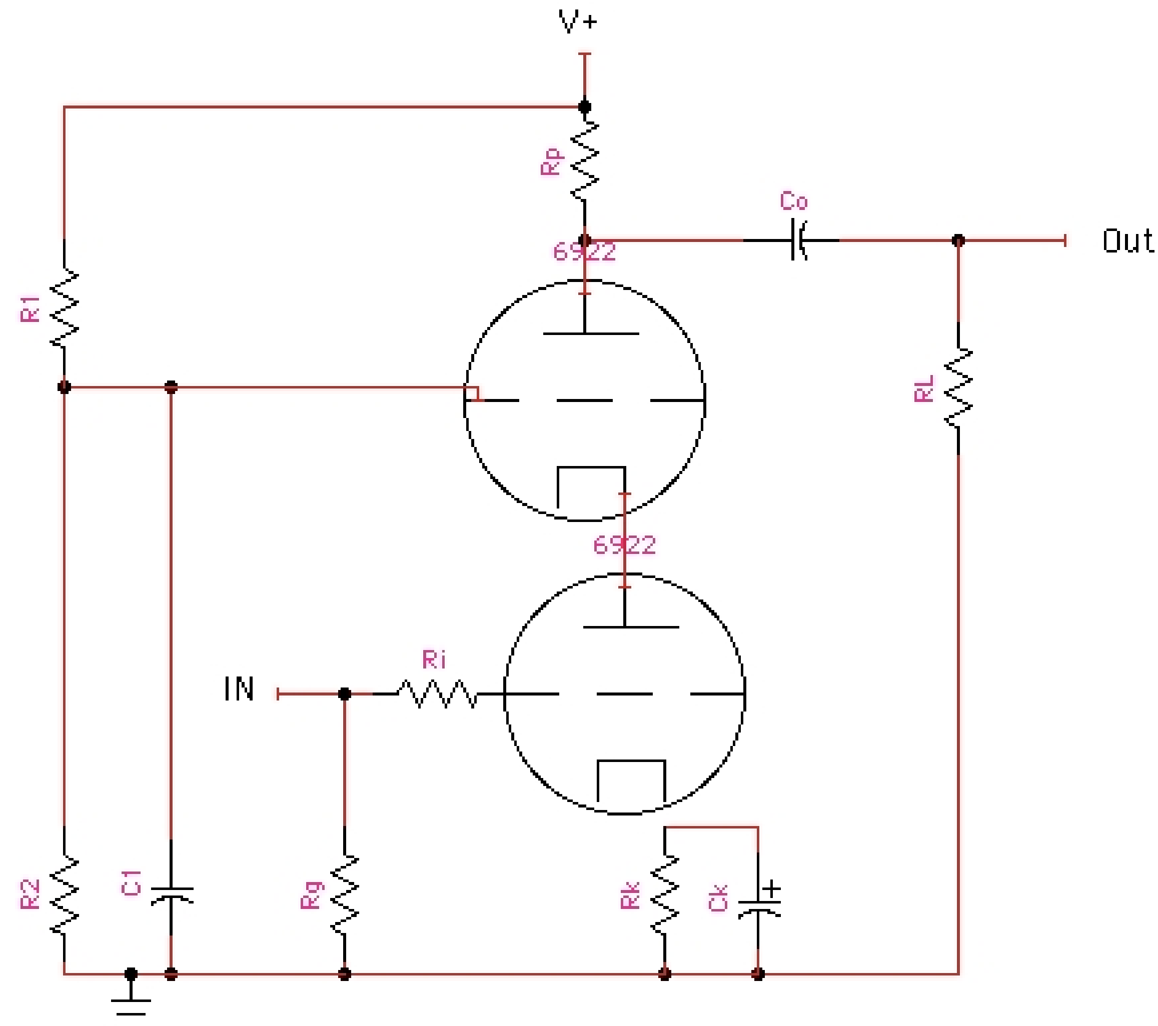
"Cascode Circuits in simple terms for the Budding DIY'er."
Alex Kenis, Aug 2005



INTRO
Ah the mysterious cascode. It can be quite an amazing circuit if properly implemented... which in itself is quite an amazing pain in the butt! The great mysteries of this circuit have proven to be elusive to the common DIY'er and even the pro guitar amp builder. To be quite brutal, part of the reason for this is that the vast majority of amp builders out there base their designs on what has been around for half a century, tweaking the values to suit the tastes of their target consumer, BUT HEY... that's ok. I hesitate to say that they 'ripped off' these designs, they just built on them ('standing on the shoulders of giants and all that.) Guitarists (stubborn luddites that they are) want what they want, and often that is just a tweak of a traditional design with a few new tricks. ALSO, in all fairness, the traditional designs can be traced directly to the little circuits suggested by the tubes manufacturers in their data pages even earlier than that.

