2A3 SINGLE-ENDED TRIODE STEREO AMPLIFIER KIT

LEGENDARIUM

Part I: Build Instructions

Part II: Tube Amplifier Explained

V08251

Analog Ethos™

WARNING: RISKS OF ELECTROCUTION OR FIRE

Be safe with this amplifier kit! Follow all instructions carefully in this manual, and for your safety, please take seriously the risks and follow the precautions below. By purchasing this kit and assembling it yourself, you have personal liability to ensure safety in the building and operation of the amplifier. DIY electronics is a great hobby, but it comes with risks including but not limited to those below.

Important risks:

- This amplifier uses mains voltage (120 VAC) which can **kill you** if you touch it and current passes through you.
- This amplifier uses a power transformer to create a **high voltage** power supply up to **400 volts DC** which will **kill you** if it passes through you, will destroy your finger or screwdriver if you touch it and create a short circuit. Do not think this voltage is safe in any way to touch with your hand or a tool.
- This amplifier uses **capacitors that are charged** when the amplifier is on and may not be discharged even when the amplifier is off and unplugged, even hours or days later, if not bled properly. These capacitors hold sufficient energy at high voltage to **seriously injure or kill** you.
- Vacuum tubes and power transformers create **high heat which can burn you** if you touch the surfaces that reach hundreds of degrees Fahrenheit. There is a **risk of fire** if the amplifier is in an enclosed space without adequate ventilation, or other objects are touching or near the tubes or transformer.
- You will need to utilize a soldering iron to build your amplifier, which operates at a very **high temperature** and will burn you if you touch it, or can **cause fire** if not properly used.

Follow these general safety precautions:

- Never plug in or operate your amplifier with the chassis open. Do not attempt to trouble-shoot the amplifier while turned on. Use safe inspection methods only when the amplifier is off, unplugged, and capacitors are discharged. Never assume insulated wire or components inside the amplifier are safe to touch while the circuit is live.
- Do not leave an exposed circuit accessible to other people, especially children or pets.
- Keep a clean work space, with no wires or other objects near your amplifier or soldering iron.
- Follow all safety instructions for your soldering iron. Unplug when not in use. Allow safe time and space to cool.
- Utilize a non-conductive work table and mat below your chair or standing position.
- When turning on your amplifier for first use after building, use a power strip switch and follow instructions to monitor for smoke, smells, sounds, or other indicators of a problem. Immediately turn off power if you detect any.
- Never leave the amplifier turned on and unattended. Always turn it off when you leave the room or your home.
- Operate your amplifier on top of a table or sturdy stereo shelf with at least 12 inches of space above the top of the vacuum tubes, and 6 inches of space around each side of the amplifier chassis. For proper ventilation, ensure the bottom perforated panel is not obstructed and the amplifier rests on the chassis feet.
- Do not place the amplifier inside of an enclosed cabinet or stereo console that has limited ventilation. The amplifier gets very hot and requires air flow to stay at a safe operating temperature.
- If you have a child in your home, do not operate the amplifier in a location where the child can reach it. It takes only a second to get a serious burn from the tubes which will glow and may attract the interest of a child.

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INTRODUCTION

So, you are ready to build a DIY point-to-point hifi stereo tube amplifier? Maybe you have read about tube amplifiers or are a curious learner and have been wanting to make the jump into this hobby, or perhaps you have already built DIY electronics in the past and want to learn more and build a new great-sounding amplifier with high quality design and components. Maybe you are experiencing something in your life and need an escape from the day-to-day and you want to put your mind and hands to work on something to take you away from it for a while.

Whatever your situation, I'm glad you decided to give this a try! Here are the goals I had when I created this kit. Hopefully this matches what you are looking for.

Goals for this kit:

1 LEARNING

You will truly learn how a vacuum tube amplifier works.

This is not simply a step-by-step guide, although you could use it that way. My intention is to show you exactly how the entire circuit works, how each component is selected and the role it plays. You will walk away with knowledge that empowers you. This may be the only kit you build, or it may be one stop on a journey of learning and building. Perhaps your next build will extend on what you have learned, and you could customize a circuit or come up with your own designs. If you want to learn, this is the kit for you!

As you can see, the instructions are extensive and filled with illustrations and explanations. Some kits include poorly written instructions that are difficult to follow, and you might get the amplifier to work, but only after frustration, perhaps a few mistakes, and certainly without learning anything new. I want your experience with these instructions to be the best you've ever had in a kit!

2 HIGH QUALITY AUDIO

You will get high audio quality, with reasonable circuit complexity and cost.

I am using a relatively straightforward, classic single-ended triode (SET) circuit design, with a bit of added performance implemented in the driver stage. There could be more advanced designs and added complexity but my intention was to have a very authentic circuit matching well with a classic high fidelity tube like the 2A3.The circuit is customized for the components included, but is not unique, and is based on designs that have been used for many years and proven to work very well. I have carefully tested it and made adjustments, with performance shown on subsequent pages.

One of the benefits of a kit is that you have everything you need in one box, and don't need to go through the difficult job of sourcing components, often from multiple suppliers, paying multiple shipping costs and needing to identify precisely the right part from a multitude of options, sometimes testing and needing to try again with a different selection. This work is done for you so you can save time, money, and avoid mistakes.

I have sourced high quality components for this amplifier from carefully selected manufacturers, but not excessive in cost. There are many audio products being sold as "high-fidelity" at outrageous prices, and with dubious claims of performance. I'm sure you've seen them—fancy speaker wire, connectors, rare new-old-stock tubes, silver and gold components, and other items that can add up to many thousands of dollars. This amplifier will sound very good and be reliable, at reasonable cost. There are also plenty of cheap components available and used in other tube amplifier kits that you may find. I did not try to build the cheapest possible kit, and I assume you are someone who wasn't looking for that.

This amplifier is good for music listening in a home, with relatively low distortion and hum, though it is not high powered or intended to be used for very large or loud listening environments or inefficient speakers.

3 VISUAL DESIGN

How it looks is as important as how it sounds.

Great visual design is important to have an end-product you are proud of. This is a showpiece in your home that your friends and family will see and ask about. I wanted to create a custom chassis to hold the components functionally but also beautifully in context of your listening environment. The kit includes a carefully crafted hardwood box and aluminum top and back panel that perfectly fit the components and physical layout of the circuit.

For those of you who don't have extensive workshop tools and finishing capabilities, this allows you to have a great-looking amplifier and not settle for an off-the-shelf, generic metal box.

But for those of you who do have tools and skills of design and construction, this kit can serve as your entry into point-to-point building. I will explain how the layout is selected and important choices about the physical construction to minimize hum and ensure heat dissipation or other considerations. You may in the future build a custom design of your own for your next amplifier and put some of your own inspiration into it! Tube amplifiers are both art and science, and I hope you'll lean into your creative side. Along the way, I'll share a few thoughts on design, inspiration and craftsmanship.

What you need to get the most out of this kit:

Basic soldering skills (and a few hand tools). You will need to solder some wires and small components in enclosed spaces. It's not always easy, and I'll share tips along the way. You don't need extensive soldering experience, but should be able to get good and clean connections in order to have a safe and functional amplifier.

Relatively high-sensitivity speakers. While you can drive any 8-ohm speakers with this amplifier, you will experience the best sound with speakers that are ideally higher than 90 dB SPL. The amplifier will typically provide up to 3-4 watts of power per channel for a consumer line level source. This may surprise you if you are used to solid-state amplifiers that may advertise 50 or 100 watts per channel or more, which may be necessary to drive low-sensitivity speakers at low distortion levels. We'll get into this later! Just know that if your speakers are below 90 dB SPL, you may not get ideal performance.

Patience! Take your time and enjoy the process. Read and observe carefully to put the right parts in the right places. If you make a mistake along the way, take a step back and try again. There are few mistakes that can't be corrected if you catch them in your process, but if you don't follow the instructions and checks carefully, it's possible you will damage components along the way or when you turn on the amplifier.

Notes on safety and information included:

As indicated on page 2 of this manual, there are important risks to be aware of with an electronics hobby. Hopefully you know that already! Most importantly, tube amplifiers operate at very high voltage. In this case, over 300 volts DC, which is more than enough to kill you in a brief moment. These instructions do not have you doing any work or testing on a live circuit.

This manual gives you instructions to build the amplifier in a safe manner using a limited set of common tools and a soldering iron. Along the way, I will provide additional tips and suggestions for builders who may be interested in expanding into a more extensive hobby, or in the theory and testing methods behind the design of this kit. This manual cannot possibly go into all the details of safe testing methods that could involve use of multimeters, oscilloscope, spectrum analyzer, variable transformer, and others. If you are a trained technician or have experience working with high voltage, it is at your own risk (I know you know this!) if you choose not to follow these instructions or elect to perform other tests using additional equipment.

When I build and test amplifiers, I do sometimes access an exposed circuit using test equipment. You should not expect to do this at all with this kit. However, so that you can understand some elements of safety, below are examples of protective steps I take:

- I use an isolation transformer so that any exposed mains voltage is less likely to have a path to ground if I were to accidentally touch it.
- I use a variable transformer ("Variac") to slowly bring up voltage when testing a new circuit.
- Turning on an amplifier on my work space requires multiple separate power switches, so others in my house can't easily turn on a high voltage circuit. I keep these all off or unplugged when I leave the room.

- I have a rubber mat beneath my work space as a ground insulation.
- I manually discharge capacitors using a resistor after turning off a circuit, or double-check the discharge is done even if a bleeder resistor is in place.
- I never, ever put more than one hand over a circuit to probe with a multimeter. I force myself to hold a small object in one hand to avoid instinctively reaching in with it (some people follow the rule of putting one hand in their pocket). Current from one hand to the other would pass through my chest (heart) and has greatest risk of death. Brushing across a high voltage potential with one hand could still cause injury but is less likely to be lethal.

You can learn more about safety through many other sources. A healthy respect for electricity and the risks outlined on page 2 are very important. I hope you'll have an enjoyable hobby, but please be safe, for your sake and those around you!

Parts list

Note on parts: Most of the small parts are provided in labeled bags. At times I buy different brands of resistors or capacitors, which means they may look different than the pictures below, but they will always be the same type and rating. I specify power rating of resistors only where it matters (where not specified, power dissipation is low and I usually include 1/2W or 1W). Resistors are all metal-film or wirewound types for lowest possible noise. Some components or chassis colors may vary depending on special options I may make available. All other parts will be as shown. The important thing to remember is to carefully identify the part using the label on the bag, and to not get resistors confused, especially those marked using color bands instead of printed values. Putting the wrong resistor in the wrong place in the circuit will cause serious problems and damage to components. I suggest you double-check resistance using a multi-meter to ensure the correct part.

 Chassis with aluminum top	 Aluminum back panel	 Perforated bottom panel	 (4) Speaker terminal posts
 (2) RCA input jacks	 Fused IEC power connector	 100K dual-gang audio potentiometer	 Volume knob

 Hammond 302AX power transformer	 10H 150mA Choke	 (2) 3.5K – 8 Ohm output transformers	 Power switch
 (2) 9-pin tube sockets	 8 pin tube socket	 (2) 4 pin tube sockets	 (3) 3-lug terminal strips (2) 4-lug terminal strips (2) 1-lug terminal strips
 (13) ring terminals	 3.3uF 450V film capacitor	 220uF 450V electrolytic capacitor	 22uF 450V electrolytic capacitor
 (2) 0.22uF 630V coupling capacitors	 (2) 100uF 100V electrolytic capacitors	 (2) 100uF 25V electrolytic capacitors	 capacitor bracket
 (2) 100 ohm hum potentiometers	 (2) 900 ohm 10W resistors	 (4) 1k ohm resistors	 (2) 2.7k ohm resistors

 (2) 30k ohm 2W resistors	 56k ohm 2W resistor	 220k ohm 2W resistor	 (2) 470k ohm resistors
 (2) 1M resistors	 5U4GB rectifier tube	 (2) 12AY7 dual-triode tubes	 (2) 2A3 triode tubes
 shielded 2-conductor wire	 Hookup wire multiple colors and lengths	 Zip ties and heat shrink tubing for wires	 2A slow-blow fuse
 Various hardware (not all shown)			

Tools and Workspace

You will need the following tools to assemble the amplifier:

- Phillips head screwdrivers of several sizes, and small hex wrench or screwdriver for the volume knob set screw
- Nut drivers or wrenches of several sizes
- Wire stripper for 18-22 gauge wire (kit includes all wire you will need)
- Soldering iron with medium chisel tip. I suggest a 40 watt pencil-style iron, or a temperature-controlled solder station. Have a sponge or wire tip cleaner, too.
- Electrical solder. I suggest 0.8mm 63/37 tin/lead rosin core solder.
- Side-cutters or other small snips for trimming leads
- I suggest small needle-nose pliers for shaping leads and holding or maneuvering wire or components in place
- Ideally you have a digital multimeter for double-checking resistance of individual components and connectivity (while the amplifier is off)
- You could also consider some type of "helping hands" tool with alligator clips or other method to hold wires or items in place as you solder them

An ideal workspace is a flat table or work bench with good lighting and room for your soldering iron to sit in its holder without risks of touching other objects or being bumped into your lap. There should generally not be a cat residing on this table. Have plenty of space to lay out the instructions and components you are working with. If you don't have a dedicated work bench, the kitchen table is fine. Tell your family that your amplifier is more important; they will understand.

To hook up and operate your amplifier, you will need:

- A pair of 8-ohm speakers and speaker wire (never operate the amplifier without speakers or load hooked up, or you may cause damage to the amplifier). For best results, I recommend speakers with at least 90 dB SPL sensitivity, and speaker wire 16 awg or heavier.
- A line-level audio source (CD player, DAC or computer audio output, phone/tablet with headphone output, etc.) and audio connector wire with RCA jacks. This amplifier does not have a phono stage driver and will not directly amplify a turntable unless you have a separate pre-amplifier for the phono source. A preamplifier may also be helpful for switching sources or if your source level is not strong.

To enjoy your amplifier in operation, you will need:

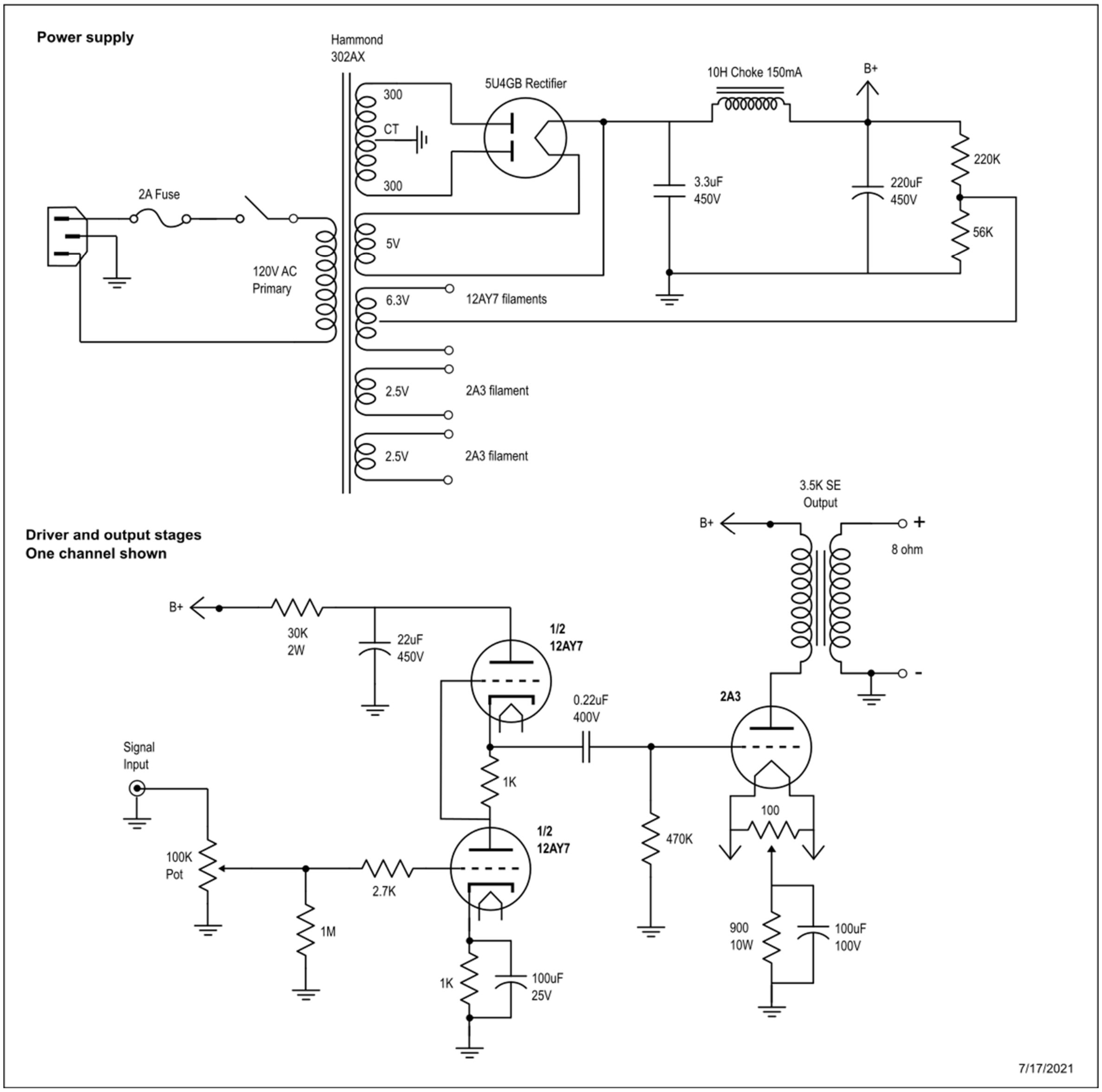
- A great album to play. I think Diana Krall would be a good first listen.
- Comfy chair, preferably with a cat in your lap.
- Celebratory drink. I recommend a gin & tonic with fresh lime.

Circuit Schematic

You do not need to know how to read a schematic to build the amplifier, but it will certainly help you understand and learn if you can try to follow it. The schematic here shows the power supply and one of the driver/output amplifier channels. Because this is a stereo amplifier, the amplification portion of this circuit would be replicated identically, one for the left channel and one for the right.

This is based on a typical single-ended circuit design[1], but it is customized to work well with the components selected for inclusion. We will walk through the details of this schematic in Part II of this instruction manual.

Single-Ended Triode Amplifier 12AY7 / 2A3



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[1] This schematic is customized for this kit and can't be easily referenced to a single source, but is certainly not unique. It has similarities to versions created or used by many others in various DIY communities or from proven circuits used for many years. Many individuals share their knowledge, talents and experiences so we all can learn and try new versions. I do not take credit for this design.

Tested Performance

Below are the tested results I was able to measure. Note that results will vary due to different tubes having different characteristics or changing over time as they age, components having tolerances, mains voltage slightly different in different houses, my test equipment is not high-end in accuracy, and other reasons. These tests are done using dummy loads, and of course actual operation is with speakers that have varying impedance and their own performance results.

All that to say, take these measurements as estimates, not as a guarantee of the results you'll get.

Summary measures:

Maximum Power Output: 3.5 watts per channel

Input Sensitivity: 1.4V RMS

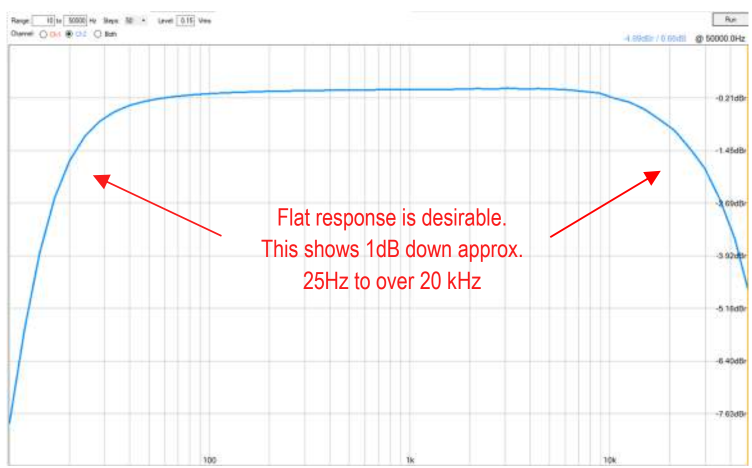
Total Harmonic Distortion: 1% @ 1W (1kHz)

Frequency response: 25 Hz – 20 kHz

Detailed measurements

Frequency Response

This shows a flat frequency response across a wide audio range. It is within 1dB from about 25Hz to over 20kHz. While very few speakers have response below 30 or 40Hz, and you typically can't hear to 20kHz, we want this to be as consistent as possible across a wide range.



THD to Power

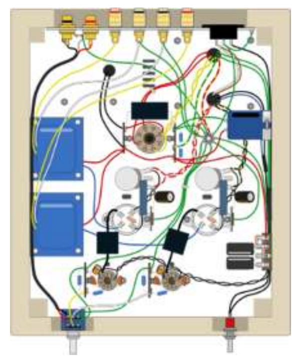
This chart shows how distortion (varying blue line) is related to output power (straight line rising). This is not a high-powered amplifier, but you can still get good sound with only one or two watts. With a sufficiently strong input signal you can run the amplifier up to about 3.5 or 4 watts before THD starts to rise to around 5%. Distortion is typically also higher at the lowest frequencies

PART I: BUILD INSTRUCTIONS

Ready to build?

I personally think it would be best if you read Part II first, learn how the tube amplifier works, and then build it. But I know it's hard to wait and I didn't want you to see that section with all the details and maybe get turned off! You don't need to know how the amp works to build it (or perhaps you already know the theory), so by all means, c'mon and let's get started building! But if you have some patience, it could enhance your experience to read Part II first, and then come back to this section to build the amp. 😊

Read each instruction carefully and ensure yours matches exactly what you read and see. In the appendix is also a **layout diagram** for your reference. Most build instructions will correspond to the orientation shown at right, where you have the amplifier upside down and are looking down into it, with the back of the amplifier away from you ("top" as shown).



Use layout diagram in the appendix

To keep your chassis finish protected, I suggest you put down some type of soft surface, like a towel on the table to avoid scratches as you shift the chassis into different positions to mount things onto it.

If you have any questions, please send an e-mail on the AnalogEthos.com website. I'll try to get back to you quickly. I want you to have all the info you need to build this. Have fun and take your time—have a nice drink and play some Led Zeppelin or something while you work. Don't try to do it all in one session. Remember building Legos? Yeah, it's not really anything like that, but those were fun, right?

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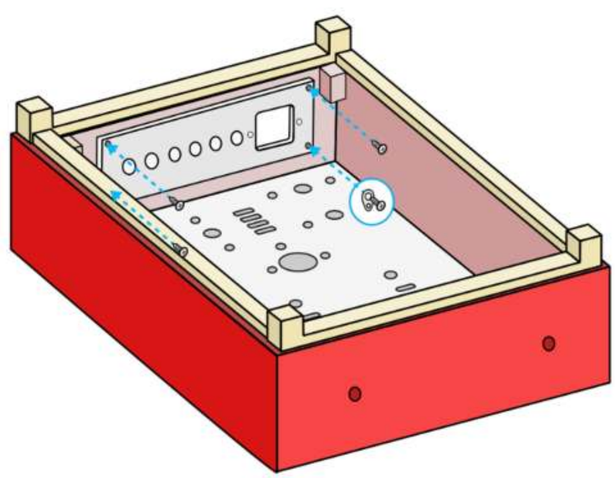
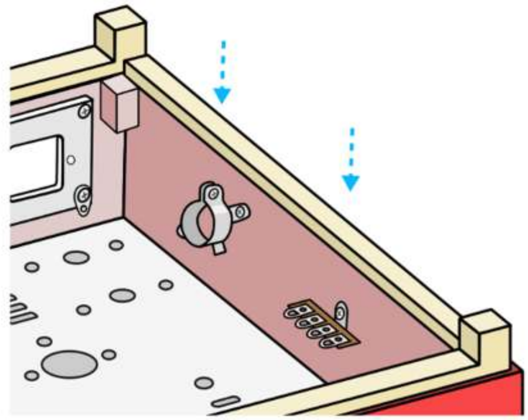
1 Attach the aluminum back panel

Turn the chassis upside down and attach the **aluminum back panel**, using **four 3/8" pan head screws** in the predrilled holes. Make sure you put the smooth finished side of the panel facing the exterior and oriented with the square hole on the right as shown in the illustration here. Also, as you screw in the lower right screw, include **one ring terminal**. You will later wire this to the earth ground lug for safety. All metal panels will be grounded just in case there was ever a loose wire inside the chassis with high voltage on it.



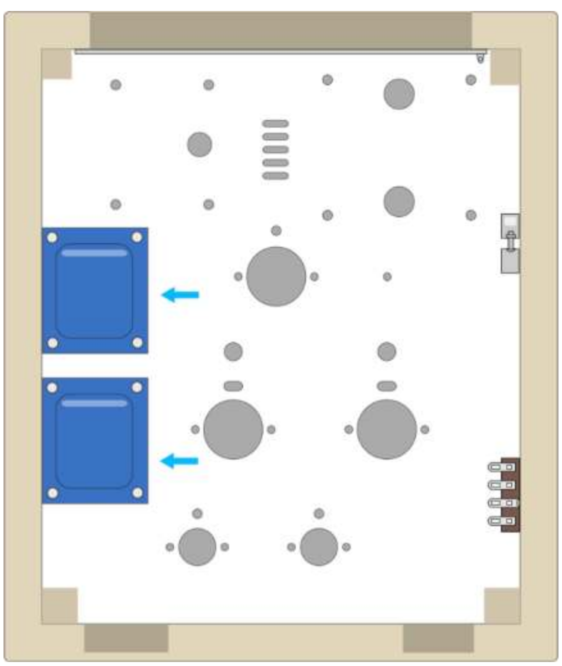
2 Attach capacitor bracket and terminal strip to side wall

Using three **3/8” pan head screws**, attach the **capacitor bracket** and a **4-lug terminal strip** to the predrilled holes on the side of the chassis as shown. Orient the capacitor bracket so that the screw for tightening it is on top.



3 Mount the output transformers

Turn the chassis on its side or whatever way works for you, and mount the two **output transformers** to the side wall using **3/8” truss head screws**. I suggest you orient these so that the red and blue wires are on the bottom (as the amplifier is upside down) closest to the aluminum panel, and the white and yellow wires are on top as you look at it. Now it is a bit tricky getting your screwdriver in there, but geez this is only step number three, you are going to do some way trickier things than this as we go on. If needed, you could take the top aluminum panel off to give yourself more access to screw these in.



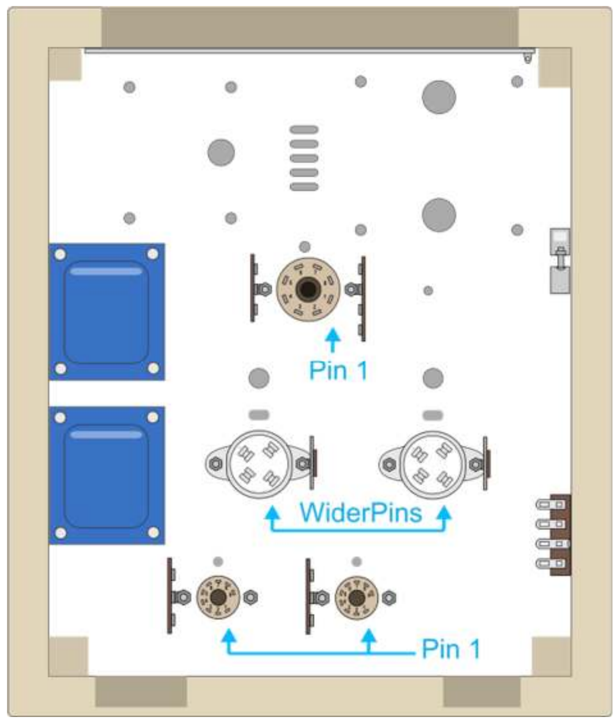
Transformer location

Now you engineering type folks who love all things symmetrical will wonder why don’t we just put one transformer neatly on either side of the amplifier? The answer is because we are trying to keep these guys far away from the power transformer, which will create a magnetic field that can get picked up in the output transformers if they are too close, causing an audible hum in your speakers. So, we’ll keep the output transformers on one side, and the power transformer over in the back corner where he can do his big bad business all by himself.

4 Attach the tube sockets and terminal strips

There are three different sized tube sockets to mount: an **8-pin tube socket** for the rectifier tube, two **4-pin tube sockets** for the power tubes, and two **9-pin tube sockets** for the driver tubes. **Important: the tube sockets must be oriented as shown.** The 8 and 9 pin sockets should have pin 1 toward the front of the amplifier, and the 4-pin sockets should have the larger & wider pins oriented on the right hand side. If you orient these wrong, bad things will happen later, probably destroying your tubes. Each one comes with a screw that you can hold from the top, and a lock washer and nut to secure it from the bottom. My preferred method is holding the screw still with a screwdriver and using a nut driver to tighten, to avoid scratching the chassis top.

Once you have each tube socket mounted, there are extra lock washers and nuts for terminal strips that will fit onto the extended screws. You'll put a **3-lug strip** on the left side of the 8-pin socket, a **4-lug strip** on the right side of the 8-pin socket, one **single-lug terminal** onto the right side of each of the 4-pin sockets, and one **3-lug strip** on the left side of each 9-pin socket. Put each terminal strip down over the existing screw and nut, and then tighten down securely with a lock washer and nut.

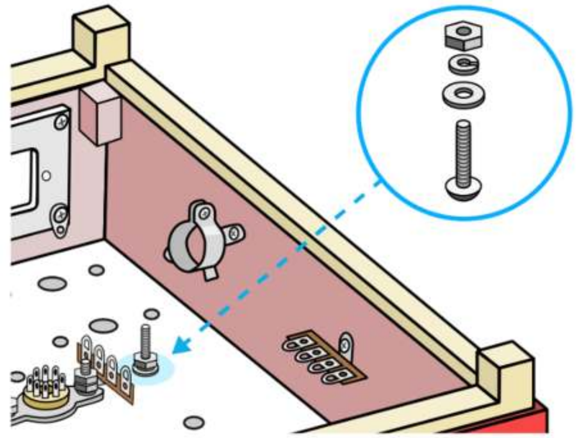


CHECKPOINT

- ☐ You have pin 1 on the 9-pin tube sockets facing the front of the amplifier?
- ☐ You have pin 1 on the 8-pin tube socket facing the front of the amplifier?
- ☐ You have the larger / wider pins of the 4-pin tube socket facing right (away from output transformers)?
- ☐ You are having a good time so far?

5 Attach the ground bolt

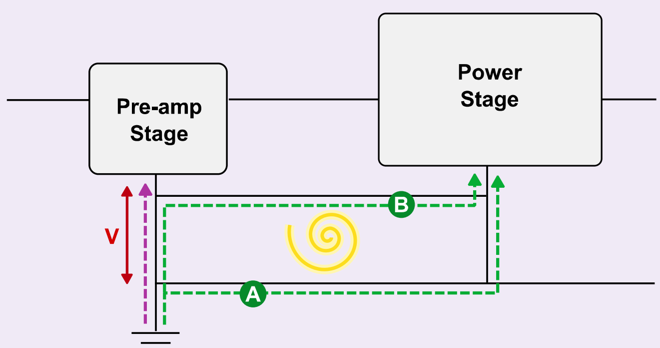
Attach the **7/8” ground bolt** with a flat washer, lock washer and nut in the hole on the aluminum top panel in the hole to the right of the 8-pin tube socket. We will use this as our star ground point and will be running wires with ring terminals to this point. Secure it very tightly. I suggest holding the screw in place with a screwdriver and tightening the nut from the bottom using a nut driver or wrench. There is an additional lock washer and nut that we will later use to secure the wires all in place. You can put these loosely on the bolt for now so you don’t lose them.



Ground loops, hum and interference

Grounding is a form of magic that few but Gandalf truly understand, and even he knows only what the ancients have made knowable. In brief, you don’t want **ground loops**, which are caused when there is more than one path to ground in the actual wiring of a device. This creates a loop sort of like an antenna that can easily pick up interference, commonly from AC magnetic fields at mains frequency (60Hz). Due to resistance in the wires, this can turn into a fluctuating voltage, causing an audible hum in the amplifier.

