Chapter 14: Layout and Grounding

Most of this book is concerned with circuit design, but some discussion of physical layout and construction is deserved. An earlier version of this chapter has proved very popular with builders over the years, especially with regard to minimising and hum. Apart from this, good layout is also important for ease of manufacture and repair, and a tidy design brings great engineering satisfaction. Layout of individual components on a circuit board is beyond the scope of this book, but there are some general guidelines for laying out the amplifier as a whole which can be covered quite quickly.

14.1: General Layout

Most amplifiers are built into a shallow, rectangular metal chassis. Most of the controls will be arranged along the 'front' side, with less-often used things like power input and speaker jack on the opposite side. In a combo amp the chassis

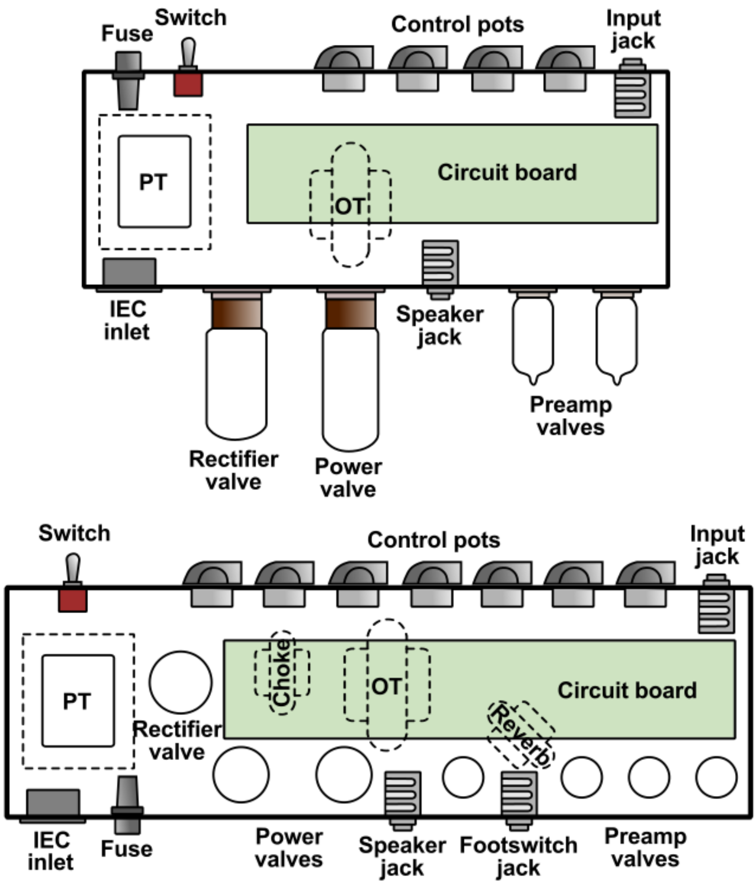

Fig. 14.1: Typical chassis layouts for a small combo (upper) and larger head (lower).

commonly hangs down, and the valve likewise hang upside-down on the opposite side to the controls.* If the amp is a 'head' then the valves and transformers will all stand on top of the chassis. Typical arrangements are shown in fig. 14.1, but the internet offers an unlimited supply of photographs of amp construction and alternative layouts.

Usually we want the wall input, power transformer, fuses and associated AC power wiring to be grouped together at one end of the chassis, which becomes the 'noisy end'. The input valve and input jacks can then be positioned at the opposite or 'quiet end'. Everything else should then follow the logical signal path, flowing from the quiet end towards the noisy end. This typically results in the power output valves – which are less sensitive to interference– being relatively close to the power transformer.

It would be nice if the output transformer could be a good distance from the power transformer to minimise magnetic hum coupling, but we also want it close to the power valves to minimise the length of the anode wires. The logical compromise is therefore to put the output transformer roughly in the middle of the chassis. This also keeps the weight distributed at least somewhat evenly, so the amp is not awkward to carry. The rectifier valve, reservoir capacitor, and/or smoothing choke often sit in the space between the two transformers.

To minimise hum coupling, the core axis of output transformer should be orientated at ninety degrees to the core axis of the power transformer, as illustrated in fig. 14.2. Often this happens by default when one transformer is a drop-through type and the other is a stand-up type. Better yet, use the headphone test (next section). Smoothing choke orientation is not usually important.

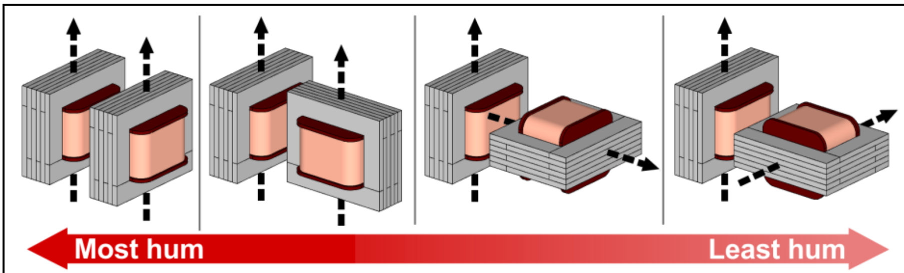

Fig. 14.2: Transformer core axis orientation for least magnetic hum coupling.

