Pedal Essentials

This article is written for electronics hobbyists and beginners who might be embarking on a path to designing their own guitar effects pedals and equipment. It covers some essential knowledge and standard practices, especially when using opamps. It does not cover the actual effect circuits themselves but rather general principles for switching, power filtering, interfacing with the outside world, etc. Hopefully it answers some common beginner's questions.

1: The Input Network:

The input impedance of a pedal needs to be high because passive guitar pickups are themselves relatively high impedance. This is a historical legacy from the days when valve equipment was the only equipment, and valves amps have high input impedance. The design of guitar pickups hasn't really changed since then. If the input impedance is too low, the high-frequency response of the pickup will become 'damped' or subdued, leading to a flatter, quieter, more mellow sound, also called tone sucking. Even if this is the sort of tone you're after, you should still design your equipment to have a high input impedance by default. You can always reduce it later and throw some tone away, but you can't always buy it back again, at least not without adding noise.

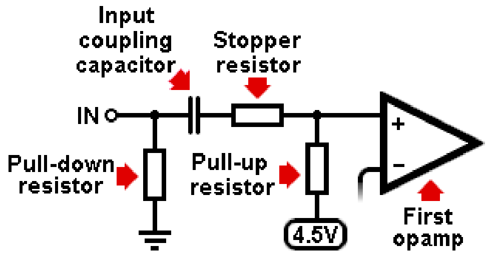

Fig. 1: Bare-essentials non-inverting input network. The position of the stopper resistor may vary.

An input impedance between about 470kΩ and 1MΩ is perfect. There is little point going higher as this makes the circuit more sensitive to picking up interference but brings little change in tone. Below about 300kΩ you may start to notice tone sucking. Active pickups and other active audio electronic devices have much lower output impedance, so can be plugged into anything down to about 10kΩ.

There are four bare-essential components that make up the input network as shown in fig. 1, plus more than are optional which we will come to (the input jack itself is covered in section 3):

- Pull-down resistor;
- Bias (pull-up) resistor;
- Input coupling/blocking capacitor;
- Stopper resistor;
- Radio-frequency suppression capacitor (optional);
- Voltage protection diodes (optional).

1.1: Input Pull-Down Resistor

The pull-down resistor provides the path for the coupling capacitor to charge up when the circuit is first switched on. In other words, it ensures the input is reliably pulled down to ground so there is no residual DC to cause pops when plugging in or operating footswitches (see also section 4.4). Since the guitar is going to be loaded by this resistance in *and* whatever comes after the coupling capacitor, which is effectively in parallel, we need to make this resistance large –anything from 1MΩ to 10MΩ is suitable.

1.2: Pull-Up / Bias Resistor

Most pedal circuits, whether opamp or transistor, need their inputs pulled-up or 'biased' to a positive voltage. For opamps running off a 9V supply rail, the bias voltage will normally be mid-rail or 4.5V. This resistor is effectively in parallel with the pull-down resistor on the other side of the capacitor, and we would like the combination of the two to amount to 470kΩ or more. Various combinations will work but 1MΩ for both is a good choice, giving a combined input impedance of at least 500kΩ (when using a high-impedance opamp like the TL07x).

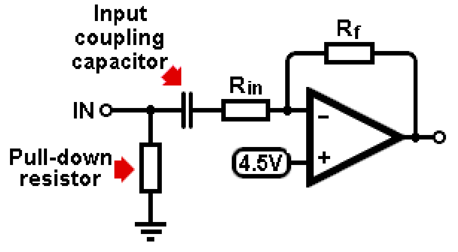

Fig. 2: An inverting opamp input stage is either low-impedance or noisy.

For circuits that go straight into an inverting opamp there is no pull-up resistor; the coupling capacitor connects to the input resistor that forms part of the opamp's feedback network, R_{in} in fig. 2. In this situation the input impedance is equal to R_{in} and since this resistance is in series with the audio signal its inherent Johnson noise (hiss) adds directly to the audio. This resistor is often made smaller than 220kΩ to try to minimise hiss, but this means sacrificing input impedance. An inverting input stage presents real design compromises so avoid it if you can.

1.3: Input Coupling / Blocking Capacitor

The input coupling capacitors serves two purposes. It blocks the DC voltage inside the pedal (e.g. 4.5V) from escaping into the outside world, and it can also be used to reduce bass frequencies if desired. The capacitor forms a CR filter with the pull-up resistor, so it can be chosen with the usual formula:

$$C = \frac{1}{2\pi fR}$$

If you're using a 1MΩ pull-up resistor then 10nF or more will pass all audio, but some designs might use 1nF or even less, to cut bass before it reaches the effect circuit proper. This has the added advantage of helping to block any 50/60Hz hum that might have jumped onto the guitar cable. Since this capacitance is small it will inevitably be a plastic or ceramic type, which doesn't care about polarity.

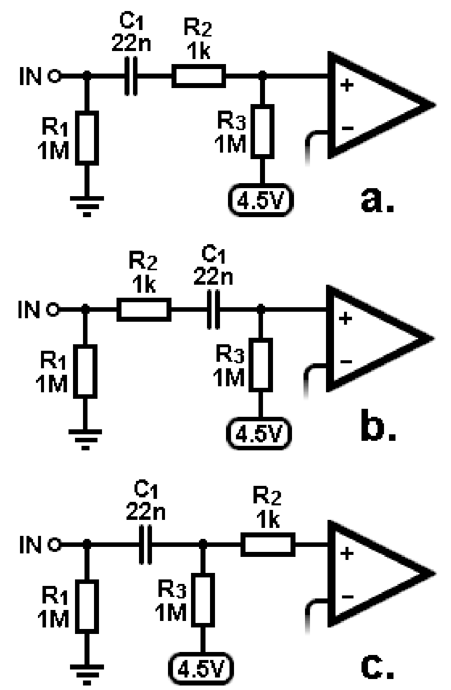

Fig. 3: Typical input networks. Stopper resistor R_2 can be placed in any of the positions shown.

1.4: Stopper Resistor

In commercial designs you will usually find a small resistor or even an inductor in series with the incoming audio. This forms a very high-frequency filter with any inherent capacitance in the circuit, which helps to filter out or 'stop' radio frequency interference. It also helps to absorb transient voltage spikes such as static discharge. Many DIY circuits go without this resistor and seem to survive, but really it is essential if you're aiming for a professional standard of design. The value is not critical –anything from about 100Ω to 4.7kΩ is fine; small enough not to add significant noise or signal attenuation. It can be placed anywhere in series with the hot signal before it hits the first opamp, as illustrated in fig. 3.

1.5: RF Suppression Capacitor

Often the stopper resistor is combined with an optional shunt capacitor as shown in fig. 4. This create an RC filter that assists in dumping radio frequency interference to ground. Any value between 10pF to 100pF can be used (this capacitor also helps to stabilise the opamp against very high source impedances, but this is a bonus rather than a necessity). You can even buy three-legged Electro-Magnetic Interference (EMI) filter components that package all this together.*

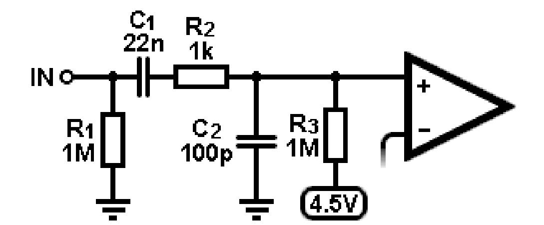

Fig. 4: Adding an RF suppression capacitor, C_2.

1.6: Voltage Clamping Diodes

A final addition found in many commercial audio products are voltage clamping diodes, D_1 and D_2 in fig. 5. These protect the first opamp from excessive input voltages that might damage it, whether large signals or static spikes. If the input signal tries to exceed $\pm 4.5V_{pk}$, one or other of the diodes will conduct, clamping the voltage to just one diode drop above 9V or below 0V. Any signal diodes can be

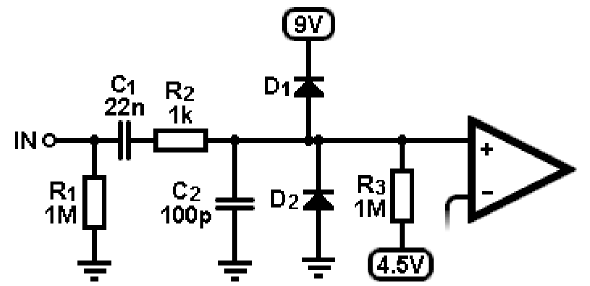

Fig. 5: Adding voltage clamping diodes, D_1 and D_2.

*e.g. the Murata DSS6NC52Ax series.

used, and 1N4148s are very common. These diodes are not always essential if a stopper resistor is in place, since many opamps have parasitic diodes inside them already. But it doesn't hurt to add them if you want the most robust design; they have no effect on the audio during normal operation.

2: The Output Network:

The output impedance of a pedal should be low. The lower it is, the less easy it is for hum and interference to be picked up on the outgoing cable, and the less treble will be lost due to cable capacitance. Keep the output impedance below 10kΩ if you can, and less than 1kΩ is best.* An opamp or buffer has extremely low output impedance by default, but this can be spoiled by adding extra components.

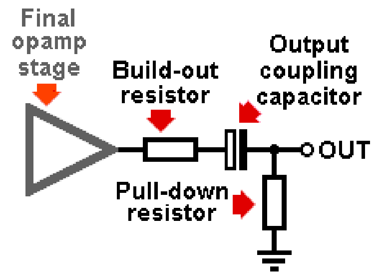

Fig. 6: The output network includes three essential components. The position of the build-out resistor may vary.

There are three components that we cannot do without, when coupling a pedal circuit to the outside world, as shown in fig. 6:

- Build-out resistor;
- Output coupling capacitor;
- Pull-down resistor.

2.1: Build-Out Resistor

The build-out resistor is a small resistance added in series with the output. Its only job is to isolate the opamp from cable capacitance and other unknown, outside influences. This is necessary because many opamps will oscillate at ultrasonic frequencies when driving too much shunt capacitance directly. You might not be able to hear this oscillation but it will still wreak havoc with normal audio, by consuming headroom or generating intermodulation products that *are* audible. It can also burn out loudspeaker tweeters. Circuits that produce strange rustling or whining sounds, or circuits that seem to work but have a murky sound quality for reasons you can't quite put your finger on, are possible signs of ultrasonic oscillation. You can waste days tearing your hair out to find such an invisible gremlin. A build-out resistor is essential to keep the opamp happy and well behaved, by making it think it is driving a nice, simple resistor, rather than a long, reactive cable.

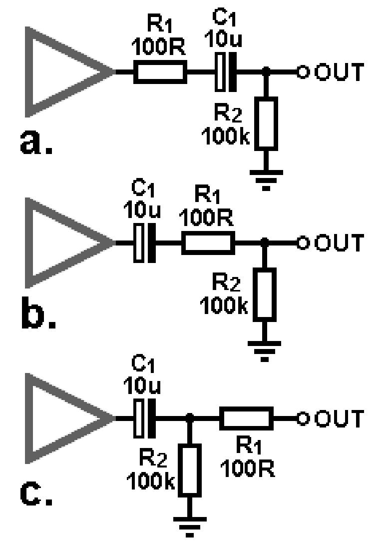

Fig. 7: Typical output networks. Build-out resistor R_1 can be placed in any of the positions shown.