Here is the lineage of modern high-gain designs (5150s, Mesa Rectifiers, Framus Cobra Top) --> Soldano SLO (origin Mike Soldano's much copied "Kontrolled Klipping" elevated cathode asymmetrical clip circuit... he should have patented that thing) --> Marshall 'Plexi' Super Lead --> Fender Bassman --> RCA's tube catalogs from the 20's and Otto H. Schmitt papers from the the 40's. So most of these circuits look alarmingly similar.

But every once in a while, someone deviates from the norm and tries something new. MOST guitar amp designs make use of a choice few circuits, most of which are VERY simple: cascaded grounded cathode triode stages, cathode followers, 'long tail' differential or 'cathodyne' phase splitter stages and straightforward push pull or single ended, transformer coupled output stages using pentode or tetrode tubes. There are a few circuits that live on the fringe of guitar amp design convention: pentode preamp stages, grounded grid designs, anode followers, etc. Our buddy here, the cascode, is one of those fringe circuits.

WHY THE CASCODE?

Good question. Arguably, the main concerns for preamp stages in a guitar amp are gain, frequency response and noise. In the case of tube stages, all these factors are related, so many concessions have to be made to gain one over the other. The cascode is a different way trading these characteristics into a preamp design, not necessarily a better or worse way in ALL cases, but different and therefore better in at least some.

The ubiquitous cascaded, grounded cathode triode stage preamps seem to have a good balance of the characteristics a guitarist likes, when applied within the design parameters of an amp... which are much more relaxed and admittedly bass-ackwards of most Hi-Fi designs. One of the reasons for this is that the frequency response can be more or less centered subjectively on the guitar speaker range (about 65Hz - 12kHz) rather than the Hi-Fi range (20Hz or lower - 20kHz), and is contoured and colored rather than having to be flat and pure. ALSO, high gain guitar preamps are designed to MAXIMIZE distortion (...um... some types that is) and INCORPORATE waveform clipping into the designs. Guitarists also LOVE things like power supply sag and transformer saturation... which many Hi-Fi guys try desperately to avoid.

SO WHY SHOULD I USE IT?

Well, remember those parameters that we talked about earlier (gain, frequency bandwidth) to put it simply, the cascode has more of these. Tell the truth, how many guitarist do you know that don't get goose bumps at the prospect of more gain? The grounded cathode amp is limited in its potential gain by the mu factor of the tube. That being the case, we are limited in our tube selection to tubes that have a significant mu. That also limits our circuit options because we are relegated to the parameters that suit those tubes.

The cascode's gain formula is not a function of resistance to mu, but rather of the TRANSCONDUCTANCE of the tube. Take the example of these stages. A 12ax7 with a plate resistor of 47K and a cascoded 6922 with a plate resistor of 47K. A quick and dirty 'in a vacuum' approximation of the gain shows the G.K. stage has a gain of about 40x, give or take, while the cascode stage has a gain of about 400x, also give or take. Do I have your attention now? We are now officially out of triode territory and into pentode territory as far as gain goes.

The other parameter, frequency response, is a bit more difficult to show, but suffice it to say the cascode has lower lows and much higher highs. Alex, you might say, what good are all those highs since we are limiting our response to 12kHz - 15kHz or so... especially when the average -3dB roll off point of a guitar's high end is around 5kHz, and the lowest note is around 70Hz (or down to 50Hz for you freaking psychotic bass-junkie down-tuned 7 string players). I am glad that you asked. Obviously, this makes the circuit more useful for Hi-Fi, computer use and transmitter systems, but what of guitar amps?