Commonly the valves are laid out in a straight line. The circuit board can then sit between the row of control pots along one edge, and the row of valves along its opposite edge. In a modern amp the pots will be mounted on the circuit board itself, and the valves may be too. This minimises off-board wiring and can make the whole

* The Fender *Excelsior* is an unusual example of a combo amp with two chassis connected together with an umbilical. One chassis carries the preamp and controls, the other chassis carries the power supply and output stage.

assembly easier to remove for repair, though PCB-mounted valve sockets are prone to cracked solder joints in a gigging amp. Valves shields or retainers are essential if the valves hang upside-down, and are still a good idea if they are upright.

Valves should be separated from each other by a distance at least equal to their own diameter to reduce mutual heating. The more ventilation the better; upside-down valves live a hard life in this regard because hot air around them cannot easily convect upwards, being blocking by the chassis. A cooling fan can bring a big improvement in component lifetime, including valves. In particular, electrolytic capacitor lifetime is dramatically reduced by heat, so keep them away from hot valves or power resistors. In vintage amps, power supply capacitors were often grouped together on a separate board which forces an inconvenient ground scheme. Components are so much smaller today that it easy to fit them on the main board, close to the stages they actually serve.

Always consider how the amp can be disassembled for repair. Try not to hide parts underneath other parts, and avoid wiring that jumps across the circuit board, preventing it from being easily lifted out. If mounting nuts are obscured under the circuit board, consider adding holes in the board to allow access for a nut-runner. Keep off-board wiring to a minimum, and consider push-on connectors if appropriate. Hook component leads onto terminals but do not wrap them around fully, otherwise they become very difficult to remove. Adding labels and expected voltages to the board is an enormous help to anyone working on the amp –this is easy with a PCB silkscreen, but a paint-pen also works for traditional turret boards.

14.1.1: Hum and the Headphone Test

All audio transformers are sensitive to picking up hum, especially from the magnetic field of a nearby power transformer. High-quality transformers are sometimes enclosed in a mu-metal can or shroud which provides some magnetic shielding, but other metals –including steel– provide very poor magnetic shielding and really only provide electric shielding. The remaining weapons against magnetic-induced hum are physical distance, and orientation.

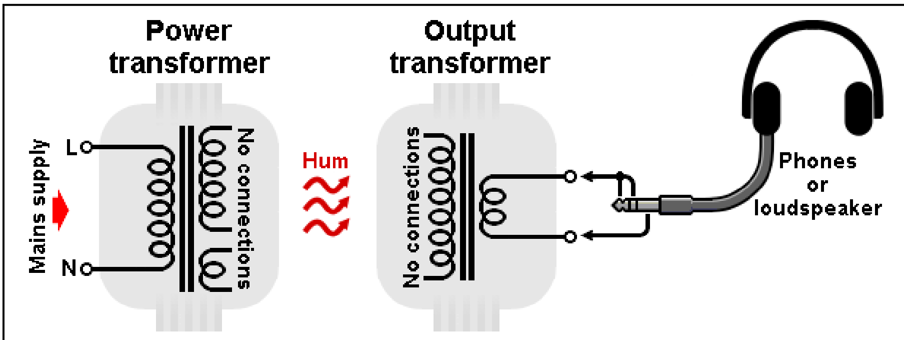

Fig. 14.3: Using headphones to listen to hum coupling between transformers.

A very simple way to optimise the placement of the output transformer is to connect some headphones to the secondary and listen to the hum while the power transformer is energised (a loudspeaker works too, but headphones are more sensitive, making it easier to hear the hum null). The power transformer should be hooked up to the wall voltage with suitable care, but no other connections are needed. We can then experiment with the positions and orientations of the two transformers on the chassis before drilling any mounting holes. Hum might not disappear completely, but a favourable minimum should be possible.

14.1.2: Wiring and Lead Dress

Lead dress refers to the physical arrangement of wires and conductors in a circuit, which is important with regards to hum and unwanted oscillation. Electromagnetic field strength is inversely proportional to the distance from its source, so it helps to maximise the distance between any conductors that we do not want to 'talk' to one another. If signal wires must cross then they should do so at right angles where possible. Allowing a noisy wire to run parallel to a sensitive signal wire is a sin. Wires to the anodes of the power valves carry the largest signal voltages in the amp, so keep them well away from preamp signal wires. Avoid solid-core wire for off-board wiring (unless for a ground bus). Solid wire can make for a visually attractive layout, but it will break due to vibration fatigue, sooner or later. Always add plastic grommets to any chassis holes that wires pass through.

Pairs of noisy AC wires, e.g. mains and heater feeds, should be neatly twisted so their opposing electromagnetic fields are forced to occupy the same space, causing them to cancel each other out. A loose twist is useless, only a tight twist will do! This is easily done by anchoring the wires at one end, and holding the other end in the chuck of a drill, keeping reasonable tension on the wires while twisting. Stretching it gently before releasing will discourage the wire from twirling back on itself.

Heater supplies normally daisy-chain from one valve socket to the next, supplying all the heaters in parallel, so current flowing in the *supply* end of the chain is greater than the current flowing near the last valve in the chain. Power valves require the most current and are the least sensitive to heater hum, so they should be at the supply-end of the chain. The heater chain can then progress logically through the amplifier, with the input valve last in the chain where the current –and field strength– is weakest. Do not use excessively thick wire for the heater chain, it only makes it hard to twist and route, and puts strain on the valve pins. Stranded 16/0.2mm wire (roughly 20 AWG) is good for at least 3A which covers most circumstances. A set of power valves might need thicker wire, e.g. 18 AWG, but there is no need to use the same boat-anchor-cable for the preamp valves too.