Since the build-out resistor is in series with the pedal output it adds to the output impedance, which we want to be small. But the resistor also needs to be big enough to stabilise the opamp against any load we might reasonably plug into output jack. The 'Goldilocks zone' turns out to be between about 33Ω and 100Ω; anything in this range is not too big, but not too small, just right for any opamp and any likely load.

This resistor can be placed anywhere between the opamp and the output jack socket. It doesn't matter if it is placed before or after the coupling capacitor or pull-down resistor, as illustrated in fig. 7. It just needs to be *somewhere* between the opamp and the outside world, so put it wherever is most convenient for your layout.

2.2: Output Coupling / Blocking Capacitor

The output-coupling capacitor is the last coupling capacitor between the effect circuit and the outside world. Its job is to block the DC voltage (e.g. 4.5V) inside the effect circuit from escaping down the cable and doing who-knows-what at the other end. There are a few things we need to consider when choosing this capacitor. It will probably be an electrolytic (i.e. polarised), so be sure to put the positive terminal towards the opamp, as in fig. 8.

The capacitor will form a CR filter with the pull-down resistor (next section) *and* whatever load happens to be at the other end of the cable. These two things are effectively in parallel, but we can't be sure what the latter will be. Sometimes it might be the 1MΩ input impedance of a valve amp, sometimes it might be the 10kΩ input

* There is an international standard for output impedance in IEC 61938, which demands ≤2.2kΩ for general-purpose consumer devices or ≤1kΩ for professional devices. Even many commercial pedals don't achieve this!

impedance of pro-audio gear.* That means the cut-off frequency could vary by a factor of one hundred! We don't want to plug into a mixing desk and discover the bass has suddenly vanished, so we need to assume the worst-case value of 10kΩ.

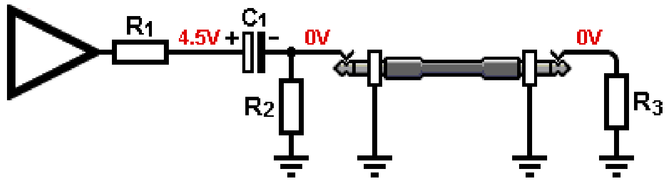

Fig. 8: The output coupling capacitor blocks the DC voltages inside the pedal from reaching the outside world. Note that R_2 is effectively in parallel with the unknown load R_3 at far end of the cable.

Now, you might think you could just pick your lowest favourite frequency and use the formula for a CR filter to find a suitable capacitance. But there is something more subtle to remember: output impedance. The reactance of the capacitor is in series with the output, so it adds (quadratically) to the output impedance. What's more, it rises at low frequencies, which is exactly what we *don't* want since it makes it easier for ambient 50/60Hz hum to jump onto the cable. In other words, try not to use the output coupling capacitor for bass frequency shaping; do that with the input coupling capacitor instead, or elsewhere within the circuit. Doing it at the output will cause the frequency response to change depending on what you plug it into, and makes the output sensitive to interference.

For example, a 1uF output coupling capacitor working into a 10kΩ load would give a cut-off frequency of 16Hz which seems fine, but at 50Hz hum frequency it has a reactance of $1/(2\pi fC) = 3183\Omega$, which is quite high, spoiling the otherwise low output impedance of the opamp. It's not a *terrible* choice –many commercial pedals use this value– but if you're aiming for the best performance a 4.7µF to 47µF capacitor is a better choice. This banishes concerns about cut-off frequency and output impedance to subterranean regions where they will never bother anyone.

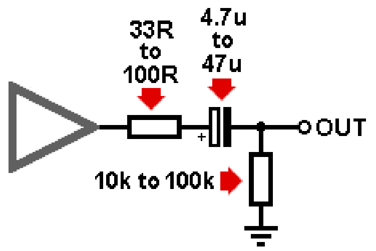

Fig. 9: Recommended component values for any output network.

Why not use a huge value, like 1000µF? The trouble here is that we have to wait for the coupling capacitor to charge up to 4.5V when the circuit is first switched on. No-one minds waiting a few seconds for normal operation to commence, but a really big capacitor could take half a minute or more to charge up, which is too long. Moreover, the bigger the capacitance the more it is likely to leak DC, which will lead to popping footswitches despite the best efforts of the pull-down resistor.

2.3: Output Pull-Down Resistor

The pull-down resistor provides the path for the output coupling capacitor to charge up when the circuit is first switched on. In other words, it ensures the output is reliably pulled down to ground, so there is no residual DC to cause pops when operating footswitches (see also section X). The smaller the resistance, the faster the charging time. However, this resistor also affects the output cut-off frequency, and loads down the opamp too, so there is a trade-off between getting a reasonably fast charging time, not losing any bass, and giving the opamp an easy life. A value of 100kΩ is usually ideal, but anything from about 10kΩ to 100kΩ should do. Fig. X shows the output network with the recommended component value ranges. You can use any combination of values shown in the figure. But there is one more thing:

2.4: Dealing With a Volume Pot

The output networks in fig. 7 are the most ideal since they are driven by an opamp and maintain a very low output impedance. But what if you want an output volume/level pot? This a very common situation in an effects pedal, but it is one that is easy to get wrong. Ideally the pot would be placed before the final opamp as in fig. 10a, or it could be part of an inverting gain stage if you want gain as well as attenuation, as in fig. 10b; either way the pot is not part of the output network.

* You may also have heard about audio gear with 600Ω input impedance, but this is well out of date. Pro-audio gear has not used 600Ω terminations since the 1970s. IEC 61938 specifies ≥22kΩ for consumer equipment and ≥10kΩ for professional equipment.

However, this is not always possible. If the volume pot absolutely must come after the last opamp then the most sensible thing is to replace the pull-down resistor with the pot, as in fig. 10c. The capacitor keeps DC off the pot, which eliminates rustling, and the pot serves double-duty as pull-down resistor (the position of the build-out resistor can vary). There are two disadvantages in placing the pot after the opamp. First, the pot will be loaded or 'slugged' by whatever is at the other end of the cable, which will therefore change its taper and cause more rapid volume changes near the clockwise end of rotation. Second, the output impedance will vary depending on where the pot is set.

The output impedance of the pot is the parallel combination of the upper and lower parts of the track, so it is worst when the wiper is at the −6dB position. In this position half the resistance appears on each side of the wiper, so the maximum output impedance is one quarter of the total pot resistance. If we tried to use a 100kΩ pot –which a lot of dodgy commercial designs do– then the output impedance can reach 25kΩ. This is very large and spoils the otherwise commendable output impedance of the opamp, making the signal vulnerable to noise and interference at the worst possible moment: right before it snakes through a long audio cable.

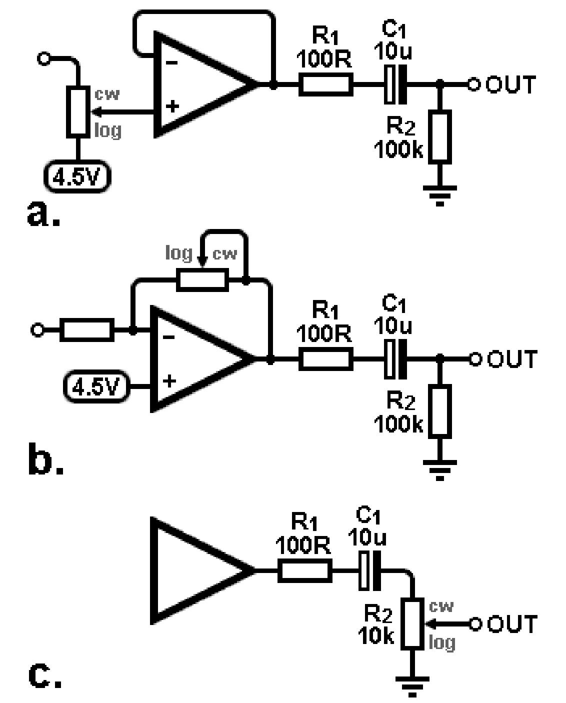

Fig. 10: If a volume pot appears after the last opamp it should have a small value to minimise output impedance and loading effects; a 10kΩ pot is ideal.

The solution to both these problems is the same: use the smallest-value pot you can. A value of 10kΩ to 22kΩ is a good compromise which will keep the output impedance under 5.5kΩ, and the taper will be hardly affected even by a fairly heavy external load.

3: The Power Supply

Most effects pedals operate from a 9V power source. This might be a battery or an external wall-adapter / wall-wart / plug pack, whatever you want to call it. A battery has the advantage of being portable and extremely low noise, but it will need periodic replacement.

If you use a linear wall adapter it should be the *regulated* kind (it will say on it) as the chapter unregulated kind nearly always produces too much hum. Alternatively, there are now switch-mode DC power supplies which are regulated by default, but these sometimes create different noise problems due to the switching frequency, and due to noise leaking from the mains onto the output. This usually manifests as 'whine' or buzz, rather than hum. Quiet switch-mode supplies do exist but results can be frustratingly hit-or-miss, and switch mode noise is not easily eliminated by simple RC filters inside the pedal. If you want to side-step these problems it is worth buying a commercial pedal power supply.

3.1: Power Input and Jacks

If the circuit is battery powered only, then all we need is the familiar battery snap connector or a ready-made battery holder. This would be the case for a circuit built into the body of a guitar, for example. However, we don't want the circuit to be powered all the time since this will needlessly drain the battery, so the usual arrangement is to use a stereo (TRS) jack socket to detect when power is actually needed, as shown in fig. 11. The battery negative (i.e. ground) terminal is connected to the 'ring' of the jack, so when a standard *mono* guitar cable is plugged in, the solid mono plug will short the ring and sleeve terminals together, completing the circuit. The guitarist just has to remember to pull the

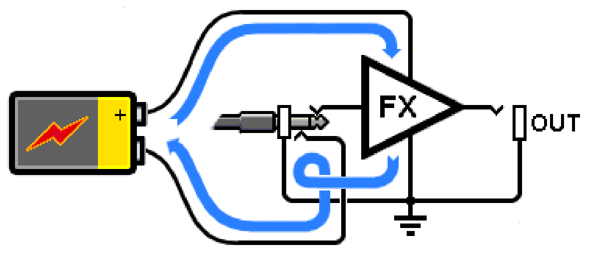

Fig. 11: A stereo (TRS) jack can be used to switch battery power on when a mono guitar cable is inserted.

cable out when not needed, to save battery life. For a circuit built into the body of the guitar there is only one jack available to do this, while in a pedal it is conventionally the *input* jack that performs this task.

Fig. 12 shows how the circuit symbol relates to the common types of jack socket. The non-insulating 'Switchcraft style' jacks are still common in American equipment but have serious shortcomings. The nut loosens easily, it allows foreign objects to be pushed into the enclosure, it forces you to make a potentially unwanted ground connection to chassis, and has a cheap 'feel' when plugging in. Insulating jacks such as the plastic 'Cliff style' are much better, and the pin connections are more obvious.