Two words, harmonic overtones. Terms like 'shimmering highs' and 'thumping lows'... get the picture? It also gives us more wiggle room in our design parameters, and more options in the coupling stages, etc. This is because the stacked design shields us from Miller Capacitance in our grid input stages, allowing us more flexibility in design. AND while the output impedance for a cascode stage is a bit high, the output impedance for a cascode stage designed around a tube that is meant for cascodes (6922, 6dj8, 6N1P) can be much lower than the output impedance of a G.C. stage designed around a high gain triode (12ax7, 12at7) at far greater gain.

Take, for example, a 12ax7 stage with a 100K plate resistor. The Zo (output impedance) is about 40K-ish with a gain of 50-ish depending on plate voltage, whereas a cascode stage with a high transconductance tube (like a 6922) can run a much smaller plate resistor... like 10K, and achieve an output impedance which ends up being around the same value as the plate resistor at 8.3K-ish with a gain of around 100-ish--that's twice the gain at a 5th of the impedance! Up that plate resistor to match the Zo of the G.C. stage, and you have a theoretical gain of 400.

Well, you say to me smugly, I can get that from a class A, single ended pentode input stage, like an

EF86 in an old Vox. WELL, I say to you, pentode gain stages are FUN, and you sure could get the same gain and shield yourself from the nasty effects of Miller capacitance at the same time, BUT a pentode suffers from a few problems that that cascode does not--division noise from the grids, microphonics from the internal components, and higher power supply requirements for voltage lost from the cathode biasing and current draw from the heater circuit, not to mention higher internal heat, a bigger layout footprint and an obnoxiously high Zo (and the equally obnoxious price and inconsistency of modern-manufacture pentodes). You can also run into impedance issues if you run a downstream load higher then 470K-ish.

OK, OK, GET TO THE MATH YOU GEEK!

Here is the fun part. Now bear in mind through all this that these numbers are not absolute. Variance in ratings from tube to tube these days is alarmingly high, as are variances in resistor and capacitor values, especially if you are using NOS parts for added 'mojo'. There are always multiple mathematical ways to skin a cat, but they all generalizations of the functionality of the tube. I have seen a few ways to go about some of these, and some handy generalizations, but all of them will get you close. That being said, the parameters that we need to establish to frame out our preamp stage are: midband gain, input lowpass -3dB point, output highpass -3dB point, and frequency response.

OK, we need to start out as always with the tube's data sheets. For our purposes, we'll be using a 6922 (ecc88, e88cc, 6dj8), dual-triode tube since I have some around, and they are cheap, around $10, and easy to get ahold of, and there are still plenty of NOS tubes left. This little fella' was designed specifically for cascode use, so it has a high transconductance rating, high anode to cathode voltage rating, and even a shield between the two triode elements to lower noise... nifty! They are also in current manufacture by Sovtek, JJ/Tesla, EH and Ei. The relevant specs (which are always a bit off from tube to tube) are as follows:

Maximum mA/V (transconductance) = 12,500mhos
mu = 33
Cgk = 1.4pF
Cga = 3.1pF
Ca = .18pF
Ri=2.6K

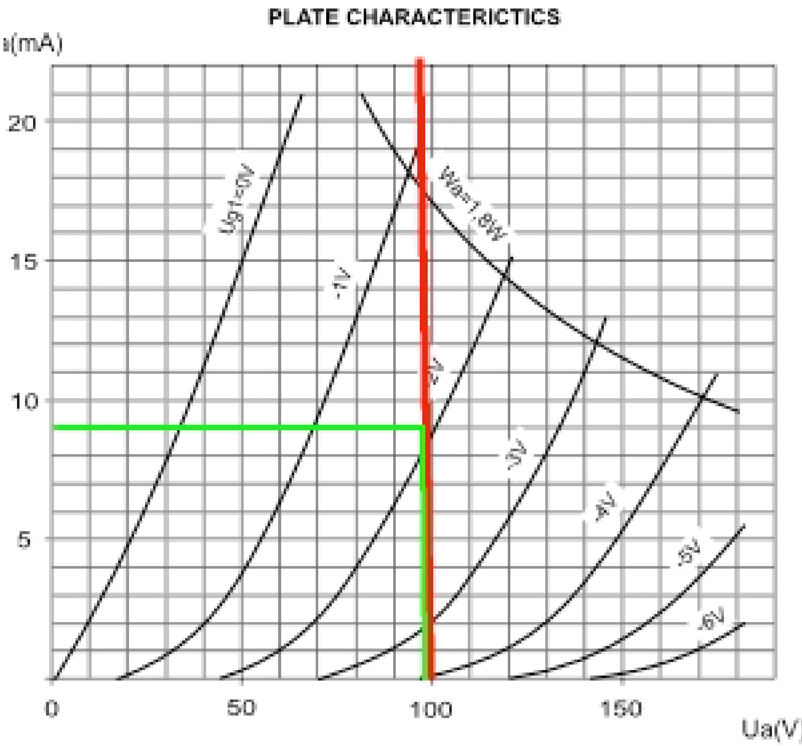
So now we can get started. The formulas are altered a bit for the cascode connection since it is useful for us to treat the two triode sections as one tube, behaving much like a multi-grid tube like a pentode. That being the case, when we look through the tubes circuit (mathematically) from cathode to anode, we have to take into account all the little elements that we see in our computations.