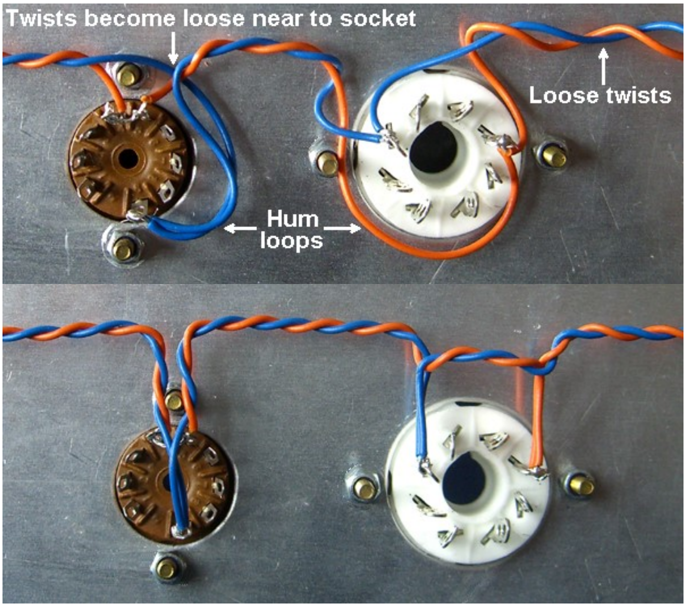

Fig. 14.4: **Upper:** Poor heater wiring with many potential sources of hum. **Lower:** Good heater wiring keeps the twisting tight, avoids hum loops, and keeps the wiring pushed against the chassis far from any signal wires.

When heater wires approach a valve socket the twisting must be kept tight right up to the socket, since the other valve pins are in close proximity here, and we must suppress the hum fields as much as possible. Allowing the twists to become loose near the socket can spoil a lot of hard work.

Do not create a loop of heater wiring around a valve socket, since any wires or valve pins inside the loop will be subject to strong EM interference. The heater wiring should approach from one side of the socket and, if it must cross it (which is usually the case for preamp valves like the ECC83/12AX7) it should go directly across the socket and straight back. It helps to orientate valve sockets so the heater wiring can approach from the edge of the chassis, so the daisy-chain of wiring can be tucked into the chassis corner.

The upper image in fig. 14.4 shows some typical heater wiring mistakes, hum loops being the most common. An example of good heater wiring is shown in the lower image. This takes care and patience, and it will often be obscured by other wiring once the amp is complete, so it is worth spending the time to get it right.

Most of the common preamp valves contain two triodes. When making connections between the valve socket and circuit board, wires ‘belonging’ to one triode should be kept away from those belonging to the other triode. Twisting the wires of each individual triode together is usually fine, as shown in the left-hand photograph of fig. 14.5. This will make it visually clear which valve each bundle is serving, as well as creating a strong physical link, preventing individual wires from moving out of place over time. The low-impedance cathode wire will also help to shield the others somewhat. Twisting the anode and grid wires does increase Miller capacitance, but this is seldom a problem in a guitar amp. The right-hand photograph illustrates a bad choice where the wires for two different triodes are bundled together, which could lead to parasitic oscillation.

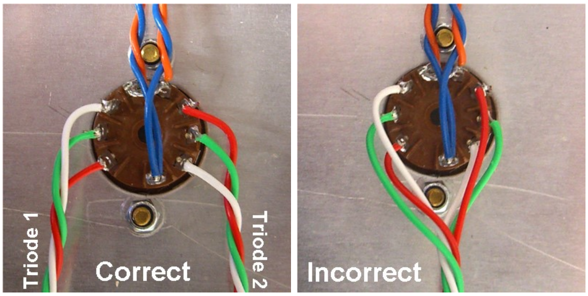

Fig. 14.5: **Left:** The wires leading to different triodes should be kept separate. **Right:** Grouping all the wires together will inevitably lead to problems.

14.2: Grounding

Ground refers to the common 'reference node' that is shared by all the parts of a circuit. It is normally represented by one of the circuit symbols in fig. 14.6. All four are more-or-less interchangeable, though **a.** is normally reserved for direct connections to the chassis or mains earth. Many of these symbols may appear in a single schematic, but in reality they will ultimately be connected together. However, when physically building a circuit it is important to adopt a suitable *ground scheme*. We should not simply connect all the ground wires to each other randomly, even though it might appear on paper that one bit of ground wire is much the same as another. Current always flows in a loop; it must find its way back to its source through those physical ground wires. Ground is not some electrical black-hole into which current disappears never to be seen again.

Fig. 14.6: Ground or earth symbols.

A perfect ground scheme is nearly impossible to achieve as there will always be some conflicting and contradictory considerations, but we can at least produce a reasonable compromise between ideal theory and practical reality, avoiding really gross errors. A good ground scheme will:

- Minimise series impedance in the signal ground;
- Avoid ground loops;
- Direct 'noisy' ground currents away from quiet signal grounds.

One important habit to observe is: do not use the chassis for grounding! Letting the chassis become part of the audio circuit by treating it like 'one big fat ground wire' is asking for trouble. This is particularly bad if the chassis is made from steel, because steel has relatively high resistivity and it may also contain noisy eddy currents induced by the transformers. Vintage amps nearly always use the chassis for grounding, with mixed results. It may not be practical or desirable to re-wire a valuable vintage amp, but there is no excuse to adopt the same strategy in a new build. The chassis is a metal box which protects the user from the circuit, shields the circuit from ambient interference, and provides a solid support for construction. It is not a wire.