In a schematic, you see many ground points ⏚ where a part of the circuit is intended to be referenced to a zero voltage potential. In our actual wiring of the amplifier, we need to find a way to make this physical connection. You might think that any connection that leads to ground is at the same zero volt potential, but this isn’t always the case. Consider the following:

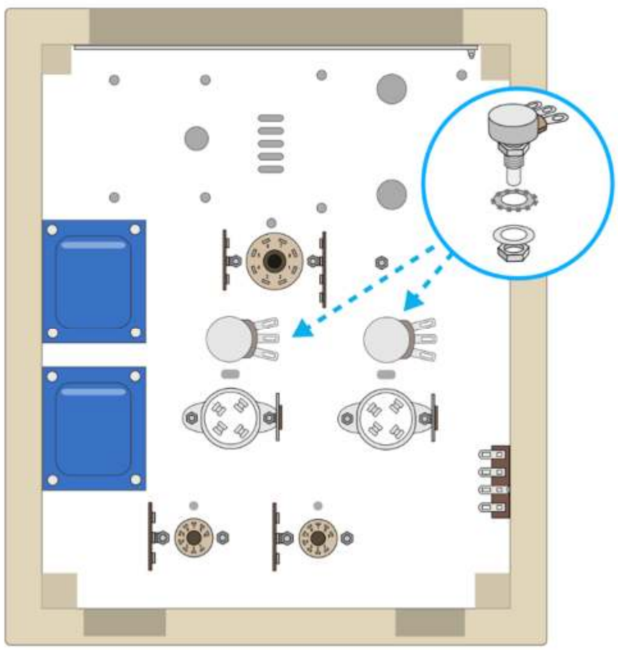


Here you see that the power stage has two paths to ground—one direct (A) and one that shares a ground wire with the input pre-amp stage (B) (the pre-amp also has a loop not highlighted). This forms a ground loop that will pick up interference or stray AC magnetic fields that are created elsewhere in the amplifier. Because the wire connecting the pre-amp to ground has some tiny amount of resistance in it (all wires do), and current is flowing through that wire, there is a voltage potential (red arrow) that is modulated by the interference current, causing hum in the sensitive pre-amp stage. The solution is to break the ground loop by using only path A or B, not both. (Ideally A, so the power stage is not impacting the pre-amp).

In our case, we are using a **star-ground** technique to independently wire different parts of the circuit to a single ground point. There are other techniques that can be used, as well as considerations for how parts of a circuit might share a ground wire or not.

6 Mount the hum potentiometers

Put the chassis carefully on its side and mount the two **hum potentiometers** in the holes behind the 4-pin sockets. Orient them so that the lugs for wires face to the side as shown. One nut and the toothed lock washer go on the inside of the amplifier, and the flat washer and other nut can be carefully tightened on the outside of the aluminum panel. Adjust the interior nut position first to expose just enough thread on top, but not more than necessary, so it will look neat and clean. Be careful because a slip of a metal wrench could easily scratch the aluminum top. Pretend like you are in slow-motion and you'll do fine. Then turn your head, face an imaginary camera and give a dramatic slow-mo nod as if to say, "oh yeah, I'm good."



What is a hum pot?

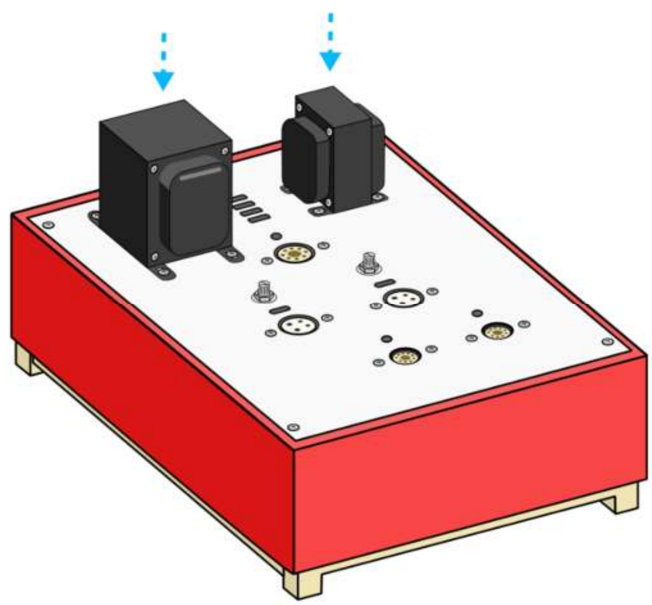
This is described more in Part 2, but here's the quick scoop. Your 2A3 tube is a directly heated tube where the filament is heated and also acts as part of the audio circuit. The filaments are powered by alternating current (AC) that fluctuates at 60 cycles per second from the transformer that uses household mains voltage (North America standard AC). If we do nothing, this frequency will interfere with our audio signal and sound like a low hum in your speakers. We can use a potentiometer to adjust the balance of voltage across the two ends of the filament and cancel out the hum. You'll see in a final step how you can adjust this. It's like magic.

7 Mount the power transformer and choke

Ok, the big boys. Pump yourself up and we'll get these guys onboard. Mounting the power transformer can be a bit tricky. It's heavy and you need to hold screws and washers and stuff in place while working from both sides of the chassis. No biggie though, right? The hardware is in labeled bags. You'll want it to go like this: screws go through the power transformer bracket from the top, then through the black fiber washers, then through the aluminum chassis panel, then secured from the inside using a flat steel washer, lock washer, and nut. Got it? The fiber washers are just used to lift it up a bit and protect the chassis from scratches. Also, you might want to keep the wire ends taped as you work with it—they can swing loose and scratch the chassis (can you tell I'm concerned it not get scratched?) Orient the power transformer so that the screws holding its bracket together are facing forward and nuts are in the back.

I find it works to set the chassis upright, put the fiber washers onto the chassis over the screw holes, put the screws into the transformer bracket holes, feed the wires down through the chassis holes, and carefully lower the transformer down with screws going through their washers and holes, now with the transformer just sitting in its intended position. Now use a little masking tape to hold those screws onto the transformer. Then you will want to tilt the amp sideways while still holding the transformer with your hand to keep it in position and avoid the screws coming loose. Now with it sideways, you can reach in and put a flat washer and lock washer on the screws and then tighten the nuts by hand. If you are an octopus you will do well at this task. I don't recommend doing this over a shag carpet because at least a few of those guys are going to try and escape your fingers. Doing it over a towel or soft surface is helpful and you also might find it useful to have a stack of books or small box or something in case you are working with the amplifier on its side and need to support the transformer. A friend or family member giving you a hand might be a good idea if you are having a hard time of it.

Do the same thing for the choke using its included hardware. It faces sideways as this minimizes the possibility for hum to be induced from the power transformer into the choke.



At this point, I recommend coming up with some way to hold your amplifier upside down with room for the transformers underneath while you work on the interior from above. I made some stands for myself out of wood with a soft pad on top. You could use stacks of books, boxes or anything. Just remember the amplifier is heavy and can be off-balance, so use something sturdy and put a little soft cloth or something down for protection.

Now, let's tie off some of the unused wires from the power transformer. You'll need many of these, but not all of them. I suggest you trim them a bit shorter and use **heat-shrink tubing** to cover them. Heat the tubing with a heat gun or by holding a soldering iron under it, ensuring the ends are fully covered. Then coil these up and secure with an included **zip-tie**. The table below shows the color code of which wires we will use (in later steps) and which ones you should tie off in this step.

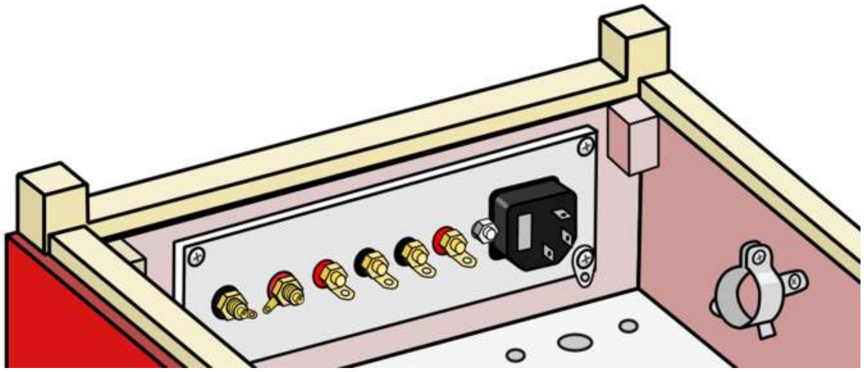
Power Transformer Lead Colors and Usage

blue black	120V primary. These will be tied together and used for one side of the mains voltage
brown white	0V primary. These will be tied together and used for the other side of the mains voltage
red (2)	These are the high voltage secondary AC (~600VAC, or +/- 300V relative to the center tap). We will rectify into DC.
red / yellow stripe	This is the center tap of the secondary high voltage winding. This will be our 0 voltage potential reference for all ground points in our circuit and will go to our star ground point.
yellow (2)	These are the 5VAC secondary winding, used for the filament of the rectifier tube.
green (2)	These are the 6.3VAC secondary windings for the driver tube filament (heater) supply.
green / yellow stripe	This is the center tap for the 6.3V winding. In some amplifier designs you might reference this to ground potential, but in our case, we will reference to an elevated DC voltage.
red / white stripe (2) black / yellow stripe (2)	These are two sets of 2.5VAC windings. We will use these for the 2A3 tube filaments.
Not used and should be trimmed, covered and tied off:	
blue/yellow stripe black/red stripe	110V primary used for other household voltage combinations.
brown/yellow stripe white/black stripe	100V primary used for other household voltage combinations.
violet	This is a 50V tap used in some types of circuits, but not needed.
white / red stripe orange	Center taps for each of the 2.5V windings. We will not use these.
yellow / black stripe	Center tap for the 5V winding. We will not use this.

When you are done, you deserve a drink of your favorite frosty beverage. Go get one.

8 Attach the AC power inlet, speaker binding posts and RCA input jacks

This is fun because the back of the amp starts to look cool as you attach all of the connectors to the back panel. Start with the **fused AC power inlet** and attach as shown here with the Live and Neutral lugs on the right hand side and earth ground on the bottom (with amplifier upside down). Use the included 3/8” oval head screws along with lock washers and nuts to secure it in place.



Next, mount the **four speaker binding posts**. The plastic washers go on each side of the aluminum panel so that the binding post is not touching the panel, insulating your output signal. Make sure it's aligned properly or you could end up shorting your output. The binding post will have a place to solder wires to in a later step. Some posts I include in certain kits may have a tab that is helpful to bend away from the aluminum panel to make sure you don't accidentally end up with a wire touching the back panel.

Finally, mount the **two RCA jacks**. Convention is for red to be on the right. Again, there are plastic washers that fit in the holes in the panel to insulate the input jacks. Orient the outer metal tabs toward one another. These carry the input signal ground and we will eventually wire them together and send to our star ground point. You'll note that we are not allowing this to be grounded onto the chassis. The input signal is a sensitive part of the circuit and can pick up hum if we aren't careful, so we will do our best to protect it!

9 Attach and wire the power switch

Mount the power switch to the chassis on the same side as the power inlet (right side when upside down). There is a nut and lock washer that will stay on the interior side of the wood chassis, and a flat washer and cover nut that goes on the outside. The threading has a slot that should orient toward the bottom of the amplifier and the washer has a tab that faces outward; this prevents the washer from rotating and damaging the surface as you tighten the nut. Be careful to not scratch the outside of the chassis as you use an open-end or adjustable wrench to get it tight. Ensure it is aligned vertically.

Some switches have a standard nut on the outside that is easier to tighten with a wrench, but that would look rather ugly, don't you think? This one has a more finished-looking round nut, with barely noticeable flattened edges for a tool to tighten. It is a bit trickier to install. Be aware that the nut is not designed to screw on more than a short distance. If you can't get it tight enough to hold the switch in place, you need to back off the interior nut so less threading is exposed on the outside. As another tip, you may find it easier to get the outside nut started if you hold the toggle switch half-way between its up/down state.

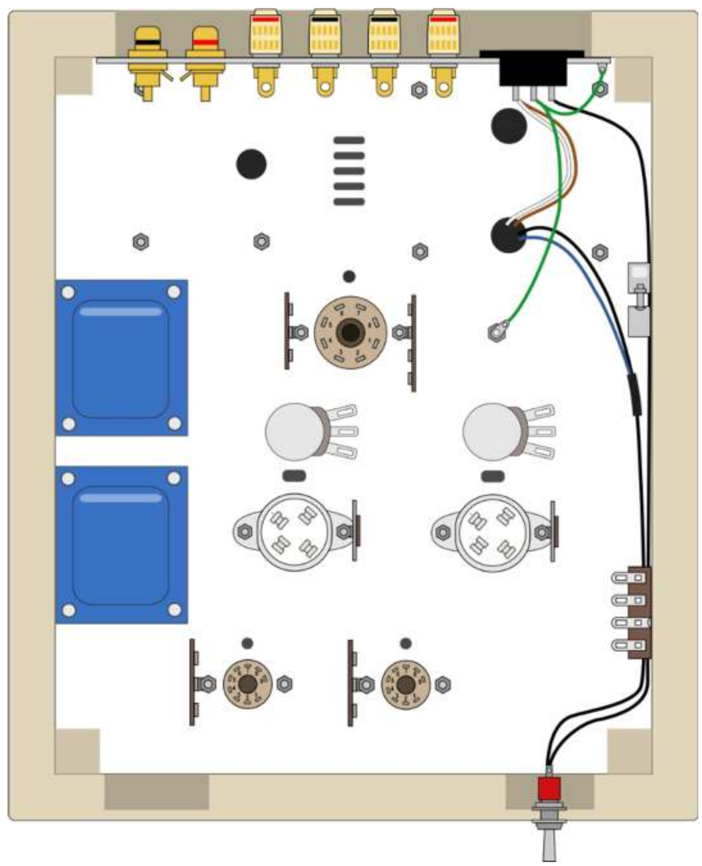
Once you have it securely in place, give yourself a high-five. You are awesome.

Now, let's wire this baby up. We're going to take power from the AC inlet and connect it through a switch to the primary side of the power transformer. You only need a single-throw power switch, but sometimes I may supply a dual-throw switch because I found a good supply source and they are just as easy to use, so if the one included in the kit has three lugs on it, that's ok, we'll just use two of them.

Trim a 14" length of **black hookup wire** (don't confuse this with the black heater wire that is in a separate bag for a later step) and strip both ends. Now solder one end to the Live lug of the AC power inlet (connection is after the fuse) and the other end to the middle lug of the power switch. Trim any excess wire so it's a neat connection.

Ideally we could just wire the transformer straight to the power switch, but the leads aren't long enough to do this, so we will need to extend it. Also, the power transformer has several wire taps that allow it to be used for North American voltage (120VAC) or also for other countries that use 220-240VAC. So to get the 120V we need, we will combine together the **blue and black wires** from the power transformer and extend this using a single additional 7" length of black hookup wire to run up to the power switch. So first, get ready with some **heat shrink tubing**, twist together the ends of the black and blue wires from the transformer, and then wrap onto them the end of the Y" black hookup wire. Run a little solder onto these twisted wires to get them securely connected, (soak in a little solder but don't create a big thick blob), and then cover over with the heat shrink tubing and seal it up by heating it. All nice and tidy and protected? Sweet.

Note that your AC connector may look slightly different than this simplified illustration.



Solder the other end of this black wire to the top lug of the power switch. Keep these wires together along the edge of the chassis. You generally want to keep your AC power wires apart from some other wires that will carry the audio signal. A zip tie can hold these together as needed.

Now, to close the circuit, you will twist together the ends of the **brown and white wires**, and solder them onto the Neutral lug of the AC power inlet. See what's happening here? Power from live lug of the mains AC voltage goes to power switch, into primary of transformer, out of primary of transformer, closing the loop back to the Neutral of the AC inlet. Cool! We have the mains circuit done. (And the fuse is already in this circuit because it's built into the IEC connector inlet.)

One more step here for safety. We are going to connect our star ground point to the safety earth ground of the power inlet, and at the same time connect the aluminum back panel so it is grounded for safety. Do not skip these steps because you think safety is for babies. This is not optional.

Trim and strip one 5" length of **green hookup wire**, and one 3" length. We need to attach a **ring terminal** to one end of the 5" wire, that will go over the star ground bolt. I use a helping hands tool as you see in the picture below while I solder one end of the green wire to the small hole in the ring terminal. The clips help to hold it steady while you solder. If you don't have one of these, you can probably manage by finding some other way to get the wire and ring terminal to stay steady while you solder.

You will repeat this process in several other places for additional ring terminals later. I won't show the details again, knowing you are a clever person and can remember.

Now, solder the shorter 3" wire to the ring terminal you had attached in step 1 to the corner of the aluminum back panel.

Finally, connect both of these green wires to the safety earth lug of the power inlet (the one corresponding to the middle prong of the cord). So now we have both the aluminum panel and star ground point referenced to the earth ground through the 3-prong house wiring. If bad things were to ever happen, we want high voltage going into the earth.

Now, with no power cord attached, flip the switch once and then clutch your chest and pretend you electrocuted yourself for a second. NO, what are you doing?! Don't pretend that! We're trying to emphasize safety here, geez. What kind of frosty beverage did you get in step seven?

10 Wire the rectifier tube socket

Ok, you got your feet wet, now let's really knock out some wiring in the next few steps. This lays the foundation for how stuff is connected together. I find wiring a little boring to be honest, but the electrons gotta make their way from Texarkana to San Antone somehow, am I right?

Let's start with the 8-pin rectifier tube socket. We need the two **yellow 5V wires** from the power transformer to connect to pins 8 and 2, using the bottom holes of the tube pins. But here's what we'll do for all of the heater wires: twist them together. Don't go crazy tight, just enough to keep the wires in close proximity to one another. This helps reduce hum, because there's a lot of current going through these guys. Trim them shorter to fit neatly. In all cases throughout your build, you want your wires trimmed short enough that they aren't turning into a big mess of wires, but shouldn't be so short that they don't reach easily—dog leash style, not dental floss, if you know what I mean.

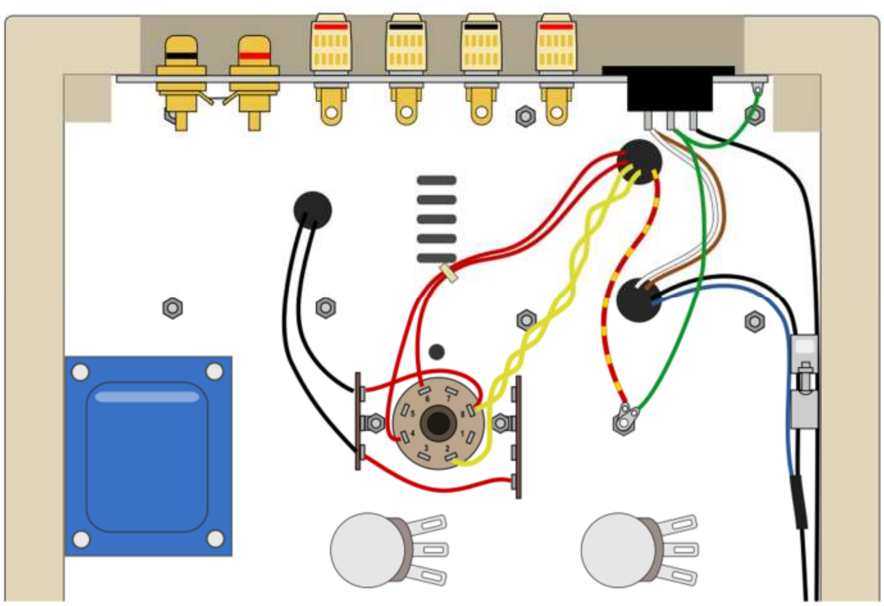
Why twist heater wires?

Tube filaments take high currents to heat up—the 5U4GB tube draws 3 Amps, the 2A3 tubes will take 2.5A each, and another 300mA each for the 12AY7. This is alternating current coming from the transformer at 60 cycles per second. If we aren't careful, this can create interference with sensitive audio signal wires, amplified and heard as a hum. In some circuits, the filament power might be rectified into DC voltage to avoid this. Our circuit leaves this as AC, but by twisting the wires, we put in close proximity the alternating voltage so electromagnetic fields cancel each other out. It also helps keep the wires organized and routed neatly, avoiding heater wires running around willy nilly.

Next wires going to the rectifier tube are the two **red high voltage secondary wires** from the transformer, connected to pins 4 and 6. These don't carry nearly as much current, and are also pretty easy to keep isolated at the back of the amp. If you want to twist them you can, or you could use a zip tie to keep them neat.

Now this little hub around this tube socket is where we do some various power supply stuff, like rectify the AC into DC and filter it so we have a clean high voltage supply for our audio tubes.

Trim and strip a **2" red wire** to connect from pin 8 of the tube socket over to lug 1 of the 3-lug strip on the left side. (Note the numbering convention I'm using to number the terminal strip lugs from top to bottom.) At the same time, trim one of the black leads from the **choke** and connect it to the same place. Use the hole in the the terminal strip; we will connect a capacitor to the upper part of the lug in a later step.
Rectification is explained more in Part 2, but the basic premise is that high voltage AC comes from the transformer into the anodes (plates) of the tube, and rectified DC comes off the cathode of the tube at pin 8. Then we smooth out the rectified signal using the choke and some capacitors.



Trim the other black lead from the choke to reach lug 3 of the 3-lug strip, and also trim a 2 ½" length of red wire. We'll connect both of these to lug 3 in the hole at the bottom. In a next step, you'll connect this red wire over to the terminal strip on the right, but you can leave it unsoldered for now, since a few other wires should go there. What we are doing is simply bridging our high voltage supply to two lugs, since we need it in several places and it would be too much to try and branch off all the wiring from one spot.

One more for this step. From the power transformer, take the wire that is **red with a yellow stripe**, trim it to length to reach the star ground point, and put a ring terminal on the end of it. This is the center tap of the high voltage secondary, and we use it as our zero voltage potential and reference everything in the circuit to this point that we can call "ground."

Neat Soldering

In all of these soldering steps, use small angle-cutters to clip off your wire ends neatly after soldering them in place so there are no tips sticking out anywhere. Inspect that there are no stray wires loose, or solder blobs anywhere. And make sure you don't melt the insulation of your wires while you solder, introducing risk of something touching where it shouldn't. All of your wiring and component leads should ideally be separated from one another by air, or by two layers of insulation in the case where wires have to cross and touch one another.

Seriously, be neat about this. You will regret it later if you have any sloppiness in wiring and you end up with a short that at best is hard to find and fix, or at worst results in damaged components.

A few other tips on soldering: position things so they are steady, heat the joint with your soldering iron and feed the solder to melt into it, then move the iron away and let it cool. The wires or components should not move while they cool or you end up with a "cold solder joint" that may not be a good connection.

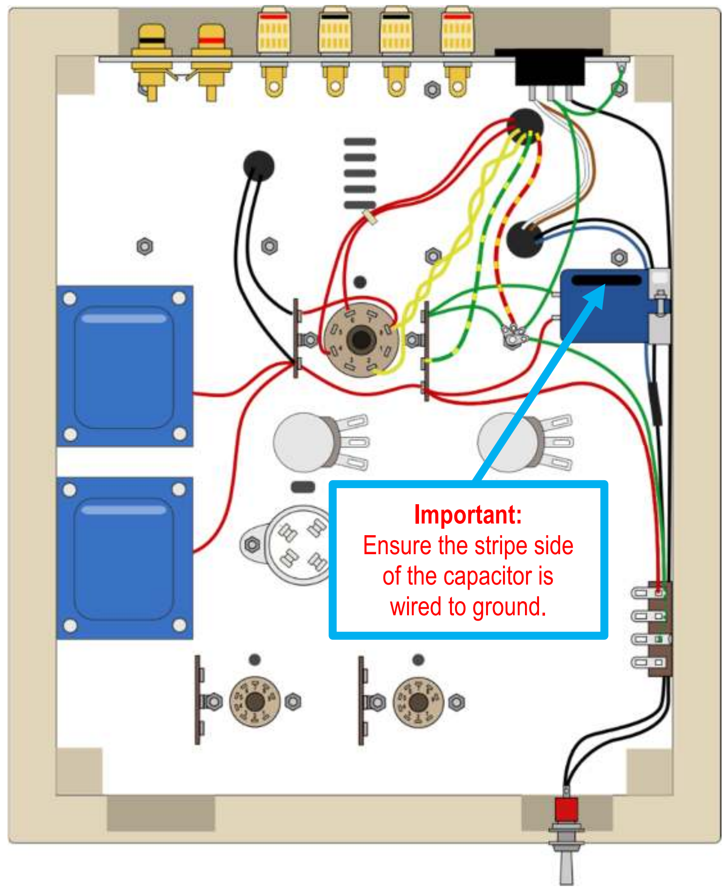
Also, see those holes where the wires come out of the power transformer and choke? The last thing you want is a tiny little metal clipping to make its way down in there like a little stowaway doing who-knows-what in there. Murphy's Law will ensure that at least one clipping will hop right down that hole, so you could consider putting a little masking tape temporarily around that spot to block it.

11 Continued power supply wiring and reservoir capacitor

Trim and strip two red wires, 4" and 10", and then trim and strip three green wires, 2", 4" and 9". Solder a ring terminal onto one end of the 2" wire, and another one onto one end of the 9" wire.

We are going to go ahead and prepare the large **220uF capacitor**. This is a polarized electrolytic capacitor, which means it has a positive side and a negative side. The negative side is marked with a stripe and **always** must be connected toward ground potential while the positive side gets the higher voltage. This is really important. If you wire a polarized capacitor backward, it will at minimum get ruined and at worst could explode. There will be several other electrolytic capacitors this in the amp, and I'll re-emphasize polarity when we install them. So take a look at the 220uF cap and find the stripe and associate the terminal with negative so you understand this.

The type of capacitor I am including has a snap-in type of connector, but we will just wrap the end of the wire carefully around each terminal and solder securely. With the capacitor and wires not yet in the amp, take your 4" green wire and solder it to the negative terminal, and the 4" red wire and solder to the positive terminal. I like to use helping hands or something to hold the wire and capacitor securely so it doesn't move while I solder. You should now have the capacitor ready to go with those wire leads, and you can secure it into the capacitor bracket, tightening the screw just until snug, no need to crank down on that guy.



Now take a look at the illustration here and let's finish out some other wires:

- Solder both the green wire from the 220uF capacitor and also the 2" green wire with ring terminal onto the hole in lug 1 of the 4-lug terminal strip on the tube socket
- Solder three wires into the hole in lug 4 of the terminal strip: the red wire from the 220uF capacitor, the 10" red wire you just trimmed, and the 2 ½" wire from the previous step that connects to the 3-lug terminal strip on the left
- Trim the green/yellow stripe wire from the power transformer to reach lug 3 of the terminal strip; solder into the hole at the bottom. This is the center tap of the 6.3V supply that we will use for the driver tubes. You'll see soon what we do with this.
- Solder the other end of the 10" red wire to lug 1 of the 4-lug terminal strip mounted on the right wall of the chassis. Bring the wire up through the hole from the bottom.
- Solder the 9" green wire to lug 3 of this same terminal strip, again coming up from underneath; the other end with the ring terminal goes onto the star ground bolt
- Trim the red wires from the output transformers and solder them to the top portion of lug 3 of the terminal strip on the left side of the tube socket

We have more components to add in a later step, but the big picture here is that this area of the amp is the power supply and we need to send that high voltage DC (we usually call this B+) through the output transformers and also up to another filtering stage for the driver tubes. And we have a few ground returns for the capacitors doing filtering (smoothing) of the rectified AC voltage so it's super clean for our audio.

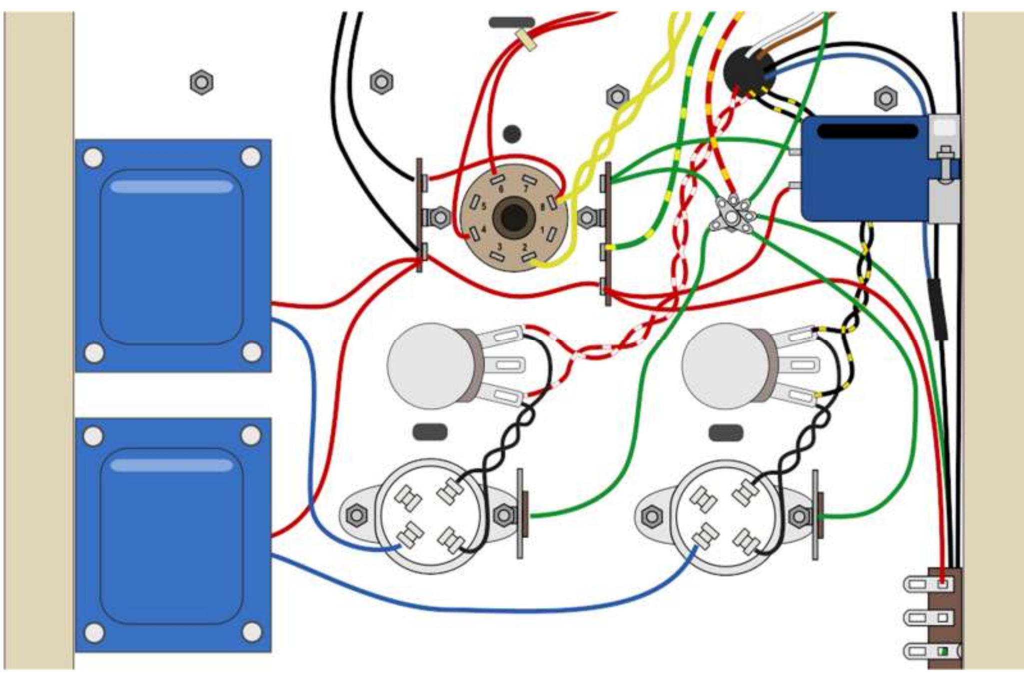
Take another look and make sure you have all the wires done and in the right places. Double check you have the negative side (stripe) of the capacitor wired with green wire, leading to ground. And make sure your solder joints are really good on the lugs of the terminal strips, and trimmed neatly.

You are the best.

12 Wire the output tube sockets

Trim the **blue wires** from the output transformers to reach the 4-pin tube sockets, noting that the top transformer as shown in the illustration should go to the tube socket on the left, and the bottom transformer wired to the socket on the right. Solder the wires to the lower-left pin as shown. This is the B+ voltage that goes to the plate of the tube after passing through the output transformer.

Next, cut a 5" length of **green wire** and solder a ring terminal on one end. Then solder the other end to the hole in the top middle of the single-lug terminal strip on the left tube socket (make sure it's in the top of the lug, not the hole on the bottom where the bracket is mounted). Repeat this with a second green wire cut to 6" and soldered to the terminal strip on the right socket. The other ends go on the star ground point.



Finally in this step, we will wire the filaments for the 2A3 tubes. Instead of going straight to the tube socket, we are going to run wires to the hum potentiometer, and then in parallel to the tube sockets. Twist the red/white stripe wires and route it neatly to the left side potentiometer, and twist and route the black/yellow stripe wires to the right side potentiometer. Trim excess wire, probably only necessary on the wires going to the right tube socket. Don't solder these to the potentiometers yet.

Now trim four pieces of **black 20 AWG filament wire** around 3-4" each (in a separate bag from other hookup wire). Note the illustration here, you will twist pairs of wire together and run neatly from the tube socket to the outer lugs of the potentiometer. My illustration uses only a few twists just to convey the concept, but you can twist a little tighter. Note that the wire lengths may not be identical since one pin or lug is further away than the other. Solder the ends to the tube socket in the two right-side pins. (These should be the larger pins a bit more widely spaced than the ones on the left—make sure you mounted these tube sockets in that orientation. Also, it does not matter which specific terminal of the potentiometer is aligned to which of the two pins; either way is ok.)

Now on the potentiometers, solder both the striped wires and the black wires to the outer lugs. See how this is going? 2.5VAC is coming across those striped wires from the power transformer to the potentiometer outer lugs, and then continues on in parallel to the tube sockets. The 2A3 tube uses a directly-heated cathode, so these wires bring low voltage and high current to heat the cathode, and we'll see in a later step how we use the middle wiper of the potentiometer to reference these wires to a DC voltage level through a resistor.