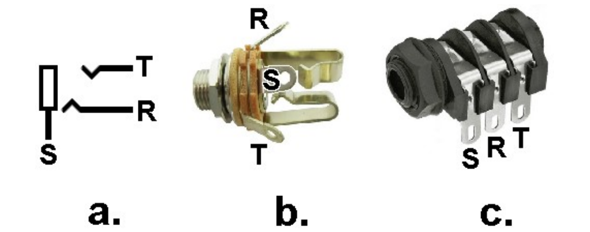

Fig. 12: **a:** TRS jack symbol; **b:** Inferior Switchcraft-style jack; **c:** Superior insulating Cliff-style jack.

If the circuit can be powered from an external source like wall adapter then the standard approach is to use a 2.1mm DC power jack (this is the diameter of the central pin), which will mate with a ¼ inch barrel plug. Avoid the 2.5mm jacks as these will only mate with 2.5mm plugs, which pedal power supplies do not normally use; the 2.1mm socket will fit both 2.1mm and 2.5mm plugs. Fig. 13 shows how the circuit symbol relates to the common types of DC jack socket, but several other styles exist.

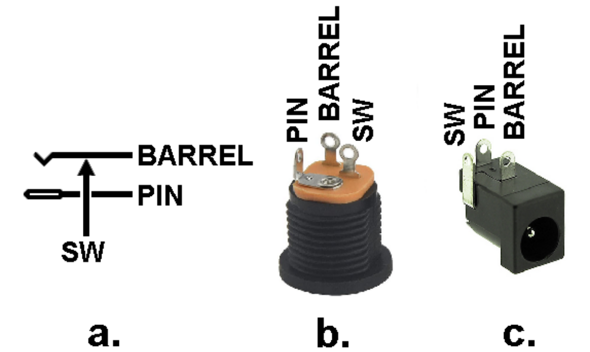

Fig. 13: **a:** DC jack symbol; **b:** Insulating panel-mount DC jack, **c:** PCB-mount DC jack.

The power jack on 9V effects pedals has been unofficially standardised as *centre negative*. In other words, the centre pin is normally 0V (ground) and the outer barrel is +9V. Annoyingly, this is backwards compared to how most other electrical appliances are built, but it is a historical legacy we are stuck with. This means you cannot use a metal-body power jack on a metal pedal enclosure, since the positive barrel would then be shorted to the grounded enclosure. It also means many off-the-shelf wall adapters are not immediately compatible with pedals.

If the pedal can be both battery *and* externally powered then it is essential to disconnect the battery when external power is being used, otherwise the external supply will try to charge the battery. Ordinary batteries cannot be recharged and may fail catastrophically if you try! Rechargeable batteries are of course available, but special charging circuitry is needed to protect them, and the average guitarist probably won't install the right ones anyway, so forget about it. The standard arrangement is therefore to use a switched DC jack, wired as shown in fig. 14. If an external power supply is plugged in it will break the switch contact and disconnect the battery.

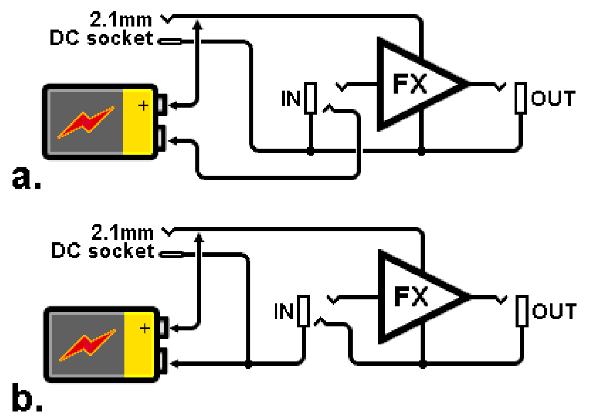

Fig. 14: Switched DC jack used to disconnect the battery when an external power source is used.

The variation in fig. 14a is standard and will switch the effect off if the guitar cable is unplugged during battery mode, but leaves the effect on if an external supply is being used. In b. the effect is always switched off when the guitar cable is unplugged, regardless of the power source. For some reason this arrangement is not popular, being found in some Korg pedals and not much else.

3.2: Positive Ground Circuits

Early effects pedals were built using PNP transistors –the first kind to become commercially available. PNP transistors naturally lent themselves to circuits using a *negative* supply rail, because they then resembled (in mirror image) the vacuum tube circuits that circuit designers were already familiar with. Circuits operating from a negative supply rail were sometimes called ‘positive ground’, i.e. the ground or common rail was more positive than the main power rail. The vast majority of effects pedals today use a *positive* supply rail, or you could say they are ‘negative ground’ if you like to obfuscate things with jargon.

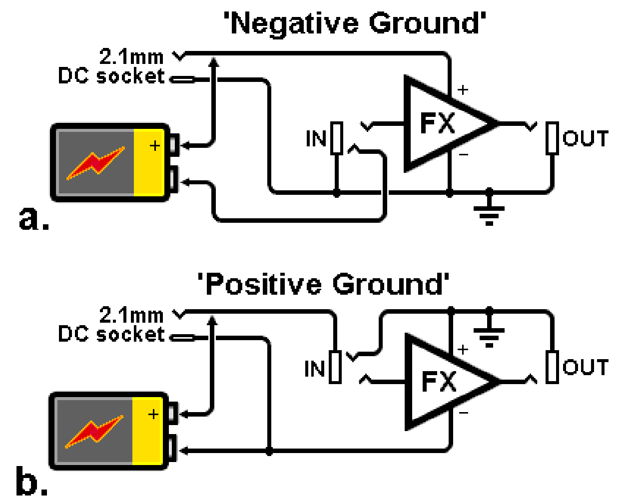

Fig. 15: **a:** Conventional positive supply rail circuit. **b:** Old style negative supply rail or ‘positive ground’ circuit. Note that the two circuits cannot share the same the same external power supply.

Fig. 15 shows the power-connector wiring needed by the two kinds of circuit. Notice that in both cases the centre pin of the DC jack is ‘most negative’, meaning it is connected to ground in a. but to the negative rail in b. In a positive-ground circuit the input jack wiring can only be the kind that switches the effect completely off, whether the supply is battery or external. Old style positive-ground pedals are annoying because they cannot share the same 9V power source as the rest of the pedal board. Positive-ground should be avoided unless you’re building historically accurate clones.

3.3: Polarity Protection

A common form of polarity protection is to add a diode in parallel with the supply rails, as shown in fig. 16. Under normal conditions the diode is reverse biased and does nothing, but if the wrong polarity is plugged in, the diode conducts as shown. The voltage across the rest of the circuit is therefore clamped at the diode’s forward voltage of about 0.7V, which is harmless. However, in this naked configuration the diode is fighting the power supply, so if the power supply doesn’t have some kind of built-in current limit or automatic shut-down then it becomes a fight to the death! Either the diode will blow open and expose the pedal to the full reverse voltage, or the power supply will cook; a battery might even catch fire.

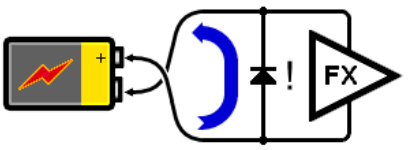

Fig. 16: A parallel diode will protect a circuit against reverse polarity, until something burns out!

To limit the fault current we must put a resistor in series with the incoming power, before the diode, as in fig. 17. It should be small enough not to drop too much voltage during normal use, so a value of 10Ω to 47Ω is typical. In other words, it will be the resistor already needed by the usual RC decoupling filter (shown faint and covered in section 3.4). The fault current will still be fairly large so diode D_1 should be a power diode such as a 1N4001 (1-amp rated). The resistor is deliberately sacrificial; with a prolonged reverse connection it will probably burn out, but the rest of the circuit will be left unharmed so only the resistor needs to be replaced.

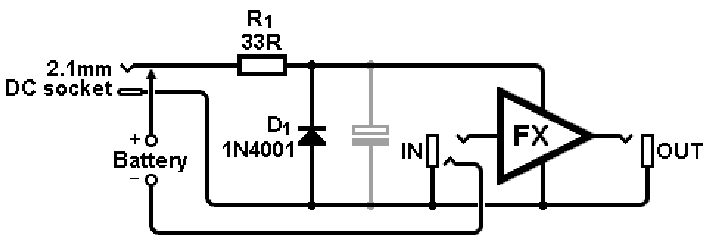

Fig. 17: Practical parallel polarity protection.

Parallel protection as in fig. 17 is not really suitable for circuits that draw tens of millamps or more, since any useful value of R_1 will drop too much voltage, eating away at our 9V supply rail. An alternative approach is to use a series diode as in fig. 18. This blocks any reverse voltage completely, so there is no fault current to worry about. The ubiquitous 1N4148 is normally used (rated for up to 300mA) but a power diode is also fine. However, this will drop about 0.6V under normal use which may be deemed excessive, especially for battery power, so a superior option is to use a Schottky diode such as the common 1N58xx series. These have a very small voltage drop, typically less than 0.3V.

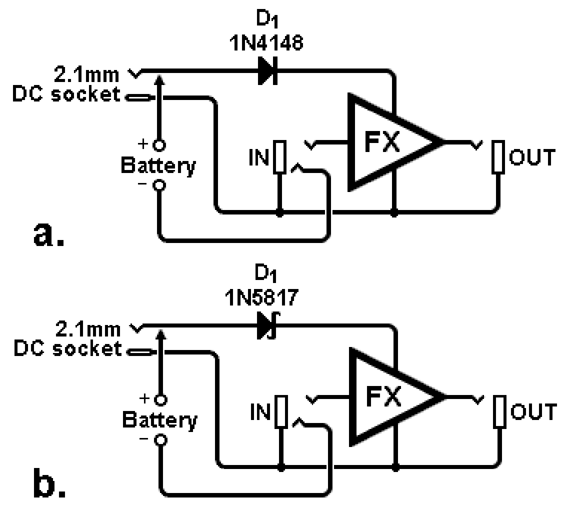

Fig. 18: Series polarity protection. **a:** Ordinary diode; **b:** Schottky diode for less voltage drop.

Either of the polarity protection methods described above will be suitable for nearly all pedal designs. Nevertheless, it is possible to go further. For many high-efficiency products that need to extract every last drop of battery voltage, even the voltage lost across a Schottky diode may be too much. A truly low-loss solution is to use a P-channel MOSFET as a smart polarity switch, as shown in fig. 19. This rather impish circuit uses Q_1 'backwards' compared to what we're used to. When the correct polarity power is applied, current will initially flow through the body diode and therefore pull the MOSFET source up to almost 9V. Meanwhile, the gate is tied to ground, i.e. the gate will be nearly 9V *below* the source. This immediately turns the MOSFET fully on, saturating it and causing it to behave like an extremely small resistance equal to $R_{DS(on)}$, which bypasses its own body diode! For the VP3203 $R_{DS(on)}$ is quoted as 0.6Ω, resulting in only millivolts of drop (other MOSFETs can reach even smaller figures but they are rarely available in the convenient TO-92 package). Conversely, if the supply voltage has the wrong polarity the body diode will be reverse biased and no voltage can appear between source and gate, so the MOSFET will remain off. As shown the circuit will safely block reverse voltages up to 20V.