14.2.1: Earthing and Safety

At the heart of the power supply is the power transformer. In a valve amp this will provide a low voltage AC supply for the heaters, and a high voltage AC supply for the HT, at the very least. As well as providing the voltages we want, the transformer also provides safety isolation from the mains wall supply. Although the secondary voltages in a valve amp might well be higher than the wall voltage, they are inherently current-limited by the source impedance of the transformer. The wall supply can dump nearly unlimited energy into your body, whereas a transformer cannot. The chances of getting a severe burn, or stopping the heart, are lower when a transformer stands between you and your energy provider.

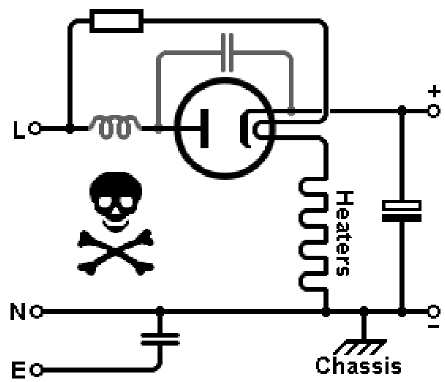

Fig. 14.7: Typical transformerless power supply found in vintage equipment. This is dangerous and is now outlawed.

Since a valve amplifier typically needs a high voltage supply for the anodes, most hobbyists have probably stopped to wonder: why not get the HT directly from the wall voltage with no need for an expensive transformer? The reason not to do this has everything to do with safety and the law. Until at least the 1960s it was common to find valve equipment using an arrangement something like fig. 14.7.[1,2] The heaters for all valves in the set were connected in series and supplied directly from the wall voltage through a dropping resistor. The HT was obtained by half-wave rectifying the wall voltage* (the small inductor and capacitor shown faint were sometimes included to suppress modulation hum in radio receivers). The chassis was connected to mains-neutral which was bonded to earth somewhere outside the building, so in theory it should be at zero volts. The chassis might also be connected to a local earth through a capacitor to bypass radio frequencies more effectively.

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[1] Bulley, E. G. (1956). Constructing AC/DC Equipment. *Practical Wireless*, February, pp113-4.

[2] Nash, L. N. (1962). Power Rectifier Circuits, *Practical Wireless*, June, pp128-31.

* Full-wave rectification of the mains was not possible since the neutral is bonded to earth, and the receiver/audio circuit also needs an earth reference, which would therefore short out a full-wave rectifier.

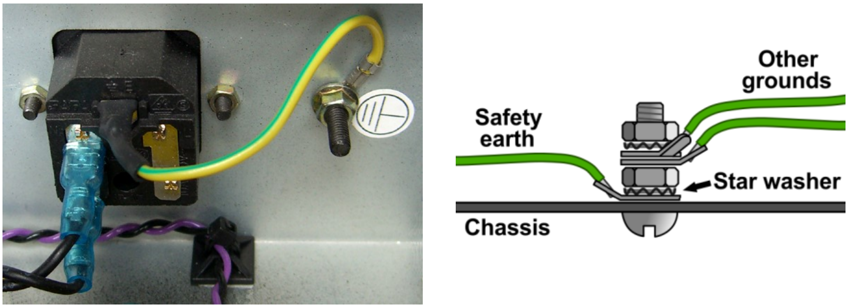

Fig. 14.8: The earth bond should be made to a dedicated screw close to the mains inlet. Other ground connections may be stacked on top if necessary.

Unfortunately, it is the chassis-to-neutral connection that is the main problem here. If an old-fashioned reversible mains plug is used, or it happens to be miswired, or if there is a break in the neutral conductor somewhere in the building, the chassis can become live. This is an extraordinary risk to the user, so this practice is now outlawed. Any appliance built into a metal chassis which can be touched by the user *must* have that chassis connected directly to earth. A corollary of this is that the user must be galvanically isolated from the mains supply, either by a traditional power transformer or an isolating switch-mode power supply. In the world of safety regulations, earthed appliances like this are called Class-I appliances, which includes virtually all audio equipment that is powered from the wall.

Where the mains cable enters the chassis, usually through an IEC inlet or sometimes a captive cable, the incoming mains earth must be connected to the chassis through a suitably heavy-gauge wire. Where this wire is bolted to the chassis is known as the main *earth bond*. It should be a dedicated stud or screw as in fig. 14.8, *not* a screw that is used to fix some other piece of hardware which might loosen over time (transformers are constantly trying to vibrate their bolts loose). The Earth wire should be soldered or crimped to a tag and fixed to the stud with a lock nut, or a shake-proof star washer and nut. Any paint or oxidation on the chassis must be scraped off to ensure a good electrical connection. Other earth connections can be stacked on top of the earth bond if necessary, as illustrated in fig. 14.8, but notice that removing the other grounds does not require loosening the safety earth itself. [†]

The earth bond is legally required and is for safety only; it plays no part in circuit operation and no current flows in it except under fault conditions. It should be regarded as just another part of the chassis. Although the terms ‘earth’ and ‘ground’ are often used interchangeably, the audio circuit ground does not *necessarily* have to be connected to earth at all. In practice, however, we do connect the audio circuit to chassis (ideally at a single point near the audio input) since this ensures the

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[†] For commercial products, UL regulations stipulate that *only* green or green/yellow striped wire may be connected to the earth bond.

amplifier's working voltages are properly defined with respect to zero volts and therefore with respect to any other equipment we might connect it to.