CHECKPOINT

- ☐ Review the previous wiring diagrams and make sure you have made all the connections
- ☐ Your wires are routed neatly in similar places to what is shown in the wiring diagram?
- ☐ Check your soldering that you don't have any stray wires or things touching where they shouldn't. Trim if needed.
- ☐ Check that you didn't accidentally melt any wires that could risk touching something
- ☐ Look for little bits of wire that you trimmed off, and throw away
- ☐ You may wish to use a cotton swab and alcohol to wipe off any flux residue that might be on some of your connections
- ☐ Pause to realize that you are really good at doing a lot of things that nobody else does.

13 Wire the heaters of the 9-pin tube sockets

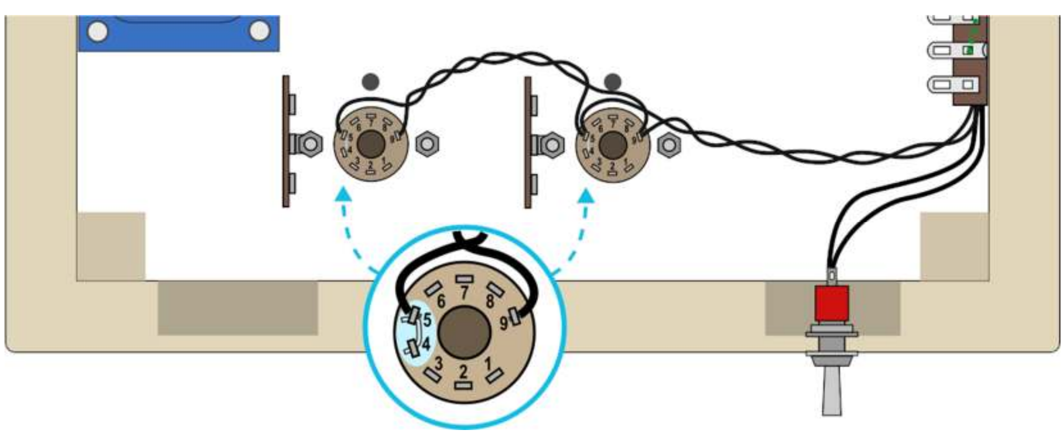
The 12AY7 tubes will use the 6.3V AC supply from the power transformer, which is the two green leads. But they aren't long enough to reach up to the 9-pin tube sockets, so we'll extend them using the **black filament wire**.

Trim and strip two lengths of the filament wire around 8" each. One at a time, wrap the exposed ends of a black wire and green lead together tightly, and run some solder over it to make a good connection, then cover with heat shrink tubing and heat it to seal well.

You will want to twist these wires for the same reason mentioned earlier about controlling hum, but I recommend just using a few zip ties or larger size heat shrink tubing to keep the green wire together and routed up along the edge of the chassis, and start twisting at the point where the black wires take over, though you could twist the entire length including the green wires if you prefer. Route the black wires over close to the right side tube socket.

We are going to wire these two 9-pin tube sockets in parallel, so trim two more pieces of black filament wire around 6" each and twist them together. Now fit all these wires roughly into position. They will connect to pins 4 and 9 on the tube socket. Shape them as needed and trim any unnecessary excess. See the illustration for the rough route to follow. These tube sockets provide the initial amplification of the audio signal, so they are sensitive to hum. We try to keep the heater wire away from signal wires, relatively short, and twisted all the way up until the tube socket area.

We are almost ready to solder them on, but first we will do a little extra step. We actually need to connect one of our heater wires to <u>both</u> pins 4 and 5, and the other one to pin 9. (This is because of how we are actually using 6.3V to power two halves of the 12AY7 filament). While you could try to fiddle a longer stripped wire through pin 4 and then over through pin 5, what I suggest as an easier technique is to take a small clipping from the ends of the 22uF capacitor leads (we won't need the full long length of these) and just make a tiny little bridge wire that you solder from pin 4 to pin 5. Then solder your heater wire just to pin 4. Make sense?



When you are ready, fit your wires into the holes in the pins, solder 'em up, and trim the excess leads so they are neat. Remember these are going in parallel—chaining first to the right tube socket and then over to the left one. So the tube socket on the right will have two sets of wires in pin 4 (bridged to pin 5) and two sets of wires in pin 9. (You do not need to keep track of which wire is which when bringing the parallel wires over to the left tube socket. In other words, you don't have to connect pin 9 to pin 9 and pin 4 to pin 4; it's ok if they are reversed.)

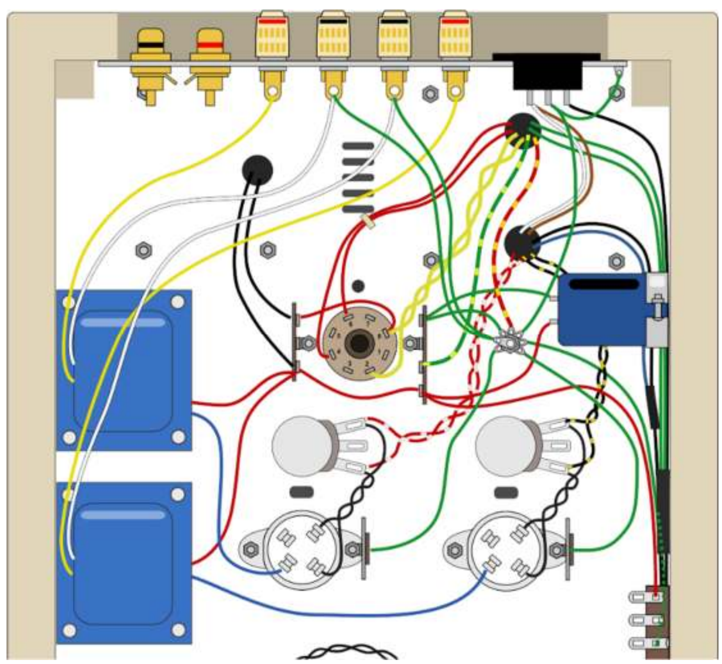
14 Wire the speaker binding posts

Let's wire the secondary side of the output transformers, which will go to your speakers. First, trim and strip two lengths of 7" **green wire**, and for convenience we will wire <u>both</u> of them to a single ring terminal. This is going to be our ground reference for the output.

Now you will trim and strip the **yellow and white wires from the output transformers** to reach neatly to the speaker binding posts. Yellow is positive and goes to the red posts, while white is common and goes to black. You'll note the speaker binding posts are arranged with black in the middle and red on the outside aligned to either the left or right side of the amplifier, and corresponding direction of the left or right speaker. We have our amplifier wired so that the left and right side tube sockets correspond, so notice in the diagram how the top transformer is wired to the left tube socket (as looking down in the amp) and the output wires should go to the binding posts to the left. Likewise, the bottom transformer is wired to the right tube socket and goes to the binding posts on that side.

Go ahead and solder the yellow wires onto the red binding posts. And solder both a white wire and one of the green wires to the back binding posts.

You will notice there is one last wire remaining from the output transformers, **white with a blue stripe**. This is an ultralinear tap, which is used in some designs with other types of tubes that have a screen grid and use a partial winding of the transformer in a sort of feedback technique. This amplifier uses triode tubes, so it isn't applicable. You can trim this wire shorter and cover with heat shrink tubing.



15 Wire and mount the potentiometer

The chassis has a recessed hole for the potentiometer, which makes it difficult to solder leads onto the lugs after its mounted, so you'll do this beforehand.

Cut a **6" length of green wire**, **5" length of green, 4" yellow**, and **6" white**. The yellow and white will be your right and left signal wires that go from the middle lugs of the potentiometer (attenuated output) to the driver tube terminal strips. The green wires are ground wires for each channel of the potentiometer.

You also need to strip and prepare the **shielded input signal cable**. This is a two-conductor cable that will carry both channel signals from the RCA input jacks to the potentiometer. You will need to very carefully cut about ¾" to 1" of the outer casing off each end, without cutting into the interior wires. It takes very little pressure to cut the casing, and by wiggling it back and forth, it will easily break free. It's easy to trim too deeply and cut into the interior wires—go lightly! The kit includes a 15" length, but you probably need a bit less, just in case you accidentally need to try again—I got your back.

There is a black and red signal wire inside, and a bare stranded shield that can be twisted into a wire. You will ground this shield only on one end, nearest the input jacks (to avoid creating a ground loop). The end of the shielded cable that is wired to the potentiometer requires only the black and red leads, so cut off the bare shield wire here. The red and black leads will go to the two gangs of the potentiometer, so one lead needs to be longer than the other. Trim and strip so the red wire reaches longer than the black one to be soldered to the terminal closer to the knob post.

The other end of the shielded wire will go to the RCA input jacks. Strip and hold up temporarily to see that they can line up to fit the two jacks. You'll need the shield wire on this end, so don't cut it off!

It's important to wire up the potentiometer correctly so that it will attenuate the channel signals in the expected way. Note the diagram below with knob post oriented to the left, wire the input signals to the top lugs, output wires to the middle lugs, and ground wires to bottom lugs, with the longer ground wire on the side with the black and white wires (white and green wires will reach further to the right tube socket). Trim any excess and inspect carefully.

Shielding the input signal

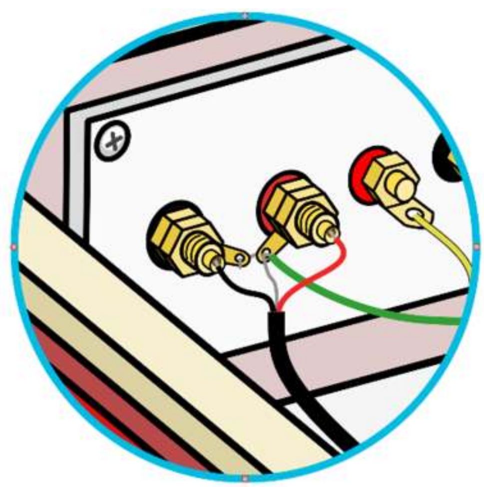
The input signal is a sensitive part of the circuit, carrying our precious audio that will be amplified. A metal shielding inside this cable is run to ground on one end to protect the signal wires from picking up noise or interference from the surrounding amplifier or room environment. We want to maximize our efforts to keep noise and hum out of the amplifier. It should be very quiet when you are done, assuming good electrical environment in your house.

We aren't shielding the white and yellow leads going from potentiometer to tube socket because they are short lengths and it becomes inconvenient to try and shield everything.

Now mount the potentiometer in the chassis. A small alignment tab fits into a pre-drilled hole so it mounts flat and oriented with wires facing up as you work on the amplifier upside down. Use the washer and nut to tighten in place carefully from the outside.

16 Wire the RCA jacks and driver tube sockets

Ok, just a few more wires, then we can treat ourselves to some capacitors and resistors, my favorites! For this step, trim three **green wires** to 8”, 9” and 10” and put a ring terminal on the end of each one. And trim two **red wires**, 7” and 10”.



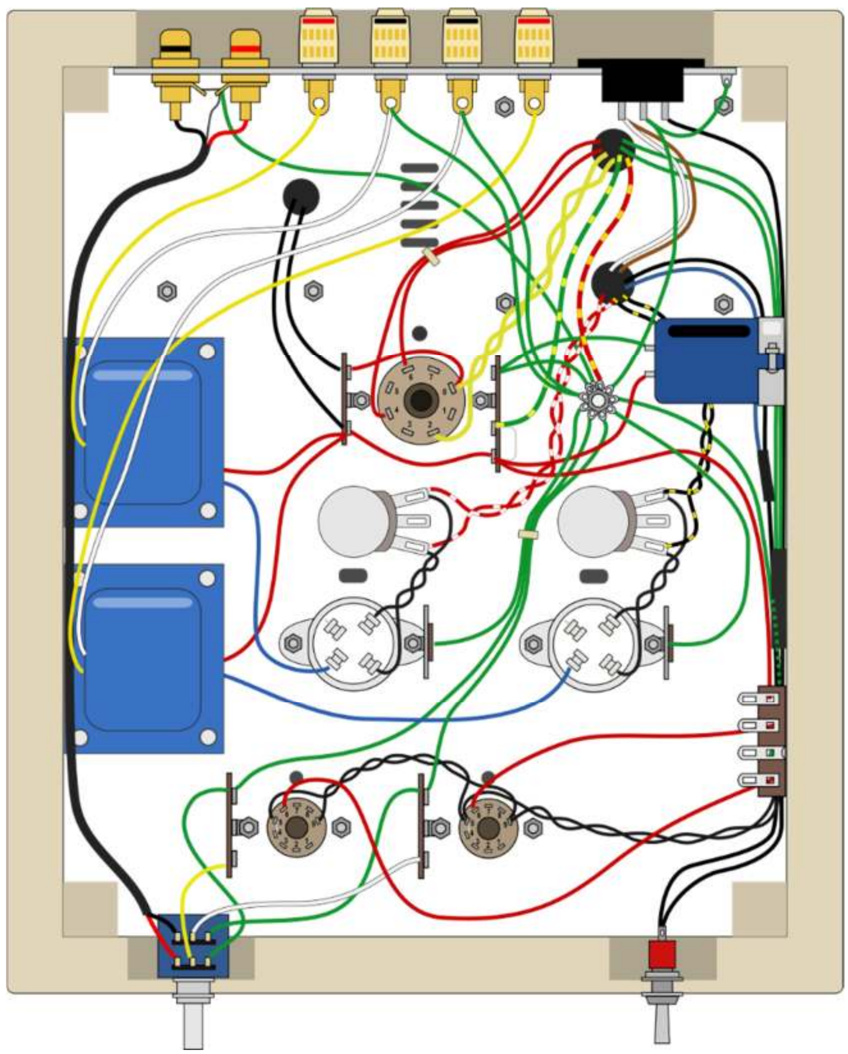
Route the shielded cable along the edge of the chassis above the output transformers to the RCA input jacks. Use the 9” green wire with a ring terminal on one end that will go to the star ground. Strip the other end with an extra-long exposed wire and run it through both of the RCA jack outer lugs. We’ll just use one ground wire for both channels. Then take the shield from the cable you prepared in the previous step and put it through one of the outer lugs or wrap it around the exposed green wire, and align the black and red wires to the respective inner connectors of the jacks. Solder all in place. See what’s happening here? We ground the common (outer) wires of the inputs, ground one end of the cable shield, and run the audio signals to the potentiometer.

Next, run the other wires from the potentiometer to the 9-pin driver tube sockets. Yellow goes to lug 3 on the left-hand terminal strip, white to lug 3 of the right-hand strip. Use the round holes on the bottom of the lugs, nearest the aluminum chassis, leaving the bigger top lug openings for components that will be added later. These white and yellow wires are the audio signal that eventually goes to each grid in the dual-triode tube. You can trim and re-strip these wires if necessary to get them as short as possible without making too tight of a connection. Trim any excess, so you don’t have leads poking out.

The ground wires from the potentiometer need to go to lug 1 on their respective terminal strips, but at the same time and in the same hole, we will solder the longer green wires with ring terminals that you just prepared, so both wires are connected in place. The ring terminal goes to the star ground bolt. And while you are at it, you could use a zip tie to keep neat some of the ground wires that take the same route up through the middle of the chassis.

Now, take the red wires you cut and solder the 7” wire to lug 2 of the 4-lug strip on the side wall of the chassis, and solder the 10” wire to lug 4 of the strip. This is going to bring high voltage over to our 9-pin driver tube sockets where you will solder these to pin 6 of each socket, using the longer wire to reach over to the left side socket. Trim neatly.

Juice, baby.



🔍 CHECKPOINT

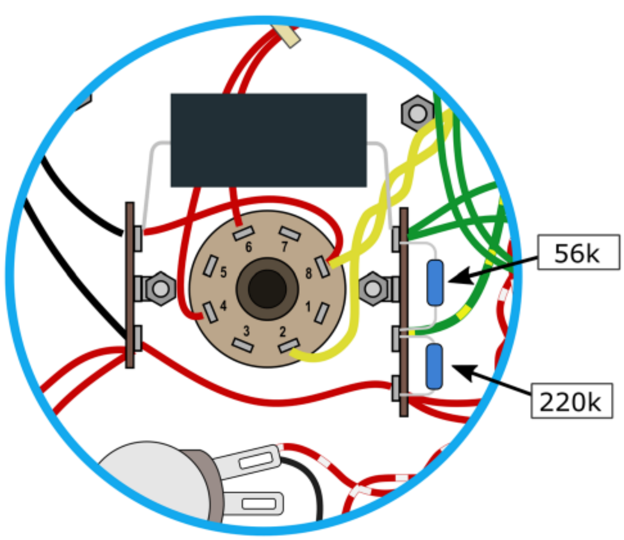
You have finished all the wiring. Celebrate your success and take a moment to review.

- ☐ Trace through the entire diagram again to make sure your wires are in the right places.
- ☐ Check all your connections that they are secure and clean, neatly trimmed
- ☐ Neaten up your wire routing if needed, keeping some along the sides of the chassis wall, use zip ties where you need to.

17 Solder rectifier filter capacitor and resistors for voltage divider

Alright, let's finish out some things around the 8-pin rectifier tube socket. The **3.3uF capacitor** will be connected from lug 1 of the left strip to lug 1 of the right strip. This is a film capacitor without polarity so it can be attached in either direction. It provides the initial smoothing of the rectified voltage and also controls the B+ voltage level to some degree. There is heavy ripple current in this location right after the rectifier, and film capacitors can handle ripple current better than electrolytic capacitors, but they are large physically, so are only practical when capacitance values are relatively low. In our case this works out well to use a film cap here. If you are not embarrassed, give that film cap a little kiss before you solder it in, just for good luck and kind wishes.

On the right side terminal strip, we will create a voltage divider from the B+ high voltage and ground potential. A voltage divider can be made with two resistors in series, so we will solder a **220k resistor** from lug 4 to lug 3, and a **56k resistor** from lug 3 to lug 1. You'll recall our 6.3V AC center tap is connected here on lug 3 and this elevates the filament voltage to a necessary DC potential for the driver tubes. These resistors also play an extra role of safety so the capacitors bleed off their charge when the amp is turned off.



Why and how to elevate heater voltage?

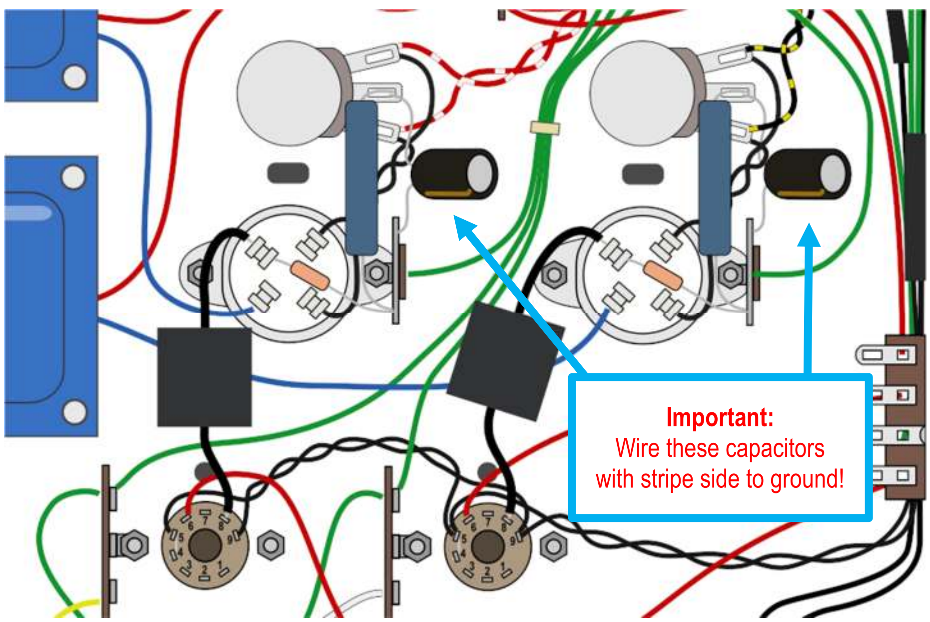
The 6.3V AC from the power transformer is used to power the filaments (heaters) on the 12AY7 driver tubes. But this voltage has to be established at some DC potential, it's not floating. In some amplifier designs where the cathode of the tube is near ground potential, we could simply put the heater also at ground potential (6.3V AC with center tap grounded means the voltage fluctuates +/- 3.15V above and below 0V). But in our design we are using a compound driver stage where the cathode of one section in the tube will be close to ground, but the cathode of the other section of the tube will be at a higher voltage of around 140V. Most indirectly heated tubes have a maximum rated voltage difference between the cathode and heater since they are in close proximity. To ground the filament while the cathode is at 140V would exceed the maximum rating. So we will elevate the heater up to a higher DC voltage, in our case around 65V, roughly between the two cathode potentials. This keeps the voltage difference between the filament and either cathode in a reasonable range.

To accomplish this, we can use a voltage divider, a common technique to provide a specific output voltage potential from a higher input voltage. By putting two resistors in series from a voltage point to ground, the ratio of the two resistors can establish a specific voltage at any point we like. We'll take our B+ from the power supply of around 325V, and if we want to get a point at 65V, this is roughly 20% of the total potential, so using two resistors of 56k and 220k we can get the right ratio (56k is 20% of the total 276k). Our center tap wire for the 6.3V supply of the transformer is then connected to the middle of this voltage potential, putting the heater supply at around 65V DC. Cool!

18 Solder components for the output tube stage

Let's add a few things to the output stage on both channels. We need the audio signal to come into the grid of the tube from the driver stage. We are going to do this using the **coupling capacitors**. These are important components because our sweet music is going through it, so we want something high quality here. I like the Clarity Cap brand in this case, not just because they make great capacitors, but the leads are pretty thick and we can shape them just right to fit across the two sockets. The capacitance value is low, so coupling capacitors are typically film capacitors, not electrolytic, so it does not matter which direction you wire these (no polarity).

Arrange the coupling caps to run from the top-left pin of one of the 4-pin tube socket to pin 8 of the neighboring 9-pin tube socket. On both of these locations, we will have a resistor also wired, so this step will focus only on the 4-pin tube socket. Shape the **470k resistor** to also fit onto this top-left pin and run over to one side of the single-lug terminal strip, which is at ground potential (via green wire). Because the 470k resistor is passing overtop the other pins of the tube socket, make sure it has plenty of air space around it so it doesn't accidentally touch them. My illustration makes it look like they are fitting in between the other pins, but you should have them arch overtop for good clearance. Once both the coupling cap and resistor are in the right shape and place, solder them onto the upper-left tube socket pin, and then solder the other side of the resistor to the ground lug. We can leave the other end of the coupling capacitor located near pin 8 of the driver stage socket but unsoldered, and we'll finish it out in a next step. Repeat this for the other channel.



The last step for the output tube stage is the **900 ohm 10W resistors** and **100uF 100V capacitors**. These will both connect in parallel from the middle lug of the hum potentiometer to the single-lug terminal strip with the green ground wire. I suggest soldering the resistor first. I like to bend the very tip of the lead so it tucks just slightly under the lug of the potentiometer making good contact, and make sure the lead doesn't poke down too deeply, getting close to the aluminum panel. Shape it so it has some good air space around it, arching up above the potentiometer and tube socket; it will get hot. And because it's a longer component, it fits better to the further side of the terminal strip, the same place you just connected the 470k resistor. (This resistor is providing the connection to ground for the cathode, through the wiper of the potentiometer, then back through the wires to the cathode of the tube, which in this case is also the filament. This resistor is also how we bias the tube to a certain level of current.)

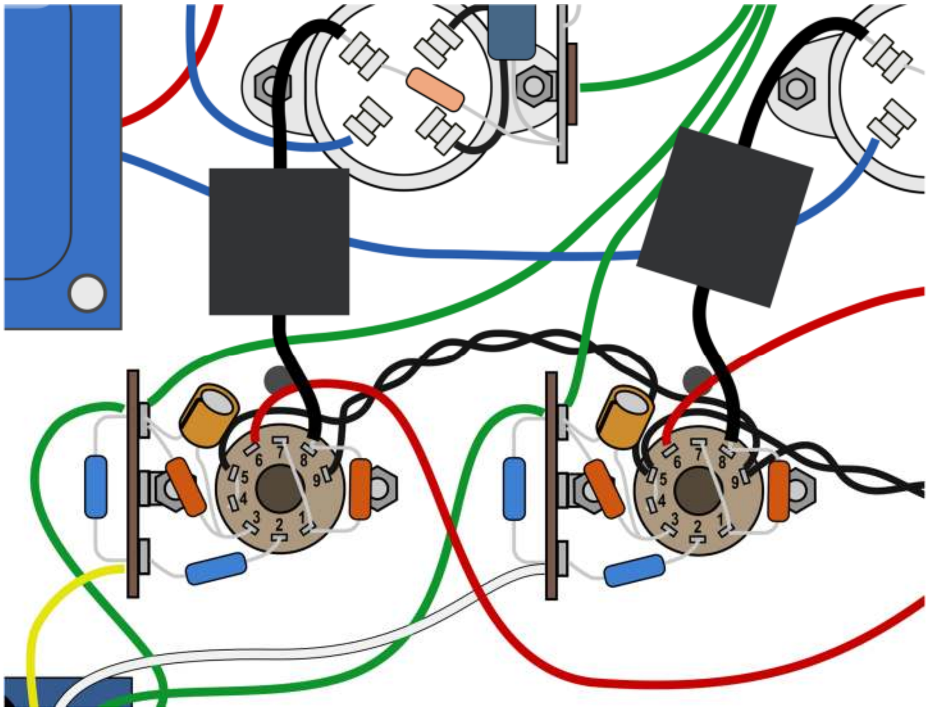
The capacitor is polarized, so **must be oriented in the correct direction**: solder the leads so that the side of the capacitor with the stripe is connected to the grounded terminal strip, and the side without the stripe is on the potentiometer middle lug. If you attach it backwards, it will be destroyed, could actually blow up, your amp won't work right, and you will wear a badge of shame. Take a second look. Everything good for the resistor and capacitor on both channels? No cold solder joints, and leads are neat? You are a superstar.

18 Solder components on the driver tube sockets

Now we'll do the components around the 9-pin driver tube sockets. We have about six things to do on each socket. Here we go. Repeat these steps for both of the tube sockets:

1) We need to **bridge a direct connection** from pin 7 to pin 1. I have included some **solid core wire** to do this, as I find it ideal for this sort of thing. You could use a spare clipping from a component lead, or other short hookup wire. Trim it to perfect length, and I like to bend a teeny little hook with small pliers for a nice mechanical connection. Solder just the pin 7 side of this to hold in place.
2) Now we will put a **1k resistor** from pin 1 to pin 8, arching across the tube socket so it doesn't touch anything. This lets us finish out soldering pin 1, which has both this resistor and the bridge wire you just made. And we finish out soldering pin 8 which gets this resistor plus the big coupling capacitor that goes to the output stage. Solder neatly, trim and inspect.
3) Next take a **2.7k resistor** and shape it to fit from lug 3 of the terminal strip to pin 2 of the tube socket. This is a "grid stopper" resistor, and is simply to protect against high frequency oscillation and interference as we bring the audio signal into the grid of the tube. Try to keep the leads as short and direct as possible with this resistor, and solder the end on pin 2.
4) Shape the **1M resistor** to arch across from lug 3 to lug 1 of the terminal strip. This is a "grid leak" resistor, providing a ground reference to the grid. It is technically optional since we have a path to ground via the potentiometer, but a potentiometer is not an obvious and deliberate method for this, and it's possible a mechanical issue in the pot might block the path and we never want the grid floating. You can solder lug 3 finishing out the connection for this 1M resistor and the 2.7k resistor you already put in place.
5) Take another **1k resistor** and shape it to fit from pin 3 on the tube socket to lug 1 on the terminal strip where the ground wire is. Solder the pin 3 side of it and also solder the other end on lug 1 of the terminal strip connecting the 1M resistor at the same time.
6) Finally, we need a **100uF 25V capacitor** also connecting on those same points, from pin 3 of the tube socket to lug 1 ground (remember this is polarized, and negative side goes to ground). While you could try to resolder and fit these into the same pins/lugs, what I like to do is just shape little hooks on its leads and then solder it directly to the 1k resistor's leads.

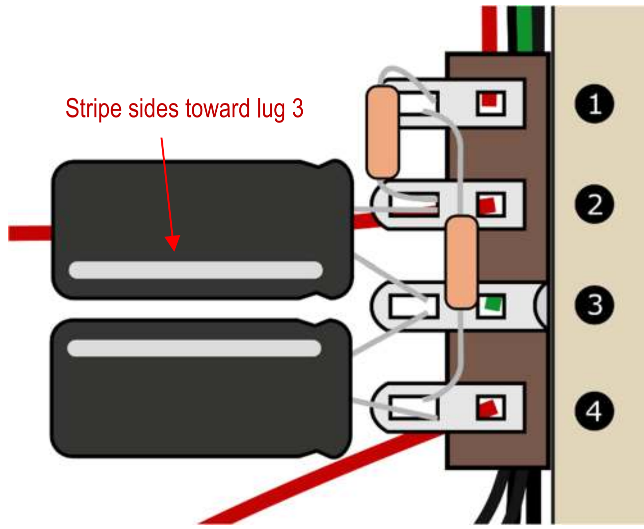
This is a bypass capacitor, so think of it like a little detour around that resistor—oh traffic jam, pardon me, I'll just go around. **Important:** Ensure the negative stripe side is oriented and connected toward lug 1 and the green ground wire.



Cool, all set. Now do a nice inspection that everything on this tube socket, including components and wiring, is neat and clean and there is no stray wire, component lead, or solder sticking out anywhere. Exposed leads should not touch neighboring components, and your wires should not be bumping any exposed leads, lugs or pins. Even though the wires have insulation, you want air space; we don't rely solely on one level of insulation which might melt if a component is hot. Trim extra leads with angle cutters, or bend and reshape things if you need to. Bypass capacitor floats neatly above the associated resistor. I know some of y'all are big picture people who might want to take a glance and say good enough and move on. Or maybe this step was a little hard for you, and you're tired and don't want to keep working on it. Be patient. Pretend you are a swiss watchmaker and are studying every spring and gear in your precious little device. Try again if you need to. When you are satisfied, take a break and think about how awesome you are.

19 Solder additional power supply components

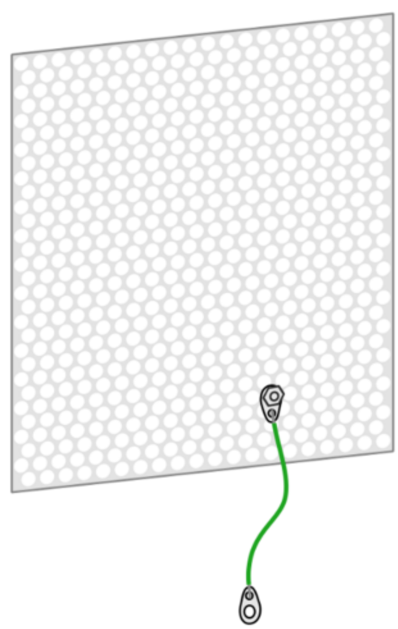
Getting really close now! Let's finish out a power supply step on that terminal strip on the side wall of the chassis. The driver tube sockets get a bit lower voltage and more filtering and decoupling of the B+ supply.



Use the two **30k 2W resistors** and trim & shape one to fit from lug 1 to lug 2, and the other one from lug 1 to lug 4 (arching across so not touching lugs in between). Now take the two **22uF 450V capacitors**, and trim & shape to fit one from lug 2 to lug 3, and the other from lug 4 to lug 3. **Important:** the stripe sides of both of these capacitors should be on lug 3, ground potential. See what's happening here? We are taking our high voltage from lug 1 and splitting it into two channels, with each one going through a resistor, and then a capacitor to ground (we sometimes call this an RC filter, for the resistor / capacitor combo). Then our red wires take this lower, filtered voltage over to each tube socket.

When you have things shaped right, solder them all in place and inspect carefully. It's hard to see underneath the terminal strip, make sure nothing is touching where it shouldn't, it's all trimmed neatly, and make sure you had good solder connections.

20 Connect safety ground to bottom panel and secure ground bolt



You will see success momentarily. The perforated aluminum bottom panel of the amplifier will allow for cooling airflow while protecting you and others from dangerous voltages inside. For safety, we will ground this panel, just in case an internal component or wire were to ever be in contact with it.

