When it comes to buffers, the most important thing is NOTHING

In other words, a great buffer shouldn't sound like anything…

Buffers? Why should you want one? Electric guitars, basses, steel guitars, etc… have all been around for decades without much in the way of buffers, so why change now? What's the big deal?

True, over the past 80 odd years since the Rickenbacker Electro Stringed Instrument Company began to produce the first electric guitars, buffers haven't caught-on much. Older buffer designs have some trade-offs; tonal coloration, noise floor, distortion, etc… problems which for most people outweighed the benefits. However, recent breakthroughs in buffer technology have made nearly ideal buffer circuits available with all the benefits and none of the trade-offs that plagued old designs. And, the benefits are tremendous!

There are some great reasons to use buffers and many D.I.Y. projects we could get into… but first, let's get crystal clear on what a buffer is all about and form a foundation to build upon. This may get a bit technical, but take the time to understand this and great tone will be easy.

The fastest way to understand what a buffer does is to hear one in action, so here's a CD quality WAV file for your listening pleasure… You'll want to hook-up your high-fidelity speakers or headphones to do this justice. Take a listen to this:
https://soundcloud.com/creationaudiolabs/redeemer-steel

Once you've listened to the sample, you might be pondering, "sounded like there was a blanket over the amp, then it was then taken off… Or, sounded like they replaced worn-out old strings with a brand new set… Or, somebody took the cotton out of my ears…" What's going on here? This is simply an example of installing a buffer inside an instrument and then switching the buffer in and out with a bypass switch… This was a good sounding instrument to begin with, so it's easy to understand why folks would think they didn't need to add a buffer, but then when you hear the improvement the question becomes "how could we have gone so long without it?"

Words to the wise, not all buffers are the same. Some buffers are less than ideal (especially older designs) and they may color the sound, or add boost, noise and distortion of their own. An ideal buffer isolates the signal coming into it from whatever you connect to the buffers' output, without coloring and without adding any noise or distortion of its own. When it comes to buffers, the most important thing is NOTHING. In other words, a great buffer shouldn't sound like anything…

So, then why did we hear such a dramatic difference in the example WAV file? The short answer is that the buffer didn't add anything; it just prevented the loss of tone you were getting when the buffer was bypassed. The cables and amp connected to the instrument were loading down on the tone of the pick-up; but, when the buffer was engaged, you hear what the pick-up really sounds like.

For a more detailed answer, we need a basic understanding of something called “impedance”. Once you have a good mental picture of how impedance affects a signal chain, you will be able to solve most of the situations that tend to rob tone and generate noise in many set-ups so it’s worth the effort to learn more about it. If you are into electronics, and if impedance is a bit of a mystery for you, please take a few minutes to read the sidebar on “Getting your Z’s” accompanying this article (see end of this document). If you are ready, let’s get into the nitty-gritty…

Why the dramatic difference in the WAV file?
With no buffer, a guitar’s output impedance is fairly high. Typically, it will be something like 10K ohms for passive pick-ups. This impedance gets even higher as the volume control (typically 250K) is dialed down; the output impedance of a guitar could rise tens of thousands of ohms when the volume knob is dialed back because the resistance of the volume pot is added to the impedance of the pick-up. When you connect this to the input of an amplifier the signal is divided between the guitars’ output impedance (the signal source impedance) and the amplifiers’ input impedance (which loads down the signal).

Here’s a visual…
For the output impedance of a guitar imagine a tree, the higher you go, the younger, thinner and more flexible the branches get. Low output impedance at the guitar would be represented by the low, thick, stiff branches; and high output impedance would be represented by the high, thin, flexible limbs. That’s for the guitar…

Now, for the input impedance of the amp imagine a weight. Low input impedance at the amp would be represented by a heavy weight; and high input impedance would be a light weight.

Now, hang the weight on a branch. If the branch is thick, and the weight is light, then the branch will not sag much. However, if the branch is thin, or the load is heavy, then the branch will start to bend. As the branch gets thinner or the load gets heavier the more the branch will sag. Like Charlie Brown’s Christmas tree (for you old folks). The same is true for your guitar signal. If your guitar output impedance is low (thick branch), and your amp input impedance high (light weight), then your signal will not lose much tone; but, if your guitar output impedance is high (thin branch), and your amp input impedance low (heavy weight), then your signal will sag and start to lose fidelity.