14.2.2: Ground Loops

A ground loop is created when two or more grounded circuit nodes are connected together by more than one path. This might occur due to careless layout, accidental or unexpected ground connections, or when two appliances are both powered from the wall supply and also connected to each other with an audio cable. Vintage amps are often full of inadvertent ground loops created by bending over the ground tab on a potentiometer and soldering it to the case, soldering a ground bus to the backs of multiple control pots, or haphazardly grounding absolutely everything to the chassis.

Fig. 14.9: **Left:** Switchcraft-style jacks guarantee bad grounding.
Right: Insulating jacks are much better.

Non-insulating 'Switchcraft style' jacks were standard in American amplifiers and practically guarantee ground loops through the chassis. These jacks also loosen easily and allow foreign objects to be pushed into the chassis; they belong in a museum, not in modern equipment. Use insulating jacks such as the plastic 'Cliff style' jacks shown in fig. 14.9.

Any magnetic field passing through a ground loop will induce a hum voltage across the loop, which will drive a hum current around the loop. Every segment of wire making up the loop will necessarily have a portion of the hum voltage dropped across it. Where a wire segment is shared with the audio signal current path, the hum voltage will add to the audio signal, and lo, it becomes audible hum. The larger the area of the ground loop, the more magnetic field it captures, and the greater the possibility of hum becomes. Alternatively, the loop may provide an unintended path for noisy power-supply ripple current to flow in a presumed-quiet preamp ground. Again, this current creates a voltage drop across the ground impedance, adding hum or buzz to the audio signal.

14.2.3: The Rectifier

The HT supply is normally derived from a power transformer, rectifier and reservoir capacitor. The rectifier may be a two-phase type or a bridge rectifier, and it may be solid-state or a valve, but this does not change the grounding rules. The current in the rectifier circuit flows in short, heavy, pulses called ripple current (section 12.1.3). This is the noisiest section of wiring in the whole amplifier; we must not let this garbage current creep into the audio circuit proper!

The transformer-rectifier-reservoir must be wired up as a single, self-contained circuit block. No other wires should connect to this noisy current loop (unless they are non-critical, non-audio circuits), as emphasised in fig. 14.10. The rest of the amplifier circuit / ground-bus can then be connected directly to the terminals of the reservoir capacitor.

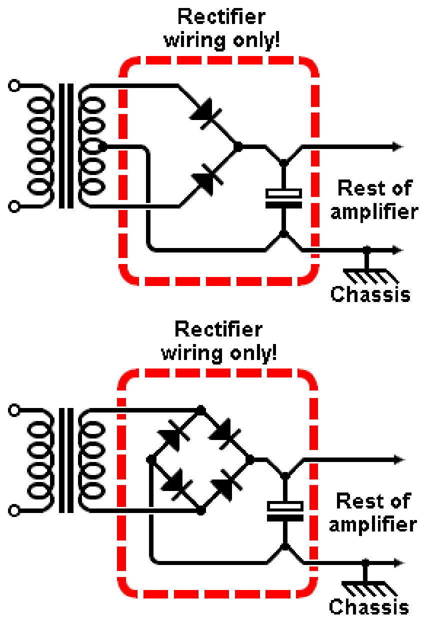

Fig. 14.10: The transformer, rectifier and reservoir capacitor should be wired directly together as a single circuit block, to contain ripple current.

Most vintage amps use a two-phase rectifier and connect the noisy transformer centre tap directly to the quiet chassis. Worse still, they often connect various other circuit grounds to exactly the same lug. Even worse still, they often use one of the transformer mounting bolts as the tie point, which will inevitably vibrate loose over time. Many amplifiers buzz because of these bad design choices. If you don't want to alter a valuable amplifier too much, a compromise is to disconnect the transformer-centre tap from the chassis and wire it directly to the reservoir capacitor negative terminal, where it belongs. Remove the ground connections from the transformer mounting bolt, and bolt down the transformer firmly and completely. You can then put the ground connection back, fixed with a second nut, as illustrated in fig. 14.11.

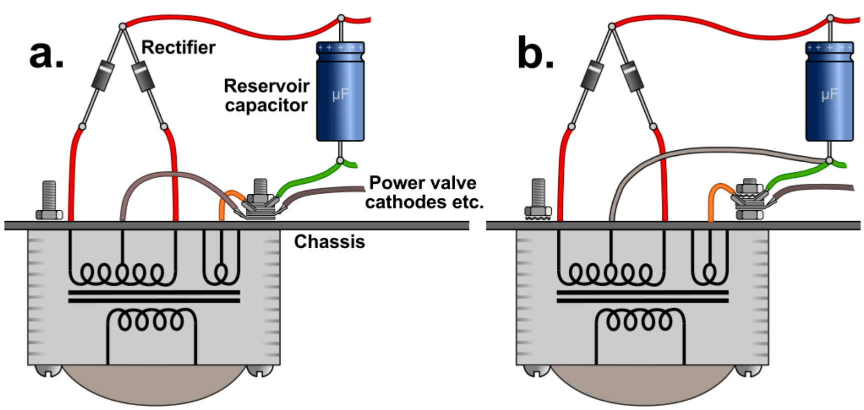

Fig. 14.11: **a:** Typical vintage amplifier grounding around the power transformer; **b.** Improved arrangement.