But before we do this, take a moment and inspect your work. Review the layout diagram if it helps. Check the interior of the chassis for any loose wire clippings or solder bits. Make sure wires are all in good positions, zip tied where you like. You might even carefully turn the chassis upside down to drop out any bits that could exist. If you taped over anything, remove it. If any of your solder joints look messy from flux residue, you might even use some 99% isopropyl alcohol and a swab to carefully clean it off. We're getting ready to close it all up.

Cut 8” of **green wire**, and solder ring terminals to both ends. Position the perforated panel in place temporarily to see how it fits. A few holes have been widened and align with pre-drilled holes on the chassis. Now choose any perforated hole on the panel in the area near the star ground and use the **#4 3/8” machine screw with lock washer and nut** to secure one end of your grounding wire to the panel and the other end goes to the star ground bolt.

Important step! Put on the final **lock washer and nut on the ground bolt** that you saved from step 3. Arrange all the ring terminals in a friendly druid circle like they are casting a spell to bless the woodland creatures, and tighten that guy up. This finalizes your star ground point.

Then, position the bottom panel in place, and secure with four **#6 3/8” truss head screws** into the pre-drilled holes.

21 Finishing touches: volume knob and high voltage sticker

Yeah, you almost forgot about the volume knob, didn’t you? Place the knob on the potentiometer post, give it a fraction of space so it’s not rubbing against the chassis, and tighten the set screw using a tiny hex wrench or screwdriver. You might want to align it so the set screw is on the bottom when the knob is turned up near the highest level. Give it a test spin and pretend like when you had your stereo at mid-volume playing AC/DC, then Mom yelled up to your room, “Turn that down!” and then you cranked it all the way up! Heh.

I included a **high voltage warning sticker** to place on the bottom of the amplifier. I know you already know, but just as safety for some future unknown person who might get this amplifier. (I know, you think I’m overdoing it, but I just want people safe, ok?)

22 Last steps and power up time!

Install the **2A fuse** into the fuse tray of the IEC power inlet. Kinda hard to open that little tray and get your fingers in there, I know.

Get the amp into a good test location. Insert the **5U4GB rectifier tube** into the 8 pin tube socket. There is an alignment notch on the center pin so it fits in the right orientation. Insert the two **2A3 tubes** into the 4 pin tube sockets—the larger/wider pins should be on the left now as you look at the amp upright. And then put the two **12AY7 tubes** into the 9-pin tube sockets. The pins will only align in one orientation. All tubes should be down securely in place with no gap underneath.

Plug in a line level audio input signal to the RCA jacks. This could be a CD player, DAC, output of computer or mobile device, preamplifier, etc. You will need your own RCA interconnect cables.

Connect 8 ohm speakers securely to the speaker binding posts (I prefer banana plugs). Do not run the amplifier without speakers connected (or 8 ohm dummy load resistors rated 5 watts or more).

Ensure the power switch is in the off position and plug in the **AC power cord**. Plug into the wall or safe power strip.

Now… I suggest you queue up a first-try song. I like *Diana Krall, S'Wonderful*, because, yeah it's wonderful that you did this, right? Pick your own, though, whatever you like. Ozzy. Beatles. Abba. Miles. You know, whatever.

With the volume at about ¼ to ½ and an input signal on, turn on the amplifier. You should see the tube filaments start to glow, and sound start to come up after 5-10 seconds. Watch for these things and turn it off immediately if you notice any:

- Strange and unexpected sounds. A few little mechanical vibrations of filaments and transformers is normal, and you will hear a hum that we will address in a moment.
- Sparks, smoke or strong burning smells. (Some heat smells are normal as the tubes and components get to operating temperatures.)
- If nothing happens after 10-20 seconds, turn it off.

Test source & speakers

I typically use dummy loads or crappy speakers that I got at a thrift store for $5 for testing until I know things work. And I use an old unused cellphone that plays some music as my source. Then after I know things are working properly, I move to my good speakers and source equipment for listening. It's up to you what you decide to connect, but I would not recommend wiring up expensive speakers and equipment for your first test.

But I'm pretty sure you'll be hearing some awesome music emerging, and probably a low 60Hz hum sound. Fear not! That's why we have the hum pots.

Adjusting the Hum Pots

The hum potentiometers let you dial in an adjustment that causes the hum to cancel out and get very quiet. The theory of it will be explained more in Part 2. But do be aware that getting to absolute silence with zero hum with your ear next to the speaker is not likely to be achievable. This is the nature of a directly heated triode tube using AC to power the filaments. You should be able to get this very quiet so that you don't hear it when sitting in a normal listening position, and it should not interfere with your music listening. Extremely sensitive speakers above 95-100 dB SPL are more likely to have the hum be evident when the amp is on without music playing.

You have a few options for how to adjust these. On a test bench with equipment, we could use an oscilloscope or other test equipment to adjust visually, but I'm not expecting you have that type of equipment, and the below options are the most practical for a listening space with speakers attached. Let the amp warm up for at least a few minutes first.

1) **By ear.** With the room as quiet as possible and no music playing, and your ear as close to the speaker woofer as possible while within reach of the amplifier, adjust each hum pot in one direction or another. You should find that there is a sweet spot somewhere in the middle that has the least audibility of hum. It can be very sensitive to your touch, even just a tiny fraction adjustment can make a difference, so listen carefully and use your gentlest fingers here like you are a professional safecracker working on a combination lock.

2) **With a multimeter.** Keeping the speakers attached, connect a multimeter across each channel of the speaker outputs. Set it for the most sensitive AC setting and you should see low millivolts being measured. Adjust until you get this number as close to zero as possible.

You may need to readjust occasionally, or especially if you ever replace the tubes.

Now celebrate! This is the time when you smile. You did it, and should be proud of yourself, right? A bunch of resistors, capacitors, transformers, and tubes, and you get this beautiful music coming out. How cool is that? Tell your friends you built your own amplifier. Turn it up. Get a gin & tonic to celebrate and chill for a while. **You. Are. Awesome!**

A few quick notes on operating your amplifier:

- The tubes will get very hot in a few seconds, and the power transformer could get hot over a longer time period (maybe an hour or more). This is normal. Obviously you don't want to touch them or allow other things to be close to them. See the safety precautions on page 2.
- Remember it is not a high-power amplifier, so you may need to turn up the volume knob near the max to get to loud listening levels, depending on your source signal level. It's all cool, turn that baby up if you need to.
- Always turn off your amplifier when not in use. This is a Class A amplifier, so it is always drawing power. It's not only a waste of electricity, but it could wear out your tubes prematurely and has risks if you leave a very hot amplifier running for hours unattended.
- When others are in your home and look at your amplifier questioningly, just slip another album out of its cover, take a sip of your Manhattan and say, "Yeah, it's a tube amplifier that I built myself." They may not understand, but that's cool. You can read Part II and tell them how a vacuum tube works.

Troubleshooting:

☹ It didn't work? Aw man. Here are a few things to check:

- Your AC cord and wall connection all ok and definitely providing power?
- Did the fuse blow? Take it out and check continuity using a multimeter. If the fuse blew, unplug the amplifier and review your circuit. There may be a short somewhere that caused heavy current; see if you can find it and re-wire. I gave you a second fuse in case you need it, but don't just put it in and try again. You need to find and fix whatever was wrong.

- Speakers are connected properly?
- Tubes are installed fully?
- Input signal is actually being generated at expected line level voltage? (Input cannot be a turntable unless you are using a pre-amplifier with a phono stage)
- Wait at least 10 minutes after turning the amp off. Unplug, open the amplifier, and trace back over all the elements of the schematic and assembly diagram. All looks right?
- The power transformer and output transformers are wired to the correct places?
- None of your polarized capacitors are wired in reverse?
- Your solder joints are secure, with no shorts, loose leads or wire strands, etc?
- Power switch seems to have continuity as expected?
- Volume potentiometer is wired properly?
- Ground bolt—all the ring terminals connected and tightened properly?
- RCA jacks and speaker terminals wired ok? Positive binding posts are insulated with plastic washers and not shorting to chassis?
- When turned on, do you see filaments glowing in the tubes? If not, tube wiring is all right?

I am not providing any live-amplifier troubleshooting tips in these instructions. It is critical that you understand safety and testing techniques before you attempt to diagnose problems with a live circuit, and I can't describe that here or be certain builders of the kit have this type of expertise and safety awareness. You should be experienced and comfortable with trouble-shooting a high voltage electrical device to do it. Consult someone who has this experience and training if you have gone through the bullets above and still need help getting it to work. The schematic in the appendix does include typical operating voltages at key points. **Never probe around in an operating amplifier** if you are unfamiliar with the safety risks or what to look for!

Also, it is possible, but unlikely that a tube or other component is bad. This shouldn't be your first assumption of what's wrong. I have used reputable suppliers and high-quality components. It is most likely something in your physical circuit build. I will of course replace any component that is not working properly. If you are still having trouble, send an e-mail or check the website, and I'll see what I can do to help troubleshoot the issue. I want you to get this working, but at the same time, please know that I'm not there in person, safety is a top priority, and I may not be able to help in all cases.

This concludes the build section. The next section explains how this single-ended tube amplifier works, so you can learn in detail what is happening inside the tubes and throughout the circuit. I hope you'll read on, because this is the most empowering part of this kit—understanding how it works so you can do even more in the future!

PART II: SINGLE-ENDED TUBE AMPLIFIER EXPLAINED

To meet the objectives of this kit, not just assembly instructions for a working amplifier, but to fulfill the learning objective of understanding how the parts and circuit work, this section will touch on some core concepts and then attempt a clear and simple explanation of the circuit. It's so fun to learn new things, you will love it!

I will not attempt a comprehensive explanation of all the physics, electronics theory and math that would make a more robust reference. I'm not best suited to do this, and there are excellent resources online or in books (some noted for reference at the end) that can teach the theory more extensively, and much broader than this one type of single-ended tube circuit you are building. This is intended for a non-technical audience, but I will assume that you have basic knowledge of electric circuits. If you already have a strong knowledge of the theory and function of a triode or pentode vacuum tube and amplifier circuit, you may have bought this kit without a learning objective, and this section may not be necessary for you. But if you want a better understanding of how tubes and this circuit works, read on!

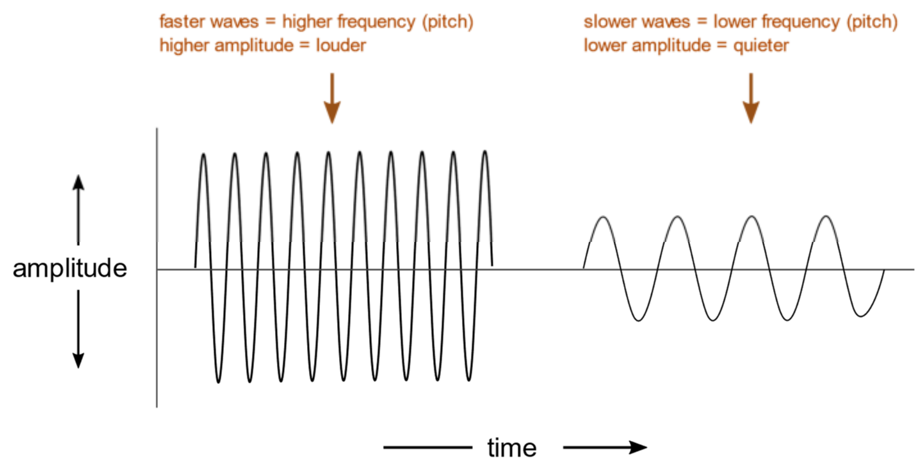
The 2A3 tube was introduced by RCA in the 1930s as a high-fidelity audio amplification tube. There are relatively few manufacturers of vacuum tubes around the world now, mostly in Russia, China, and Slovakia.

Core Concepts

What is sound?

Sound is a type of energy created by vibrations. When things collide or vibrate, there is a physical process that moves the air around those things, and sound travels through the air as pressure waves that compress and expand based on the vibration source. Eventually, these sound waves reach and vibrate within our ears, creating signals that our brain interprets as music, speech, or other noises.

This barely describes the phenomenon, but a key takeaway is that sound waves can be caused by vibrations that go fast (high pitch) or slow (low pitch), and that move a small amount (quiet) or a lot (loud). We can describe basic sound waves using these characteristics—**frequency** and **amplitude**—and plot them on a chart.

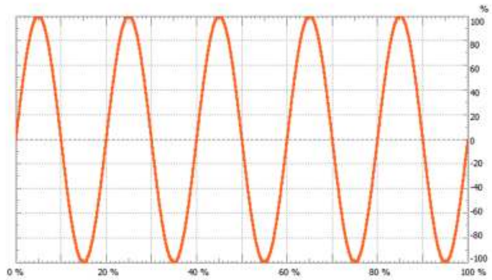


Electronic audio recording equipment converts actual sound waves moving through the air into electric signals using a microphone that reacts to the sound waves creating a voltage at a frequency and level corresponding to the sound. A recording device can capture this stream of varying voltage information, representing the sound waves, saving it for later. A playback device can take the stored information, convert it to a voltage signal again, which is then amplified to a larger, more powerful signal. We then need a device to turn it back into sound waves in the air. This is the loudspeaker, often made using a cone that is vibrated magnetically and this physically moves the air to generate sound waves that a listener can hear. There is much more to this entire process and the physics of loudspeakers, but the important concept is to understand that an audio signal in our amplifier will be a **voltage changing over time.**

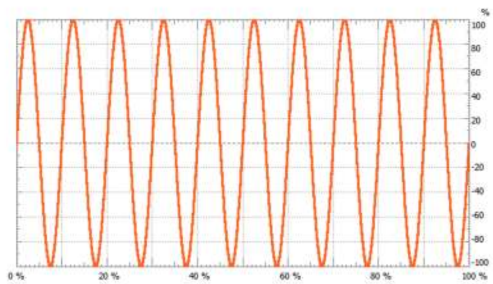
We have two ears that can each hear sound waves separately and interpret spatial location from them, and stereo recordings have two separate signals that are recorded or engineered, and eventually played back, one for each speaker to recreate a form of dimensional soundstage. In most cases through this manual, we will discuss a single process of audio amplification, but know that this process is duplicated, one for each **channel** (left and right).

Pure cycles of rising and falling amplitude over time are **sine waves** and can be described with math formulas that I won't introduce here. But you could think about sine waves as a type of building block that, in complex combinations of frequency, duration and amplitude, can make up music or other audible sound. Combinations of multiple waves will add to a compound wave, as shown in a simple example below. This will be important when we start to discuss distortion and harmonics.

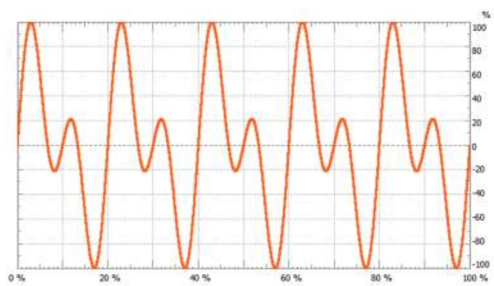
80 Hz
sine wave



160 Hz sine
wave



resultant
waveform
when
combined

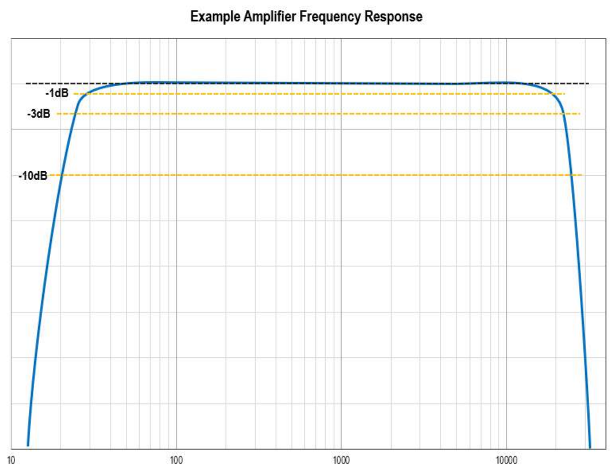


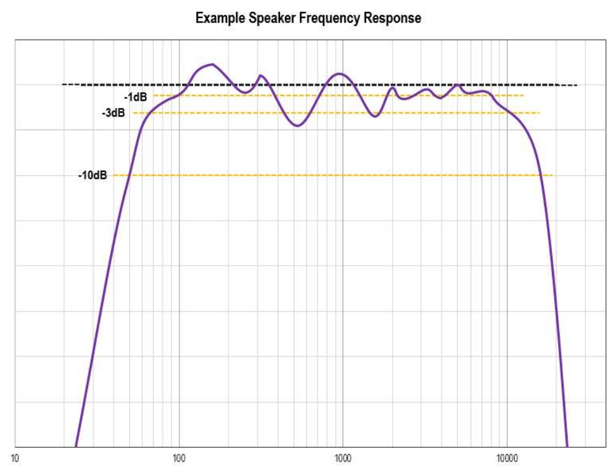
Humans can hear sound only within certain frequencies. To cover human hearing adequately, most audio equipment is designed or evaluated in the range between 20Hz and 20,000Hz. Hertz (Hz) is a measure of the number of wave cycles per second. A vibration at 20 cycles per second is very slow, and we would probably be feeling this very low "thunder" more than we really hear it. On the other hand, 20,000 is such a high pitch that most of us cannot even hear it—especially as we age or lose hearing from exposure to loud noise or bad marching bands. Although it is rare that a music recording spans 20Hz-20kHz or that a loudspeaker could accurately reproduce that wide of a frequency spectrum, we still will design, measure and expect our amplifier to be able to reproduce as accurately as possible within this range of audio frequencies.

The charts of sine waves above (and visualized on an oscilloscope) are in the time domain, with frequency illustrated as the number of peaks and valleys over time on the horizontal axis. Another commonly used graph for audio measurements is in the frequency domain—a horizontal axis representing frequency from low to high, and the vertical showing a measurement of amplitude that a device may reproduce at each frequency.

Analog vs. Digital

I will take a moment to point out that this entire process of generating, transmitting and hearing sound is **analog**—continuously variable movement and interpretation of sound waves. And the process of recording and playback is also analog using a continuous signal voltage. Conversion of the signal to digital information and then later back to analog is common now in recording and playback, and can be done with sophisticated hardware and software to preserve the original analog information as closely as possible, but the natural physics of sound is of course not digital. I'm not a purist, and I use digital music streaming among other devices, both digital and analog. But there is a fascinating beauty and pleasure in learning and understanding the physics and electronics of analog music playback using tube amplifiers and passive loudspeakers (and perhaps other analog devices you use, such as magnetic tape or vinyl).





The chart on the left here shows an example ideal flat frequency response that we might have with an amplifier: frequencies across the audible range of 20 – 20,000 Hz can be reproduced at an equal amplitude. The chart on the right shows an illustrative speaker frequency response—wow, it's very choppy, huh? There are some peaks and valleys where some frequencies are reproduced louder than others. This is typical of a speaker, where a very flat response is difficult to achieve and involves a wide range of physical implications in the action of the speaker drivers (woofer, midrange, tweeter), crossover points where drivers are transitioning responsibility, diffraction of sound from the shape of the speaker, and many others. In fact, the listening room will have a high impact on how we perceive the sound due to reflections. There is an extensive field of study of loudspeakers, room treatment, and other areas—more fun for the DIY hobbyist to explore! Just note for now that the frequency response of your speakers is incredibly important in achieving high-quality sound. It could require large and often expensive speakers to have a flat frequency response and one that extends down to the lowest ranges around 50 Hz and below.

A common measurement unit for frequency response is decibels (dB), a non-linear unit to measure the intensity of sound relative to a reference. If the reference level of 0 dB represents the threshold of human hearing, then a normal conversation might be 60dB in intensity, while a loud music concert could be 100-120dB. It is on a logarithmic scale because our hearing responds differently to low intensity sounds than it does to high intensity ones: 0dB is near silence, 10dB would be 10 times as powerful, 20dB would be 100 times as powerful, 30dB is 1000 times as powerful, and so on. A rule of thumb is that a 10dB increase is perceived as twice as loud.

In both charts, near the bottom and the top ends you see the frequency response start to fall off. On a response chart, the roll-off point that reaches -3dB point relative to a normal level is referred to as the cutoff point, where calculated power at that point is technically half of the normal reference point. Measuring a response that fluctuates within 1-3 dB might be considered flat with minimal perception of change, but more than that could start to become noticeable in listening. For example, a speaker that could reproduce a flat response across a range, but rolls off with a cutoff at 100 Hz means it is down 3dB at 100Hz relative to the maximum level. As the rolloff continues it might be down 10dB by 80Hz (or half the perceived loudness of the higher frequencies) and you might feel it sounds thin or lacking in bass because these frequencies are not loud enough relative to others.

Ohm's Law: voltage, current and resistance

It's worth quickly highlighting the basics of a circuit: a closed loop involving **voltage (V)**, the difference in electric charge from one point to another, **current (I)**, the rate of change of electrical charge measured in Amperes (Amps), and **resistance (R)**, which opposes the current flow and is measured in Ohms. These three are the foundation to understand how a circuit is operating. Some type of power source creates a voltage that is higher in one place in the circuit relative to another. This voltage, sometimes referred to using a metaphor of "pressure", will force electrical charge to flow through the circuit as much as the resistance will allow, and this flow is measured as current. As current flows through the resistance, or the "load" of the circuit, the potential voltage drops until it is used up by the time the circuit is closed back to the power source.

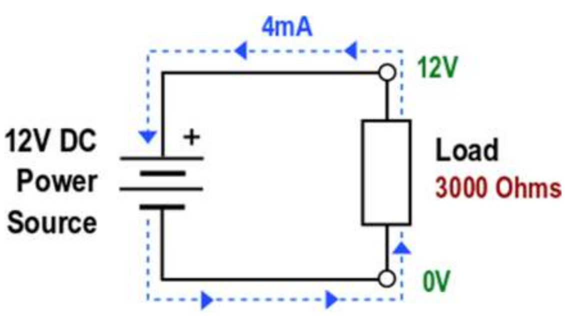
We can use one of the greatest magical formulas ever, **Ohm's Law**, which describes the relationship between these three (and we can solve for the third if we ever know the other two):

$$V = IR$$

$$I = V/R$$

$$R = V/I$$

In a **direct current (DC)** circuit, there is a source of positive charge and electricity flows in one direction. Perhaps the voltage source creates 12V DC, and the resistance in the circuit could be a simple resistor or could be some component that performs work when current is flowing, causing resistance or load on the circuit. In the example below, there is 12V of positive potential on one side of the battery, relative to the other side that closes the circuit. In between is a load that represents 3000 Ohms of resistance. Using Ohm's law, we can calculate that this load will draw 0.004 amps, or 4 milliamps (mA) of current (I = V/R).



Direction of current

You will notice I drew arrows in the direction from negative to positive to represent the current. Don't worry about direction. There is a history and convention of thinking about current flowing from positive to negative, and we often refer to a "voltage drop" that happens across the load that makes us think about the starting point being higher and moving to a lower potential. Electrons actually move from negative to positive. Don't let it tangle you up. It's two sides of the same coin. The key point is that there is a difference in charge between the two points in the circuit, and the amount of resistance between those points, as well as the amount of difference in charge (voltage) determines how much current (rate of change) we have.

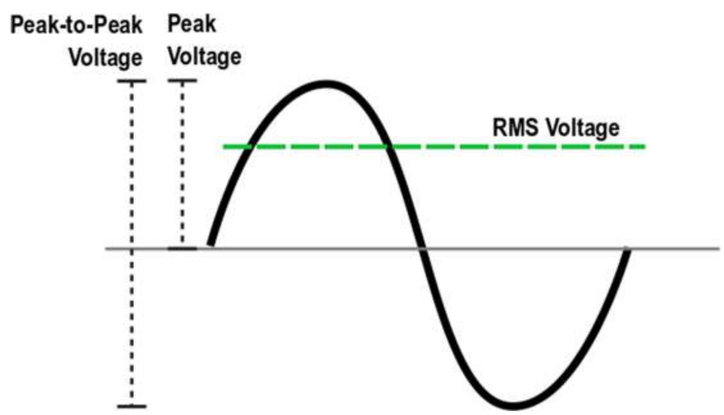
If there were no load, or no resistance (essentially a short-circuit), then Ohm's law would tell us there is 12V divided by 0 Ohms, or infinite current that would flow. This is obviously impossible in the real world, but we know that a short circuit will draw as much current as the power supply can provide, which could damage components, blow a fuse, etc.

Our houses use **alternating current (AC)** as the power source because of limitations that make it difficult to transmit DC over long distances. Alternating current is a voltage that changes rapidly back and forth from positive to negative at some frequency. In our homes, we have 120V AC at 60 cycles per second (Hz).

A circuit can have a load that functions on AC, such as a light bulb. But in many cases, an electronic device will need to convert the alternating current into direct current for the circuit to operate. We will discuss this process later when we go over power supplies and rectification.

Sound waves discussed in the first core concept can also be represented as AC voltages changing over time positive and negative at various frequencies or complex AC waveforms.

AC introduces a question if we wish to perform some measurements or calculations. What is the actual voltage of an AC power source if it is continually changing? We need a few more ways to describe this voltage. **Peak voltage** is the highest positive voltage in the cycle, and **peak-to-peak voltage** is the difference from the highest to lowest point in the cycle (usually twice the peak voltage). **RMS voltage** (root mean square) is a way to measure this AC voltage and express it as an equivalent DC voltage that would produce the same power dissipation. (Some digital multimeters can measure RMS voltage while others use techniques that estimate it assuming an AC sine wave.) RMS voltage can be calculated by multiplying the peak voltage by 0.7071.



So in your home, if you measure the voltage from a wall outlet, it may be 120V RMS, but the actual peak-to-peak voltage is about 340V.

Power

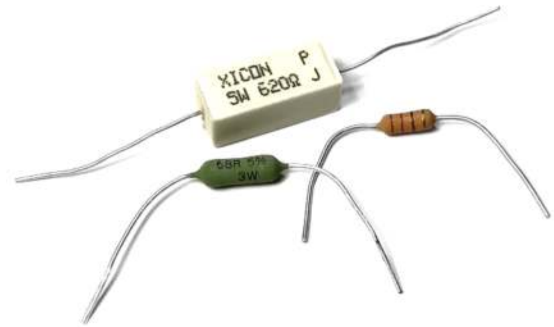
Finally, while we are on the subject of Ohm's law and the voltage and current through a resistive load: **power (P)** represents the rate that energy is produced or used in a circuit. It is measured in Watts and is the product of current times voltage (P = IV). Or, knowing Ohm's law, you could calculate power knowing other combinations, such as resistance and voltage. For example, a circuit with 500 Ohms resistance and 24 volts of potential would dissipate 1.15 Watts of power. Hopefully this power is doing some useful work! Sometimes power may be transferred to heat energy.

Common Electrical Components

Resistors

You are likely familiar with a basic resistor: a device that intentionally holds back current and is rated in Ohms. I won't go over these in much detail other than to mention briefly a few types of resistors and to cover wattage ratings.

Resistors are made in different ways and you'll see them categorized—metal film resistors, carbon film resistors, carbon composition resistors, wirewound resistors, etc. There are simply different ways to construct a resistor for varying objectives and you end up with different attributes, sizes, costs, etc. In my amplifiers I use metal film resistors and wirewound resistors, which tend to have the lowest noise. Noise is an unwanted side effect of a resistor that impacts the signal passing through it. It can be thermal noise, or current noise caused by the structure of the resistive material when current runs through it. While we want to minimize noise, this is not in my opinion the largest problem we need to deal with compared to many other aspects of circuit design and selection of high-quality components such as tubes and transformers. Resistors are relatively inexpensive components and have a pretty easy job to do if selected and rated properly.



Note that wirewound resistors are generally available in relatively lower resistances due to their method of construction. I use them sometimes for power filtering or cathode bias resistors, which are often less than 1 kOhm. Wirewound resistors can be inductive, but in this application, it will not have a noticeable impact.

Resistors are manufactured with a power rating: 1/2 watt, 1 watt, 2 watts, 5 watts, etc. As voltage is forcing current through a resistor, electrical power is converted to heat energy. The resistor is designed to handle a maximum amount of power before it is destroyed by too much heat—if you've ever made a mistake in a circuit, you will know you can easily burn up a resistor! Consider a circuit that has 100V causing 8mA of current to flow through a resistor that is 12.5kOhms (Ohms law validates these relationships). The power dissipated will be 0.8 watts ($P = IV$). So you would need at least a 1W resistor to handle this power. But a good rule of thumb is to use a resistor rated for at least double the power your circuit needs. I would select a 2W resistor in this case. There is no problem using an overrated resistor, other than cost and size. I often use 1 or 2W resistors even when power required is much lower because I buy them in bulk and they are physically larger than tiny ¼ or ½ watt resistors and I can work with them better.

Capacitors

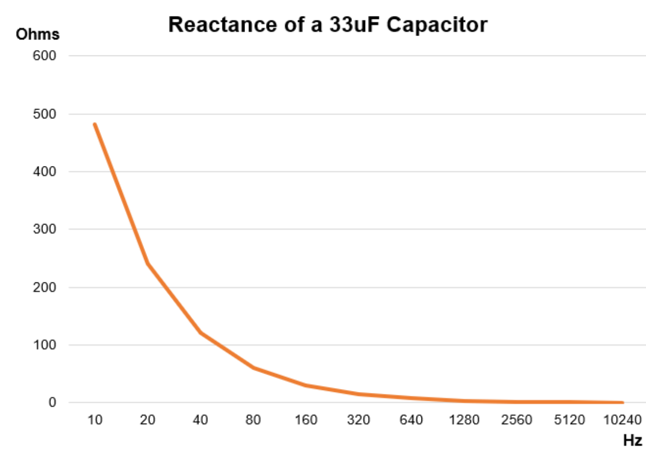
A capacitor stores energy in an electric field. It can be created in various ways, but commonly is done using two conductors (or plates) separated in some way, such as by a film or ceramic material or dielectric. There is no electrical connection between the two conductors, but because they are physically close, a voltage potential between them causes a positive charge to build up on one plate and a negative charge on the other. The physical characteristics of the capacitor

determine how much energy can be stored in this way, and we measure capacitance using Farads, or more commonly microfarads (μF or uF), which are one millionth of a Farad.

Since there is no electrical connection, capacitors do not allow direct current (DC) to pass through them. But a change in voltage will cause the plates to charge or discharge, allowing alternating current (AC) to pass across the capacitor as it changes rapidly from positive to negative. This is an important principle: the current in a capacitor is directly related to the rate of change in voltage—a very slow-changing or steady voltage will have low or no current, while a very fast change in voltage will have higher current. We can quantify the action of a capacitor to oppose lower frequency voltage changes using Ohms, the same unit of measure we use for resistance. But in this case we would refer to it as **capacitive reactance** (Xc)**.** I promise I won't use many formulas, but you might find it helpful to see how we can calculate the reactance of a capacitor, since it will vary based on frequency and capacitance:

$$X_C = \frac{1}{2\pi f C}$$

For example, a capacitor that is 33uF in capacitance that has an AC voltage at 120Hz across its conductors would have about 40 Ohms of reactance at that frequency. What would you guess is the reactance at a lower frequency, like 60Hz? Yes, lower frequencies would have lower current passing, so it's a higher reactance of 80 Ohms. How about a very high audio frequency, like 8kHz? Plug that into the formula and you'll see the capacitor would present only about 0.6 Ohms of reactance. Cool, huh? And very useful! Visualized here is a plot of a 33uF capacitor's reactance at various frequencies.



One more example, let's see how this reactance changes based on higher and lower capacitance. Imagine this was a bigger capacitor of 150uF instead of 33. Now, because the capacitor can hold a greater charge, those same frequencies we just looked at have different reactance: 120Hz would have reactance of only 8.8 Ohms and 8kHz would have reactance of 0.13 Ohms. So a higher capacitance will lower the reactance at a given frequency.

Capacitors are rated for a certain voltage, and many are not manufactured with high precision in capacitance, often +/- 20%. Higher voltage rating and capacitance will require a physically larger (and usually more expensive) capacitor. Always choose a capacitor with a higher voltage rating than you expect it to see in the circuit. Exceeding the voltage rating will lead to the failure of the capacitor.

Capacitors, like resistors, come in a variety of types. For high voltage and capacitance values, we typically need to use electrolytic capacitors. These have a few drawbacks in terms of lifespan and some characteristics, but are still our best choice. Most electrolytics are polarized, so you must wire the negative side to the lower voltage potential or it can be destroyed or even explode. Electrolytic capacitors have a liquid inside of them and are sensitive to high temperatures and “ripple current” that can create internal heating of the capacitor, shortening the life if not rated sufficiently for the application.