STEP 1: BIASING

First the subjective part. We have to first choose the plate resistor value and a V+ value. In a G.C. stage, we would normally start with at least twice the internal plate resistance of the tube, but we can use other parameters such as desired gain and output impedance to set the value instead. It will also give us our V+ voltage drop so that we don't fry the plate of the tube if the V+ is high. Let's say we don't care about the Zo, and instead focus on the gain. To keep things in the small signal world, lets not go TOO overboard. The input stage of a typical guitar amp like a Marshall, has a theoretical gain of around 100 (even though in circuit gains fall somewhere closer to 60). Just for comparison, let's shoot for a theoretical gain of 100 or so. (This number is our gain if we ignore the effects of Rl loading impedance.) That would mean that we should take the gain and divide it by the mA/V of the tube to get a 'ballpark' figure on the Rp. 100/12.5=8K So our resistor would be somewhere around 8K. We'll up it to 9K just to give a little bit of a cushion. For our V+, we'll choose 200v, but you can use whatever your design dictates really as long as it does not exceed the tube's max plate voltage spec after calculation for voltage drop at the chosen bias current. This is not the number we use to calculate the Rk, but we need to know it to get the voltage from the divider os R1/R2.

NOW we have an extra step, just for cascodes. The upper triode's grid is tied to the power supply through a voltage divider formed by R1 and R2. This sets the voltage at the anode of the bottom tube, which we will then use to calculate the cathode bias resistor value (actually, the bottom triode sees this voltage PLUS the top triode's Vgk , but that is very small, like 2 volts, so we'll ignore it for now because 100v is such a nice round number.) So if we make a 1/2 ratio divider (R1=1M / R2=1M or any multiples thereof), we end up with 100 volts from a 200 volt V+. Of course, you can go higher if you would like by using an elevated DC filament voltage reference or a larger Rp, but I digress. The capacitor C1 is there to decouple the junction of the voltage divider, but we'll put it to better use later on.

So now we arrive at the actual biasing. Our x-axis voltage is the whatever we have at the upper tube's grid + the upper tube's Vgk, which is about 2, but we'll just call it 100v. There are a few ways to find the starting point on the x-axis when working with a triode, but both have similar results. In a cascode the slope is nearly vertical, and most certainly off the chart, so we just draw a line that is more or less straight up:



Then we pick a point that gives us a little up and down swing. This part is subjective, so you can try different values, but we'll pick one that gives us a little up and down play. Don't have many choices since -1v is outside the maximum disapation, and -3v biases us really cold, so it looks like 2v is the winner. This sets our operating point. Then we look across to see how much current we need to bias the circuit at that point. Looks like 8mA. Now we plug that into Ohm's law R=E/I or Rk=2v/8mA to get 250r. We'll use the next closest common value of 240r.

THEORETICAL GAIN VS. ACTUAL GAIN

Theoretically, a cascode can achieve a gain of the tube's mu squared. On paper that is possible, in reality it is not. If you remember, our basic guideline for a cascode's gain is transconductance*Rp. That approximates the gain of the circuit, while ignoring the effects of the following gain stage's loading. Also, a tube's transconductance figure is not constant. It varies with the amount of current that is passing through the tube. Therefore, the operating point that we selected previously has a great effect on gain. A tube's data sheets are one of the keys to selecting the current for maximum mA/V figures, but a bias point naturally effects the tone of a circuit as well, so personal taste plays a role. The transconductance (mA/V*1000) figure of a tube will also change as the tube ages, so gain is not constant at a particular operating point. It is that figure, combined with Zo, after the loading effects of the following stage are accounted for, that we get our gain from.