14.2.4: Signal Currents

When the amp is idling, the current drawn from the power supply is steady. But when it is amplifying a signal the current demands are continually changing. This can alternatively be viewed as an AC signal current superimposed on top of the idle DC current. In a valve stage this signal current flows in the loop formed by the valve and the smoothing capacitor which supplies it, as illustrated in fig. 14.12.

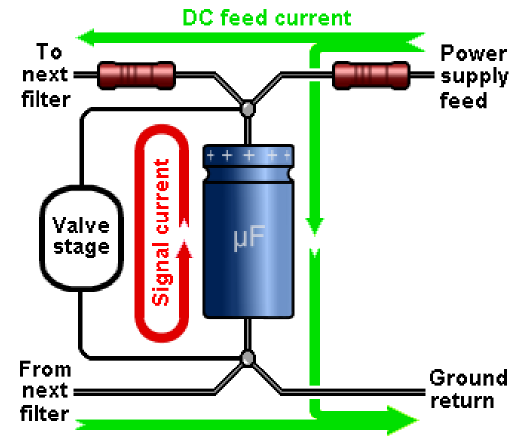

Fig. 14.12: Signal and power supply currents should be kept separate, as far as possible.

For the quietest operation the signal current should be kept separate from the power supply current that keeps the capacitor topped up, because that current is likely to contain residual ripple. The smoothing capacitor should ideally be positioned close to the valve stage, with short connections to it. If the capacitors are all grouped together, vintage style, then ground wires from the valve stages should try to route to their associated capacitor terminals. But if only one ground wire to the capacitor bank is feasible, at least make it a thick one; a multitude of grounding sins can be hidden with thick-enough ground wire.

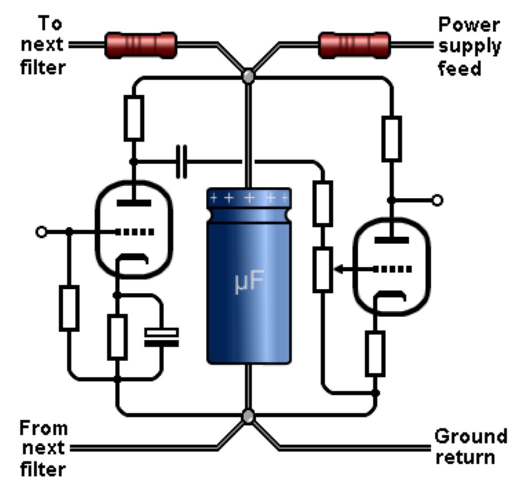

Fig. 14.13: Best-practice layout for two valves operating from the same smoothing capacitor.

When two valve stages are cascaded, components which come after the coupling capacitor 'belong' to the following valve's grid-leak path and should be returned directly to its cathode circuit. Fig. 14.13 shows an example where the two cascaded stages are supplied by the same smoothing capacitor.

14.2.5: Bus Grounding

One logical ground scheme is the bus ground. This is involves routing a single wire, called the bus wire or bus bar, from one end of the audio circuit to the other, following the natural path from the reservoir capacitor, to power amp, through preamp, to input stage. All ground connections are then made progressively along the bus in the same natural order. This tends to encourage a long thin layout but it can be bent into any convenient shape of course. Use the thickest wire you practically can, to minimise ground impedance. The bus bar should be connected to the chassis at one point at the input end of the amplifier. Do not solder it to the backs of all the pots like a vintage Marshall; that is not bus grounding, it is random chassis grounding.

A 'first principle' bus ground is shown in fig. 14.14a. It closely follows the way a circuit diagram would normally be drawn, and in a simple circuit like this one no problems should be encountered. This circuit does not use global negative feedback, so the output transformer secondary is grounded directly to earth / chassis.

By taking even more care with the exact positions of the ground connections, as shown in fig. 14.14b, the first principle ground bus becomes a close approximation of a multiple star ground (next section), and this is preferred when building more