In some cases when we have smaller capacitance needs, we can use some type of film capacitors. These are better for certain audio purposes than electrolytic capacitors, but would be too large physically for other uses when capacitance needs to be higher. You’ll see in this circuit that we use a film capacitor for coupling between the stages of amplification—a sensitive part of the circuit where we don’t need much capacitance. Audiophiles love fancy coupling capacitors and you can find some for outrageous prices, probably made by elves using ingredients that cost many gold coins and precious gems. I believe in good caps, but only so far, like most things.

Inductors

Inductors (some called “chokes”) also store energy, but instead of an electric field as in a capacitor, it is stored in a magnetic field. These are usually made of some type of insulated wire that is wound into a coil, sometimes around an iron core. When current flows through the coil, a magnetic field is created. We can measure “inductance” with a unit called Henries (commonly using the symbol L) and it is based on number of turns of the wire, length and cross-sectional area and core material.

Under DC conditions through an inductor, current flows and a magnetic field is created. At this point, the inductor acts as though it were a short-circuit, with the only resistance being the natural resistance that the coiled length of wire would have.

However, when there is AC, the current is trying to change rapidly from one moment to the next. But when energy is built up in the magnetic field from increasing current, the inductor will tend to maintain that same level of energy, which is related to the amount of current. Think of it a bit like momentum and inertia: something put in motion will tend to continue in that same motion, or something not in motion will tend to stay not in motion. So when the current rapidly changes, the inductor resists the change. The net effect of this is that the inductor forms a voltage between its two connectors in opposite polarity to the change in current.

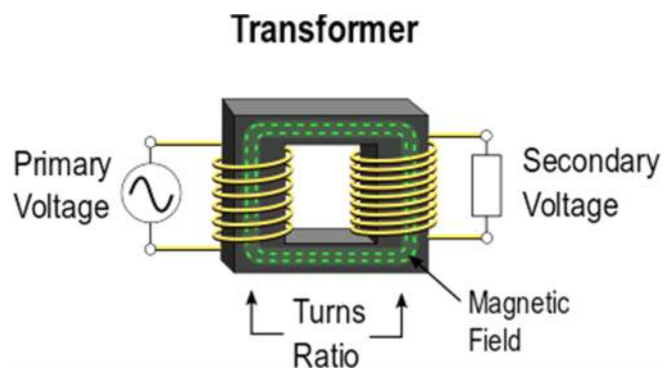
I know, this requires some heavy thinking, physics, force fields, ESP, and Jedi training to really get the theory of it, and I have not explained it with much depth. But the main takeaway is that inductors resist changes in current, and the voltage across the inductor is proportional to the rate of change of current. This is exactly the opposite of a capacitor, where current is related to the rate of change of voltage. Inductors have “reactance” similar to capacitors, that varies based on frequency. Higher frequencies will have greater inductive reactance than lower frequencies. The inductive reactance (X_L), measured in ohms, based on frequency (f) and inductance (L) is:

$$\boldsymbol{X_L = 2\pi f L}$$

You may see inductors (chokes) and capacitors in amplifier circuits performing important roles of blocking or allowing DC or AC, or filtering a power source to remove ripples in the voltage or current. I'm not touching on many other aspects of these components, including how phase of AC is altered by these components, but hopefully this gives some of the basics to understand our circuit.

Transformers

A transformer also uses principles of magnetic induction. Two coils of insulated wire can be wound on a core. When a voltage is put across one of the coils (the "primary" side of the transformer), it will magnetize the core and induce a voltage onto the other "secondary" coil. The two coils can have a different number of turns, and the ratio of these turns will result in a higher or lower voltage on the secondary side. This is very useful when we want to "transform" a voltage from one level to another. We use this in two places in an amplifier: to convert household mains voltage from 120V AC to some higher voltage needed in the amplifier circuit, and also after amplification to convert from a high voltage signal down to a low voltage usable for speaker outputs.



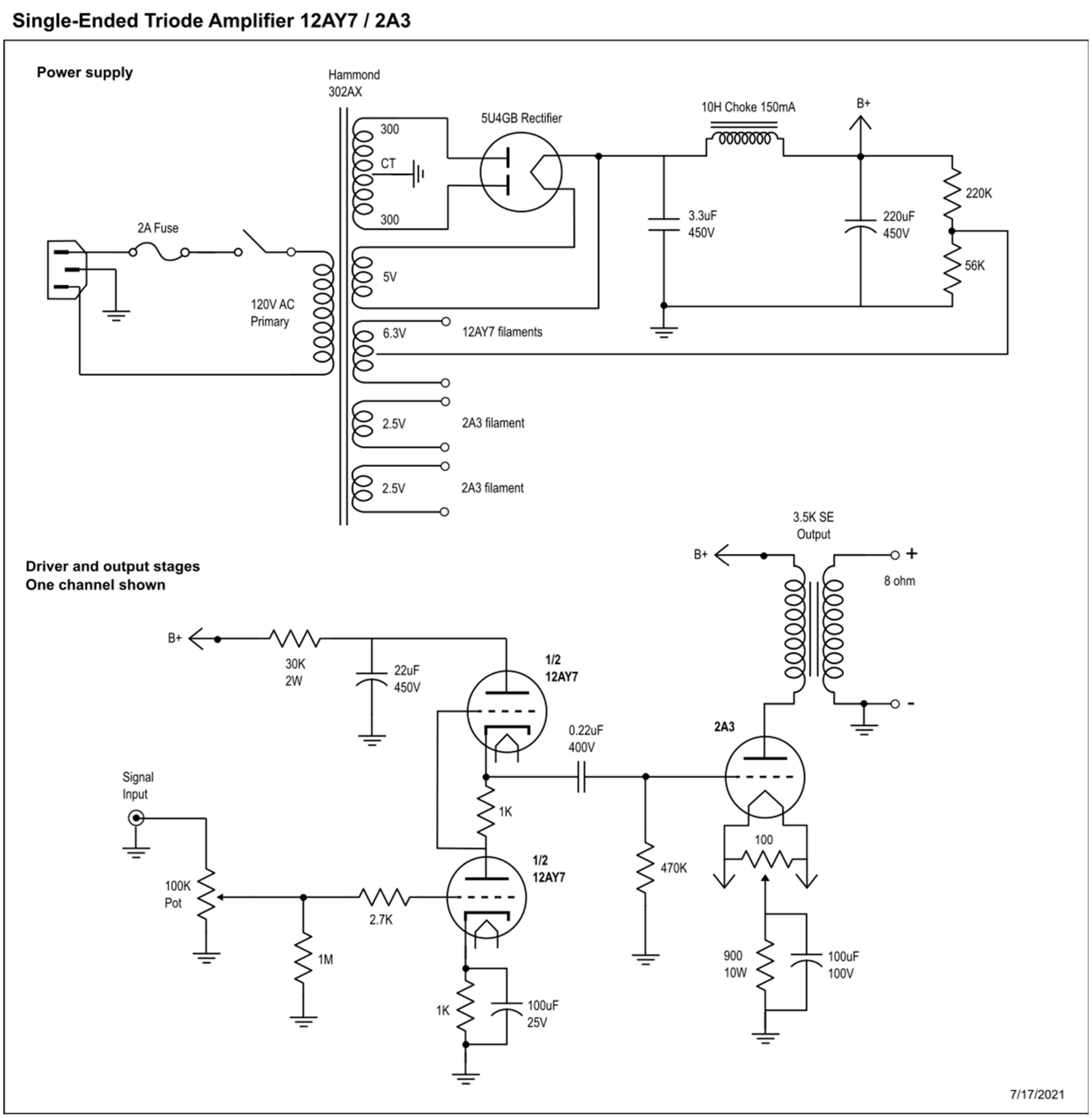
A transformer works with AC only. There is no electrical connection from primary to secondary, and DC would pass across the primary side as a short circuit (possibly damaging it). Remember how the inductor resists changes in current and will create a voltage to try and maintain its state of magnetic field? Under AC voltage conditions on the primary, a voltage will be created by the transformer on the secondary side as an inductive response, with current in opposite direction to the primary.

Keep in mind that this is a passive electrical activity (unlike an amplification process). We are putting the circuit load on the secondary side of the transformer where there is going to be a voltage, load resistance and resulting current draw. On the primary side, that load will appear differently due to the turns ratio so the current will also be different. If for example, a transformer has a 1:4 primary to secondary turns ratio, then voltage will transform from 120V on the primary to 480V on the secondary. A load on the secondary that results in a current draw of 100mA would have that current appear on the primary side using an inverse ratio as a draw of 400mA of current.

All that said, this is a simplified view and a transformer is not perfect, there are some losses in efficiency in several ways we won't discuss. Some power is dissipated as heat, and a power transformer can therefore become hot under a full load, and is typically designed and rated to allow for this.

Big picture of the circuit

We will go into detail on each part of the circuit, but for now, let's get up on the balcony and take a look at the big picture. Refer to the schematic, and you'll see one section is the power supply and the other is the amplification portion with two stages, driver and output. The amplification stages are duplicated in the actual amplifier, one for left and one for right channel, but only one is shown for simplicity. There is, however, only one power supply for the circuit.



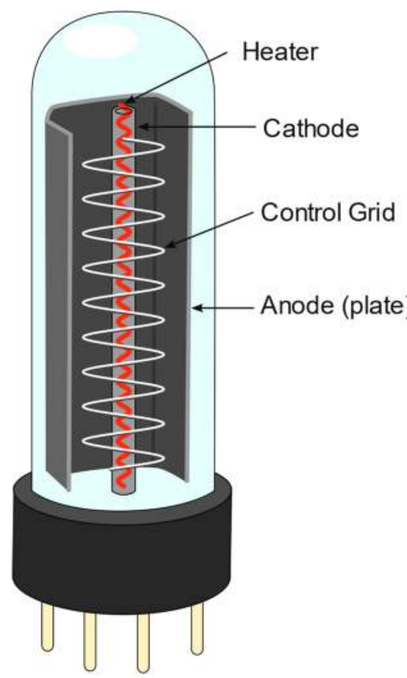
A later section will go over the power supply in detail, but for now, just know that the purpose of this portion of the circuit is to take AC voltage from your wall outlet ("mains" voltage) and convert it to high voltage DC, referred to as "B+". This is a historical term from when batteries were used as power supplies and this was the positive voltage. You may also see this referred to as High Tension or HT, also an older terminology. In our case, in comes the household 120V AC, and out goes the B+ of about 325V DC. You'll see later why we need this high of voltage.

The arrow on the right-hand side illustrates that the B+ is an output of the power supply circuit. Similar arrows are shown in two places in the amplification part of the circuit (driver and output stages), indicating that the B+ voltage is used to supply power to two parts of the circuit. See those spots? Just a convenience in showing the power supply and amplification circuits separately instead of a single schematic.

In the driver and output stages, you can see the schematic flows from left to right, with the input signal entering on the left, the 12AY7 tube performs a first level of amplification ("driver"), then the 2A3 tube performs a larger ("power" or "output") amplification. The 12AY7 tube is a dual-triode tube, meaning it is two triode sections inside one glass envelope. The schematic shows each "half" of the tube in its own circle symbol, but in the real world it is a single physical tube. We use both halves for our driver stage in a special type of compound arrangement. The 2A3 is a single triode. We will go over the details of these tubes and how they work. Finally, there is a transformer to convert back from high voltage to something usable for the output of the amplifier that will go to your 8 ohm speakers.

How does a vacuum tube work?

At the heart of this circuit is a vacuum tube doing its little magic. I will cover the basics of how vacuum tube amplification works so you can understand what's happening. I won't try to convey all of the physical science involved, but you are a lifelong learner I know, and can read more about it from others who can go into more depth and robust explanation.



Vacuum tubes used in amplifiers are also called "thermionic valves" referring to the way that temperature causes the release and flow of electrons. The basic type we will start with is a **triode tube**. Inside the glass enclosure of a triode tube are three main components: the **cathode**, the **anode** (also called the "plate"), and the **control grid**. There is often also a **filament** to act as a heater.

The cathode is typically coated with a certain type of metal, and it is heated up to a high temperature. In the 2A3 tube, the cathode is directly heated by running current through it, but in many other types of triodes, including the 12AY7, the cathode is heated using a filament physically close to it, but not connected electrically. The filament is what you see glowing inside of the tube, sort of like a filament inside a light bulb. For this first section, let's consider an indirectly heated triode like the 12AY7. I will explain more about the 2A3 later.

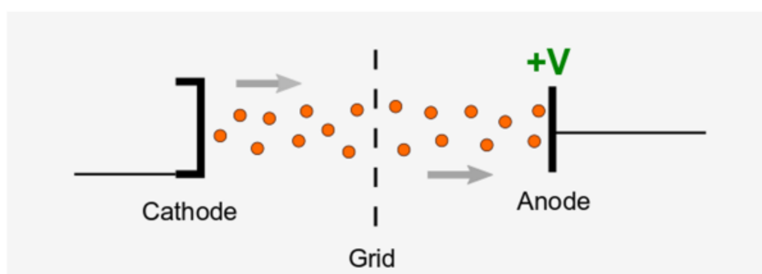
As the cathode reaches a high temperature, it begins to emit electrons. They build up in a cloud and, without any other action, eventually there are so many that the space around the cathode reaches a point where no more will be emitted. Why not? Because electrons have a negative charge and they hate being close to other negative charges, and all those other electrons bumping elbows are making the place pretty dang negative. What do electrons love? Positive stuff. They are attracted like crazy to it. So what would happen if we introduced something positive into the mix here? Yeah, those guys would go for it.

The anode is referred to as a plate because it's a metal plate surrounding the cathode, and we can put on the anode a juicy and delicious positive voltage with respect to the cathode. You will soon start to see why we need high voltage in a tube amplifier. If you just put a few volts on the anode, the electrons say, yeah man, cool, but I don't even get out of bed for that kind of voltage. To be sufficiently attractive, it has to be high.

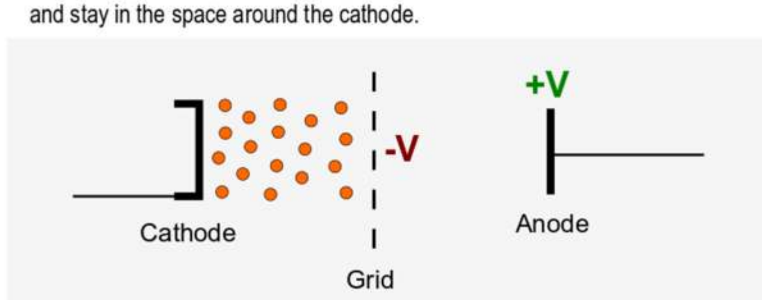
The glass tube enclosure is sealed and there's a vacuum inside, remember? So those electrons are free to fly around without colliding into air molecules. So when there's a nearby high voltage potential on the anode, they are attracted and fly to it at ridiculous velocity, like around a million meters per second or something. Wow, right?

Now let's take a step back and think what's happening here. We heat up the cathode and it emits bazillions of electrons that flow at a million meters per second to the positive potential of the anode, continuously. Sounds a bit like…current? Yes. When the cathode is heated, electrons and current flows. (Don't get tangled up in directivity…the electrons go from cathode to anode, but we sometimes refer to current flow from positive to negative. It's just the way we measure current as a rate of change of electrical charge.) You'll note that it flows only one direction (a "diode" at this point). We heat the cathode and electrons can go to the anode. There is no way for electrons to go the other direction.

1. When the grid is not negative with respect to the cathode, electrons flow to the positive voltage of the anode.



2. When the grid is negative with respect to the cathode, electrons are repelled and stay in the space around the cathode.



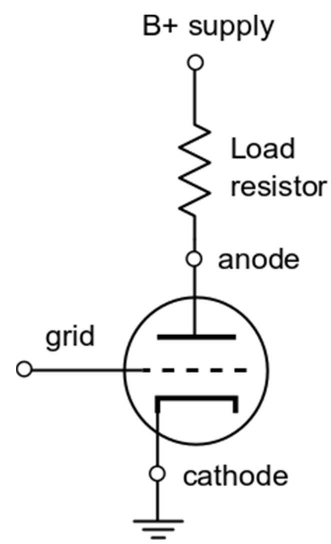
Alright, so an operating tube is allowing current flow (the "valve is open"). Now, there's one more component to make this a triode: the control grid. This is a wire mesh in between the cathode and anode that is spaced wide enough to allow the electrons to pass through. But what might happen if you applied a negative charge to it? You son of a turtle, say those electrons! We are not going through that negative fence you set up, we don't care what's on the other side. So now we have a way to control those electrons and if we raise or lower the voltage on the grid we can influence how strongly the electrons are repelled or allowed to pass. A very negative charge? No electrons pass and no current is flowing—

we refer to this as "cutoff" of the tube. A smaller negative or zero charge? Electrons and current flows freely (maximum flow sometimes referred to as "saturation" reflecting the temperature and physical constraint where the anode is pulling in all of the electrons that the cathode can produce).

By altering the voltage of the grid, we can "open and close the valve," allowing current to flow more or less. Awesome! This is why a tube amplifier is sometimes referred to as a "valve amplifier." If we were to put an audio signal on that control grid, then the changing voltage over time of the audio signal will allow current to flow in alignment to the audio signal.

We are getting close! But how does this amplify the input signal? The answer is that the voltage change on the grid has a large influence over the current flow. How much current flow? To really understand, we need to get into a circuit a bit more and discuss load lines. You will love it. Hang with me.

First, we need one more quick addition of a load resistor to put the tube in context of a circuit. Now, I have to tell you, this isn't the circuit technique we are using in our driver stage of this amplifier, but it's a good way to get started understanding how this works using a load line. We'll come back later and I'll take you through a different approach once we have these basics.



We already said that we would put a high voltage potential on the anode to attract the electrons and allow current to flow. We also will want a **load** on the anode, in this case a simple resistor, so that there is sufficient resistance in our circuit so we don't have an unreasonable amount of current flowing and also so that we can make use of the voltage change across that resistor. Ohm's law will tell us there is a known relationship between resistance, voltage, and current, right? And you love Ohm's law, right? Me, too.

Here's a very simplified circuit using a tube symbol. We won't worry about how we generated the B+ voltage or how we are setting the grid voltage, but assume the B+ is some high voltage potential, the cathode is at 0V, and the grid could be a few volts negative. We have enough for a working illustration of an operating circuit. (We usually do not show the heater filament in a tube schematic unless it is directly heated, so just know the heater is operating.)

For the sake of a quick calculation to get started, let's pretend that we have a 30k Ohm load resistor and 400V supply, and we pick a grid voltage that is allowing some amount of current to flow, let's say it is -2V. How much current is there if we measure the voltage on the anode and it is 250V? Well, 150V must have dropped across the load resistor to get from 400 to the 250, and using Ohm's Law:

$I = V/R$

$I = 150 / 30{,}000$

$I = 0.005$ Amps or 5mA

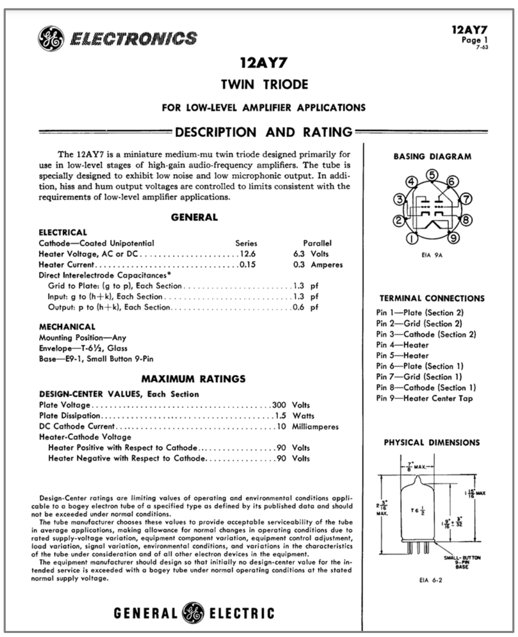
So in this made-up example, -2V volts on the grid is allowing 5mA of current to flow. All we are doing here is using an easy technique to calculate current using a known resistance and measured voltages, using Ohm's law. But I want you to have the load resistor and Ohm's law in mind as we get a step further into the operation of the tube.

Tube characteristics, load lines, and operating point

The physical characteristics of each type of tube—materials, how far apart is the cathode, grid, anode, etc.—determine how the tube will operate and the effect of different voltages. Tube manufacturers provide datasheets that include a variety of information about these characteristics and limiting values. Search online and you'll easily find these as PDFs—often looking like bad photocopies of documents from the 1950s—and of course there's a long history of tubes from that era or earlier, so it's no surprise.

If you haven't studied these, they might seem confusing, but you are a brilliant learner and this is how you will be empowered to begin understanding or even designing your own circuits. Let's use our 12AY7 tube and take a look at an example datasheet:

12AY7 Datasheet (example pages)


GE ELECTRONICS

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12AY7

TWIN TRIODE

FOR LOW-LEVEL AMPLIFIER APPLICATIONS

DESCRIPTION AND RATING

The 12AY7 is a miniature medium-mu twin triode designed primarily for use in low-level stages of high-gain audio-frequency amplifiers. The tube is specially designed to exhibit low noise and low microphonic output. In addition, hiss and hum output voltages are controlled to limits consistent with the requirements of low-level amplifier applications.

GENERAL

ELECTRICAL

	Series	Parallel	
Cathode—Coated Unipotential			
Heater Voltage, AC or DC	12.6	6.3	Volts
Heater Current	0.15	0.3	Amperes

Direct Interelectrode Capacitances*
- Grid to Plate: (g to p), Each Section .... 1.3 pf
- Input: g to (h+k), Each Section .... 1.3 pf
- Output: p to (h+k), Each Section .... 0.6 pf

MECHANICAL

Mounting Position—Any
Envelope—T-6½, Glass
Base—E9-1, Small Button 9-Pin

MAXIMUM RATINGS

DESIGN-CENTER VALUES, Each Section

Plate Voltage .... 300 Volts
Plate Dissipation .... 1.5 Watts
DC Cathode Current .... 10 Milliamperes
Heater-Cathode Voltage
- Heater Positive with Respect to Cathode .... 90 Volts
- Heater Negative with Respect to Cathode .... 90 Volts

Design-Center ratings are limiting values of operating and environmental conditions applicable to a bogey electron tube of a specified type as defined by its published data and should not be exceeded under normal conditions.
The tube manufacturer chooses these values to provide acceptable serviceability of the tube in average applications, making allowance for normal changes in operating conditions due to rated supply-voltage variation, equipment component variation, equipment control adjustment, load variation, signal variation, environmental conditions, and variations in the characteristics of the tube under consideration and of all other electron devices in the equipment.
The equipment manufacturer should design so that initially no design-center value for the intended service is exceeded with a bogey tube under normal operating conditions at the stated normal supply voltage.

BASING DIAGRAM

EIA 9A

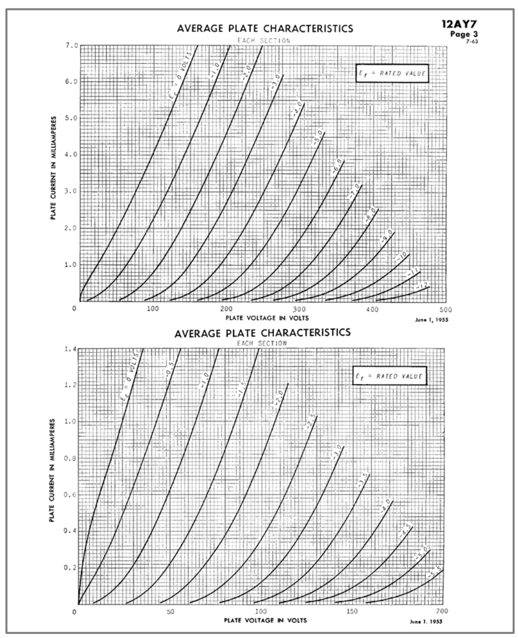
TERMINAL CONNECTIONS

Pin 1—Plate (Section 2)
Pin 2—Grid (Section 2)
Pin 3—Cathode (Section 2)
Pin 4—Heater
Pin 5—Heater
Pin 6—Plate (Section 1)
Pin 7—Grid (Section 1)
Pin 8—Cathode (Section 1)
Pin 9—Heater Center Tap

PHYSICAL DIMENSIONS

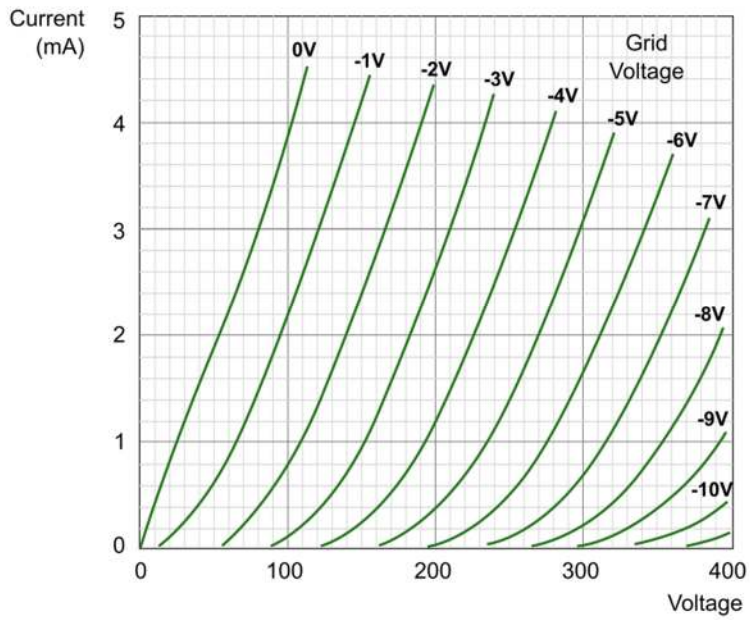
SMALL-BUTTON 9-PIN BASE
EIA 6-2

GENERAL ELECTRIC

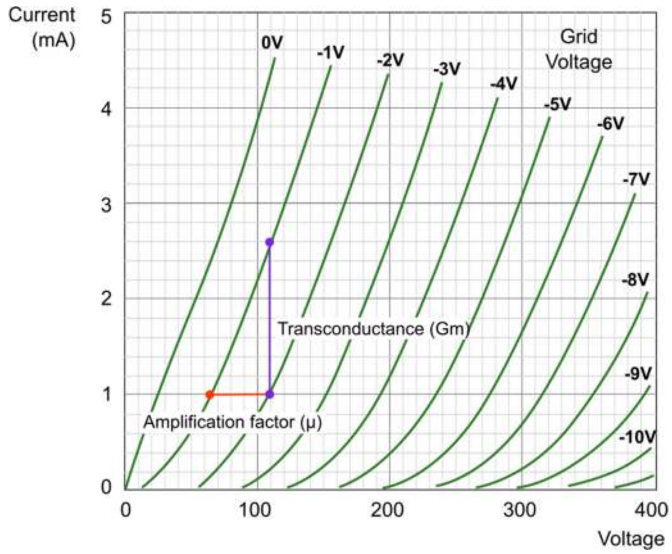


Go search for one of these online (e.g. "12AY7 datasheet") and pull one up for reference. We won't go into all of the details, but you'll find some useful information. I always keep these handy especially for the pin diagrams to tell you which pin number is the anode, grid, etc., or to know how much current the heaters will draw, or what maximum voltages can be used.

One of the charts you will find is the plate characteristics. On the x-axis is voltage and on the y-axis is current. There are a series of curves that represent different voltages that you could possibly have on the grid, and this will tell you what current would correspond to a particular anode voltage (plate voltage). Using the chart below, if you had the grid at -3V and you put 200V on the anode, then the tube (valve) will allow about 2.6mA of current. You will notice these are curves, not straight lines, because the tube does not operate as a perfectly linear device. We will talk about this later, regarding distortion.



Before we look at an actual circuit and load line, let's consider a few attributes of the valve that we can visualize on this chart. First, remembering that grid voltage controls the amount of current, let's see what this ratio is. If we pick a place on the chart and hold anode voltage constant and measure the distance between two grid curves, we can see that a 1V change in grid voltage results in around 1.6mA of current change or so. This is the purple line on the chart below, and is referred to as **transconductance** (Gm), often measured in a funny unit called mhos (reverse spelling of ohm, conductance being the opposite of resistance!) and tube datasheets usually use micromhos (one millionth of a mho). Look on the 12AY7 datasheet and you see transconductance of 1,750 (depending on operating conditions), which would be relatively close to our chart estimate after converting units.



Now, consider another property called **amplification factor** (a ratio abbreviated with the Mu symbol: µ). Holding current constant, if we measure between two grid curves, we see that a 1V change in grid voltage will result in a change in anode voltage of around 44V (red line above). Aha! Here is the leverage that we have been looking to understand. We could swing 44 volts of anode voltage for every one volt on the grid. Powerful, yah? So the µ of the 12AY7 is 44 and you'll see this on the datasheet. Some tubes have lower or higher amplification factors that could range from around 20 to 100. After we plot a load line and calculate the gain, you'll see that we won't expect to get this full factor of amplification depending on the type of application.[2]

Now let's take our basic circuit and consider what happens when we have a particular anode load. Let's say we had a load resistor that is 100k Ohms and we supplied 300V B+. If there was zero current flowing (tube totally in cutoff), what voltage is on the anode? Ohms law tells us that with no current, there would be no voltage drop across the load resistor, so the anode will have the full 300V. Let's plot a point at zero mA and 300V representing this extreme situation. And imagine the opposite end of the spectrum—what if the valve was wide open so that maximum current flows and the entire 300V were to drop across that resistor, and there was zero volts on the anode. Ohms law in this case to solve for current:

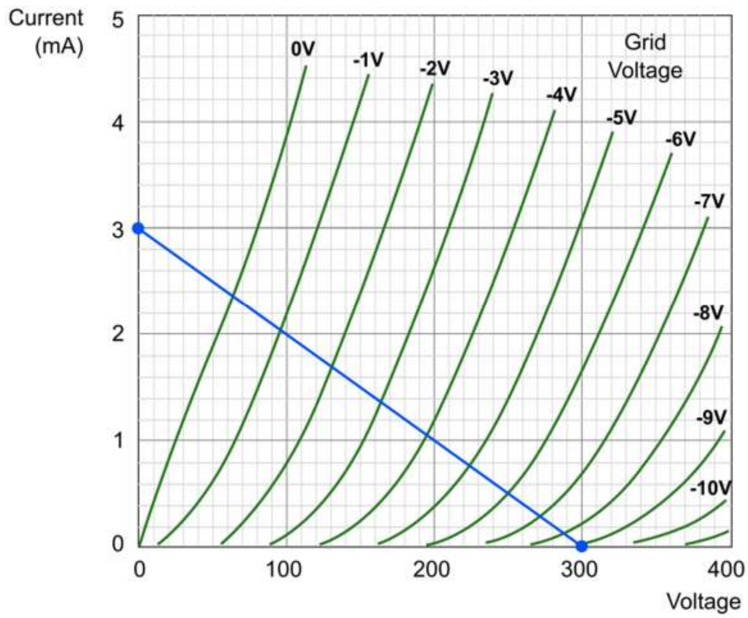
I = V/R

I = 300 / 100,000

I = 0.003A or 3mA

So let's plot another point at 3mA current and 0 volts on the anode. Ohms law is a linear relationship, so this is all we need to draw a load line between these two points.

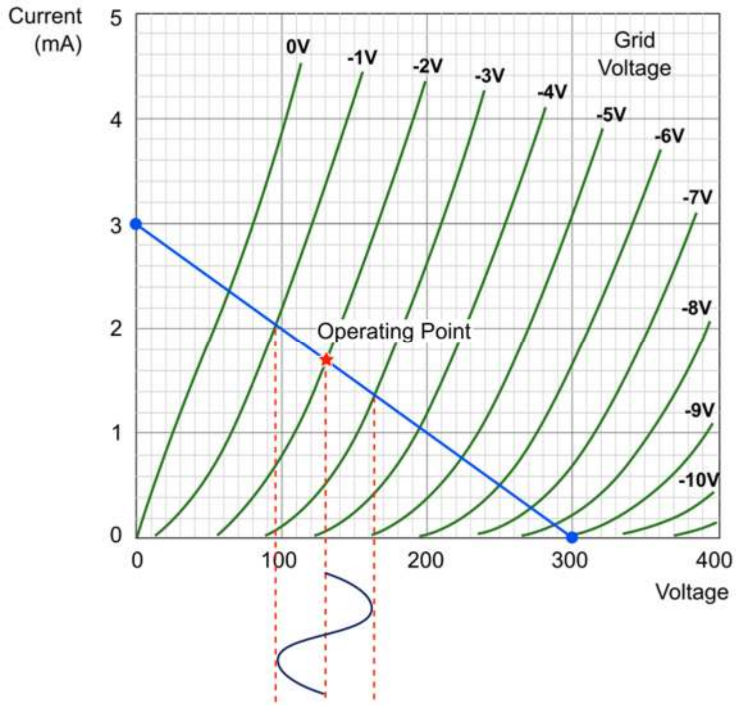
[2] Techniques such as a regulated current source can be used to maximize amplification factor but will not be covered.