If you really want to get technical, consider this example: If the guitar's output impedance is 10K ohms, and the amps input impedance is also 10K ohms, the signal would be divided evenly between the two. Because of this, only half of the original signal will make it through. Think of it like a balancing scale. So what if the amps input impedance was 100K ohms and the guitars output impedance stayed at 10K ohms? We are now dividing the signal across a 10K to 100K ratio. This results in 90% of the signal passing through to the amp. Low guitar output impedance plus high amp input impedance equals more signal getting to the amp. That's why a good amp will have very high input impedance. An amp with a 1M ohm input would get about 99% of the signal from a 10K pick-up.

Lowering the guitars' output impedance has the same effect as raising the amps' input impedance, but with the added benefit of noise immunity (more on that in a minute). So, what about choosing lower impedance pick-ups, wouldn't that help? It turns out that high impedance pick-ups are more sensitive (louder, hotter, brighter) for the reason that the impedance of the pick-up is a load on the strings. The vibrations of the flux surrounding the pick-up is a signal source with an impedance of some value (depending on the thickness of the strings, strength of the magnet, etc…) and the impedance of the pick-up is a load on that signal source, so the higher the pick-up impedance, the more signal gets through. So, lowering the impedance of the pick-up is a trade-off that wouldn't really help much… Sure, the signal from the guitar to the amp won't sag as much, but the signal from the strings to the pick-up will sag some, so it's a compromise. In the end, you have to like the tone your pick-up produces, and low impedance passive pick-ups haven't caught on in the market place.

Cables:

It would be nice if all you had to do was turn-up the amp to make-up for the losses. But, it's not that simple. The cables you're using to connect the guitar to the amp have their own impedances which are also hanging on the guitar's output. A cable has a capacitive impedance that changes over frequency; it starts out as a high impedance at bass frequencies and becomes a low impedance at treble frequencies. A typical 20ft guitar cable might act like a nice high 2M ohm load impedance at bass frequencies but drops down to be a heavy 10K ohm load at treble frequencies… In other words, with a 10K pick-up almost 100% of the bass can get through, but only about half the treble can make it through your cable to the amp! It just gets worse when you dial back the volume knob on the guitar, that raises the guitars' impedance and everything turns to mud! The amount of treble roll-off will be different with every different cable you use; so you can't just make-up a bit of treble on the amp or stick a treble bypass cap on the guitars' volume pot and forget about it… It's always been that way – most people never realize what's been missing because it was never there to begin with!

When you add a good buffer inside the guitar the problem can be totally solved. An ideal buffer acts to isolate what goes on inside the guitar from whatever might be going on outside the guitar.

On the inside of the guitar:

The buffer used in the example WAV file has an input impedance well over 20M ohms. Coming from a 10K pick-up, the signal loss is divided $1/2000^{th}$ across the two impedances; so 99.95% of the signal enters the buffer. Even if you raise the impedance inside the guitar by dialing down the volume control you still get 99.5% of the signal, left after the volume pot, into the buffer. For all practical purposes you can say it's 100% either way! So you can roll back the volume and it doesn't turn to mud.

On the outside of the guitar:
The buffer used in the example WAV has an output impedance of less than 50 ohms. Suppose you were given a crappy guitar cable that has the impedance of a 5K resistor at treble frequencies? Without the buffer you would lose about 67% of the highs; but with the buffer, the signal loss is divided 1/100th across the two (50 ohms/5K ohms) and you still have 99% of the treble making it through the cable to the amp! You can still buy a $100 cable – but with a $50 buffer installed, it won't hurt your signal to use a $10 cable.

Also, with such a low output impedance, you can now plug your buffered guitar or bass directly into the line or mic input of a sound system without the need for a tone-robbing direct box. The 50 ohm output impedance of a buffered guitar can easily feed the 10K ohm line input impedance of a typical audio console with practically no signal loss.

What's really cool (to geeks like me), is how a low impedance signal traveling through a cable is almost completely immune to picking-up stray noise and cable static (that micro-phonic sound that cheap cables make when you shake them around). Here's a visual, remember the tree? Noise is like the wind, the higher thinner braches (high impedance signal wires) pick-up and lot more wind and move around (picking up noise from the environment). The lower thicker branches (low impedance signal wires) hardly move at all (even though there is noise in the environment, it doesn't affect the signal as much). Cables driven by low impedance unbalanced outputs can be nearly as immune to picking up noise as cables in a balanced signal connection.