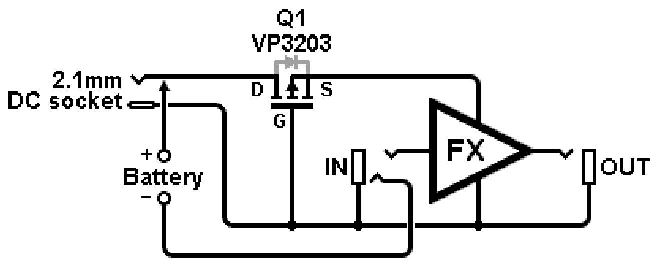

Fig. 19: Smart polarity protection using a P-channel MOSFET for extremely low voltage drop.

3.4: Power Filtering

No matter how clean your power source, you still need to take good care of the power rail by providing some RC filtering, as illustrated in fig. 20. The purpose of power filtering is twofold: Firstly it attenuates any ripple, hum, and noise coming from an imperfect power source; this process is often called power supply *smoothing*. Secondly it suppresses signal-induced modulation of the power rail. This is caused by the ever-changing amount of current demanded by the various stages of the audio circuit while amplifying a signal. These fluctuations in current cause a corresponding voltage drop across the resistance and inductance of the power feed wiring. In other words, the rail voltage in the pedal will try to fluctuate along with the audio signal, and this can feed back into the power pins of the opamps and other stages, creating unwanted havoc or even oscillation. A large capacitance connected across the rail helps to suppress this by acting as a local energy-storage tank, averaging out the current fluctuations. This is often called power supply *decoupling*. A power-supply filter can do both jobs, effectively working in two directions at once.

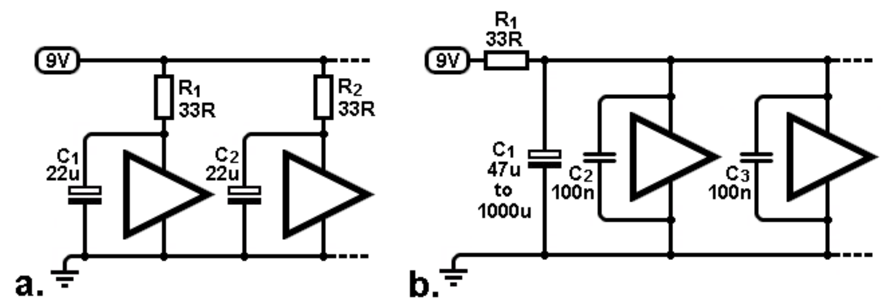

Fig. 20: **a:** Individual RC power-supply decoupling for each opamp;
b: Single RC filter compromise with optional local decoupling capacitors.

Ideally, each IC in the circuit would have its own decoupling filter as in fig. 20a, but this is often impractical. A typical compromise is to use one big RC smoothing filter which supplies everything inside the pedal, then add a ceramic capacitor close to each IC to provide local decoupling at high frequencies, as shown in b. These local ceramics can be any convenient value from about 47nF upwards. However, in a small, purely analog, opamp-based pedal (e.g. no digital/logic signals) it is normally fine to omit the small local capacitors. Up to eight low-current opamps can usually be fed from one power supply filter without problems. However, higher-current circuits using the NE5532 or headphone/speaker drivers really do need their own, dedicated power supply filters. The same often goes for opamps when used as oscillators, as the local filtering will help to suppress whine or thumping.

The larger the resistance and capacitance the better the filtering of the incoming power, but a *small* resistance and large capacitance provides better decoupling between devices. The main limitation is how much DC voltage drop we are willing to sacrifice, since this will eat into our voltage headroom. Typically a 33Ω to 47Ω resistor is used, resulting in about 0.2V drop when supplying a couple of TL072s (~6mA), which is satisfactory for a 9V circuit. A circuit using a higher rail voltage could tolerate more voltage drop and therefore a larger resistance. The capacitance is not critical; anything from 47µF to 1000µF is normal.

4: Footswitches and Bypassing

In previous diagrams the whole effect circuit was represented by a generic triangle. Any footswitching was therefore assumed to be contained within that triangle, as it had nothing to do with the rest of the wiring under discussion. We will now zoom into that triangle and deal with footswitching.

4.1: Simple Bypass and Tone Sucking

Some vintage or cheap effects pedals use a single-pole footswitch for bypassing, wired as in fig. 21 (sometimes the switch is double pole but other half is used for switching an LED). The trouble with this arrangement is that, even when bypassed, the input of the effects circuit is still connected to the guitar; the guitar has to drive the effect circuit *and* whatever the pedal has been plugged into. This can lead to excessive loading on the pickup, which will dampen its natural resonance, draining its characteristic tone and brightness. This is commonly known as tone sucking. It is most noticeable with vintage transistor-based circuits which often have wincingly low input impedance, and the problem gets worse if several such pedals are connected in a chain, all bypassed at once, since they will all load the pickup simultaneously. For this reason true-bypass or electronic bypass circuits are preferred.

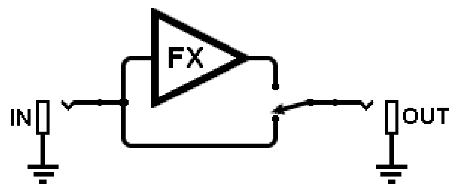

Fig. 21: Simple bypass can result in tone sucking.

4.2: True Bypass

'True bypass' means the effect circuit is mechanically and completely disconnected from the audio 'hot' conductor, when in bypass mode. True bypass is subject to a lot of audio lore. Proponents claim true bypass is superior because it preserves the 'purity' of the signal chain when the effect is off, by disconnecting the effect from the pickup completely. Some of this paranoia is inherited from the 1960s and 70s when various vintage effects –mostly wahs and fuzzes– only had the simple bypass described above. Compared to them, true bypass is a considerable relief. However, true bypass does not entirely unburden us from tone sucking, because the guitar pickup still has to drive a variable length of cable, depending on how long the pedal chain is and how many effects happen to be bypassed at once. A guitar cable is basically a long capacitor; the longer it is, the greater the potential tone suck. This is something that buffered bypass solves (section 5). Nevertheless, there are some true advantages to true bypass: It is conceptually simple (easy for beginners to implement); it has no

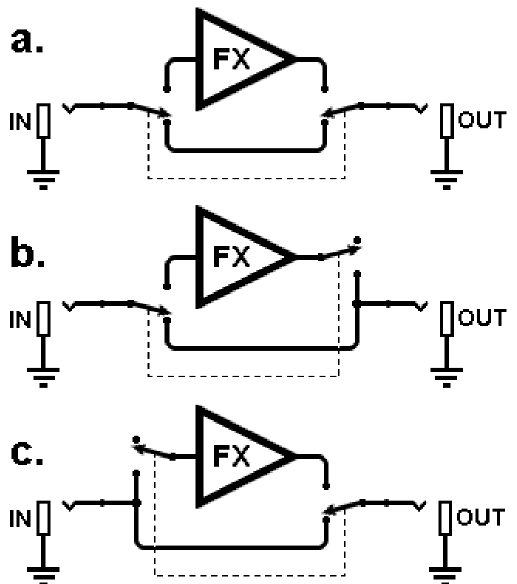

Fig. 23: Three ways to do true bypass.

headroom limit; it works even when your battery is dead; it has marketing appeal.

From a technical point of view there is very little to be said about implementing true-bypass –it requires a DPDT switch or relay, and that's it. There are three possible configurations as illustrated in fig. 23. The version in a. is perhaps the most obvious, but the version in b. can also be exploited to switch an LED, as explained in the next section.

4.3: Status LED

Modern effects pedals nearly always include an LED to indicate when the effect is active. Traditionally this requires an extra pole on the footswitch. This in turn implies that true bypass with an LED requires a three-pole double-throw (3PDT) switch, as illustrated in fig. 24. Footswitches of any kind are a specialist item, but three poles are even more specialist. Admittedly, 3PDT footswitches are much easier to buy nowadays thanks to the internet, but good quality ones are not exactly cheap. What's more, they take up a lot of valuable space in the enclosure.

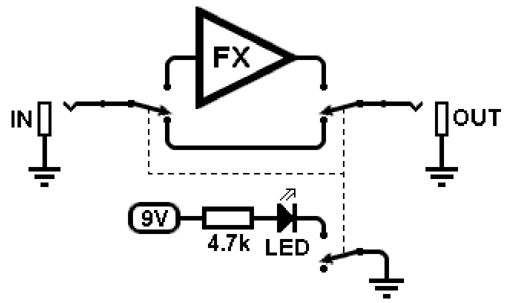

Fig. 24: True bypass with LED, using a 3PDT footswitch.

An alternative electronic solution is shown in fig. 25. This uses a more common double-pole double-throw (DPDT) footswitch for bypassing, and a MOSFET to switch the LED. The MOSFET has near infinite input impedance which means its gate can be pulled up (on) or down (off) even with very large resistances. In this case the pull-up is actually provided by a reverse-biased diode D_1 which behaves like an enormous (hundreds-of-megohms) resistance. When the effect is engaged the diode is free to pull the MOSFET gate up to 9V, turning it fully on and lighting the LED. But when bypassed as shown, the gate is pulled down to 0V by the (relatively) much smaller resistance at the output of the effect, switching the MOSFET off. Now, even though we are switching a DC voltage which would normally cause a pop, here the amount of *charge* needed to transition between the two voltages is exceedingly small thanks to the super-high resistance of the diode. In other words, a pop does *technically* happen, but it is too tiny to be audible. Thus we can get silent, true bypass, with an LED, using a DPDT switch. Note that connecting the LED to the MOSFET source as shown, rather than to the drain, raises the turn-on threshold which makes the circuit more compatible with different MOSFET characteristics. Most N-MOSFETs will work including the BS170, VN2222, and 2N7000. R_1 determines the current for the LED and can be changed to get the brightness you want.