So what we see here is the linear relationship between voltage and current for a 100kOhm load resistance and 300V B+ supply. Our tube must operate on this line somewhere. Where? That depends on what voltage we put on the grid. Look again at the grid curves and find the points that intersect with our load line. If we set the grid to -2V, then in this circuit we will have about 1.75mA of current and 130V on the anode. If we change the grid to -1V (less negative), then we will have around 2.1mA of current and 95V. Notice that this is a change of 1V on the grid and a change of 35V on the anode—not the full 44 amplification factor because our load line isn't horizontal, it has a slope. If you were to alter the supply voltage or the load resistance, you can control the position and slope of this line, which impacts gain (and distortion).

Now it's time to visualize your audio signal on this load line. The input signal is an AC voltage that goes peak to peak from, let's just say, +1V to -1V (depending on your source level). If we simply put this signal onto the grid, it would cause the grid to fluctuate both positive and negative. We don't have any positive grid curves shown here. Why not? Because when the grid is positive it is attracting electrons just like the anode. This isn't what we intend and will leak current out of the tube through the grid, which would then further impact the voltage potential between grid and cathode, etc. It's a problem we will avoid by keeping our grid operating in a better space, more central on our load line.

Let's pick a spot to represent the **operating point**, or the quiescent state when there is no audio signal impacting the grid, but there is enough room above and below this point for the audio signal to raise/lower the grid voltage. If we pick an operating point where the grid is -2V as we looked earlier, this puts us down closer to the middle of the load line and there will be a steady-state current of around 1.75mA, and 130V on the anode.



Now envision an AC audio signal on the grid that causes it to have a range between -1V and -3V and the anode voltage will fluctuate from around 95V to 165V. You can see a sine wave visualized on the horizontal axis. You should also recognize that we have current flowing continuously, it just varies in how much, based on the input signal and grid voltage. This is a **Class A** type of amplifier, conducting current across the entire input signal, not going into cutoff at any point. You can see that Class A consumes power continuously regardless of input signal amplitude and is therefore less efficient than other options, but it has excellent characteristics for high fidelity amplification and simplicity in our design. A **single-ended** tube amplifier stage uses one tube to produce an output, as opposed to other options such as a push-pull design using two tubes amplifying the signal in different ways. (We will discuss this concept a bit more later.)

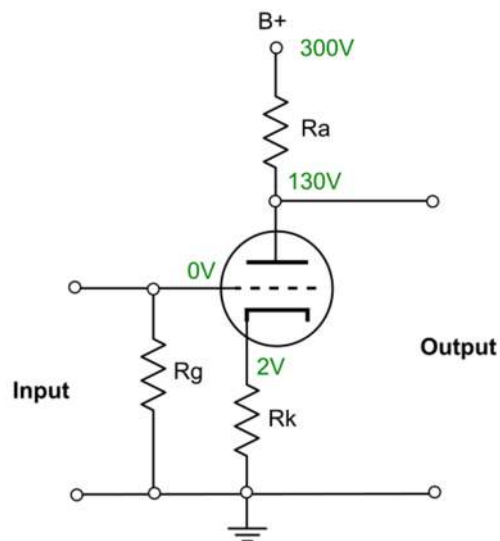
One more consideration regarding load line and operating point. The tube will have maximum rated limits of operation. In the case of the 12AY7, the datasheet tells us that the anode cannot be higher than 300V in steady operation[3]. So our operating point must be left of that point. And the plate is rated for maximum power dissipation of 1.5 watts. Our operating point needs to be within that rating. 130V and 1.75mA of current would be only 228mW of power (Power = Voltage times Current). On this small-signal tube, we are not even close to maximum power, but on the output stage you will see we get much closer to it.

Now let's figure out how to get our grid to be at our desired voltage for this operating point. One option is to use a negative DC power supply and adjust it so that it is 2V lower than the 0V potential of the cathode. Some amplifiers use this technique and it's referred to as **fixed bias**. It requires

[3] This is technically the maximum anode-to-cathode voltage (or "plate-to-cathode")

calibration to ensure the right relative voltage between grid and cathode to achieve a target operating current.

In our case we will choose another method. The grid needs to be negative with respect to the cathode in order to hold back the electrons, but we can achieve this in other ways rather than a negative DC voltage on the grid. We could keep the grid at 0V potential and elevate the cathode to a higher voltage. By inserting a resistor between cathode and 0V ground potential, we can put the cathode at a positive 2V potential so that the grid is now -2V relative to the cathode. This is a method called **cathode bias**. It's sometimes referred to as automatic bias or self-bias because if the steady-state current were to change for some reason (such as the tube aging and changing in properties), then by Ohm's law, the voltage drop across that resistor would change, so our cathode level would "automatically" adjust itself.



Ok, consider the new circuit shown. We inserted a cathode resistor Rk. What value should we use? If we want to elevate the cathode to +2V so that we have quiescent current flowing of 1.75mA, then Ohm's law will tell us that we need a value of:

R = V/I

R = 2 / 0.00175

R = 1,142 Ohms

Now we have technically increased our total load on the B+ voltage to the sum of the anode resistor and cathode resistor, so our original load line isn't quite right anymore, but this value is very small relative to the 100k Ohm load so we won't worry about it, or you could re-calculate the load line with this larger value of 101,142 Ohms. (And of course 1,142 is an unusual number and we could round this cathode resistor value to one that is typically available such as 1k or 1.2k and alter the operating point slightly.)

You will also notice a resistor Rg between grid and ground. This is called a **grid leak resistor**. We need something to reference the grid to the 0V DC potential, allowing the input AC signal to then be applied onto it to control the tube. We want this to be a high resistance value so that we don't attenuate the input signal (keeping the input impedance high relative to the source impedance), but there are some other considerations. There is a very small amount of current that flows in the grid ("leaking") and it could alter the bias of the grid. We will use a value of 1M Ohms with the 12AY7.

Congratulate yourself for understanding this far. We aren't done yet, but I hope you feel good about what you've learned so far. You might need to re-read a few times to get it, and consider additional resources I reference in the appendix if you want to learn at a deeper level. Pause here, get a drink, scratch dog behind ears, etc.

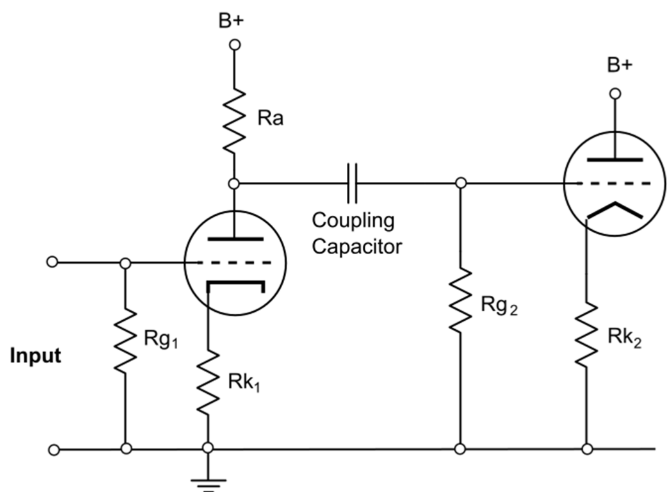
Coupling, AC load line, and cathode bypass capacitor

You have the basics. Now it's time to broaden our circuit a bit more and deal with a few more issues. The triode tube we have seen so far is used as a driver stage with still a relatively low level of current and output voltage. We need to put it through a power amplification stage to really get it to the level of current and amplification needed to drive our speakers and move some air on the journey of sound back to our ears!

We will take the amplified voltage from the anode, which you already know in this example operates around 130V DC, fluctuating up and down with the audio signal. We can consider this an AC signal riding on top of the DC voltage. We will want to feed this signal into another tube—in our case a 2A3 power tube—for further amplification, but we can't put 130V onto the grid. This high voltage will cause all sorts of problems on the grid which is intended to be negative, likely destroying it. We want only the AC portion.

The **coupling capacitor** is our solution. As you know, capacitors block DC and allow AC. The capacitance value can be small. We simply want to block the DC and allow all audio frequencies to pass. In our case, we will use 0.22uF as a commonly used value.

The coupling capacitor is directly in the signal path and so it is a very important component, and we want to use something high quality that will pass the signal without noise or distortion. Some type of film capacitor is best, and there are very high-end audiophile grade coupling capacitors produced, some at outrageous prices. Note that the voltage rating of this capacitor needs to be high enough to handle whatever voltage could be on the anode of the driver stage. Typical ratings for coupling capacitors in this type of application could be 400V or over 600V.

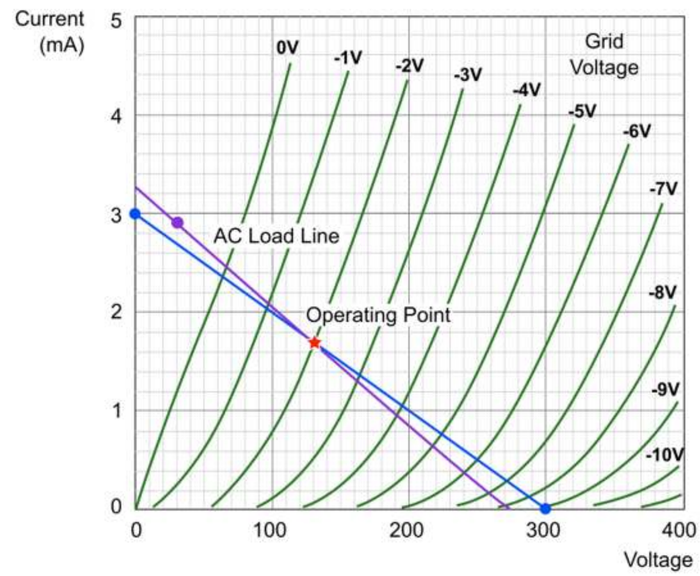


We will get into the output stage soon, and also come back to the driver stage for a more complex version, but first let's consider a few things with our driver stage. Our load line was fine for defining an operating point when there is DC voltage without audio (AC) on the grid, but since we are allowing AC voltage to pass on to the next stage through the coupling capacitor, we need another load line to understand the load under operating conditions: an **AC load line**.

The AC load will be the combination of two things: the anode load resistance we have already been dealing with, but also the impedance of the next stage, in this case a path to ground through the next stage's grid leak resistor. Do you see in this simplified 2-stage circuit shown how Rg2 is in parallel with our driver tube (with regard to AC voltage, not DC)? Let's pretend that Rg2 is 470k Ohms. The formula to solve for parallel resistance is:

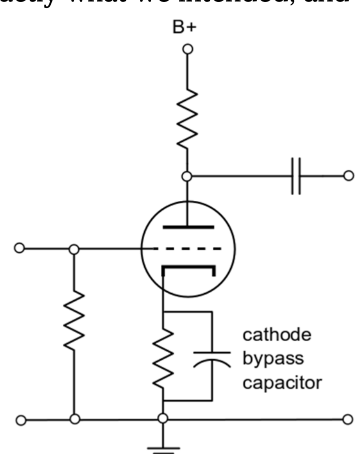
$$R = \frac{R_a \times R_{g2}}{R_a + R_{g2}}$$

Solving this with 100,000 and 470,000 as our Ra and Rg2 values tells us that the AC resistance would be about 82.5k Ohms. Now, let's find our new AC load line. The operating point will stay the same, and we can choose to plot some other point to get our line. Let's pretend under AC voltage the anode drops by 100 volts. Ohms law will tell us that if our AC resistance is 82.5k Ohms, then the current difference for this voltage drop is 1.2mA. So we can plot a point that is 100V lower than our operating point, and 1.2mA higher in current. Now this is what our true working load line will be.



Our circuit is coming together! We will move on to the power stage soon, but first, one more consideration to address. Remember how we wanted our cathode to be +2V relative to the grid. But think for a moment what is happening as the grid rises and falls with an audio signal—use a sine wave as an example and think about the voltage rising and falling over time. When the input signal is +1V, then the grid becomes less negative with respect to the cathode, and more current is allowed to flow. When more current flows, what will happen across our cathode resistor? Dang it. Voltage on the cathode will rise, right? Ohm's law again. On our AC load line, if the grid rises to -1V, then current is somewhere around 2.1mA. Remember how we solved to find our cathode resistor value and came to 1,142 ohms so our cathode would be at 2V. Well, 2.1mA across 1,142 ohms in Ohm's law is about 2.4V, instead of our intended 2V. The opposite is true when the signal goes the other direction: move down the AC load line, less current flows, which reduces the voltage across the cathode resistor. So the cathode voltage is fluctuating along with the input signal to some degree. Not exactly what we intended, and the net effect is that it counterbalances the amplification of the tube, reducing gain.

In some amplification stages, this can be used to an intended advantage for reducing distortion (referred to as cathode degeneration), and in others we might want to prevent this loss of gain. The solution to this is a **cathode bypass capacitor**. By putting a capacitor alongside the cathode resistor, we can hold the cathode at a desired DC voltage, but allow AC to pass through the capacitor. As the grid changes in voltage at audio frequencies, and current rises or falls accordingly, the AC currents will no longer impact the cathode voltage, it will remain at the intended DC voltage while the AC current can bypass it.



This is usually an electrolytic capacitor because capacitance needs to be relatively high, up to 100uF or more, to allow current from low audio frequencies to pass. The voltage rating needed is relatively low given the expected voltage on the cathode. I often buy 25V or 100V caps for this purpose.

Output stage

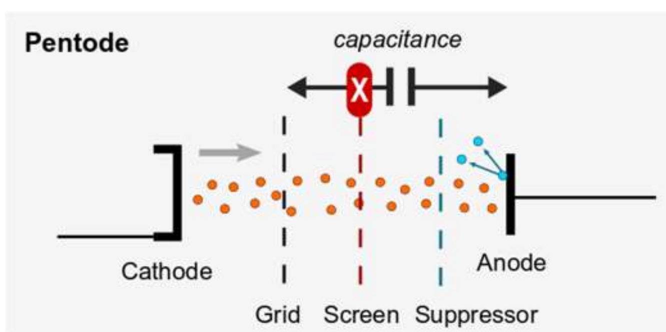
I will need to take you back to the driver stage a bit later to explain our actual circuit that isn't using just a resistive load, but for now let's get to a working amplifier by moving on to the 2A3 output stage. And I'll give you more context on what makes a single-ended triode (SET) amplifier different than some other types.

The general principle of the power stage tube is similar to the driver triode tube: put high voltage on the anode, put the grid at a voltage that is negative relative to the cathode and modulate it with the voltage signal from the driver stage. But the output tube will be working with higher current and voltage swings.

A **triode** has a small amount of internal capacitance that exists between the electrodes, notably between the anode and grid, referred to as Miller capacitance. Historically, this had caused problems in particular when attempting to use triodes for radio frequencies. To deal with this, new types of tubes were invented. First the **tetrode** introduced a **screen** in between the anode and control grid to shield the grid from the anode, reducing this capacitance. The screen could be held at a constant voltage while most electrons would still pass through to the anode.

However (there's always a however!) to make it work properly, the screen must be held at a relatively high DC voltage, and this introduced a new complication in the expected current flow in the tube. At certain voltages, electrons will hit the anode with high velocity, dislodging extra electrons which bounce back and are absorbed by the high voltage screen instead of the anode. This is a form of emission from the anode, impacting its voltage at certain amplitudes of the signal, causing a bend in the grid curves, and distortion in the amplification process.

To deal with this side-effect, the **pentode** was invented[4], which adds yet another grid called the **suppressor** in between anode and screen, held at a low voltage (often tied to cathode) and this keeps those bounced electrons from being attracted to the screen, and they are then recollected by the anode. The electrons emitted by the cathode are moving at such a high velocity that the suppressor has minimal effect on them, only the deflected electrons.



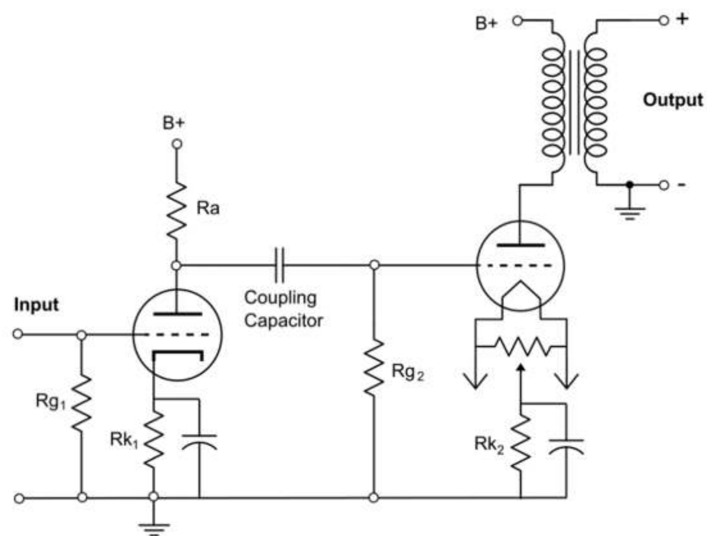
The pentode screen grid has another effect on the tube, which is that gain is increased, and this is an attractive feature for a power amplification stage. Because the screen is held at a constant

[4] The beam-tetrode was also invented around the same time, solving similar issues in different ways.

voltage, it continuously will attempt to pull a steady flow of electrons from the cathode toward the anode (as much as the control grid will permit), so the tube can conduct current more efficiently. This is different from a triode where the voltage of the anode rising and falling with the signal is the only form of electron draw—for example, as the triode grid voltage moves more positive, current rises causing a drop in anode voltage across the load, but the lower anode voltage is less attractive to electrons than otherwise could be possible. This is a sort of headwind to realizing maximum triode gain that is solved with the pentode.

The 2A3 is a triode, so we will simply live with the lower gain in our amplifier, but I wanted you to at least understand these other options and why the triode design is lower in output power than might be possible using different tubes. The linearity and distortion characteristics are also different for a triode and a pentode, and some would say the triode design has a different sound signature than the pentode (I will touch on distortion soon). Enthusiasts will say that the triode sounds better, though of course sound quality can be subjective! In any case, the triode is a very classic and pure design without the use of a screen grid.

I have other amplifier kits that use EL84 or EL34 pentode tubes and I'll also mention that any pentode can be wired to operated in "triode mode" by simply connecting the screen to the plate so they operate at the same voltage. The screen grid also has an option for "ultralinear" operation that uses a type of feedback from the output transformer to optimize power and distortion. We will not cover these options in detail here.



On the schematic here showing both a driver and output stage, you can see again some familiar components on the output tube stage, but with some differences. We have another grid-leak resistor. We see a cathode resistor with bypass capacitor, but will look at a few extra things on the cathode in a minute. And for the load—wait…where's the load resistor? The B+ in the output stage is going into the output transformer primary, and out the other side of the primary, to the anode. Aha! We don't have a resistive load in this case, we have the speaker as the load, and the fluctuating voltage across the transformer is going to drive—or do the work—of moving the speaker coil. But speakers are not designed for high voltage (and it wouldn't be safe to have this exposed outside of the amplifier anyway), so the output transformer will convert our amplified plate voltage to a different voltage and current level suitable to drive the speakers.

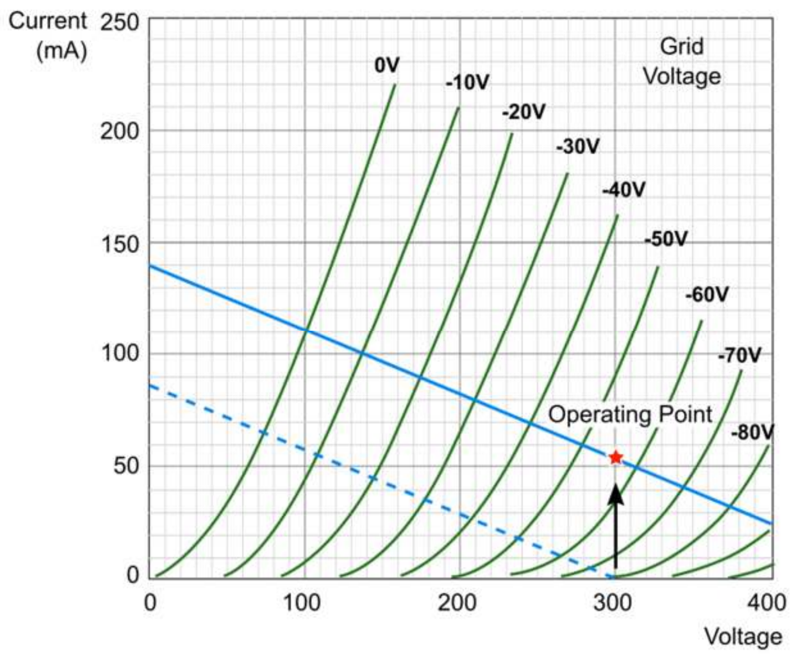
Ok, you are saying, but wasn't the whole point to amplify the signal? Are we reversing our process? No. Remember that the transformer will transfer the same power from the primary side to the secondary side, but the number of windings in the transformer will determine how current and voltage are changed. In our case, we are lowering voltage down to levels below 10V, but for power to be the same, current must increase. So we will have a large AC current driving our speakers. This is a transformation to the final step of our audio signal and we hope our trusty output transformer does this as a faithful and accurate reproduction. The quality of the output transformer is very important in maintaining a flat frequency response across a wide bandwidth at our desired output power. This kit includes transformers that I believe are very good quality for this circuit, tubes and power output. There are smaller and larger sizes of transformer ("iron" as you might say to your DIY tube amp buddies), and larger ones will be heavier and more costly, but also will ensure a wide frequency bandwidth, low distortion and higher rated power output. The takeaway is that not all are created equal, so this is one place in your amp where you want to choose carefully a trusted and high quality manufacturer.

So if the speaker is the load on the power tube, how big of a load is it and can we calculate the load line again? This amplifier is designed to work with an 8 ohm speaker impedance, but the windings ratio of the transformer will make this impedance look much larger to the tube which is what we need for the tube to operate properly. We select this ratio when choosing the output transformer. Our design will use a transformer that will be around 3,500 ohms on the primary side of the transformer for an 8 ohm secondary impedance. You could choose a transformer with different values, depending on the load you want on the tube and the impedance of your speakers. I chose an 8 ohm output for this kit because this is the most commonly used speaker impedance. And 3.5k ohms gives us a load that will work effectively for our supply voltage and characteristics of the 2A3 tube.

Speaker impedance

It is important to remember that the speaker is not a uniform resistance of 8 ohms. All speakers have impedance that varies with frequency. They are rated typically at 4 ohms, 8 ohms, 16 ohms, but this is just a nominal value generally close to the overall impedance. A typical 8 ohm speaker could actually have a wide range of impedance from 3 or 4 ohms at some frequencies or 10 or 20 ohms or higher at other points. The job of the speaker is to reproduce frequencies as uniformly as possible across the audible frequency spectrum, and there are physical properties to the cone and suspension and a wide range of other things that will cause the impedance to be higher or lower across frequencies.

Let's say in our example that B+ voltage is 300V and we have a 3,500 ohm load, we can start to work on a load line and operating point. As with the 12AY7 driver tube, we can look at the 2A3 tube characteristics on a datasheet from the manufacturer. The process we use will be a bit different because of our output transformer and speaker load. I will mention that we are just getting somewhat close to the theoretical operating point and it becomes important to test and modify the circuit in actual operation to optimize it.



In the chart shown, the blue dotted line is the initial load line for 300V and 3,500 ohms (86mA of current if the entire voltage were dropped). But remember that we do not have a resistive load. (Actually, the transformer has a small amount of DC resistance in the primary winding, but this is small enough that we will ignore it.) So at the quiescent point with no AC signal, nearly the entire B+ voltage will be on the anode, so our operating point voltage must be around 300V. But if we stay on our initial load line at this point, it would not be useful because it's at cutoff and could then only amplify the positive side of the signal. We need to bias the tube and move this load line up.

What we will do is choose an amount of current that we want at the 300V operating point. To maximize our power from this tube, let's pick a level just below the maximum rating. The 2A3 tube has a maximum plate dissipation rating of 15W. At a plate voltage of 300V, we would hit this maximum at around 50mA of current (P = I * V). So we can shift our load line up, keeping the same slope until we reach an operating point that is 300V and somewhere around 50mA. You'll notice I picked a spot just a bit higher, closer to 55mA. I'll explain in a minute.

Finding the nearest grid lines, this point is somewhere between -50V and -60V, let's call it 55V. See that? Now, if we need -55V on the grid relative to cathode, then we can again use the cathode bias technique and hold the grid at 0V while we elevate the cathode to +55V. Using Ohm's law, if we are estimating 55mA of current dropping across 55V, this gives us a resistance of 1,000 ohms. This will dissipate about 3W of power through that resistor, so we would choose one rated at least double for a margin of safety. I use a 10W resistor in the kit. As in the driver stage, we will also bypass this cathode resistor with a 100uF electrolytic capacitor, rated for 100V.

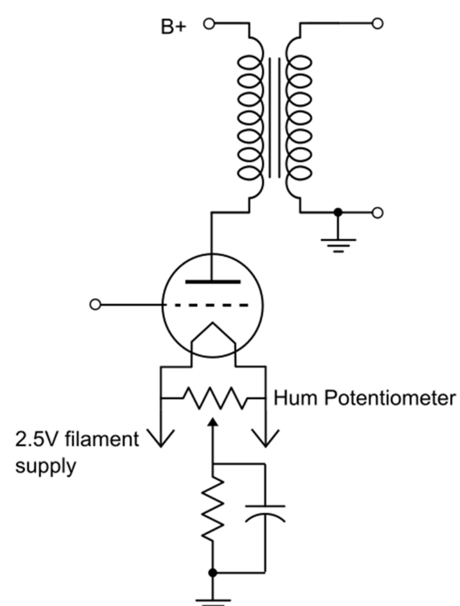
The reason I chose an operating point at 55mA instead of 50 is because the tube plate dissipation rating is actually calculated just using the voltage difference between the anode and cathode. Since we are holding the cathode at 55V, that means only 245V actually drops across the tube. So calculating power for 245V and 55mA is around 13.5W, within our rating. But as I mentioned earlier, this is theoretical, and you really need to test an actual circuit to optimize this. The final schematic and voltages used vary a bit from these numbers from real life testing.

Are you still with me? I know it's a lot, but you are getting it, right? Summarizing for a moment… we put 300V on the anode and because there is little resistive load under DC conditions, this is our operating point voltage. We elevate the cathode to 55V and our tube will be dissipating 55mA of current in its quiescent state, shifting our load line up. Now under AC conditions the input signal will vary the voltage of the grid by some amount depending on amplitude of the music and amplification in the driver stage, and from the load of the speaker (across the transformer) the varying current will swing the anode voltage very widely. This alternating current across the transformer is transferred back down to a low voltage and higher current to drive the speakers. Notice here that the anode voltage can actually rise higher than the B+ supply because the transformer stores energy in its magnetic field and it will resist the change in current, causing it to create a temporary higher voltage.

A few more quick notes. We haven't illustrated the AC load line in the chart, and will not try to do this because the speaker impedance varies across frequencies. But you could visualize an AC load line pivoting around this operating point, sometimes a higher load and sometimes lower, altering the slope of the line, but always around the operating point.

Directly Heated Filaments and Hum Potentiometer

One final thing to explain for the 2A3 tube. This is a directly heated tube, where the cathode and filament are the same piece of material inside the tube. We put 2.5V across the filament and it will draw about 2.5A of current to heat it up like a little light bulb. Wow, that's a lot of current, huh? Yeah. We'll cover the power supply later. At the same time, this is also the cathode, and we are connecting the same filament through a cathode resistor to ground. (This is different from other tubes like the 12AY7 where we run 6.3V into a filament that is just nearby the cathode, heating it up.)



So you see in the diagram the two arrows that represent the 2.5V filament power supply connections. While we could just connect the cathode resistor to one side or the other of this filament, we won't do that. Why not?

The 2.5V to power the filament is AC coming from our power transformer and this is fluctuating positive and negative at 60 cycles per second from the household AC, transformed down to our needed 2.5V. At the same time, the cathode resistor is closing the circuit for the tube that will be allowing around 55mA of quiescent current and this is holding our cathode at around 55V DC. The 60Hz AC of the filament supply is going to cause variation in the voltage of the cathode, making an unpleasant 60 Hz low hum sound in our amplified output.

To address this, we'll use a magical solution called a hum potentiometer or "hum pot." A potentiometer is a sort of variable resistor that has two end connections across the resistance, and a wiper in the middle that is adjusted by turning the knob of the potentiometer and altering the amount of resistance from the wiper to either end of the pot. We use these as volume controls, and in this case we use one to control hum.

The hum pot is a linear potentiometer of around 100 ohms or so that we connect across the filament supply, with the wiper of the potentiometer as the connection place for our cathode resistor. What this does is create a sort of adjustable center point for the filament. When one end of the filament is positive 1.25V with respect to the cathode, then the other end of the filament is negative 1.25V with respect to the cathode and they cancel each other out. Another variation on this is to simply use two resistors of equal value to make this type of "center tap" divider. But the tube filament is not a perfectly balanced piece of material, and it can even change a bit over time as the tube ages. So we use a potentiometer so that we can dial in this center point at the ideal balanced position to neutralize the hum.

I will also note that another solution you may see is to rectify and use DC voltage for the filament supply instead of AC. I won't describe this here. Because of the large current draw of the filament, it is not simple to rectify and filter this voltage. And in my opinion, it isn't necessary. The AC voltage and hum pot solution works very well and is a simpler design with fewer components.

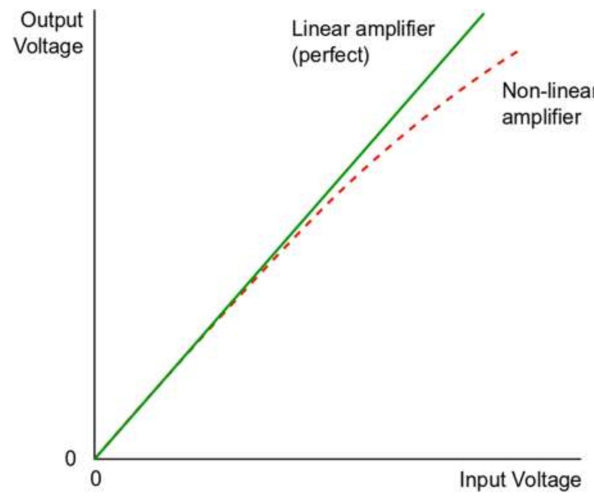
Ok, we're all set with our output stage. Think you got it? You are pretty smart.

Understanding distortion

It's time to try and cover the topic of distortion. It certainly sounds like a bad thing for a high fidelity amplifier, but what exactly is it? Let's take a closer look, and we may dispel a myth or two in the process. First, I should say that there are multiple types of distortion, and I will mainly be discussing one type here, **harmonic distortion**, which is commonly analyzed in an amplifier—and even this we will only just begin to explore.

In a perfect amplifier, we would have an input voltage that varies over time (the audio signal) and an amplified output voltage that varies over time exactly proportional to the input voltage but at a larger amplitude. We want this to be a **linear** relationship: $V_{out} = V_{in} * gain$, no matter what level of V_{in}. As the input voltage rises, the larger output voltage rises proportionally.

But in the real world things are not perfect. Perhaps over the range of possible voltages, the tube is doing its best (c'mon give the guy a break!) but as the input voltage on the grid moves up and down, the output voltage on the anode is changing in a similar, but not exactly identical way across all voltage levels. Perhaps we would expect 1V input to result in 10V output, but the amplifier actually puts out 9.5V.



