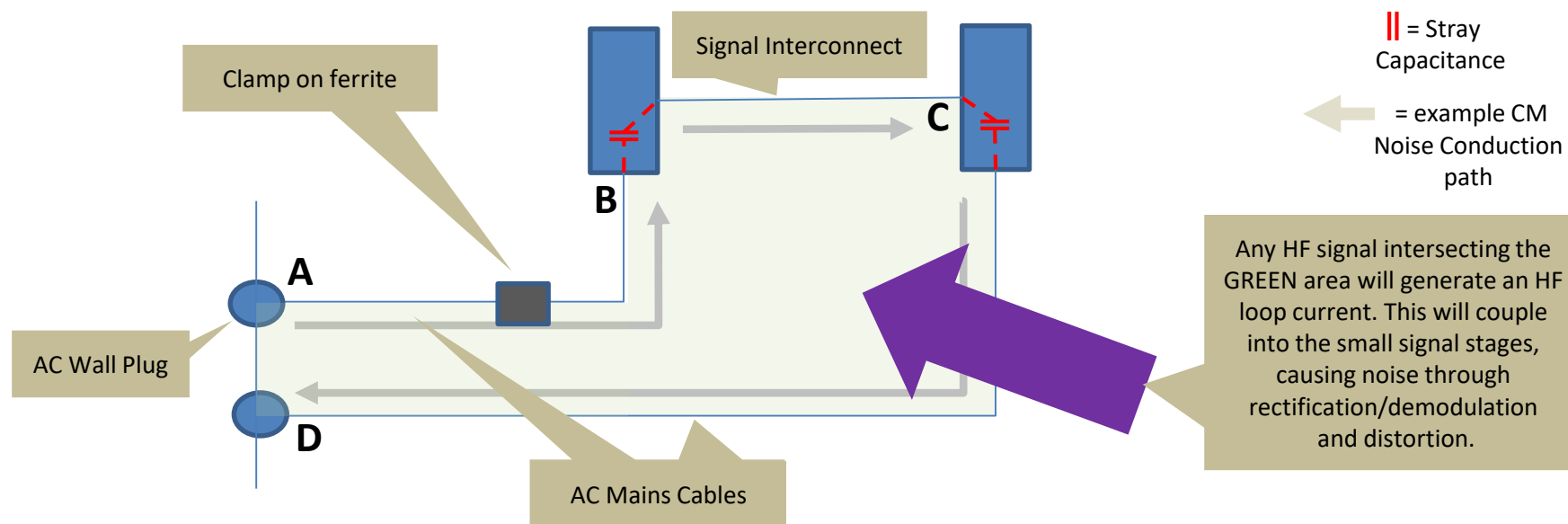


Here we see one example of a potential noise conduction path. In this example, at the noise frequency, the stray capacitances shown offer the lowest impedance conduction path. *The conduction path will change depending upon the frequency and the relative values of the stray capacitance and the interconnection inductances.* Since the coupling mechanism in this type of noise is predominantly electrostatic (i.e. via the electric field), screening (conductive metal housings and screened cables for external connections) are particularly effective.

HF Conducted Noise Mitigation:-

1. Use of good quality mains filters (Schaffner and Schurter for example)
2. Use appropriate X and Y caps on the power supply input as close to the mains inlet as possible
3. Use HF L pad filters at the amplifier input
4. RFI ground the interconnect cable screen to the chassis via a small capacitor where it enters the housing
5. Use a conductive metal housing
6. Good quality, braided interconnects
7. Transformer inter-winding screen
8. Clamp on ferrites around the mains cables, or the signal cables (frowned upon by some audiophiles of course) – see next slide
9. If your equipment uses a SMPSU, pay special attention to positioning, layout and fully understand the conducted emissions emanating from the power supply.

HF Common Mode Noise and Ferrite Clamps



Similar to the classic AC ground loop, HF common mode noise also causes loop currents. However, unlike LF loop currents, these more often usually end up getting injected into the loop through capacitive coupling. Ground lifters will not solve the problem, although Y capacitors in *earthed* systems will help.