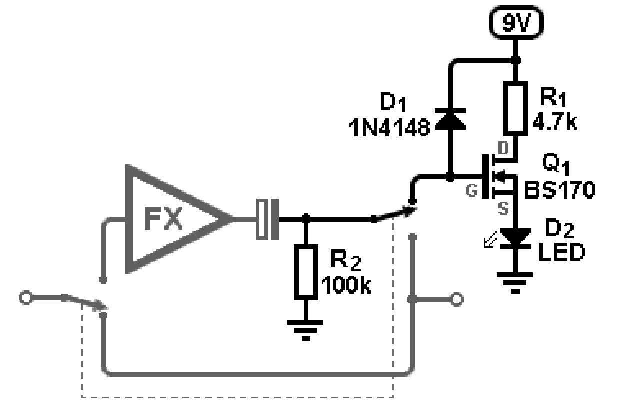

Fig. 25: True bypass with LED, using a DPDT

4.4: Avoiding Pops

When the LED is switched on or off there will be a corresponding change in the power supply current. In fact, in some pedals the LED uses more current than the effect itself! Depending on the quality of the power source, this sudden change in demand can cause a small jump in the power supply voltage which may leak through the audio circuit and be heard as an annoying pop. Opamps are less susceptible to this than discrete transistors, but still it is worth adopting good practice. Where possible, the LED should be supplied directly from the power source (after any polarity protection), so its current does not share the same wires as the audio circuit, as far as possible. Similarly, any power supply filtering should supply only the effects circuit and not

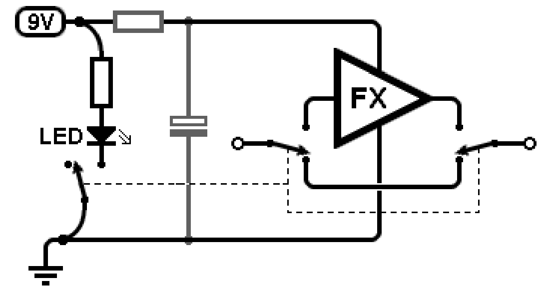

Fig. 26: To minimise pops, the LED should come before any power supply filtering and be connected directly to the power source terminals.

the LED, as shown figuratively in fig. 26 (this remains true even if the switch is actually a MOSFET as in fig. 25). After all it's just an LED, it doesn't need a very clean power source.

If a pop persists despite good wiring then the modification in fig. 27 will usually solve the problem. Here the current-limiting resistor is split into two equal parts and C_1 is connected to the junction. It takes many milliseconds for the capacitor to charge/discharge when the LED is switched, so instead of a 'snap' we get a fast fade. The resistance values are not at all critical; the total resistance can be adjusted to set the LED brightness as usual, just make them roughly equal.

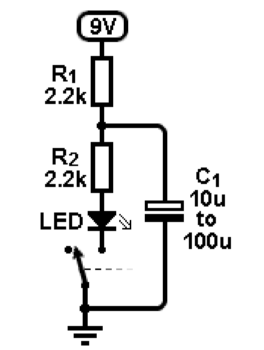

Fig. 27: Reducing pop by slowing down the LED on/off transition.

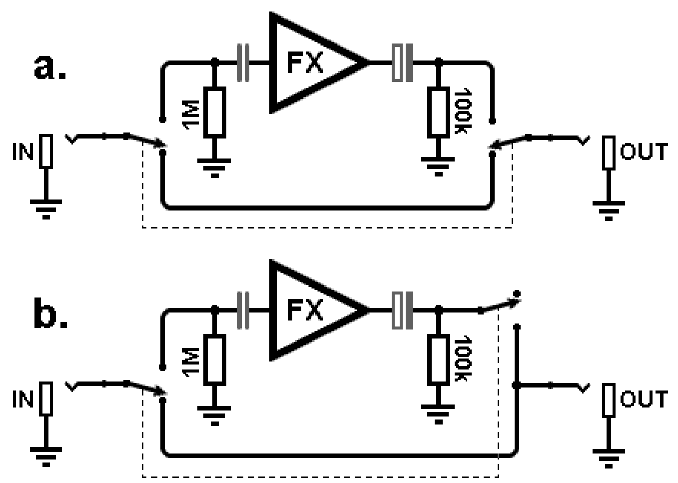

Fig. 28: Input and output pull-down resistors are essential to prevent pops. The output pull-down may be substituted with a volume pot instead.

Switch-pop will also happen if the two sides of the switch are not at exactly the same DC voltage, e.g. 0V. For example, a common mistake is to forget to include pull-down resistors for the 'outside ends' of the input/output coupling capacitors. This means that during bypass they will start to discharge through their own internal leakage, so the unconnected end will begin to climb up towards 4.5V, causing a pop when they are switched back into the circuit again. It is therefore essential to include some form of pull-down resistance at both ends of the effect, typically 1MΩ to 10MΩ at the input (to keep the input impedance high), and 10kΩ to 100kΩ at the output (because it often uses an electrolytic capacitor which is more leaky). Often a volume pot already performs this duty at the output, as described earlier in section 2.4. This is shown in fig. 28 for both common types of true bypassing. It is assumed that the guitar, amplifier, or other effects that may be plugged into the pedal, also contain such resistances, so there should be no need to duplicate their function by putting resistors on the other poles of the footswitch as well.

5: Electronic Bypass (Analog Switching)

When it comes to switching analog signals we don't always have to use mechanical switches; there are various electronic ways to route and re-route audio signals, and various reasons you might want to use them:

- We can accomplish elaborate routing schemes all controlled from one place or by one mechanical switch or button;
- We can automate the switching or interface it with a microcontroller;
- The routing devices can be placed close to the circuits they actually serve while the control device can be far away, which improves layout and immunity to noise or instability;
- We can achieve silent 'soft switching' free from clicks;

We still have the option of bypassing the effect circuit completely for a kind of quasi-true-bypass but, typically, circuits that use electronic bypass also leave one or more buffers in-circuit at all times, in which case it may be called buffered bypass. This has the advantage that the guitar always sees the same load –the input of the first buffer. The buffer then breezily drives everything after it, meaning there is never any unintended change in pickup response.

5.1: CMOS Analog Switches

There are several so-called analog switching ICs on the market. These are solid-state switches that can be electronically controlled with logic signals. Among the most common devices are the 4016, 4066, and 4053.[*] These all come in different 'families' such as the 'CD' series (e.g. CD4016) and the 'HEF' series (e.g.

[*] You can also check out the 4051 which contains one eight-way switch, and the 4052 which contains two four-way switches.

HEF4016). There is also the 74HC series (e.g. 74HC4016) which is only rated up to 11V rail voltage; enough for 9V pedals but not much more.

Unlike mechanical switches, CMOS switches behave more like electronically controlled resistors. When open or 'off' they have very high resistance, hundreds of megohms, and when closed or 'on' they have low resistance, but not zero. The on-resistances will typically be a few hundred ohms which is still low enough for most switching applications. Like any IC they need power (only a few microamps), and they can only handle voltages that swing between the rails.

The 4016 and 4066† both contain four independent analog switches, one of which is illustrated in fig. 29a. To switch audio it's essential that both sides of the switch are biased up to the half-rail voltage or 4.5V, with R_1 and R_2. The blocking capacitors C_1 and C_2 should be chosen to give the desired cut-off frequency depending on whatever else happens to be loading the output, but 100nF will be suitable for most applications. If the signal comes directly from an opamp that already idles at 4.5V then it's not essential to pull-up that side of the switch, but if you're not sure do it anyway.

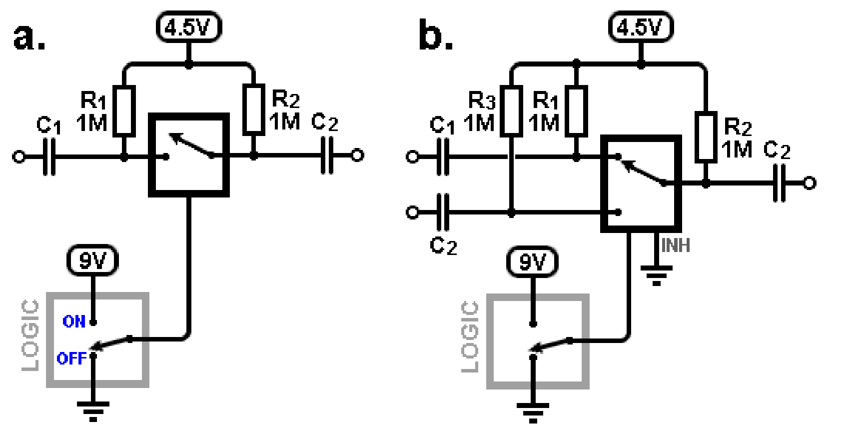

Fig. 29: CMOS analog switches. **a:** 4016 or 4066; **b:** 4053.

Each switch in the 4016/4066 has a control pin. Pulling this pin to ground turns the switch off, making it high resistance and blocking the audio. Pulling the control pin up to the rail turns the switch on, or low resistance. The control pin is high impedance so it consumes no current, so the control voltage can be derived from other logic ICs or from a mechanical switch, or whatever. You can control multiple CMOS switches with the same control signal.

Fig. 29b shows a similar switching circuit using the 4053. This IC contains three double-throw switches, so it can take the place of a 3PDT footswitch. Each switch has its own control pin as before, but this time 0V or 9V flips the switch from one position to the other. This IC also has an 'inhibit' pin which must be tied to ground to allow the switches to be controlled. Pulling it high will set all the switches to 'off' regardless of their individual control pins.

A minor shortcoming with CMOS switches is that they switch at the speed of logic, snapping instantly from one state to the other with no way to slow down the transition. If live audio is running through them this will result in an instantaneous interruption (a sharp corner or edge to the waveform) which sounds like a click. If there is a lot of treble-cut after the switch then the click might be filtered out and pass unnoticed, but if we need to avoid it completely –and with footswitch bypassing we usually do– then we need a soft switch or 'fast fade', which is better accomplished with JFETs.

5.2: JFET Soft Switching

Fig. 30a shows how a JFET is configured as a series switch. Both sides of the JFET need to be at the same DC voltage, so in a pedal environment this means pulling them both up to the 4.5V reference with R_1 and R_2. The blocking capacitors C_1 and C_2 should be chosen to give the desired cut-off frequency depending on whatever else happens to be loading the output, but 100nF will be suitable for most applications.

†The 4066 has lower on-resistance so it is preferred for pro-audio and hi-fi. Either type can be used for guitar effects.

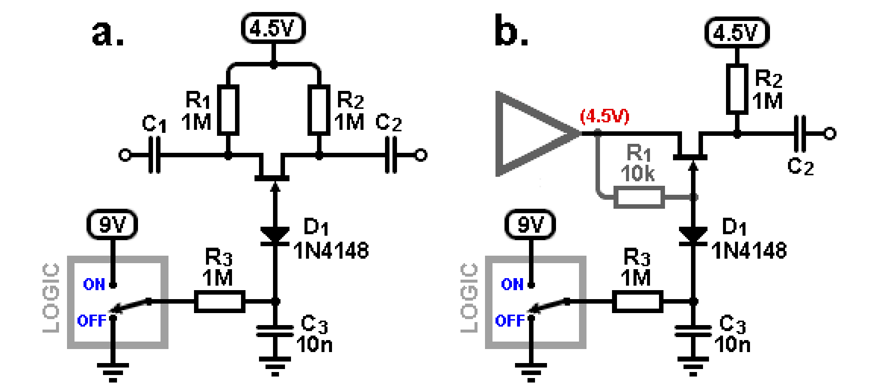

Fig. 30: JFET soft switch. Suitable JFETS include the J112, J113 and J201. The drain and source are interchangeable.