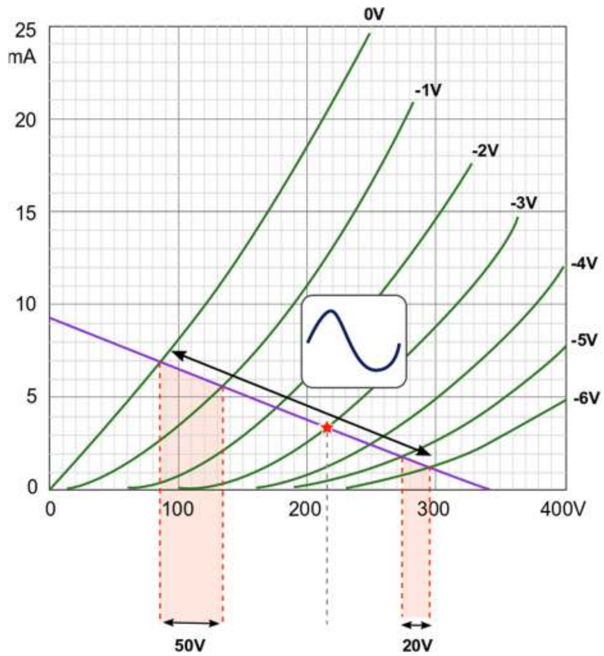
This non-linearity of the range of output voltages relative to the range of input voltages is distortion. This is an attribute of all tube amplifiers, and some might argue part of their "tube sound." In that respect, zero distortion might not actually be the goal, but certainly we want the output to be as close a representation of the original as possible, so we will aim to have relatively low distortion.

Ok, so how can we visualize and understand distortion even more? First, I want to emphasize one important point. The amplifier has no idea about the concept of an audio signal or sine wave, which incorporates time. The tube is not first listening to your Bob Dylan song and then playing it back to you louder, nor is it looking at a sine wave for a millisecond or two and then recreating a new sine wave afterward, hopefully similar. The amplifier sees an input voltage at a point in time and puts out an output voltage at that exact point in time, or close enough to consider instantaneous. This will be important as we get into visualizing distortion and discussing feedback. We use sine waves to communicate concepts of frequency and distortion, but the behavior of the amplifier occurs at a single point in time. That said, there are elements of time in the ability of the amplifier to react quickly to fast changes in voltage and demands on current in order to perform its job properly at the present point in time, but the point I'm making is that we need to consider distortion of a sine wave as an effect that we observe over time, but that is happening at any given instant.

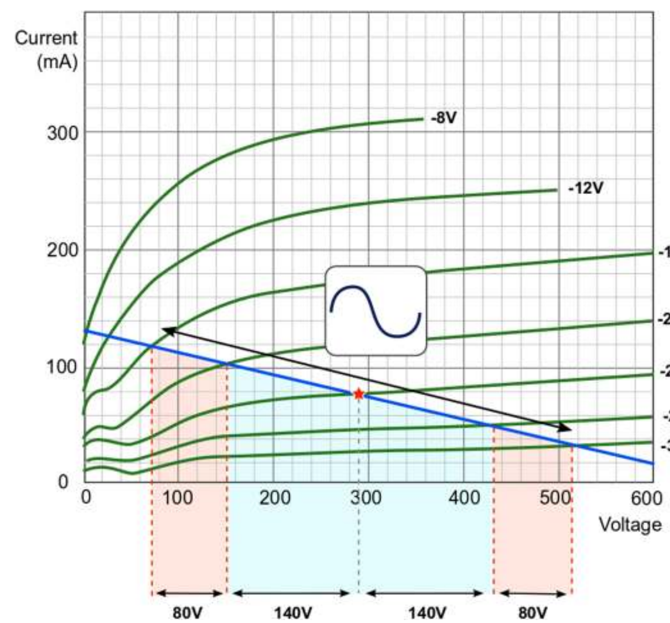
Now let's reintroduce the concept of time and consider a sine wave as a voltage changing over time, and the output voltage isn't perfectly identical in shape to the input sine wave. Remember how we drew a straight load line, expecting that variation of the grid voltage would cause the anode voltage to swing up and down on that line. But if the characteristics of the tube means the grid lines are not evenly spaced apart, then we can't expect the output to be a perfect replica. Two examples are illustrated below, where grid curves are either closer together at one end, or at both ends, causing non-linearity.

Examples of harmonic distortion

If grid curves are wider on one side than another, gain is asymmetrical, creating even-order harmonic distortion:



If grid curves are wider in the center than at the extremes, this causes symmetrical, odd-order harmonic distortion



You can see in these examples that an equal change in grid voltage would not cause a proportionally equal change in anode voltage at all areas of the load line. When the gain is asymmetrical around the operating point, the output waveform will be misshapen, or **distorted**, on one side but not the other. This will cause a type of harmonic distortion that is even-order. If the non-linear effect is symmetrical on both sides of the waveform, then this causes odd-order harmonic distortion.

You might also consider what happens if the operating point were too far to the left or right on the load line, or if the input signal were too large relative to the span of grid curves—if the input voltage pushes into saturation (near or above 0 volts on the grid) or down to cutoff (deeply negative grid curves, with low or no current), then obviously the output signal will be extremely distorted and a sine wave would appear as flattened on top or bottom. This is what we would refer to as **clipping**. Guitar amplifiers operate closer to these conditions to achieve a desirable overdrive or distortion sound, but obviously in a hifi amplifier, this is undesirable.

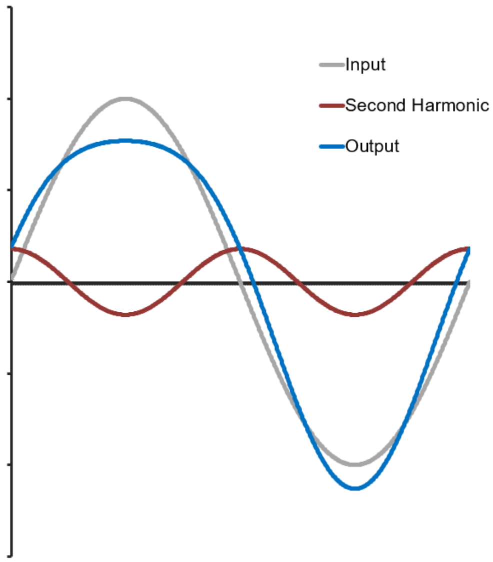
Now, we're ready to look at harmonic distortion another way to visualize these even and odd-order harmonics. I love this part, because the natural world, physics and math are sometimes like magic!

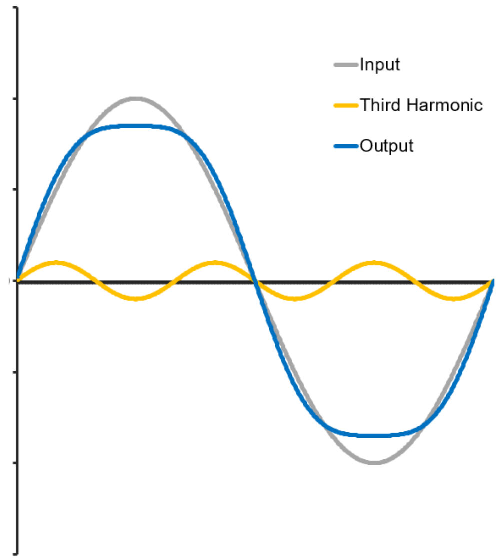
The sine wave that we input is at a frequency, let's say 1000 Hz. We can call this the **fundamental frequency (FF)**. Multiples of this frequency are the **harmonics**: the second harmonic is 2x the fundamental frequency, or 2000 Hz; the third harmonic is 3x the fundamental frequency, or 3000 Hz; and so on…fourth, fifth, etc.

An output sine wave that has been distorted by a non-linear amplifier will have a waveform that doesn't look exactly like the original sine wave. And this distorted waveform is equal to the fundamental frequency plus some combination of harmonics at lower amplitudes. See the charts below that are illustrative examples if we took a pure sine wave input and add a second or third harmonic at lower amplitude. The output is a combination of those frequencies added together.

Distorted waveforms

In both examples here, the blue distorted waveform is equivalent to the combination of the input sine wave and a second or third-order harmonic (at 2x or 3x the frequency).





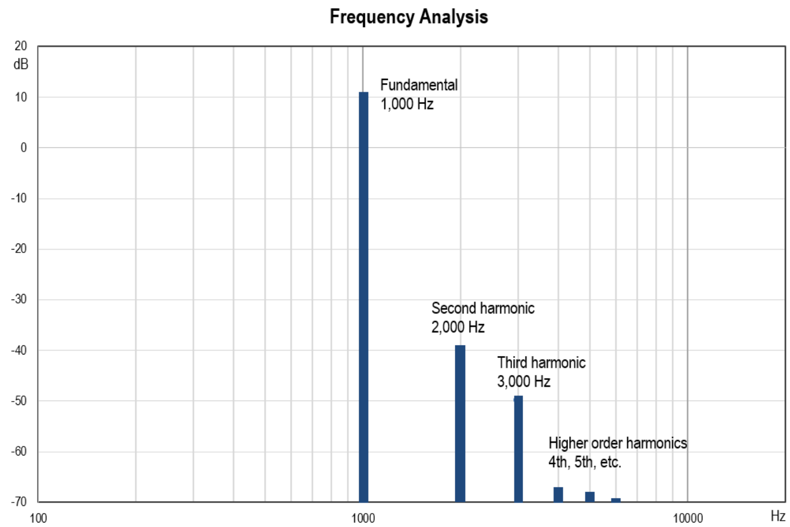
Are you getting it? The distorted waveform is **the same** as multiple sine waves at different frequencies and amplitudes added together.[5] Going back to our amplifier, it's important to re-emphasize: the output waveform is distorted due to various causes, and this is equivalent to a fundamental frequency plus harmonics. We could be tempted to have a mental image that the harmonic frequencies are created in some other way and then added to the original signal, with harmonics as the cause of a distorted output. I suggest this is not the best way to think about it. Remember how I pointed out that amplification is happening instantaneously. The waveform is distorted because gain is not uniform across all input levels, and when that happens, we can watch a waveform over time that can be described as the original fundamental frequency plus harmonics. The net effect is, however, exactly the same as if we did truly have multiple sine waves generated at different frequencies, amplitudes and phases and combined together.

What this means is we have a way to measure the harmonic distortion of the amplifier. While you could look at the waveform on an oscilloscope and subjectively say, "well, it looks pretty close to a sine wave," and this is fine for basic observation and detection of heavy distortion and clipping, you would not be able to easily observe more subtle distortion. We can do better.

Since the distorted waveform is identical to multiple sine waves at different frequencies, we can measure and visualize the amplitudes of those harmonic frequencies. Here's where we need a new graph: instead of showing amplitude versus time of a waveform, we can show amplitude versus

[5] Harmonics may also be at a different phase than the fundamental frequency, but this is not introduced here. For illustrative reasons, the second order harmonic shown here is offset by 90 degrees in phase.

frequency. A frequency analyzer can do this for us. Below is an illustrative chart demonstrating measurements of harmonic distortion on the frequency spectrum.



You'll see this uses decibels for the vertical amplitude, with a 1000 Hz fundamental frequency at a certain level, and the second harmonic is much lower about 50 dB below the FF. The third harmonic is lower still, and very tiny amounts of higher order harmonics. This is typical of a single-ended tube amplifier: most distortion is second and third harmonic.

We could then calculate a summary measure to add up all these harmonics and this is what you see reported as Total Harmonic Distortion (THD) usually as a percentage of the fundamental frequency. High quality modern solid state amplifiers will have extremely low values, like 0.01% THD. Tube amplifiers by nature will typically have higher THD, and harmonic distortion will nearly always be proportional to output level—higher volume (higher grid voltage change) will have more distortion.

We have not yet discussed what harmonic distortion means in terms of how the amplifier sounds. How much distortion would be audible? What does second-order harmonic distortion sound like versus third-order or higher? You can find examples online or create your own if you have computer software or signal generators, to hear a sine wave with a second or third harmonic mixed in. You will notice that second and third order harmonics have distinct tonal qualities. In music, doubling the frequency is the same as a one octave higher note, and some will argue that a second-harmonic is "better" or more acceptable in sound because it is "in tune" whereas some odd-order harmonics are not musically related. There is much debate on this and conflicting tests and research about people's perceptions of which sounds better. There is typically consensus that lower-order harmonics (second

Measure or Listen?

I believe in measurements to help understand performance of the amplifier or speakers. I've learned that my ears can play tricks on me and my own psychology can lead me to think something sounds good because I want it to (or vice versa). Remember also that one of the most critical parts of how it sounds is your speakers. There's a whole other world of speaker selection (or DIY design!) and room environment and treatments to think about, and that's all part of the fun of this hobby. But a listening test is just as important as measurements, and at the end of the day, if you can play a system and it sounds good to you, you win!

and third) are more acceptable than excess amounts of higher order harmonics.

On the subject of how much THD is acceptable, again there is much debate and probably the answer is: it depends, on many factors—the type of distortion, source, etc. Purists will say it should be as close to zero as possible. Some research was done years ago that gave clues many people may not be able to detect it audibly below 0.75% and that it may not be noticed or considered interfering with the sound until 2-3% or even higher with complex sources such as music.[6] This enters into complex or subjective areas of what people believe sounds good or not, learned experience of critical listening, variability in human hearing, etc.

I should emphasize again that there is much depth to this topic and I'm only covering some simple concepts to explain it. There are other types of distortion, such as intermodulation distortion, that can be important, too. For now, I hope you will at least understand some basics of harmonic distortion, examples of how it could be caused and how we can see or measure it.

Negative feedback (for context)

If we believe an excess of distortion is not ideal, then the question remaining to ask is: how can we limit it? I'm going to briefly cover a technique that can be used just to give you context of a choice to be made, even though we are going to choose not to use it. We'll move into a more complex subject next, but to make this educational section more thorough, I think it's important to mention **negative feedback**.

As with many other things, there are varying points of view about the use of negative feedback. Some may view this as an undesirable way to improve the performance of the amplifier, somehow compromising on sound quality. Certainly if the circuit design, components and performance is poor, and negative feedback is used to try and put lipstick on a pig, then I can understand. But to categorically view negative feedback as something to avoid is, in my opinion, missing a beneficial technique. I chose not to use negative feedback in this 2A3 amplifier not because I believe it somehow compromises on the sound quality, but because it is not necessary due to the tubes and circuit design that already has very good performance and acceptable level of distortion. My objectives for this amplifier were not to minimize distortion, but to have a very authentic type of single-ended triode design using classic tubes and their expected, normal performance.

So what is negative feedback and how does it work? I'll try to explain it in the way that makes sense to me, acknowledging there are others who can cover the theory and equations much better if you want to learn more. Feedback as a general concept can be found in all sorts of places where the actual result is compared to a reference level. Consider a few examples:

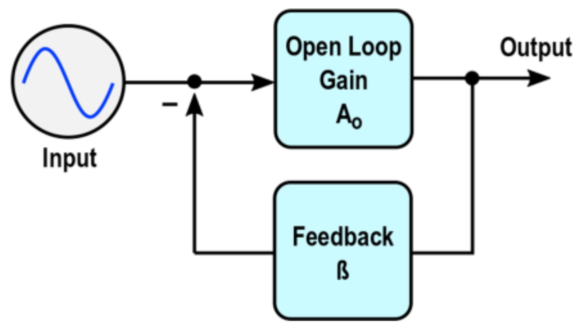
- A thermostat detects the room is too cold and turns on the furnace until the temperature meets an expected level and then the thermostat turns it off.
- Your car's cruise control measures how fast the car is going and modulates the gas to the engine if the car is going too slow or fast relative to a certain level.

[6] Check out the *Radiotron Designer's Handbook* , published in the 1950s and available online in PDF, for some interesting information about distortion, among other things.

- Your toilet has a float that detects the water level and opens or closes a water valve until the tank is filled to the expected point.

In the amplification process we have looked at so far, we have an input voltage and an output voltage that is larger based on the gain of the amplifier. This can be called "open loop gain" (meaning there is no feedback loop) and we know this gain is not perfectly uniform for all input voltages.

A negative feedback loop can be used to change the circuit and create a different "closed loop gain" that takes a portion of the output voltage—the "feedback fraction"—and subtracts it from the input to create a new control voltage. A general feedback structure is shown here.



Taking a portion of the output and subtracting it from the input will attenuate the control voltage, lowering overall gain. This is a small sacrifice made to use negative feedback, and presumes the amplifier has a substantial amount of gain to begin with. If we were to tie the input to the output at a certain relationship, then the actual gain of the amplified signal will now be determined entirely by this feedback fraction, instead of the open loop gain on its own. In order to achieve a state of equilibrium, the control voltage will compensate higher or lower depending on the relationship the feedback loop sees between output and input. This is exactly what could be used to deal with non-linearity and is why it will reduce harmonic distortion.

I'll mention how this could be designed in a circuit, but I won't go far here because I don't want to really distract from explaining our actual 2A3 amplifier. I do use negative feedback in several of my other kits, and it can be implemented in various ways. One example could look like this: if we make a connection from the positive terminal of the output transformer (the same place that goes out to the speaker), and run this through a resistor back to the cathode of the driver tube, then we would have established a feedback relationship with some fraction of the output voltage being effectively subtracted from the driver stage by adjusting the voltage level at the cathode (and to do this, the cathode resistor cannot be bypassed with a capacitor). By wrapping the amplifier circuit in this feedback loop, we would call this "global negative feedback." It will reduce gain a bit, and will improve distortion by keeping the output and input in a more linear relationship.

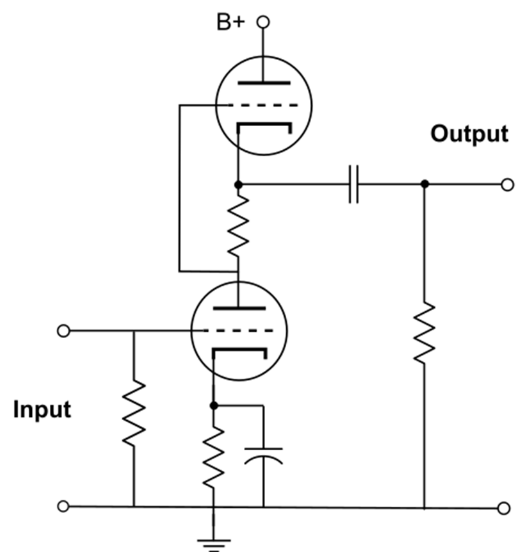
I know I've only barely described this, and poorly! I hope you get the general concept: using the output as an influence on the input to achieve a controlled gain level. If you haven't gotten it just yet but want to know more, this could be a topic you choose to study more using additional resources.

SRPP Driver Stage

Ok, we have covered a lot and you have a working amplifier circuit and an understanding of distortion. You have probably noticed on the full schematic that there are actually two tubes shown in the driver stage (actually two sections of one physical dual-triode tube), but so far have discussed only a single driver tube and output tube. This section will be an advanced topic to explain why we are using two tubes and what's happening in that stage. This is not a simple subject, and I have recommended reading material in the appendix that will explain the theory better. I will do my best to cover it sufficiently, though still briefly.

Amplifier circuits can of course be very complex. In some cases you could have multiple stages of amplification happening—a tube stage leading into another tube stage, and so on. We refer to the stage just prior to the output tube as the "driver stage" but you could have multiple stages doing some form of amplification, buffering or other things. If you find this subject interesting, you can read and learn more about all sorts of complex multi-stage amplifier designs. Sometimes, more than one tube can be used in a single "compound stage" and that's what we have here: a compound stage that is referred to as **SRPP**, or "Shunt-Regulated Push Pull." If your head hurts already from the name of it, just grab an iced coffee and come on back.

Remember how I first explained a 12AY7 driver stage using a load resistor, and the varying current across that resistor resulted in a voltage fluctuating (Ohm's law). We drew a load line to represent that load on the tube and could visualize the signal on the grid varying the anode voltage along that line. Well, in some cases we don't just use a fixed resistive load, we can use other techniques. Resistors are considered "passive" components, not able to provide any gain or control current on their own. Tubes (and transistors or other things) are considered "active" components, capable of controlling the flow of current. So in an SRPP design, we replace that load resistor with another tube—a "tube on top of another tube" if you see what I mean. Let's take a closer look.



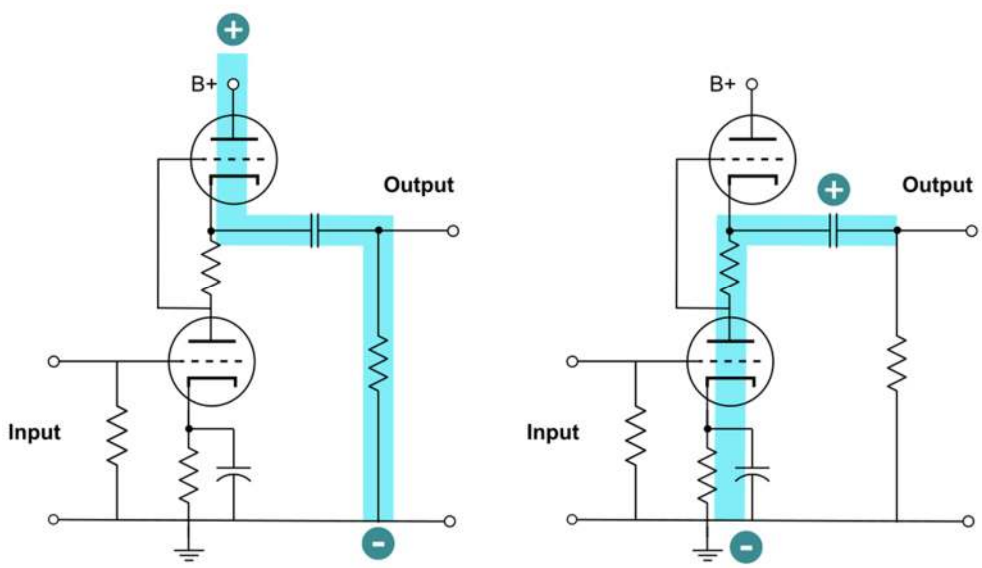
The bottom tube should look familiar to you. We put our input signal onto the grid, and this opens and closes the valve to allow some amount of current through the tube. But look up above the anode of the bottom tube and you see a few things: a resistor through which some current will flow (and we should expect a voltage change as that current varies), and look how the top of that resistor is on the cathode of the top tube, and the bottom of that resistor is also connected to the grid of the top tube.

So think about what could be happening here: the signal on the bottom tube grid allows more or less current to flow through that middle resistor causing a voltage change across it. And since that resistor effectively represents the grid-to-cathode potential difference of the top tube, it will cause that top tube to open and close its own valve allowing more or less current. As more current flows in the bottom tube, the voltage drop of the middle resistor is larger, meaning the grid on the top tube is increasing its potential difference to its cathode (more negative grid) which is actually closing the valve of the top tube allowing less current through. So the two tubes are working in opposition—one opens allowing more current, which closes the other allowing less current. This is what we could call a "push-pull" operation, with the tubes working in opposite ways, and the net result at the steady-state operating point being a regulated, or relatively constant current through both tubes. (Some power amps are designed as push-pull operation through the output stage, but I won't be going into that type of design here. This amplifier is still a single-ended design, even though this portion is using a form of push-pull behavior.)

Ok, cool so far; the same total current obviously must pass through both tubes since they are in series with each other—but that is only true at the quiescent point with no input signal. Let's now think about what happens under AC conditions when we are playing our Grateful Dead songs. Remember there is another current path for AC when we take our output voltage through the coupling capacitor on to the next stage of amplification. You'll see we take this signal from the cathode of the top tube, and then we have the grid leak resistor of the next stage representing a load under AC conditions. In our case, that resistor is 470k ohms, so it's only going to draw a small current.

So, now consider an AC signal that is on its negative cycle, causing the bottom tube to increase the grid-to-cathode voltage difference, constricting current, while the top tube sees a decrease in its grid-to-cathode voltage, allowing more current. To help us think about the behavior, let's even use an extreme example where the signal voltage is at such a point that the bottom tube is at full cutoff—nothing going through it. Now, the top tube is conducting, but where can the current go? Not through the bottom tube, but instead through the coupling capacitor and the next stage load. See this diagram here on the left to illustrate the path.

And now think of the other side of the cycle, the input signal is very positive, causing the bottom tube to conduct while the top tube goes into cutoff. But hold on a minute—how can the bottom tube conduct if the top valve is closed to the B+ source? The answer is that our coupling capacitor is discharging after having been charged up on the other half of the cycle. The top tube delivers current into the load, and the bottom tube draws it out. Now the other consideration is that this arrangement really does only work effectively in Class A—where the tubes always have current through them across the range of the audio signal. We used extreme examples as illustration, but would not be actually driving the tubes into full cutoff or saturation.



Yeah, I know. I really just want to go get an ice cream bar, too. But hang in there. Summarizing, under AC conditions the tubes are taking turns conducting more or less current, and the **difference** between their current is going through the coupling capacitor to the next stage load. And in our case, since we aren't driving a heavy load, we care most about the resulting voltage at the output.

Why the heck are we even doing any of this? What good is it? The takeaway here is that when we have balanced current sharing between the tubes, we will get some cancellation of second-order harmonic distortion as one tube conducts in one direction while the other conducts in opposite phase. Can you see how that might be? If one tube is non-linear in its amplification, the other tube is in opposite phase, similarly non-linear but in the other direction. It isn't perfectly balanced, as in some arrangements, but it should make for a measurable reduction in THD. Depending on the values of the output load and the cathode resistors used on the tubes, we can optimize this distortion reduction and output impedance of the stage.

I realize we are not really using the load lines originally drawn for the 12AY7 and are not trying to visualize graphically, but I thought it was important to understand the load lines for a general understanding of tube operation. This amplifier design is deceptively simple, with some complexity of its actual behavior. I know it's not easy. If you didn't quite catch it all, that's ok. Maybe you have a rough idea of how it works. And if you love math and deeper electronics theory, you can read the references in the appendix.

SRPP vs. Active-Loaded Gain Stage?

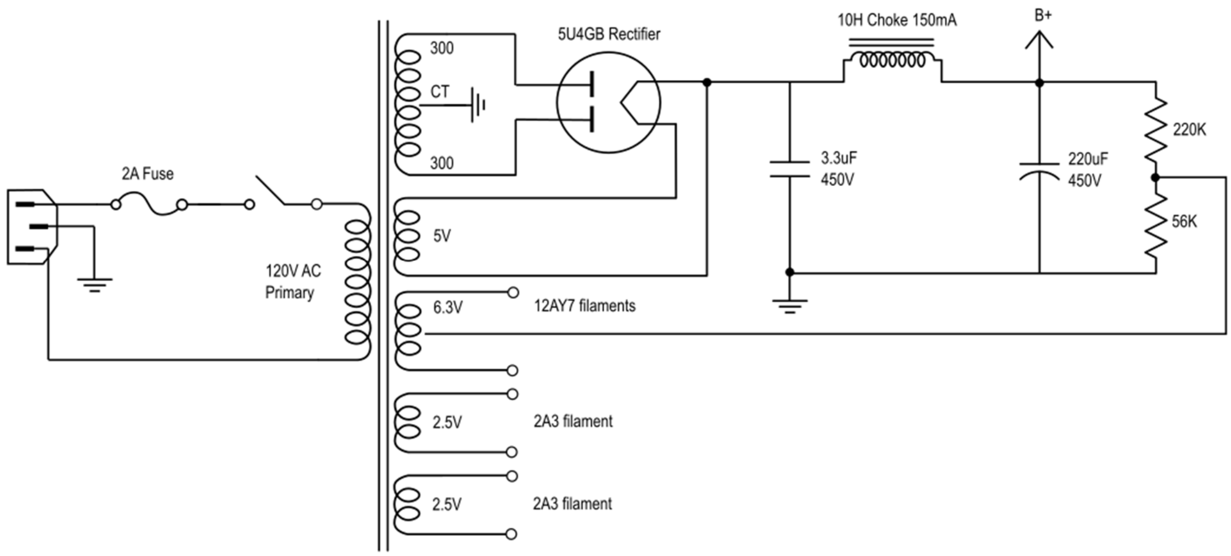
Now, I need to make clear that usage of this design would be considered debatable by some. Everything in high fidelity audio is of course debated hotly! Some would argue that the application of SRPP is best used when more current needs to go into the load. If we had no output load draw at all, then some would argue it's not even SRPP behavior, but is just an active-loaded single-ended stage with a regulated (though not truly constant) current.

That's fine, we can debate how much this is really taking advantage of SRPP benefits versus active loaded stage behavior. In any case, the benefits of low distortion voltage gain seem to be evident, and I am not at all being original in this design, as others have used nearly identical circuits to drive similar types of tubes. I've tested the circuit and found it to measure well, and to sound great. So off we go with it!

Power supply, rectification and filtering

We have covered the main parts of the amplification circuit. Now let's back up and understand the power supply. Why are we doing this last? As you saw with the load lines and tube explanations, we have choices that we can make about the supply voltage and operating point that determine the voltage and current demands of the amplifier. Having this information helps understand the choices in the design of the power supply.

Looking at the schematic, let's start on the primary side of the power transformer. Mains voltage comes in from your household electrical outlet and we have a few components the hot side passes through in series.



First, a 2 amp fuse is for protection in case something in the amplifier is drawing more current than it should, such as if you had a short somewhere. We would rather the fuse blow than your components to be destroyed or things catch on fire, but even this fuse is not a guarantee that improper wiring or a short wouldn't do damage to components, it just will break the circuit to prevent continuous high current that could be dangerous. This is a slow-blow type fuse, so it will allow a brief heavy draw of current, which is typical from the inrush that can happen when the amplifier is first turned on.

Next, we have a simple switch to turn on or off the amplifier. When on, the hot side of the mains voltage connects to one lead of the primary side of the power transformer and the other lead of the primary closes the loop back to the neutral side of the mains.

Remember that a transformer uses windings at a certain ratio to transfer power from the primary winding to the secondary winding and convert the voltage and current to different levels. In our case, we are wiring a transformer to take 120V AC (U.S. mains voltage) on the primary, and we will get 600V AC on the secondary for our high voltage supply. This transformer is designed for tube amplifiers and it has additional windings on the secondary side. One will provide 5V as the power for the tube rectifier filament. Another is 6.3V, to power the filaments (heaters) of the 12AY7 tubes. There are also two separate 2.5V windings to supply each of the 2A3 tube filaments.

You will notice that on this transformer the high voltage secondary has a center tap to use as a 0V potential. This is convenient so we can reference each 300V half of the secondary relative to this point. This becomes our ground reference throughout the amplifier circuit. In some cases, the transformer will not have a center tap and you would use a different technique to create a 0V reference.

The transformer secondary is still AC, now at a higher voltage, but our amplifier will require a high voltage DC supply as our B+ voltage. In fact, we need this DC voltage to be as pure and steady as possible. The fundamental activity of the amplifier is to modulate this DC supply voltage based on the input signal. If the supply is not clean, we will not get a high-fidelity output and may even hear an audible hum or buzz. You'll see why soon.

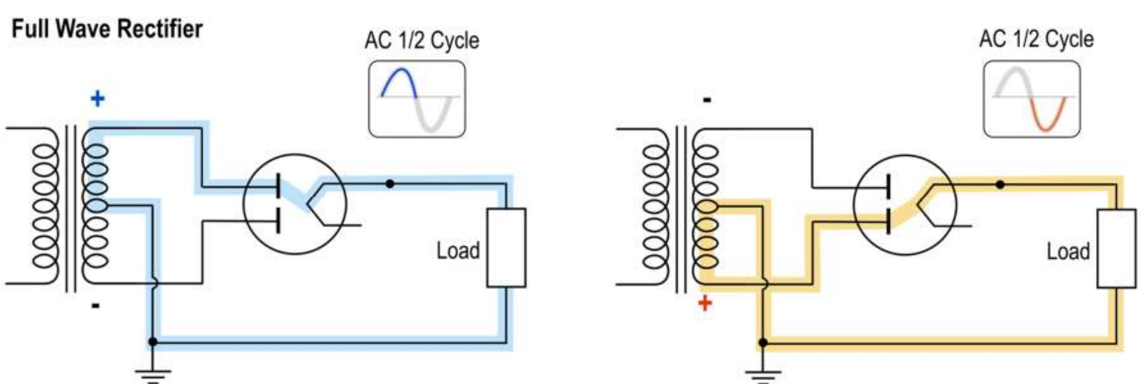
To convert AC to DC, we need a rectifier—something that will allow current to flow only in one direction, so we have only positive current. Amplifiers historically used tube rectifiers, and that's what we will use in our circuit. From our earlier topic, you understand how a vacuum tube works—with a cathode emitting electrons and an anode pulling them in, allowing current. Importantly, this current can pass only in one direction. So using a rectifier "diode" tube (no control grid), you can rectify from AC to DC.