A solution where there is HF common mode noise 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 inductance of the loop $A > B > C > D$. 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.

You can theoretically put the clamp anywhere in the loop, but most audiophiles would of course object to having it in the signal interconnects – rest assured however, it would not affect the audio signal integrity one iota.

Radio Frequency Interference (RFI)

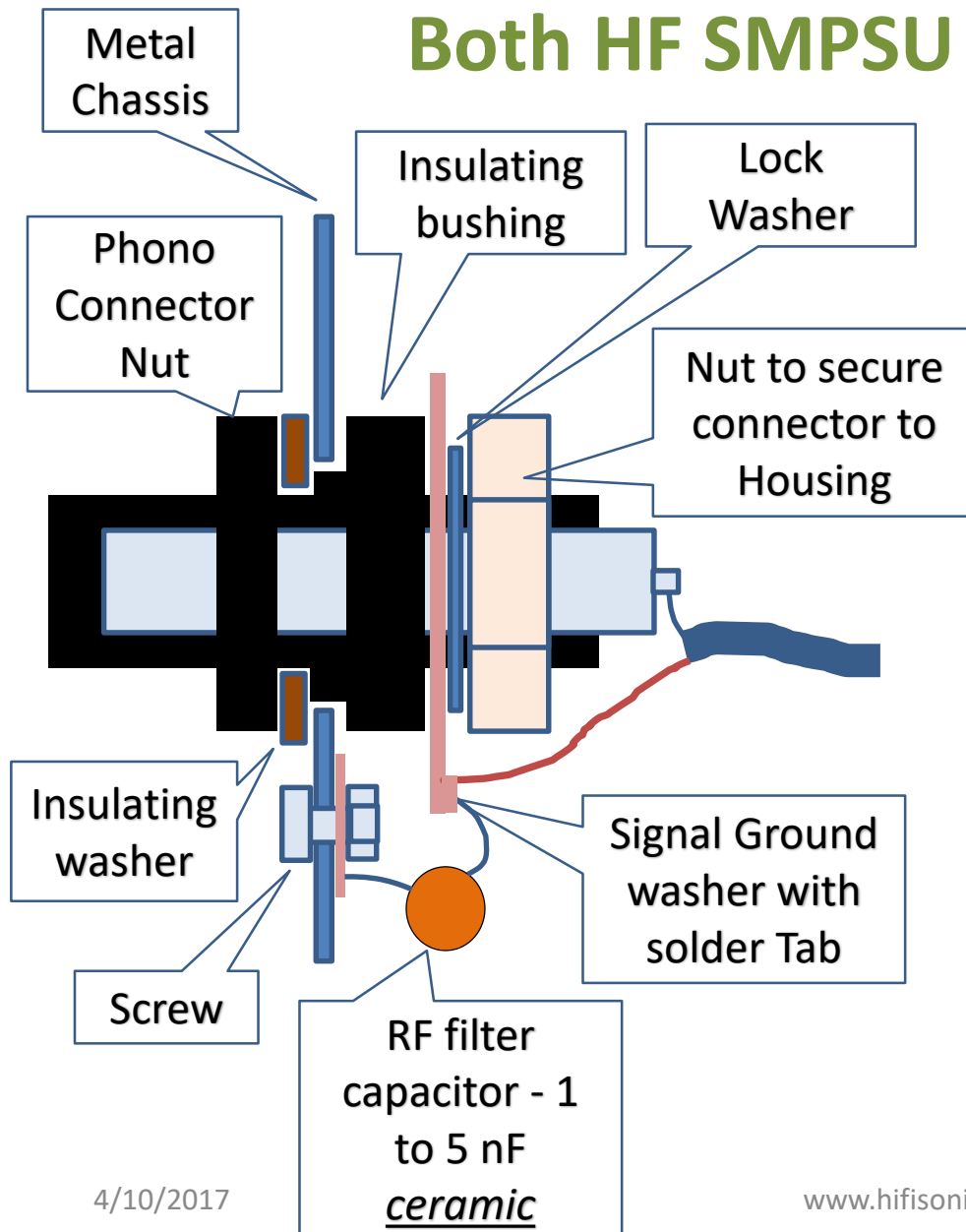
How does RFI manifest?