To switch the JFET off, i.e. to block audio, the gate voltage must be pulled well below the source voltage (in this application the source and drain are interchangeable; it doesn't matter which way around the JFET is connected, the source is whichever one happens to be at the lower voltage at a given moment). This happens when the switch is flipped to the ground position, pulling the JFET gate to ground through D_1 and R_3. It is essential that the gate voltage stays below the lowest audio peaks or the JFET will momentarily switch on and let the peak through. In fact, the gate must be *even lower* by an amount equal to the cut-off voltage of the JFET, $V_{GS(off)}$. We don't have much voltage to play with in a 9V pedal, so we need a JFET with the smallest $V_{GS(off)}$ rating we can find; smaller than −2V is ideal.* The J201 is rated for −0.3 to −0.15V and is perfect if you can get it, though it is obsolete. Most J113s and some J112s are also suitable, but it is worth testing them until you get one that reads less than −2V, using the method shown in fig. 31. You can use any other JFETs too if you search through them for ones that meet this test.

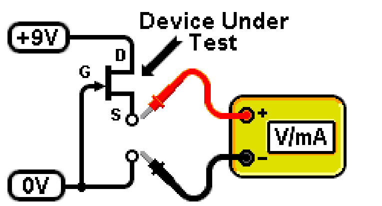

Fig. 31: A simple way to test N-JFETs. Set the multimeter to volts to measure $V_{GS(off)}$, and to milliamps to measure I_{dss}.

Returning to fig. 30, to turn the JFET on (so audio can pass) we need to pull the gate up to the same voltage as the source. But the source will be bobbing up and down with audio voltage, so we must let the gate follow it. This is why D_1 is needed. When the switch is connected to the 9V positive rail, D_1 becomes reverse biased and the gate voltage will be pulled up to the source voltage by the JFET's own internal leakage. R_3 and C_3 slow down the rate at which the gate voltage can rise or fall, since C_3 must charge or discharge through R_3. This in turn slows down the switching speed of the JFET. The time constant has been set at 10ms which creates a fast fade, too fast for the ear to detect any distortion when mid-way between off and on, but slow enough to produce a silent, soft switch.

The circuit in fig. 30a is general purpose; it can be used to switch signals anywhere in a pedal. But if the signal comes directly from an opamp that already idles at 4.5V then we don't need to pull up both sides of the JFET; the simpler version in fig. 30b can be used. R_1 is not essential but can be included to give extra pull-up, which lowers the on-resistance of the JFET. In both examples the 0V to 9V control signal could come from almost anything that switches from rail to rail, whether an actual mechanical switch or a logic circuit running from 9V. However, if we use the JFET in the virtual earth of an inverting opamp stage as in fig. 32, then the source will always be at 4.5V when 'on', so the control voltage can also be 4.5V (or higher). This means it could conveniently be controlled from a microprocessor running off 5V, for example.

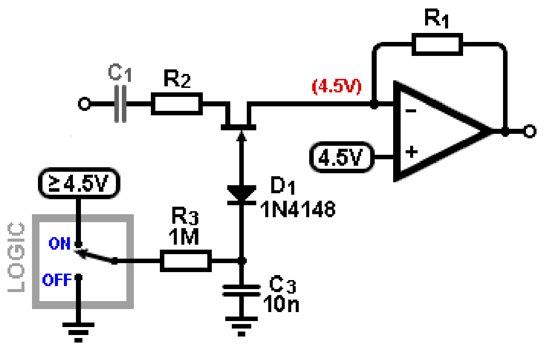

Fig. 32: If the JFET is in a virtual earth the control voltage can be equal to V_{ref} (or higher).

* We are helped by the fact that ordinary opamps cannot swing rail to rail, so the audio probably won't swing lower than about 1.5V above ground.

Fig. 32 used N-channel JFETs which are the most common type, but P-channel devices exist too. These work in the opposite fashion –you need to make the gate more positive than the source to turn the device off. You can use exactly the same circuits as before, except the diode must be flipped so it points *towards* the gate. You can even use one JFET of each type to make a two-way switch that operates from a single control voltage, as shown in fig. 33. Now one signal path turns on just as the other turns off (note the orientation of the diodes). Suitable P-channel devices include the J177 and many J176s if they are selected to have a cut-off voltage of less than 2V.

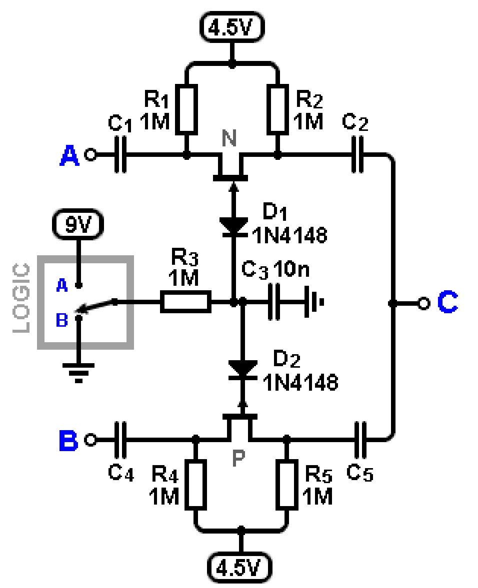

Fig. 33: Two-way soft switching using N- and P-channel JFETs.

Nevertheless, the scarcity of P-channel devices means most designers stick to N-channel JFETs throughout. Therefore, if we need to switch one JFET on at the same time as switching another off, we need two opposing control voltages. These are easily provided by a flip-flop circuit as described in the next section.

5.3: Momentary Footswitches and Flip-Flops

Many commercial pedals use a momentary footswitch. This is attractive to manufacturers as it means a low-cost PCB button can be used, with a specially-designed foot pedal enclosure and some sort of shock absorber –such as foam rubber– sandwiched between the pedal and the button, to absorb most of the impact. It is not easy for the DIYer to replicate this setup, but we can still use panel-mounted, momentary stomp switches, which have a pleasing smooth action compared to latching ones. Either way we will need some sort of electronics to turn that momentary button action into a latching control signal that can control the analog switches or JFETs. This could be done with a microcontroller of course, but the analog solution is a flip-flip circuit.

Fig. 34 shows the textbook two-transistor flip-flip circuit used in Boss pedals and countless others. Any NPN transistors will work. To visualise how it functions, imagine that Q_1 is already turned fully on so it acts more-or-less like a short circuit, pulling its collector down to ground. This means no voltage is applied through R_2 to the other transistor's base, so it must be fully-off and its collector is pulled up (to about 6V), which provides the voltage needed to turn Q_1 on in the first place. Each transistor is therefore holding its partner in the opposite state.

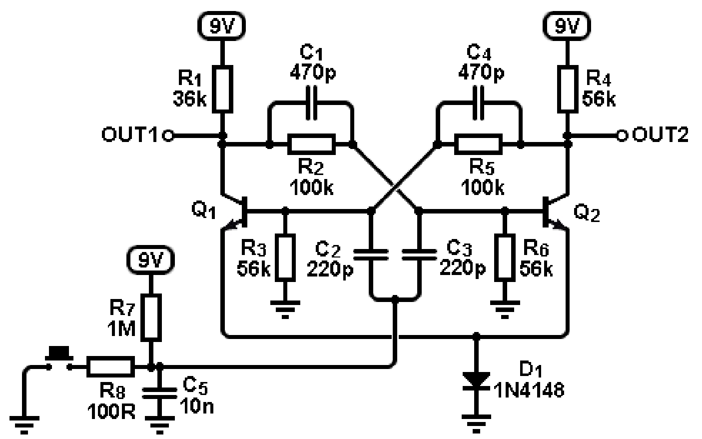

Fig. 34: Boss-type flip-flop circuit converts momentary footswitch action into latching control signals.

C_2 and C_3 are normally pulled-up to 9V through R_7, and when the footswitch is pressed it pulls them to ground. Since these capacitors momentarily look like short circuits this momentarily pulls both transistor bases to ground too. This make no difference to Q_2 which was already off, but it turns off Q_1 so its collector voltage rises. This sudden rise in collector voltage is passed through C_1 as a transient to the base of Q_2, turning it on, which pulls its collector voltage down. This sudden drop is passed through C_4 this time as a down-going transient that ensures Q_1 *stays* off. Hence the situation has flipped. Pressing the switch again will repeat this process in mirror image, flipping everything back again. The two outputs are therefore always opposites of one another (complementary), snapping alternately between 0V and

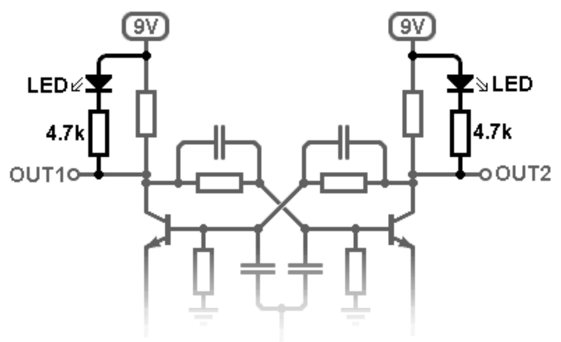

Fig. 35: Adding status LEDs to the flip-flop (one or both can be added as necessary).

6V every time we hit the footswitch. R_8 and C_5 filter out any glitches as the switch is pressed and released, when it might bounce between states. The two collector resistors R_1 and R_4 could be made equal but, by using dissimilar values as shown, the circuit will always power up with Q_2 on. D_1 effectively creates an elevated ground which allows the footswitch to reliably pull the bases *below* this local ground, for more reliable switching.

The two complementary outputs can now be used to control our audio switching circuitry. Adding a status LED is easy –the flip-flop transistors already behave like switches. Simply connect an LED and current-limiting resistor in parallel with one or other of the collector resistors, as shown in fig. 35 (4.7kΩ resistors are shown but they can be adjusted to get the desired brightness). You can even add LEDs to both sides of the circuit, as shown here, which will alternate according to the footswitch selection.

The Boss circuit has been around for a very long time but uses a lot of components –there are lots of ways a beginner could wire it wrongly. If you want an easier life then you might prefer to use a logic IC to do the job. Fig. 36 shows an example, similar to that found in many Dod pedals. This uses a pair of logic inverters which can be found in the CD4049 or HEF4049. To see how it works, imagine the output of inverter A happens to be high, causing C_1 to charge to 9V through R_2. The output of B must be low, and this is fed back through R_1 to the input of A, so everything is held firmly in this state. If the switch is now pressed the voltage on C_1 will be applied to the input of A, causing its output to go low and the output of B to go high, which again is fed back and holds everything in this new state after the switch is released. C_1 will now discharge ready for the next press which will flip the state over again. C_2 is not essential but can be included to ensure the circuit always powers up in the same state, with OUT1 high.

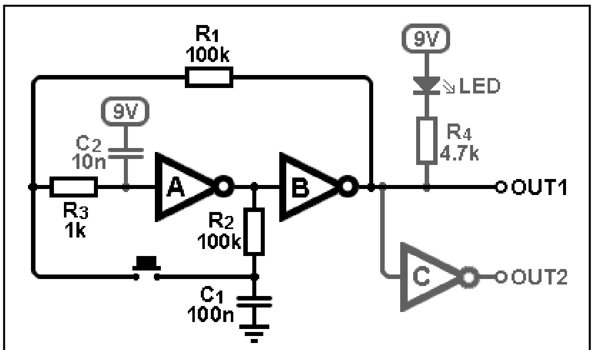

Fig. 36: Dod-type flip-flop circuit converts momentary footswitch action into latching control signals using a 4049 logic inverter IC.