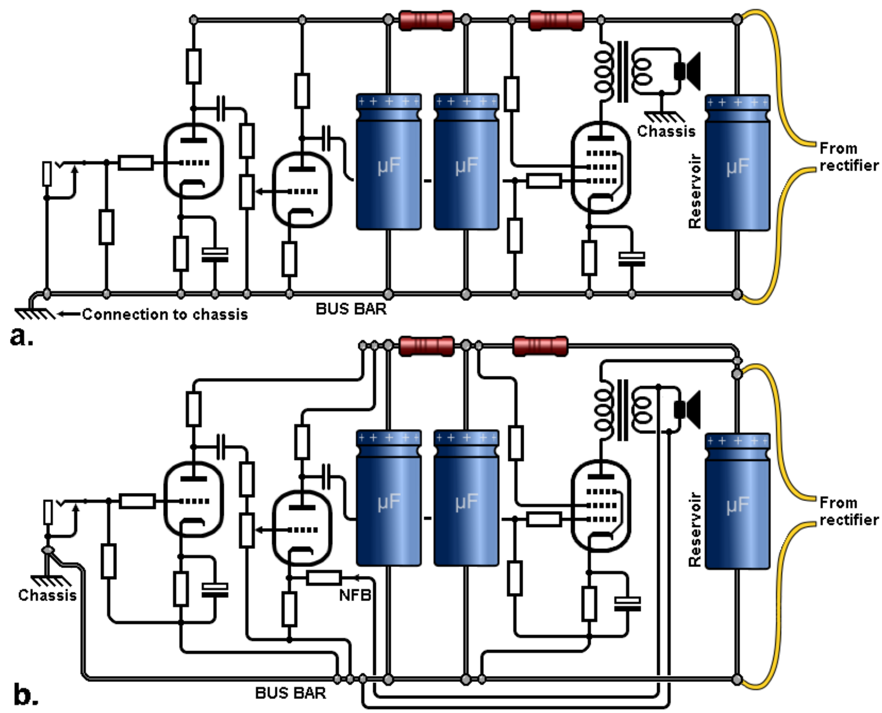

Fig. 14.14: **a:** First principle bus ground. **b:** Improved bus ground that closely approximates a multiple star ground.

complex or high-gain circuits. All power and ground connections are made much closer to their relevant smoothing capacitors, minimising the interaction of audio and power currents, and all grid leaks are now connected to their respective cathode resistors, rather than directly to the bus. This circuit uses global feedback, so the transformer secondary has been grounded at the stage where feedback is applied.

This approach to grounding is great because it offers near-ideal performance while being simple, methodical, and intuitive. It is well suited to hand-wired designs, and once all the components are soldered to it, it can form a pleasingly rigid structure.

14.2.6: Star Grounding

The ideal star ground is one where every ground connection in the amp is brought to a single point, which is then connected to the chassis. Since all the wires radiate away from this point, the name 'star ground' is obvious. This approach tends to encourage a horseshoe-shaped layout, as illustrated in fig. 14.15. With a single star, ground loops and interaction of ground currents become impossible. Actually, there is a second, hidden star in the diagram: where the rectifier connects to the reservoir capacitor. This ensures ripple current does not flow in the main star. However, a single star ground becomes impractical in a circuit with many ground connections, so the next best thing is a *multiple star ground*. This is really a flexible version of the improved bus ground in fig. 14.14b, dispensing with the rigid bus bar.

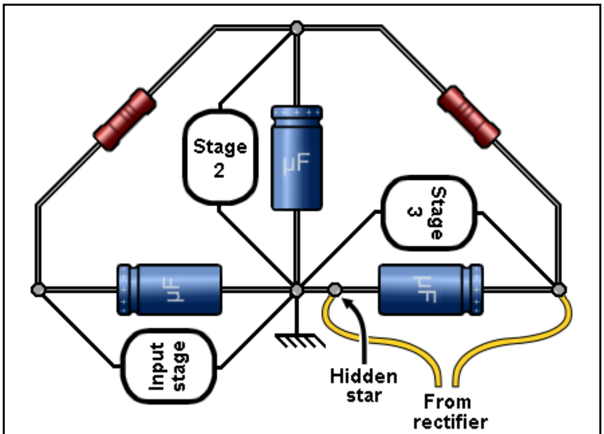

Fig. 14.15: A single star ground is theoretically ideal, but impractical in a complex circuit.

As usual, the transformer-rectifier-reservoir trinity should be built first as a single circuit block. Every smoothing capacitor thereafter forms a local star, and all circuitry associated with a given capacitor is grounded directly to its star. All the local stars are then daisy chained together in the same order as the positive side of the power supply.

Fig. 14.16 shows an example of star grounding in a practical power output stage. In most guitar amps the power valves are pentodes or tetrodes, and it is more important that their screen-to-cathode voltage remain noise free, rather than the anode-to-cathode voltage. Therefore, the local star is made at the screen-grid smoothing capacitor (this was also seen in fig. 14.14b).

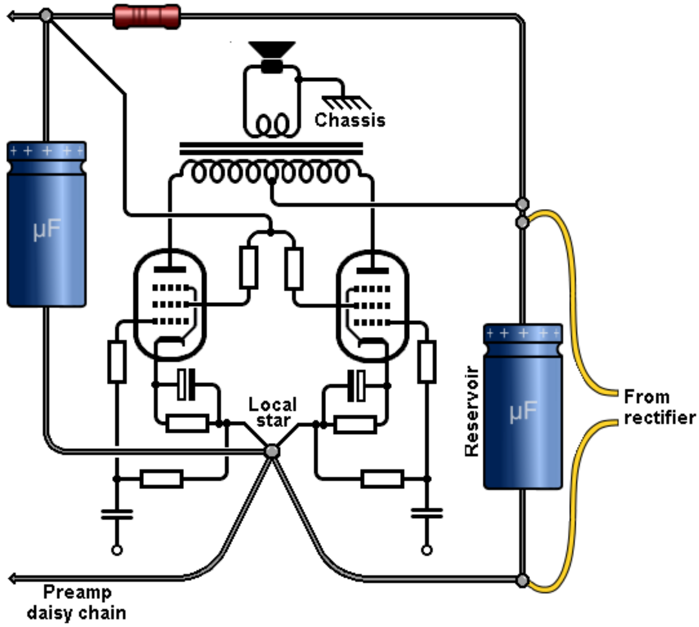

Fig. 14.16: Star grounding a typical cathode-biased power output stage.

In a fixed-bias amp the negative bias supply should be treated like another small power supply, so the same grounding logic applies. The whole bias supply is built with its own star (or possibly bus) ground scheme, and the last stage –often a bias adjustment pot– is finally connected to the audio circuit, as in fig. 14.17.