- 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
- Hissing or 'shhhh' sound (not to be confused with Johnson thermal noise)
- 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)

- Wire 1nF ceramic capacitor from the input socket 0V to the chassis right at the input socket. At RF this effectively makes the source equipment chassis, the screen and the receiving equipment chassis a single enclosure, maximizing RF Immunity through screening (see slide 25)
- 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 RF Filtering Helps Reduce Problems With Both HF SMPSU Noise and RF



- This is how to add an RFI/HF noise filter to a phono input connector, shown here in cross section.
- The connector is isolated 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 1~5nF will usually be at least an order of magnitude higher than the interwinding capacitance of an HF SMPSU transformer and will thus shunt any HF noise to the chassis and away from the amplifier inputs.
- 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 Pontificating.
Lets get down to the
Practical Stuff**



Follow These Basic Rules #1

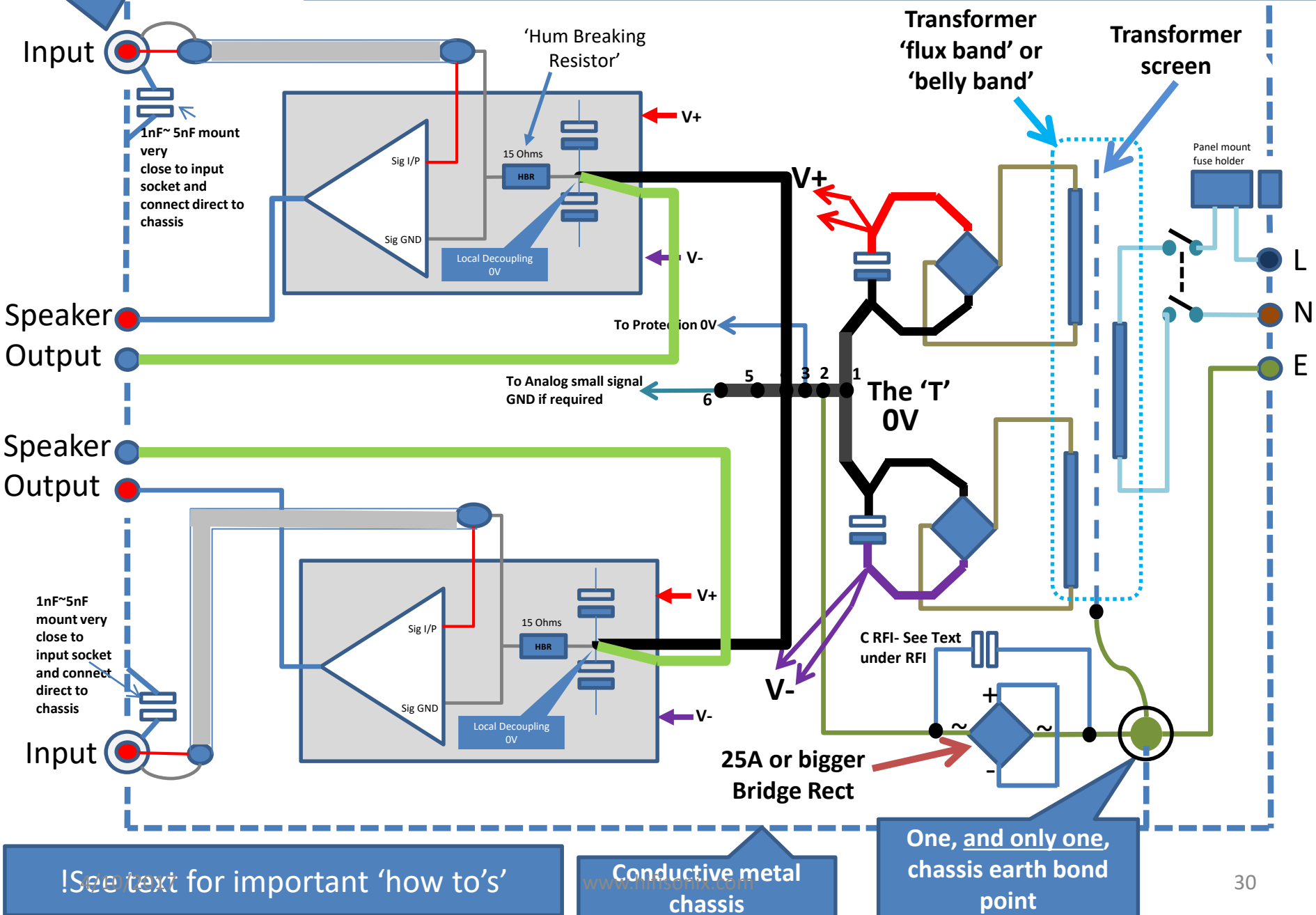
- Mains wires to the fuse, switch and to the transformer primary: - use good quality 16 Amp SHEATHED mains cable for the mains side wiring. This ensures the live and neutral (hot and neutral) are close together and therefore minimize radiated magnetic fields. Being sheathed is also good for safety
- 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 on the pages that follow
- 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. Be careful not to introduce any common impedance coupling - use a star ground on the PCB