What about active pick-ups? Active pick-ups are essentially pick-ups with built-in buffers. However, they have a few limitations. The most notable is that they can't have a truly low output impedance. They typically have about 2K ohms output impedance (more than 40 times higher than the buffer in our example). They have to do this on purpose because you want to be able to blend together two or three pick-ups; and on guitars with two separate volume controls, rolling the volume to "0" ends up shorting its pick-up to ground. So they have to add the 2K resistor to the output of active pick-ups to prevent them from shorting out to each other or to ground. Because they can, active pick-ups will typically use 25K volume pots, so when you dial back the volume the output impedance only raises a few thousand ohms (you can't do that with passive pick-ups because a 25K volume pot would load the pick-ups down before the signal ever gets out of the guitar!) Active pick-ups might be better for driving the cables and the amplifier than a passive guitar, less sag and mud, etc… but it's not as good as putting an overall buffer right before the output of the guitar and lowering the overall impedance as much as possible. Also, with active pick-ups you hope they used a good buffer because you're stuck with the sound they have, no room for experimenting with bypass switches, etc…

What about a bypass switch? Some effect pedals, especially old discrete designs like the infamous Fuzz Face might sound better with an un-buffered passive pick-up (again, impedance is the reason). You can't bypass the built-in buffer of an active pick-up, but you can use a switch to bypass an overall output buffer on a passive guitar – that's exactly what was done to record the example WAV file. Also, imagine if the battery suddenly dies in the middle of a set, it would be nice to bypass the buffer and be able to keep on making music… FYI, some buffers, like the one used in our example WAV, still pass signal without power so you don't always have to have a bypass switch for that reason alone.

Now, I can hear the critics… "Suppose I like the muddy sound?" Well, if you start with a container of clean water you can always muddy it up later (all it takes is a spoonful of dirt); but if you start with a container of muddy water, it will always have some mud in it no matter how much clean water you add later… In other words, if you start with a clean guitar tone, you can muddy it up on purpose with an effect; but, if you start with a muddy guitar tone, you can try to process out the mud, but you will never get back to clean. You'd also be processing the original signal mixed in with the mud, so by attempting to filter out the mud; you filter out some of your original tone as well.

Another critic might point out that "by the time you add all your pedals and amplifier to create your unique sound, there's so much added distortion and noise why should you care if the signal was totally clean to start with?" Suppose you are cooking up a batch of soup? You add in vegetables, herbs and spices (your FX pedals); and you've got a great recipe all your own! Now, would you rather start with a pot of clean water, or a pot of water with a spoonful of dirt in it?

Then there's the technical critics who can point out that "the guitar's cable capacitance combined with the guitar's pick-up inductance creates a unique response curve that is a part of my sound". Let me point out that different guitar cables are going to have different capacitance values; if your special cable ever goes bad and you're forced to borrow another one, there goes a part of your sound. However, with a buffer you can deliberately add capacitance inside your guitar to model the unique response curve of that perfect guitar cable (but that's a subject for another article); meanwhile the buffer protects your sound from the unpredictable loading effect of various cables and pedals on the outside of your guitar. If you really want the mud in your sound for a particular effect, you can install the buffer with a bypass switch for those occasions.

To sum things up, an ideal buffer will have a very high input impedance (at least several mega-ohms, the higher the better), a very low output impedance (at most 250 ohms, the lower the better) and does not sound like anything – no tone, no boost, no distortion, no noise, no nothing! It should only take what the guitar gives it and send that identical signal out – only the impedance changes. Once your guitar is buffered, you will be able to plug into almost anything using almost any cable without losing any signal in the connection. So whether you go wireless, through a pedal chain or directly into a mixer, your original tone won't suffer.

Now that you have a better understanding of the trade-offs, you can decide the best way to manage your particular set-up. If you have any questions, comments or criticisms; or if there's a topic you'd like me to address in the future, feel free to contact me through our website at: www.CreationAudioLabs.com.

“Getting your Z’s”

Since I don’t know who might be reading this, I can’t assume you know electronics 101, so I am going to get basic. For you advanced readers, it doesn’t hurt to review the basics once in a while…

To understand how impedance affects a signal, it helps to get clear on how resistors, capacitors and inductors work; and what they do to a signal. You’re also going to want to understand how voltage dividers work. I’m going to attempt to explain these things without getting into Ohm’s law or any math…

The place to start is with the resistor. A resistor is a device with a fixed impedance. Its resistance value is the same as its impedance value. What it does is resist (or impede) the flow of electrons around a circuit. In elementary school, we connected various light bulbs with lantern batteries, wires and switches to demonstrate how electricity flows around a circuit and makes things happen. If the switch was connected, current would flow and the light bulb would come on. The closed switch is like a zero ohm resistor in that it doesn’t impede the flow of electricity at all. An open switch is like a resistor with infinite impedance in that it completely stops the flow of electricity. The relationship between the value of an impedance and the flow of electricity, if you want to dig into it more, is described by Ohm’s Law.