Fig. 14.18 shows how a typical preamp would be arranged using multiple star grounding, and it can be seen that this turns out more-or-less the same as the improved bus ground from fig. 14.14b; the bus bar has become a daisy chain. Global feedback has been included this time, showing how the output transformer secondary should be grounded at the stage where feedback is applied, rather than directly to chassis / earth.

Needless to say, all these connections should be as short as possible. Any non-audio grounds (e.g. for relays) should be considered noisy and should not return directly to an audio star but to the reservoir capacitor. Note that the entire ground system is connected to chassis at a single point –the input jack.

14.2.7: Miscellaneous Ground Connections

Some transformers have an internal screen between the primary and secondary coils to reduce stray capacitance between the two. This screen should be connected to chassis at the main earth bond, but connection to a mounting bolt is acceptable. Similarly, the heater-winding centre tap should be connected to the main earth bond, though any convenient point on the chassis is usually good enough.

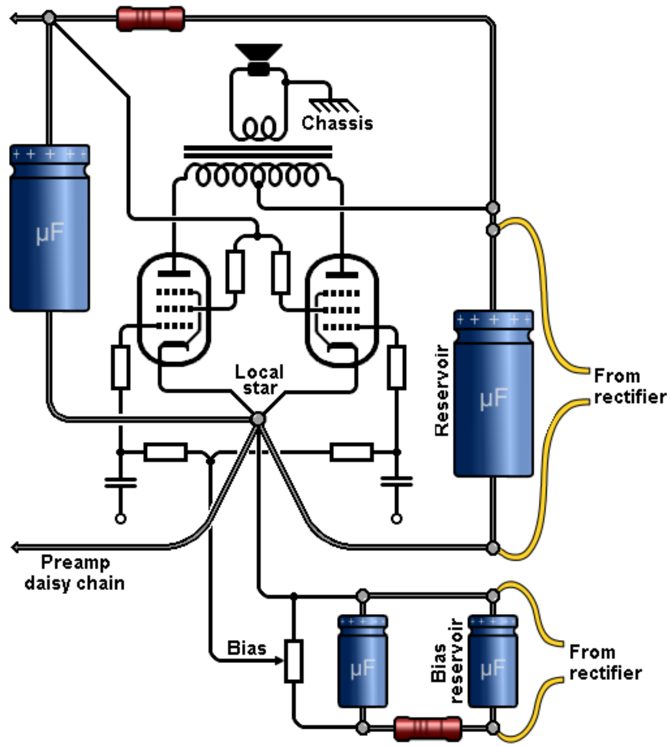

Fig. 14.17: Star grounding a typical fixed-biased power output stage.

Older amplifiers often used multi-section capacitors commonly known as *can-caps*. These usually contain two or three capacitors with a single, shared negative terminal. They were convenient at the time since they saved space and presumably money,[3] but by having only one negative terminal they force us to create a ground star that might be inconvenient. At the very least, try to use a single capacitor for the reservoir, then use the can-cap for later smoothing stages.

The output transformer secondary should always be wired directly to the speaker jack using suitably heavy-gauge wire. This is true no matter what ground scheme is used. A separate wire (which does not necessarily need to be heavy gauge) should then run from the negative connection of the speaker jack to the main earth bond, but a chassis connection close to the speaker jack will also do. However, if global feedback is used, this ground wire should instead run from the speaker jack back to the local star where feedback is applied, which is often the phase inverter, as in fig. 14.18.

[3] Mountjoy, G. & Finnigan, C. W. (1942). Low-Capacitance A-C Power Supplies, *RCA Review* (April), pp455-62.

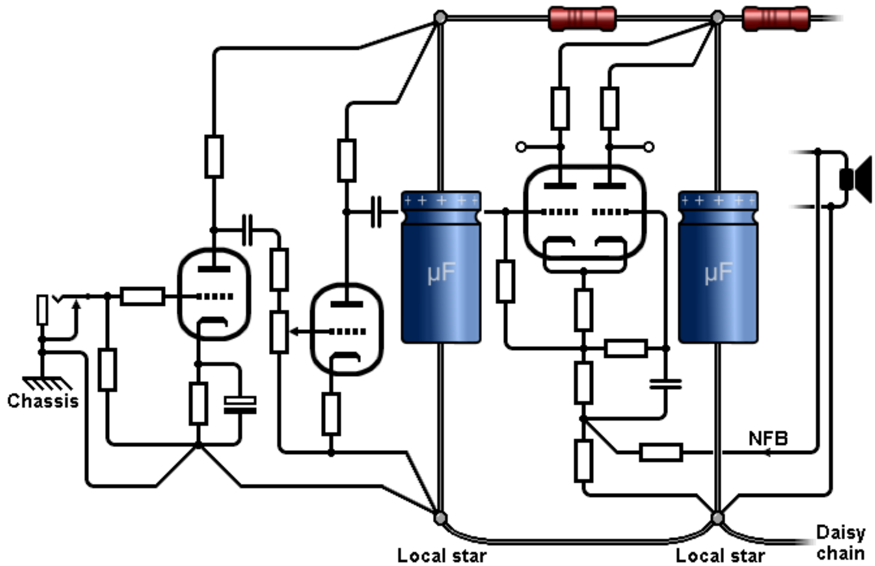

Fig. 14.18: Star grounding a typical preamp.