RCA I/P sockets must be insulated from the chassis

EXAMPLE #1 – Split Secondary Rectification with GND Lifter





This is how
to do it
practically!

To transformer
secondary's

Single chassis Earth
bond point

To mains
inlet Earth

Where shown,
twist all wires
tightly! Keep all
connections
SHORT

!No connections
inside this area!

The 'T' 0V

Left
channel
power

Right channel
power

Small Signal Return

Protection and/or
digital circuit 0V

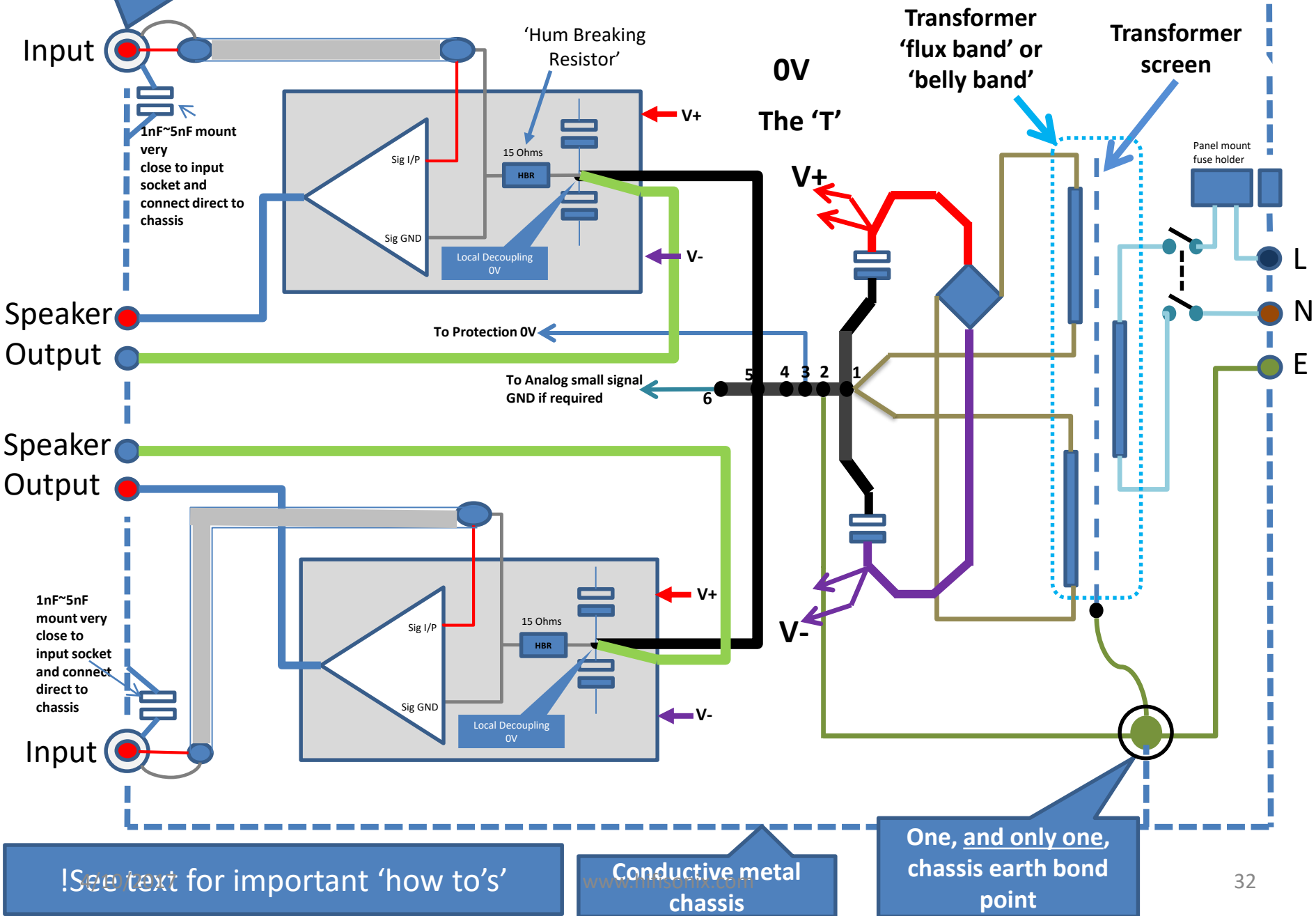
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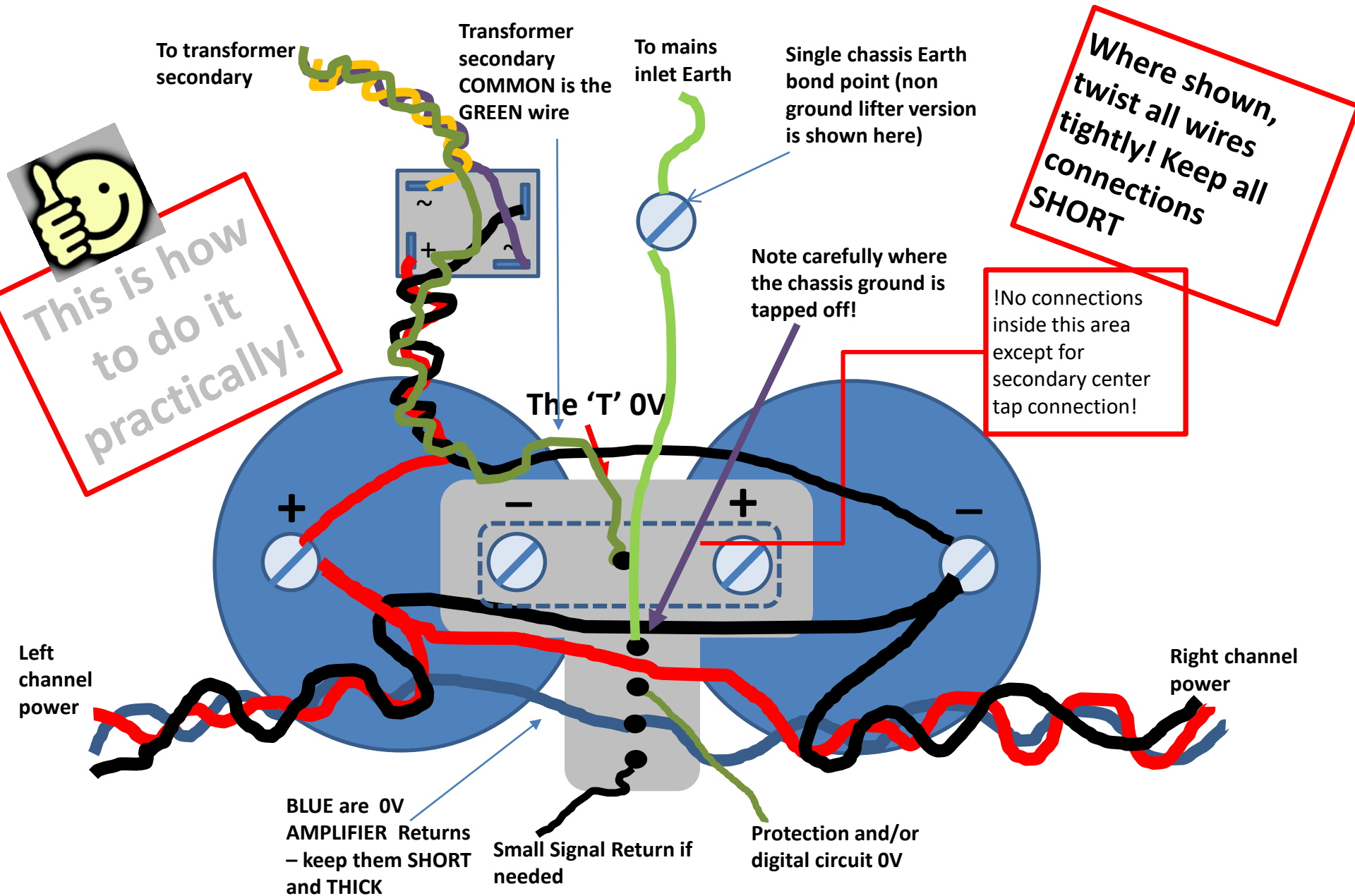
www.hifisonix.com