Calculating the loading effect is easy. It is Rp II Ri II RL. BUUUUUUT, in our case, Ri is modified, remember. It is (ra'+ra*(u+1)) , or around 91 like we calculated before. With our modified Ra in parallel with our Rp of 9K, and a RL of a 1M potentiometer, we get something like 8.1K. If we look at our data sheets to find out the mA/V at our 3mA current, then we can calculate gain, OR we can use the formula rp*[(operating current/bias current)^(1/3)] to find it for our purposes here. So if we assume that we actually arrive with a mA/V figure of 66.7% of our total 12,500, then our gain is not the originally hypothesized 100, but rather (8.334mA/v*8.1K) or an Av of 68, which is right around Soldano/Mesa territory. Bear in mind though, that we can up this figure DRAMATICALLY by maximizing our transconductance by applying more current, and then increasing our voltage swing by raising our B+ and upping the value of our Rp. With the Soldano/Mesa Rp of 220K and B+ of 360 -400v, on paper we could have a gain of over 700x.

CATHODE OUTPUT IMPEDANCE AND THE SHELVING FILTER EFFECT-- THE EASY STUFF PART 1

The bottom triode looks up through the top triode to see the plate resistor+the top triode's internal resistance, and we have to take its value and divide it by the top triode's (mu+1), or 34 in our case to get a perceived plate resistor of 350r. That is in parallel with Rk (240r). So we see around 142r down there... we'll call it 140r. To find out the frequency response of the mid band gain, we plug the numbers into this formula: f = 1/(2*PI*Zo'*Ck) or 1/(2*PI*140*Ck). We'll use the Soldano value of 1uF for Ck to find that the low end roll-off of our gain is around 1137Hz... YIKES! We want the value to be about 10 times lower than that, so we need to increase Ck to effect the change. If we use a 7.5uF Ck, then we get a shelf at 150Hz... that's about right for a modern high gain screamer.

ANODE OUTPUT IMPEDANCE AND THE LOW FREQUENCY RESPONSE-- THE EASY STUFF PART 2

A quick and dirty approximation of the output circuit's Zo is to use the value of Rp and have at it. But if you want to get all technical, than you just take this formula for unloaded anode output impedance: Zo = Rp ll (mu + 2)*internal tube resistance = 9K ll (35)*2.6K = 9K ll 91 = 8.2K. As you can see, we could have just guessed using 9K and been pretty close. We then plug all that into f = 1/(2*pi*(Rl+Zo)*Co) and try out values for Co. The Rl is usually around 1M, but occasionally it is lower. We'll use 1M here for our example.

A typical stage in a modern high gain amp uses a .022uF coupling capacitor with a Zo of 48.7K to get a low end roll-off around 6.9Hz. Some lead amps decrease the Co value by a factor of 10 to .0022uF, which ups the cutoff to 69Hz. With our lower Zo and a value of .022uF, we would get a roll-off point of 7.2Hz... close enough considering that we can't hear ANYTHING down in the that sub-harmonic 'elephant fart' range anyway.

INPUT CIRCUIT -- THE TRICKY PART

For guitar amps, we can assume 1M for out input impedance. Usually, we use the grid stopper Ri in conjunction with the stage's Miller capacitance to set the -3dB point for rolling off the treble going into the stage, BUUUUUT our Miller is low due to the top triode shielding us from its nasty effects. So what we do is figure out the gain of the lower tube half like normal G.C. triode stage EXCEPT that the bottom triode sees that 9K plate resistor as being divided by (mu+1) or .265K, and then divide by (Rp+internal tube resistance) = (.265K+2.6K). That gives us an AV (stage gain) of around 3.

Then we figure out the miller in out capacitance of the bottom tube as per normal using out trusty equation: Cgk + Cga*(Av + 1). But to be safe, I'll throw in some stray capacitance from components on the input circuit (1pF) to each figure as well as the Ca of the top tube, so (Cgk+stray)+(Cga+stray)+Ca*(Av+1)= 19pF. We'll say 20pF for simplicity. Not too bad considering that a G.C. 12ax7 circuit would be about 8 times that.