Since the output always snaps between 0V and 9V it can be used directly to drive JFET analog switches or other logic circuits. A status LED can be added as shown; it is better to arrange the LED this way because the IC can sink more current than it can source. The 4049 includes six individual inverters, one of which could be used to create a complementary output as indicated here. Any unused inverters should have their inputs grounded (leave their outputs unconnected).

5.4: Managing Multiple Footswitches

Fig. 37 shows another way to deal with momentary switches, this time up to four. Whichever button is pressed, the corresponding output will be pulled up to 9V (high) and the others will be automatically reset to 0V (low). The CD4028 (or HEF4028) is a decoder IC that latches the change so the correct line stays high after the button is released. In other words, the circuit only ever selects *one* of the four outputs when the corresponding momentary button is pressed. The IC cannot drive much current itself so the output resistors should be at least 4.7kΩ. The control signals can then go on to feed other logic ICs or JFET switches, etc. The indicator LEDs are optional and only one limiting resistor is needed (R_5) since only one LED is lit at a time. If you only need three buttons then leave just leave out S_4, R_4, D_4 and D_8.

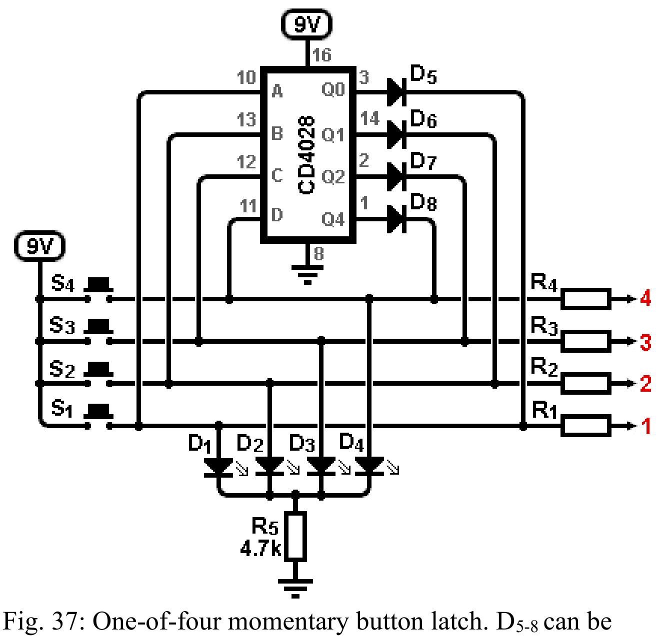

Fig. 37: One-of-four momentary button latch. $D_{5\text{-}8}$ can be 1N4148. $R_{1\text{-}4}$ should be at least 4.7kΩ.

5.5: Buffered Bypass

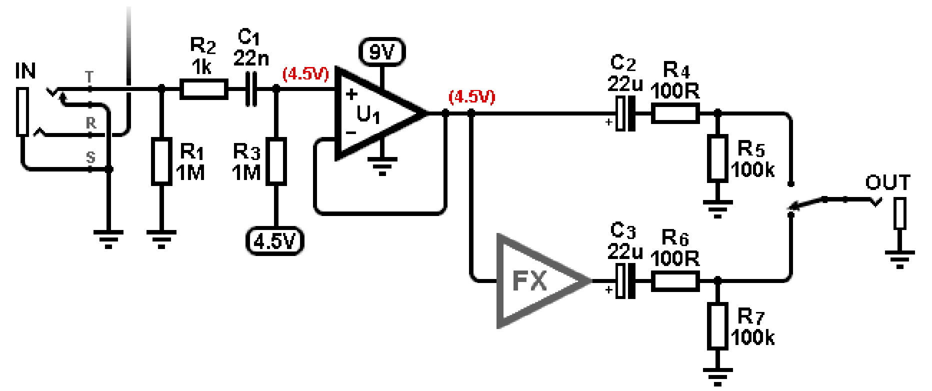

Fig. 38: Example of buffered bypass using mechanical switching.

Many pedals that use electronic switching methods also leave one or more buffers in circuit. For example, fig. 38 employs an input buffer U_1. This means the loading on the guitar pickup never changes and the pedal always does the hard work of driving whatever comes after it, whether it is in bypass or not. Buffered bypass may use purely mechanical switching as shown here, but we can of course utilise JFETs or CMOS switches as in fig. 39.

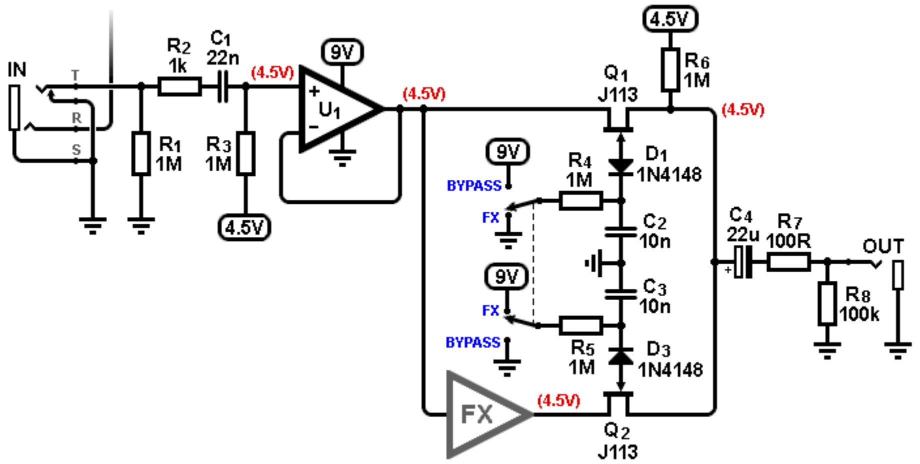

Fig. 39: Example of buffered bypass using JFET switching.

Since JFETs provide a fast fade there is less worry about pops caused by tiny differences in the idle DC voltages of the two signal paths, so a shared output network has been used here. However, you could use individual output capacitors (plus an extra pull-up resistor) as in fig. 33 earlier, if necessary.

6: Tips 'n' Tricks

The supremely low output impedance of opamps allows a neat way to switch between them using a single-pole switch, as shown in fig. 40a. This can save money, and space on a PCB. When the switch is open the signal from B flows through the 10kΩ resistor to the output. Closing the switch allows the low output impedance of A to completely override the signal from B. The resistance is a compromise between not actually shorting the two outputs together, while not introducing too much noise and increasing the total output resistance from B; 10kΩ is just small enough that it can reasonably drive an output directly without further buffering, if necessary. The same idea can be extended to an SPDT switch with a centre-off position, allowing us to switch been three opamps, as shown in fig. 40b.

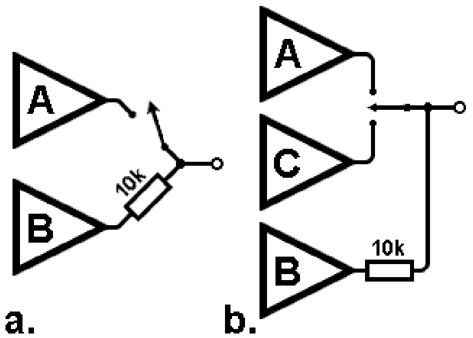

Fig. 40: **a:** Switching between two opamps using an SPST switch. **b:** Switching between three opamps using a SPDT switch with centre off.

This same principle can also be used to make a highly effective blend pot, as in fig. 41 Here the output can be swept smoothly from 100% A to 100% B, with any combination in between. If there is any difference in the DC voltage at the output of each opamp then it will be necessary to add a coupling capacitor to one or both, to prevent rustling noises when turning.

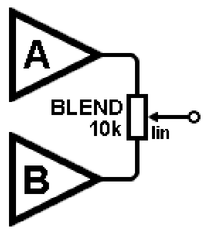

Fig. 41: Blending between two opamps.

6.1: Good Switching Practice

Fig. 42a shows a typical beginner's approach to switching between two components –perhaps two different coupling capacitors, each producing a different amount of bass cut. This will work but is not ideal because the circuit is completely broken, momentarily, when the switch is flipped. Depending on the charge on the capacitors or on the signals present at the time, this can lead to an annoying pop or thump. A better way to do this is to leave the highest-impedance component in circuit at all times, and switch the other one in parallel with it, so the circuit is never completely broken. We could choose component values so the parallel combination gives the same result as C_1 alone in the previous case. Fig. 42c shows an alternative arrangement where we short out one component or the other, again avoiding complete circuit interruption while achieving exactly the same end result as in the first example. The same principle can be applied to resistors.

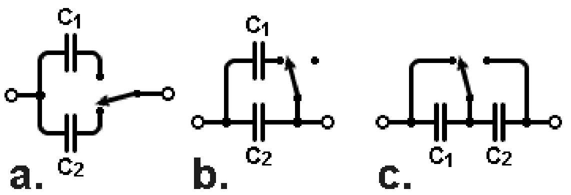

Fig. 42: Breaking a circuit while switching can lead to pops and clicks.

7: Signal-Presence Indicators

A signal-presence indicator can be useful for knowing when a piece of equipment is receiving signal, especially in a complex signal path. Figuring out why there is no sound coming from of a rack of effects with dozens of knobs and switches can be frustrating! Besides, a light that dances along with the music is also a cool visual effect –a popular styling is to use an engraved acrylic faceplate with the LED mounted on the edge, bathing all the engraved edges with a soft glow.

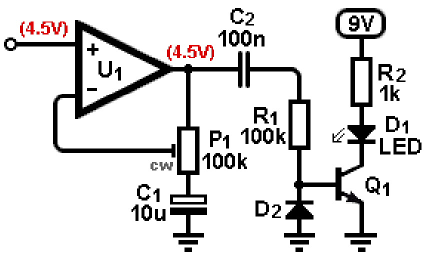

Fig. 43: Simple signal presence indicator or sound-to-light circuit.

Fig. 43 shows an economical signal presence indicator, which in the DIY world is sometimes called as a sound-to-light circuit. It is simply a non-inverting amplifier driving a transistor, Q_1. Any opamp and NPN can be used. When the output signal reaches about $0.6V_{pk}$ the transistor will start to turn on and allow current to flow in the LED, which will grow brighter as the signal level increases. D_2 allows C_2 to discharge during negative half-cycles and can be any diode. Trimpot P_1 allows the gain to be adjusted, but could be replaced with fixed resistors of course. If the circuit is monitoring the signal directly from the guitar then it will likely need a gain of around ×20 to ×40, whereas if it is placed later in the signal chain less gain may be necessary. Don't forget the input needs to be biased up to 4.5V.

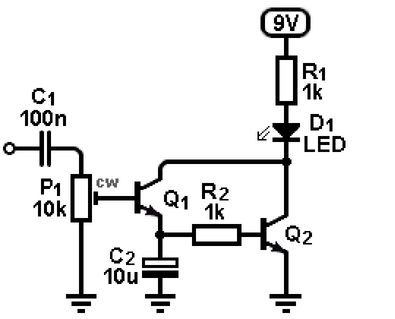

Fig. 44: Transistor signal presence indicator or sound-to-light circuit.