The AC voltage is cycling at 60Hz (US mains frequency) and each terminal of the high voltage secondary of the transformer is alternating back and forth at this rate, opposite from one another and positive or negative with respect to the 0V center tap. The tube rectifier will allow current to flow in one direction only and does not allow current to go in reverse. The tube we are using is a 5U4GB, with two anodes, one for each terminal of the transformer secondary, and we refer to this as "full wave" or 2-phase rectification (versus "half wave" that would only rectify part of the cycle).

Tube rectifiers vs. silicon diodes

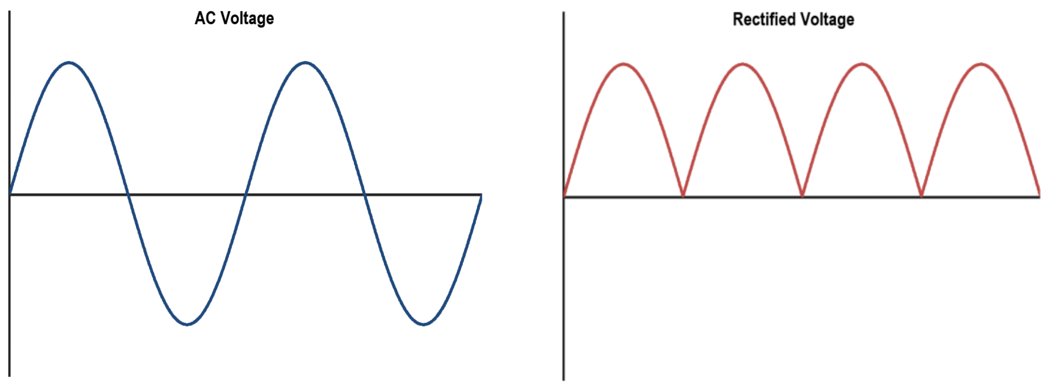
Rectifier tubes have some disadvantages, in that they drop a significant amount of voltage, require current to heat the filament, and add cost and physical space required in the amplifier. The other solution that is available is to use silicon rectifier diodes. There are debates about whether a tube rectifier is better: does it have a desirable "sag" under current loads impacting the sound and so guitar players may prefer it in their amps, is it better to bring up the DC voltage slowly due to the filament warm-up time, what about switching noise of a silicon diode, etc. I won't try to cover the differences, but I will say that I believe silicon diode rectifiers are very good at doing their job and are fine to use without compromising the sound or amplifier behavior. In this case, I chose to use a tube rectifier in part to make the amplifier a bit more authentic to original types of designs, and this transformer happens to have more voltage than we really need, so dropping some voltage works out fine for our B+ supply.

On the first half of the cycle when voltage swings positive on one terminal (with respect to center tap), that anode conducts current while the other terminal is now negative and its anode is not conducting. On the second half of the cycle, the opposite occurs and the other anode will conduct.



We take the rectified voltage off of the single shared cathode to go do useful things with it like power a load. The illustration here does not show the 5V filament supply used to heat the cathode, which in the case of the 5U4GB, is a directly heated cathode (not a separate heater filament).

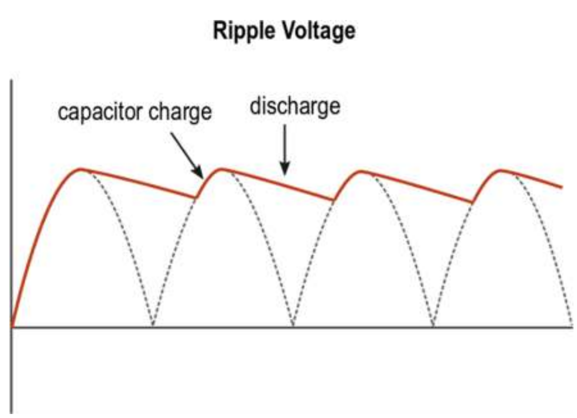
If you visualize the effect of this at the output of the rectifier, the voltage potential with respect to the center tap is always positive—first from current flowing through one anode for the first half-cycle, and then from current flowing through the other anode for the second half-cycle. The rectified voltage now looks like the graph below.



We are making progress, but our intention is to have smooth DC voltage, not large peaks and voids like this. We need to filter this power supply to smooth this out. There are various ways to do this, but the two main components to use are capacitors and chokes (inductors).

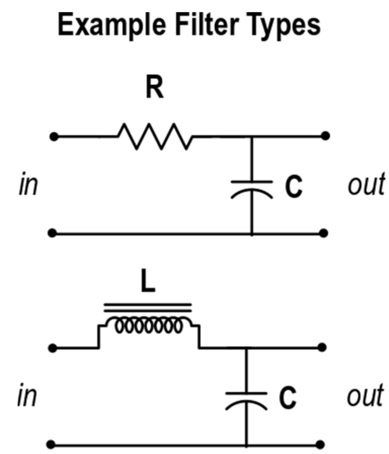
By putting a capacitor in parallel with our supply voltage, the rectified voltage will charge it up on the up-cycles and then when the cycle is falling, the capacitor will discharge, supplying current to the amplifier load. We sometimes call this a "reservoir" capacitor because it's like we have a tank holding a supply of water. While the faucet may be turned on and off continuously to keep it filled, we can tap the barrel from the other side to draw a relatively steady stream out.

A capacitor will make our DC voltage look like the chart here. Note that we still have some ripple voltage as the capacitor is discharged, but it's certainly better than the peaks we had previously. In our circuit we are using a 3.3uF capacitor as our first capacitor. This is a small value, and the ripple voltage will be large. You could use a lower or higher capacitance, and I will explain this choice in a minute, but all tube rectifiers have a maximum rating for capacitance because it will draw pulses of heavy current in order to charge the capacitor, and can exceed the tube's ability to handle that current. Depending on operating conditions the maximum could be up to around 40 or 50uF or so. I will not try to describe the calculations of maximum ratings, or what size ripple voltage you would have for a given power supply, capacitor, and load, but the point right now is that we have more work to do, even after putting in place this capacitor.



If we used this DC as our B+ supply, this ripple voltage would be modulating our plate voltages by a certain amount at a frequency of 120Hz (since this rectified voltage represents two half-cycles of the original 60Hz AC). You would hear this as a sort of buzz or hum in your amplified output.

We can do more to continue to refine this power supply and get the DC supply as clean as possible, with ripple below an audible level. While you might just be tempted to use a bigger reservoir capacitor, there are limits to how much this can reduce ripple, and it has some other downsides I won't go into here.



What we are attempting is to allow DC to pass while we filter out this ripple—think of it like AC at 120Hz riding on top of the DC voltage. The most common techniques are to use low-pass filters using resistors, capacitors, and inductors. The simplest is an RC filter—a resistor and another capacitor to create a type of voltage divider that would attenuate frequencies above a certain point. This type of filter is inexpensive and works quite well. The downside is that it requires some voltage to drop, sort of wasting a bit of the power supply. This also dissipates as heat.

An alternative is to use an inductor, typically called a choke in this application, as an LC filter (inductors denoted with the symbol L). Remember we covered that capacitors block DC but allow AC (a simplistic way of describing it). And inductors are the opposite, reacting against AC current changes while allowing DC to pass. Putting the inductor in series in the filter would have minimal impact on DC, while reacting against the AC change at the ripple frequency.

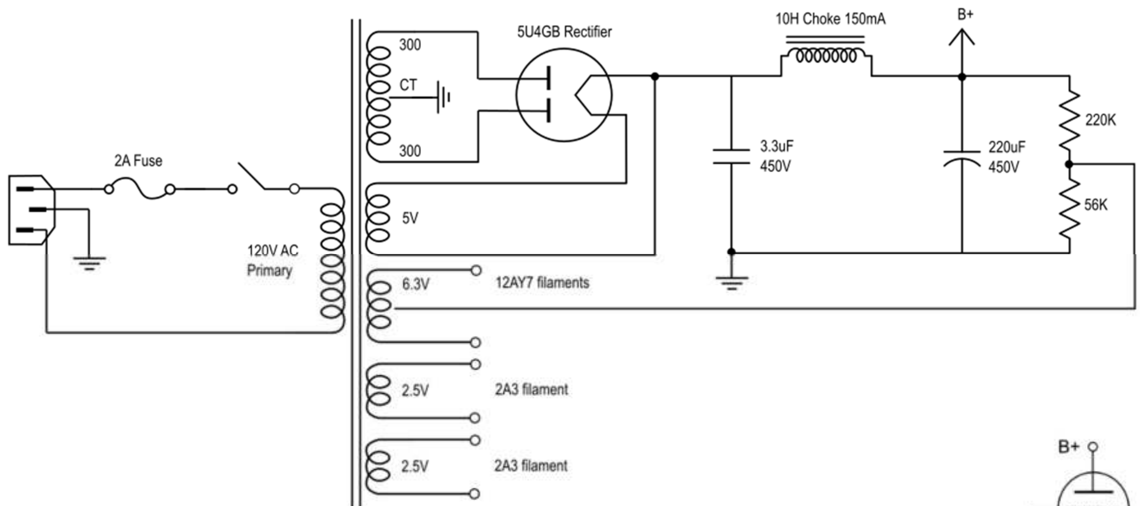
There are some downsides to using a choke. Most notably they can be expensive and heavy when they have enough inductance to do adequate filtering. In our case we are using a large 10H choke (inductance measured in Henries) and it has about 100 ohms of DC resistance, since all wires have some amount of resistance. DC resistance in a choke is generally not the intention and becomes another factor in selection/cost, though at times you may want more or less DC resistance. We are then using another capacitor, this time a much larger value of 220uF as the last part of the filter.

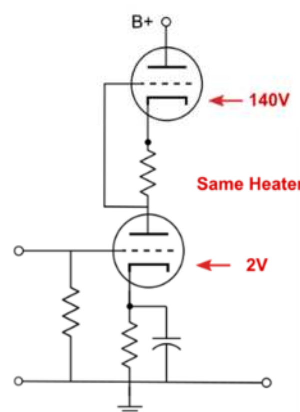
So looking again at our schematic, we have our rectified power supply going through a capacitor/inductor/capacitor sequence. The end result is a filtered B+ that should have very little ripple voltage, which means our amplifier should have a clean power supply we can use for an amplified audio signal, and silence when there is no signal.

How much DC voltage will we get as our B+ after this rectification and filtering? First, remember that AC can be measured in RMS volts, sort of like an "equivalent" steady voltage measurement because it's actually changing voltage throughout its cycle. This transformer is designed as 600V center-tapped (usually labeled 300-0-300), meaning 300V RMS on each half-cycle of the secondary that we have rectified to be a positive voltage, which means the peaks you see in the illustration are going a lot higher. A commonly used formula is that peak voltage is the RMS voltage times 1.41, so our 300V RMS is actually a voltage that could reach nearly 425V at the peaks, and in theory this is what our capacitors could be charged up with. However, tube rectifiers drop quite a bit of voltage, so the amount wouldn't actually reach that high. Also, I wanted the B+ supply to be around 325V in order to optimize the power dissipation in the 2A3 tubes without exceeding their rated limit. This is why I selected a 3.3uF capacitor instead of something larger for that first capacitor. We can control our maximum B+ by using a smaller capacitor in this position. I won't go into details of why this is, but it relates to the physics of how a capacitor is charged over time. So our final B+ supply turns out to be around 325V and could be tweaked a little higher or lower by adjusting that capacitor value.

We select capacitors for a rating of at least 450V to allow for a higher voltage as the tubes warm up and the load isn't yet at its full draw. And because the first reservoir capacitor is a low 3.3uF value, we can use a film capacitor, which has better characteristics than an electrolytic capacitor. The first capacitor in particular sees heavy pulses of current as it charges and discharges which can strain the capacitor. I will use electrolytic capacitors in some cases, but they should be rated for high levels of ripple current to avoid risks of overheating and shortening their lifespan. The 220uF capacitor is much too large for a film cap, so we use electrolytic in this position.

Elevating heater voltage, and bleeder resistors





Looking again at the schematic, you notice one more part of the power supply—a pair of resistors that form a voltage divider with 220k ohms on top and 56k ohms on the bottom. We connect the center tap of the 6.3V filament supply to the middle of this voltage divider and it raises the 6.3V AC to a higher DC reference point instead of putting it at ground level. Remember from our section on the SRPP driver stage that we had connected the anode of one tube section to the cathode of another. Most indirectly heated tubes have a maximum voltage difference allowed between the heater and the cathode. Imagine the cathode were at 140V DC while the filament was 6.3V AC referenced to a 0V DC ground potential. This large voltage difference between those components creates a risk to safe tube operation, with possibility of arcing voltage between the cathode and filament. In some arrangements, we could set each of the filament voltages to a different potential, but we have only one 6.3V supply and are using two sections within a single dual-triode tube, so it is the same heater supply for both cathodes.

The 12AY7 tube has a maximum rating of 90V between heater and cathode. Our SRPP upper tube will have its cathode close to 140V and lower tube cathode close to only around 2V, so what can we do? We will pick a value somewhere in between and elevate the filament voltage to around 65V or so. Now this is within the 90V limit to the upper tube and also within 90V to the lower tube. If our B+ voltage is around 325V, then a voltage divider with common resistor sizes of 220k and 56k would proportionally split that voltage at a point approximately 66V. Sounds good.

The large resistor values means we don't waste a lot of current; I would use 1 or 2W resistors here. This pair of resistors serves one more purpose of acting as a bleeder resistance for the capacitors, for safety reasons. When you shut off the amplifier, this will take a few seconds to dissipate the energy that has been stored in the capacitors so they are at a safe level. If somehow you had no load on the circuit (such as without tubes installed) but charged up the capacitors, you could turn off the amplifier and unplug it and there could still be a very dangerous high voltage charge in the capacitors hours or even days later. Even if we didn't need the voltage divider, we would put a bleeder resistor here to ensure the voltage drops down to a safe level after several seconds.

Current demand on the transformer

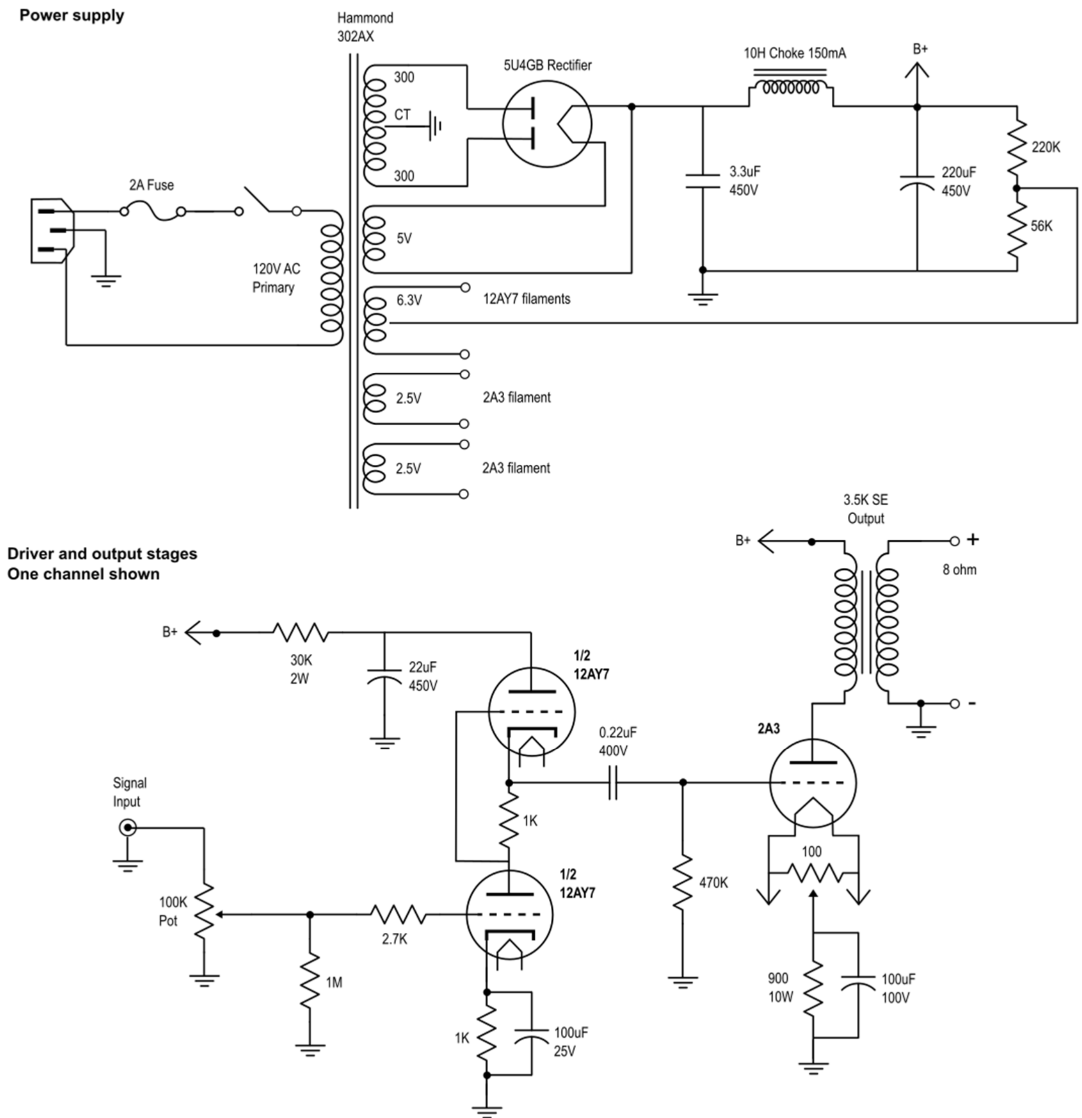
Finally, we should also talk about current demand of the circuit. Transformers are rated for a certain amount of current. The one used in this kit is rated for 230mA, more than we need. If we add up the demand of our expected circuit based on our load lines, we would have approximately 50-52 mA per channel for the power tubes and 2mA each for the driver stage, totaling around 105mA or so.

There is also a current demand of the filaments. The 5U4GB requires 3A, each 12AY7 requires about 300mA, and the 2A3 tubes each require 2.5A. This is rated separately on the transformer, and since ours is designed for these sorts of tubes, the ratings match up well.

There is far more depth to power supply design than I'm able to cover, and other very different techniques that could be used to regulate voltage or current. In this kit, you are seeing one design and hopefully this helped explain the basic principles of transforming the AC voltage, regulating it to DC, and filtering it.

Bringing it all together

Let's look one more time at the schematic, I will point out a few final elements, and you should have a complete understanding of this circuit.



You will see there is filtered B+ that goes to the output stage, but there is also one more RC filter, using a 30k resistor and 22uF capacitor on the driver stage. This accomplishes several things. It provides more filtering for the more sensitive driver stage and also plays a role in decoupling the driver stage from the rest of the power supply that is feeding the output stage. By adding a capacitor between these, we can help to send any AC noise to ground to keep the input stage power supply as clean as possible. The driver stage also does not require as high of voltage as the output stage, so the large 30k resistor can be used to drop it to a more useful level.

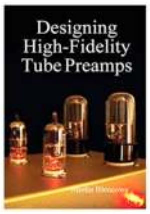
There is a 2.7k resistor leading into the grid of the 12AY7 tube. This is referred to as a "grid-stopper" resistor and is used to help avoid stability problems. It combines with the internal capacitance of the tube from grid to cathode to act as an RC filter, small enough that it does not impact audio frequencies, but large enough to stop any very high frequency interference that can create instability that you may not be able to hear but could lead to oscillation and damage to the tubes. Don't worry too much about this resistor—it might typically range from 1k to 5k or so. Some designs do not even use them, and you'll notice I do not use one on the upper section of the 12AY7 or the 2A3 tube, but I think it's a good idea in some cases.

You also see the input signal entering the circuit and going through a 100k potentiometer, which is acting as a voltage divider to attenuate the signal depending on the position of the volume knob. 100k is the amount of resistance this potentiometer uses. When the knob is turned to one end of its range, the signal goes straight to ground. At the other end of the extreme, there is 100k of resistance, allowing nearly the full signal to be applied to the grid. And in between has some variable amount of resistance that can reduce the level of the signal to some degree.

That's it! We have walked through the entire circuit and I hope you feel you've had enough overview to understand each part of it. If you need (and want) to, re-read this Part II and think about what's happening in your amplifier. I don't know about you, but I'm the type of person who needs to go over it a few times to really get it. Knowledge is powerful, and it's great fun to learn. I hope you find this useful and perhaps you'll want to keep learning more!

Additional Resources:

Here are a few favorite books and resources that I’ve found useful or inspiring in case you want ideas of further ways to learn more about making your own tube amplifiers.

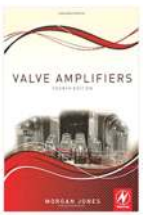


Designing High-Fidelity Tube Preamps

Merlin Blencowe

Also, information on his website: www.valvewizard.co.uk

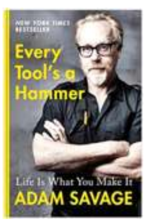
Excellent information and well-written for understanding.



Valve Amplifiers

Morgan Jones

A great book, quite deep on some theory.



Every Tool’s a Hammer

Adam Savage

Also, his website www.tested.com and YouTube channel

Great inspiration on the general topic of being a maker!

RCA Radiotron Designer’s Handbook

A classic text that has extensive information. It is available online in PDF form if you search for it, or you can find used printed copies.

SRPP Theory

http://www.valvewizard.co.uk/SRPP_Blencowe.pdf

https://www.tubecad.com/may2000/index.html

The Valve Museum website

www.r-type.org

A great collection of information and articles

Online communities:

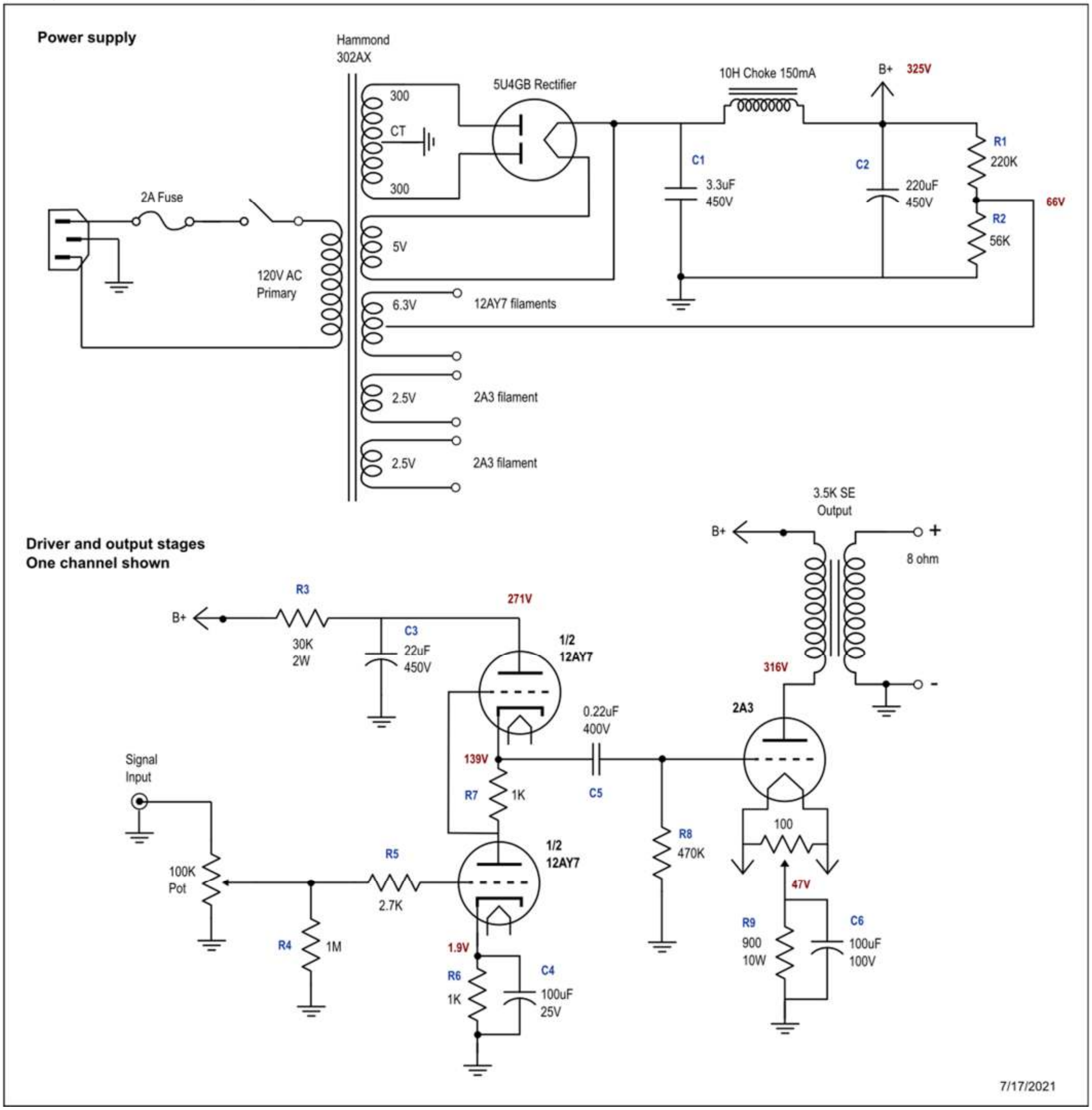
www.audiokarma.org

www.diyaudio.com

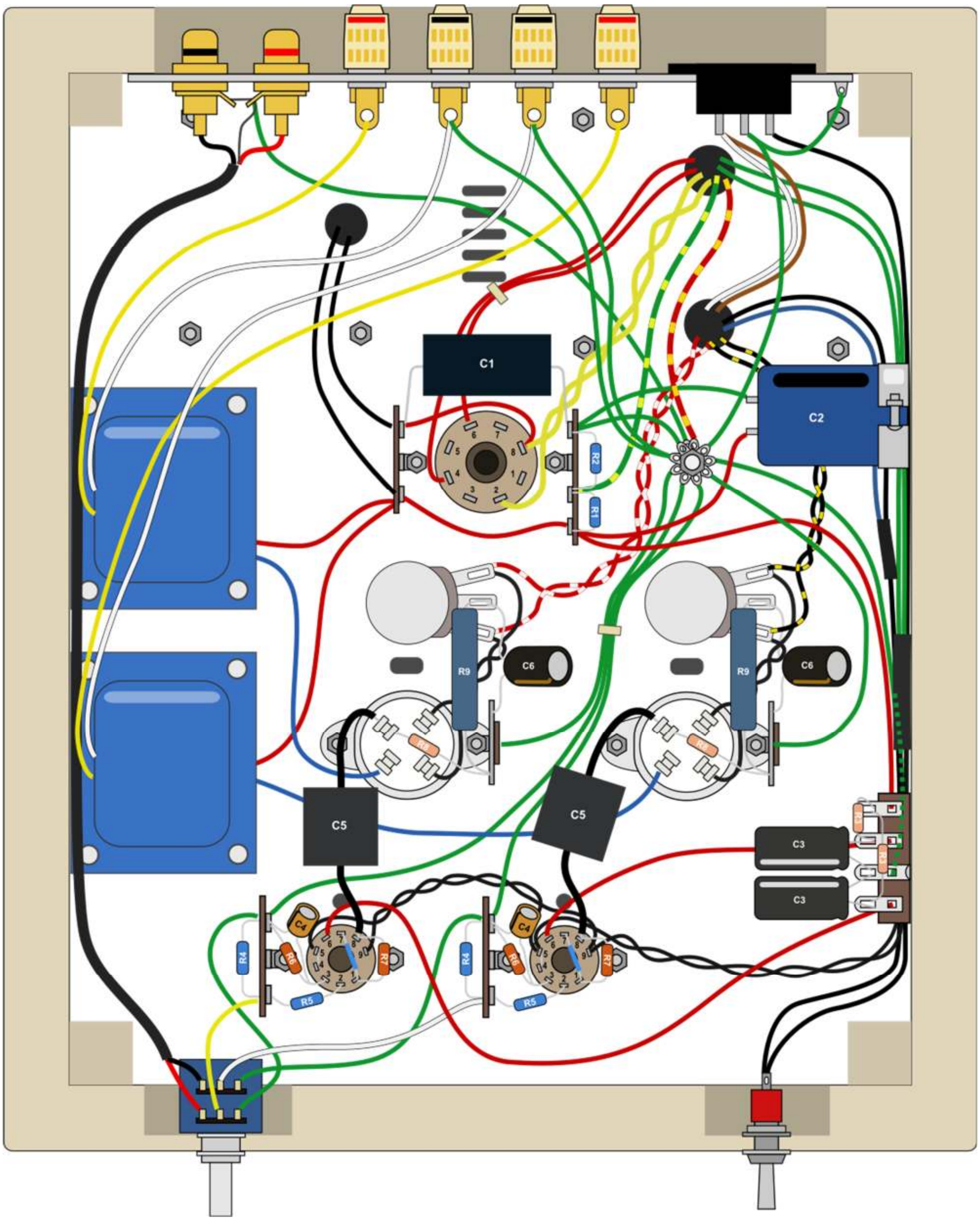
Facebook group: *Tube Amp Builders (DIY)*

APPENDIX - Schematic

Single-Ended Triode Amplifier 12AY7 / 2A3



APPENDIX – Layout Diagram



APPENDIX – Component Reference

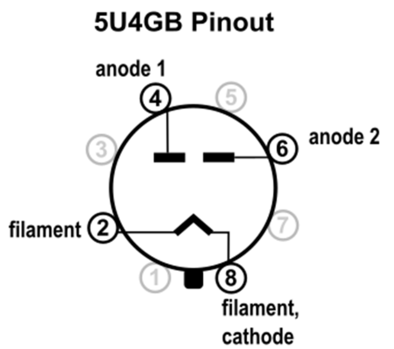
Component Number Reference:

C1	3.3uF 450V polypropylene film capacitor
C2	220uF 450V electrolytic capacitor
C3	22uF 450V electrolytic capacitor
C4	100uF 25V electrolytic capacitor
C5	0.22uF 400V film coupling capacitor
C6	100uF 100V electrolytic capacitor
R1	220k ohm 2W resistor
R2	56k ohm 2W resistor

R3	30k ohm 2W resistor
R4	1M ohm resistor
R5	2.7k ohm resistor
R6	1k ohm resistor
R7	1k ohm resistor
R8	470k ohm resistor
R9	900 ohm 10W resistor

Tube Reference:

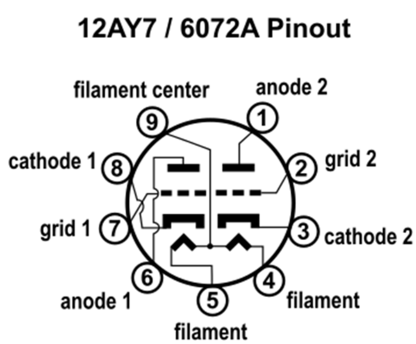
Pinouts and commonly used values are below. Reference actual datasheets for more information.



5U4GB Values

Filament voltage: 5V

Filament current: 3A



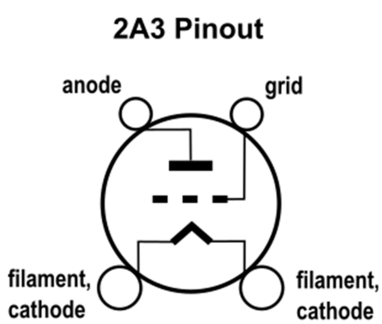
12AY7 Dual-Triode Typical Values

Filament voltage: 6.3V parallel (12.6V series)

Filament current: 300mA parallel

Maximum plate voltage: 300V

Maximum plate dissipation: 1.5W



2A3 Typical Values

Filament voltage: 2.5V

Filament current: 2.5A

Maximum plate voltage: 300V

Maximum plate dissipation: 15W