So using that we can figure out our treble roll-off at the input by using the formula f = 1/(2*pi*Rout*Cin). That assumes that we know the Zo of the previous circuit. For simplicity again, we'll assume that is it 40K, which would be about the Zo for a 12ax7 stage... OR for a humbucker- equipped guitar at the input stage. That would set our roll-off point at f = 1/(2*pi*((40K)ll1M)*20pF) = 207kHz roll-off. That is a BIT high for guitar purposes, so we start throwing in numbers for Ri. A typical 12ax7 input stage usually has a 68K Ri, which would put the roll-off at 11kHz if we assume a 40K guitar pickup output impedance, which is a bit on the high side. With the cascode, the 68K would give us

82kHz... not particularly useful, but still low enough to block most FM radio stations.
In fact, we would have to go ten times higher just to drop the roll-off down into the audio spectrum, and at that point, we are losing some signal voltage AND increasing contact noise, but that is the beauty of the cascode, more frequency range than we know what to do with. So here is my suggestion. Instead of using Miller capacitance to set the input hi filter, use a simple RC filter and just wire in a small value Ri right on the grid resistor to block out RF noise picked up my the input components and to prevent high frequency oscillations. The standard 68K would do that just fine, or you could up it to 100K-150K or more just to make sure. I have some nice 2 watt NOS Holco metal films at 150K, so I use those to drop things down to 50kHz. If you are using a cascode for an input stage, then there is not too much worry about rolling off the guitar's high end, since a typical guitar starts to roll off around 4kHz- 5kHz anyhow. If you run EMG's or take out your tone control potentiometer like I do, that roll-off will be a bit higher though. ALSO, capacitance of a typical 20' guitar cable will be around 500pF, so you have to throw that into the mix as well at the input stage.

DRAWBACKS OF THE CASCODE
There are always drawbacks aren't there? The only one that I can see with this circuit is its TERRIBLY susceptible to power supply noise... it rejects less than 1dB. The standard 12ax7 G.C stage has a crap PSRR too... about 9dB, but at least it is SOMETHING. So what to do about it? Well, you make your power supply quieter for one thing by regulating the voltage coming in or improving the filtering, or you can just cancel it out, or both if you want to go totally nuts. There are also other configurations of the cascode as well such as the folded cascode, the ultralinear cascode and the self-bias cascode, which imbue it with differing characteristics.
The circuit has 2 immediately obvious inputs... both grids. The top grid can be used to apply a bit of the power supply noise, which is mixed, out of phase, with the main output. This can be done easily by bypassing the upper voltage divider resistor (R1) with a capacitor to form a capacitive voltage divider with C1. We now have a voltage divider within a voltage divider... cool huh? For all solid state heretics out there, THIS WILL NOT WORK WITH A SOLID STATE DEVICE IN THE TOP POSITION. You just can't get any gain out of those things in this configuration... sorry, triodes only. So the ratio of the voltage divider should be equal to the gain of the top triode to cancel out whatever noise happens to creep in up there... makes sense. In our case, the gain of the top triode is 3.05. That poses a little problem because the ratio is not a whole integer. We can fix this by placing a potentiometer between the two capacitors to allow us to change that ratio on the fly. Then just tweak until it sounds good.
Also, for lower noise, lower cost, more linear performance and even more ridiculous gain, you can replace the BOTTOM triode with a Jfet, like something in the 2sk family like the 2sk170 or the awesome 2sk369. I have used those little suckers before and they rule. All the design parameters are scaled down though, so your upper grid reference voltage needs to be dropped, as well as the current. These suckers have about twice transconductance of any dual triode, so they can REALLY scream. If you dropped one into our circuit here, you could end up with about twice the output voltage.

CONCLUSION
Draw your own conclusion. In guitar amp building, everything is subjective. I conclude that the cascode is a powerful circuit which can be of great use as either an input stage, a lead channel booster, an effects loop/reverb recovery stage, as an input stage for a power amp to drive a differential phase inverter, or as a sole preamp in a simple circuit. It can rival the gain of 2 cascaded grounded cathode stages, but without the compounded noise. Experiment for yourself and find out.
The first tier of a classic Marshall mod is to parallel the input stages of the two channels. The second tier is to cascade them for more gain. Another option could be to cascode them for an intermediate gain boost with lower noise. Once you understand a circuit, it adds one more spice to your rack, or one more trick up your sleeve.

Thanx to SY, EC8010, and cerrem and everyone else who helped me through this thing.