If you have no spare opamp, fig. 44 shows a transistor solution used in some Boss circuits. When the input audio exceeds $0.6V_{pk}$ Q_1 turns on and lights the LED while also charging up C_2. When the audio stops, the voltage stored across C_2 keeps Q_2 turned on for a little longer while it discharges, giving the LED a short fade out. P_1 adjusts the sensitivity. The transistors can be any NPN type.

8: Driving Headphones

Headphones and loudspeakers can be difficult loads to drive because they need a reasonable amount of power, and they are very low impedance. Headphones are normally 16Ω to 32Ω (each ear). A typical listening level needs only 0.1mW but loud passages could reach a hundred times more, or 10mW. A premium-quality headphone amp can deliver as much as 100mW of continuous power (beyond a couple of hundred milliwatts there is the risk of dangerously-high sound pressure levels in the ear and the headphones may burn out, so be careful of plugging headphones into outputs designed for loudspeakers). However, for casual guitar monitoring and bedroom practice a few milliwatts is enough, and is achievable with opamps running at 9V. By the way, headphones are wired with the jack tip to the left ear, ring to the right ear.

One of the simplest ways to drive headphones is to use a 'beefy' opamp like the NE5532 or NJM4556, which can drive much heavier loads than most. Fig. 45 shows an example. In this case we can drive both left and right ear from the same opamp, since guitar signals are usually mono. If you need stereo then simply break the connection to R_4 and drive it from a duplicate amplifier circuit (you get two opamps in an NE5532). Note that because phones are very low impedance the output coupling capacitors need to be fairly large to get full bass response. The build-out resistors R_3 and R_4 are added for stability, and because headphones are *designed* to be driven from a non-zero source impedance.

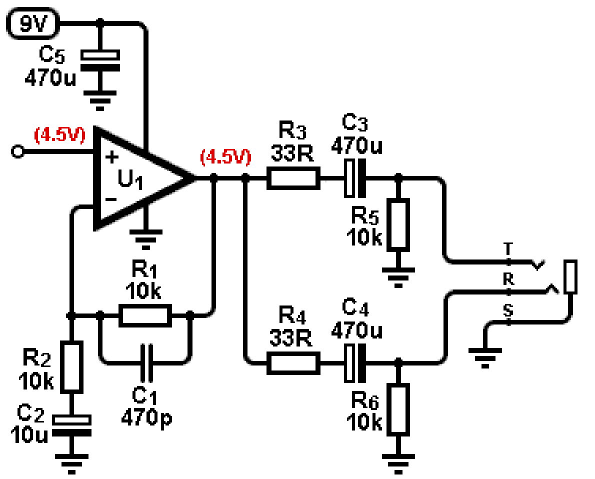

Fig. 45: Single NE5532 or NJM4556 headphone driver (this will not work with most other opamps!). Delivers about 17mW into 32Ω or 12mW into 16Ω, but supply current is fairly high. The voltage gain can be adjusted with R_1/R_2 in the usual way.

This circuit can deliver 17mW into 32Ω with distortion below 0.02% until clipping. The gain is set with R_1/C_1 and R_2/C_2 in the usual way and can be adjusted to suit other circumstances, including unity gain. The power supply bypass capacitor C_5 must be placed fairly close to the IC to ensure stability at full power. The price we pay for this excellent performance is the supply current which is 9mA for an NE5532, rising to 20mA at full power. This is fine if we get power from the wall, but it's not great for battery life, in which case the following circuit is a better choice.

Fig. 46 shows a basic headphone driver using a regular TL07x opamp plus a pair of 'helper' transistors. At very low levels the opamp drives the headphones directly through R_3, but when the opamp's output voltage exceeds $0.6V_{pk}$, Q_1 and Q_2 alternately turn on to provide the extra current needed. This transition does lead to some crossover distortion which would worry an audiophile, but performance is more than good enough for guitar monitoring. R_1/C_1 and R_2/C_2 are the usual feedback components and can be adjusted to get whatever gain you need, including unity gain.

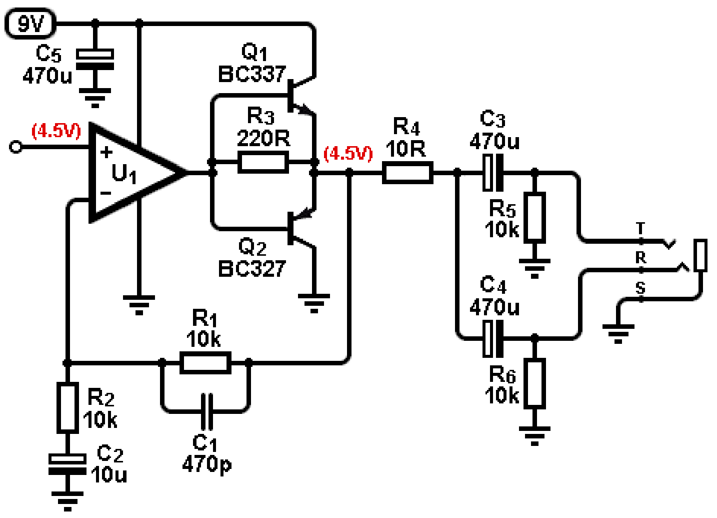

Fig. 46: Using transistors to boost the power of a wimpy opamp like the TL07x while maintaining low idle current consumption. It will deliver about 14mW into 32Ω or 18mW into 16Ω. The voltage gain can be adjusted with R_1/R_2 in the usual way.

Using a TL07x opamp the circuit can deliver 14mW into 32Ω, with distortion at about 0.2% at 1mW. The best feature is that the transistors are both off at idle, meaning the supply current is purely that of the opamp (1.5mA for each TL07x section). Current only increases when the extra power is actually needed, reaching 10mA at full output. Also, it does not need special biasing or protection components, unlike more advanced transistor designs. This makes it a great low-cost headphone output. A duplicate circuit could be used to feed C_4 for stereo applications.

Headphone jacks used to be ¼" (6.35mm) and pro-audio equipment still uses this standard. However, the rise of personal music players and smart phones has pushed consumer headphones towards the smaller 3.5mm jacks. You can of course buy adapters for converting one sort of plug to the other. Which size of headphone socket you build into a pedal is down to personal preference. But what if we want to use the pedal for headphone listening *or* as part of a normal pedal board? The next section explains how to use the same jack socket for both functions.

8.1: Combo Heaphone / Line Output

A headphone output is really a line output with the ability to drive a heavy load when necessary. However, headphones are stereo whereas guitar signals are normally mono. That means if you plug a mono cable into a stereo headphone jack, one of the headphone driver channels will be shorted to ground by the sleeve of the jack plug. In other words, the headphone driver is now very heavily loaded by nothing but its own build-out resistor. This is a problem for battery life since the driver will now needlessly demanding maximum current from the battery even though we're only trying to plug into another pedal or amp, not into headphones. Moreover, having one channel shorted might drag down the level of the still-active channel, and in some cases it might actually damage the driver circuit.

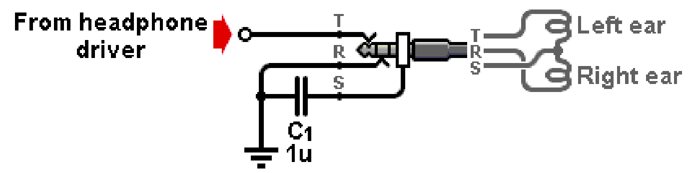

Fig. 48: Combination headphone and (mono) line output jack wiring.

As long as we're only dealing with a mono guitar signal there is dirty trick for avoiding these worries completely. The trick is to wire a stereo (TRS) jack socket so the phones are driven in series, as illustrated in fig. 48. Notice that the ring terminal is grounded, *not* the sleeve as would normally be the case! With this arrangement you still get sound in both ears when monitoring with headphones, or you can safely plug in a mono guitar cable –the sleeve and ring will be shorted together by the body of the mono plug. Thus we get a dual-function output jack that works with headphones or as a regular (mono) line output.

There is a compromise here, however. When wires in series the sound in each ear will be out of phase. This has the effect of making it seem like the sound is coming simultaneously from opposite sides of the room rather than from inside your head as with normal headphone wiring. This weird effect can be improved slightly by adding the 1µF capacitor C_1 from sleeve to ground. This will reduce the treble in one ear and boost it in the other, as well as bringing the relative phases closer together, partially slewing the image back towards the middle of your head. This capacitor also helps to shunt hum and interference off the headphone cable shield to ground. It's not perfect, but for casual monitoring and bedroom practice it's good enough.

9: Driving Loudspeakers

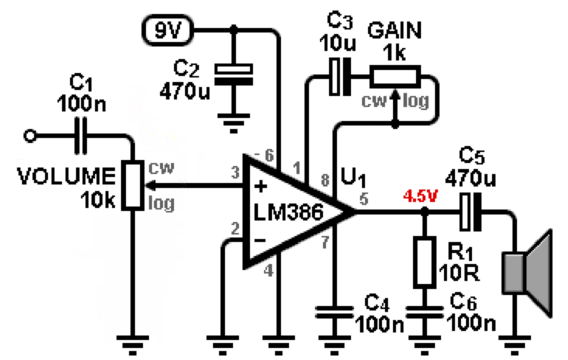

Fig. 49: The LM386 is a small power amplifier IC useful for driving loudspeakers or heavy loads.

We're not interested in big power amplifiers here, but we might want to drive a speaker to practice volumes, which only needs a few hundred *milli*watts. However, most loudspeakers are 4Ω or 8Ω which is too low for an opamp to drive, even a beefy one. The simplest alternative is to use a special-purpose power-amp IC like the LM386. A nice feature of the IC is that the input does not need to be biased to half-rail, it should be referenced to ground –biasing is taken care of internally. The output will automatically rest as half rail. Cheap PCB kits are readily available and can be easily modified. Fig. 49 shows a typical circuit.

The gain of the IC can be set with an external resistor between pins 1 and 8, allowing us to push it into clipping. In this example the gain pot adjusts the gain from 40 (32dB) to 200 (46db), as given in the datasheet. If you leave these pins unconnected the gain will be lowest at 20 (26dB). R_1 and C_6 form a filter sometimes called a Zobel network, which is needed to stabilise the IC against the inductance of the loudspeaker. The output coupling capacitor C_5 needs to be quite large to pass full audio into a 4 to 8Ω speaker, but it could be smaller of course, to cut bass for a tighter sound. C_4 is not essential but improves the rejection of power supply noise.

With a 9V supply the circuit can deliver up to 0.6W into an 8Ω speaker (enough to annoy your neighbours) with about 0.3% distortion. The IC is highly efficient, consuming less than 5mA when idle, increasing to over 100mA at full power, so a battery will last for a reasonable duration if you're not playing at maximum all the time. The supply voltage could also be increased to 15V maximum, for more output power, but you probably won't notice much difference in actual loudness.

A disadvantage of the circuit is the low input impedance, as set by the volume pot and the 50kΩ input resistance of the IC itself. To plug a guitar in directly it would be better to add an input buffer. For even higher powers you can buy ICs that must be mounted to a heatsink, or ready-made class-D amplifier modules, but that is straying out of pedal territory.