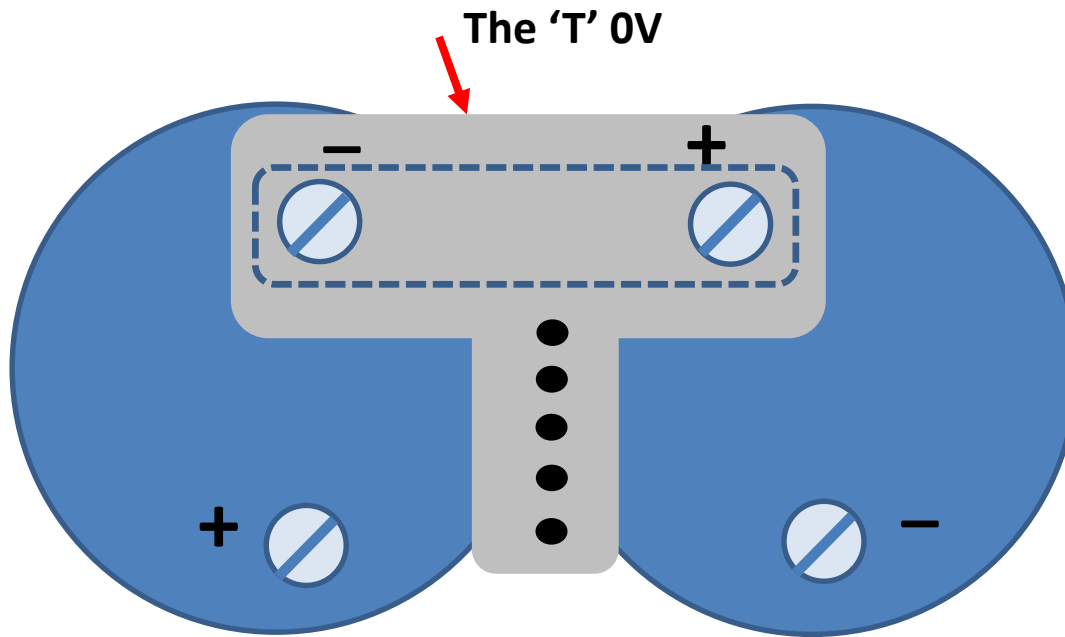
EXAMPLE #1 – Split Secondary Rectification How to do it Practically