Capacitors and Inductors are devices with a complex impedance. Whereas the impedance of an ideal resistor has a fixed value at all frequencies, the impedance value of capacitors and inductors change with frequency.

An ideal capacitor will start off with an infinite impedance at zero hertz and move towards zero ohms at higher frequencies. Inductors are just the opposite, ideally they will start off with zero ohms at zero hertz and move toward an infinite impedance at higher frequencies.

Voltage dividers are simply circuits that divide voltages. Examples of voltage dividers would be the faders on an audio console, or the volume pot on your guitar. The signal is applied to the top of the fader, which is just a long resistor to ground, and as the wiper is moved along the fader it divides that long resistor into two shorter resistors. The signal that comes out at the wiper is a divided down version of the original signal at the top of the fader. That would be an intentional voltage divider meant for a purpose, but because the world isn’t perfect, there are unintentional voltage dividers that can have detrimental effects on your tone.

Here’s where I hope you are going to get that “Aha” moment … In the real world, every output has some sort of output impedance and every input has some sort of input impedance. Like the two halves of a fader, the output impedance of a guitar would be like the resistance between the top of the fader and the wiper; and the input impedance of the amp would be like the resistance between the wiper and the bottom of the fader. ~Selah (read that again, then pause and calmly think about it!).

If we were just talking about pure resistances, you would make up for the loss by turning the amp up a notch and that would be the end of that. But the pick-up in a guitar is a big inductor; imagine adding a resistor to the top half of the fader that increases in value at higher frequencies. And, the cable you use to connect the guitar to the amp has capacitance, like adding a resistor from the wiper to ground that decreases in value at higher frequencies. If you are still with me, then you are starting to get the picture that the higher frequencies are being rolled off. And, just in case you think that's the rest of the story, let me throw a wrench into your gearbox; capacitive impedance and inductive impedance are complex numbers (numbers with phase and magnitude) so they don't divide in a nice way. Depending on your pick-ups' inductance and your cables' capacitance there can be a bump around 3 or 4 KHz.

For our purposes, 99% of the time you normally want the output impedance of a piece of gear to be as low as possible and the input impedance of the next piece of gear to be as high as possible to minimize that unintended voltage divider effect. That's the rule of thumb I want you to leave with. But there are a few things to keep in mind when applying this rule of thumb.

A low output impedance is less likely to pick-up stray noise, but having a high input impedance is just the opposite. Fortunately, the output impedance will dominate in the noise war as long as things are all connected; but if a dirty pot or switch in a guitar creates a momentary disconnect, having too high an input impedance to the next stage can exaggerate those popping switches and scratchy pots. If you are trying to design an amp with infinite input impedance, you better be sure to drink your Ovaltine and check your noise specs.

Also, guitar pick-ups have to have high output impedance to be sensitive; you can't have a really low output impedance pick-up and get a useful signal too. So you can't apply this rule of thumb to designing a passive pick-up.

And, sometimes you want to match impedances. Matched impedances deliver the most power. A great example of wanting to match impedances is when you use a transformer to power a speaker. Also, when hooking up some vintage gear, especially if they use transformers, you want to match impedances to "power" that input transformer…

So to sum it up, when connecting gear an unintended voltage divider is formed across the output impedance of the first piece and the input impedance of the second piece and some signal is lost. When capacitance and inductance is involved, this can color the tone and cause phase shift. To minimize these effects you usually want output impedances to be as low as possible and input impedances to be as high as possible. If you have any questions get in-touch and I'll try to find the answer.

About the author: Alex "Skip" Welti is currently the V.P. of Research at Creation Audio Labs, Inc. a Nashville based pro audio service facility which also designs custom circuits and upgrades for pro audio gear and manufactures a line of products for guitar and bass. Skip is an abbreviation of "Skipper", a nickname Alex earned as leader of the Soundcraft USA service crew before Creation Audio Labs opened. Alex spent ten years at Soundcraft where he was the U.S.

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