RCA I/P sockets must be insulated from the chassis

EXAMPLE #2 – Single bridge and no GND Lifter







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 (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.

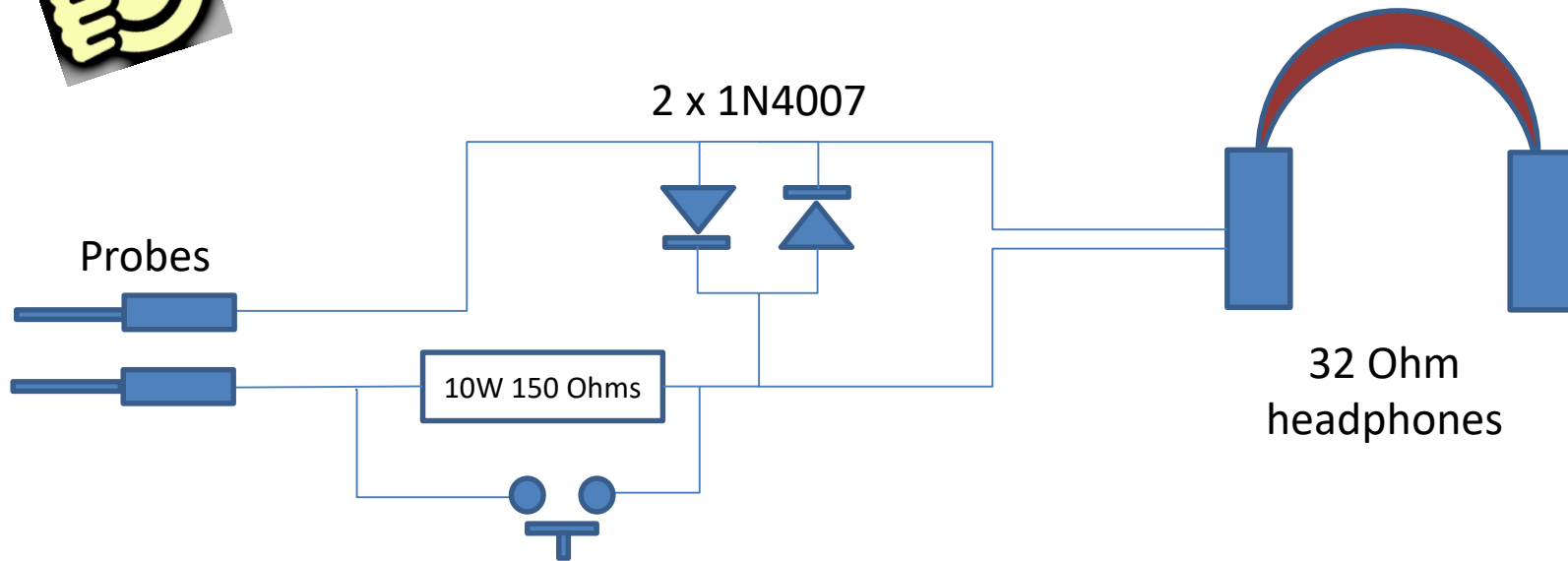
Connect a pair of headphones directly to the output of your amplifier (**do this AFTER it has been switched on and the outputs have settled**) and without any input source connected.

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.

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 if 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!

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](#)
- 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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