EXORDIUM

Stereo Tube Amplifier Kit

Analog Ethos™

V0605

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 or bench. Have a rubber or non-conductive mat below your chair or standing position. Wear shoes with rubber soles.
- 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.

Table of Contents

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.

First, I am using a straightforward single-ended circuit, mostly to achieve the objective above for you to learn how it works. Before moving on to more complex circuits that could provide higher output power or other characteristics, you should know how a triode tube amplifies the signal, understand rectification and filtering of a power supply, basics of negative feedback, and several other elements. The circuit used here 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 add up to thousands of dollars. This kit amplifier will sound very good and be reliable, but at reasonable cost. There are cheap components available and used in other tube amplifier kits that you may find on auction sites or other distributors. 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 typical listening in a home, with relatively low distortion and hum, though it is not high powered or what some might refer to as “audiophile” (but what does that mean?) If you build this kit, learn how it works, and want to build an even better performing amplifier, you can expand to other more advanced circuits, use larger output transformers, or try other tubes and components.

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 output and distortion levels.

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.

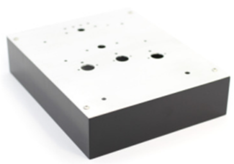
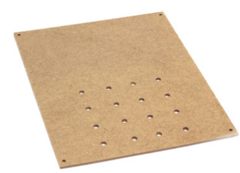
When I build and test amplifiers, I do sometimes access an exposed circuit using test equipment. You should not expect to do this at all with this kit. However, so that you can understand some elements of safety, below are examples of protective steps I take:

- 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 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	 Fused IEC power connector	 (4) Speaker terminal posts
 (2) RCA input jacks	 (2) Rubber grommets	 (4) Rubber feet	 Perforated bottom panel
 Power switch	 (10) ring terminals	 Volume knob	 (3) 9-pin tube sockets
 Hammond 270EX power transformer	 (2) Edcor XSE 5K – 8 Ohm output transformers	 (4) 5-lug terminal strips (2) 4-lug terminal strips (1) 3-lug terminal strip	 100K dual-gang audio potentiometer


(2) 1N4007 rectifier diodes


120uF 450V electrolytic capacitor


68uF 450V electrolytic capacitor


22uF 450V electrolytic capacitor


(2) 0.22uF 450V coupling capacitors


500 ohm 10W resistor


5.6k ohm 2W resistor

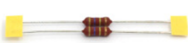

(2) 1M resistor


(2) 47k ohm 2W resistors


(2) 2.7k ohm resistors


(2) 680 ohm resistors


(2) 6.8k ohm resistors


(2) 470k ohm resistors


(2) 270 ohm 2W resistors


(2) 4.7k ohm resistors


(2) 100 ohm resistors


220k 2W resistor


12AT7 dual-triode tube


(2) EL84 pentode tubes


2A slow-blow fuse


shielded
2-conductor wire


Hookup wire
multiple colors and lengths


Zip ties and heat shrink tubing for wires


Various hardware
(not all shown)

Tools and Workspace

You will need the following tools to assemble the amplifier:

- Phillips and flat head screwdrivers of several sizes
- Nut drivers/sockets or wrenches for #4, #6, #8 nuts
- 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 tweezers for 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 90-94 dB rated sensitivity, and speaker wire 16 awg or heavier.
- A line-level audio source (CD player, 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.

To enjoy your amplifier in operation, you will need:

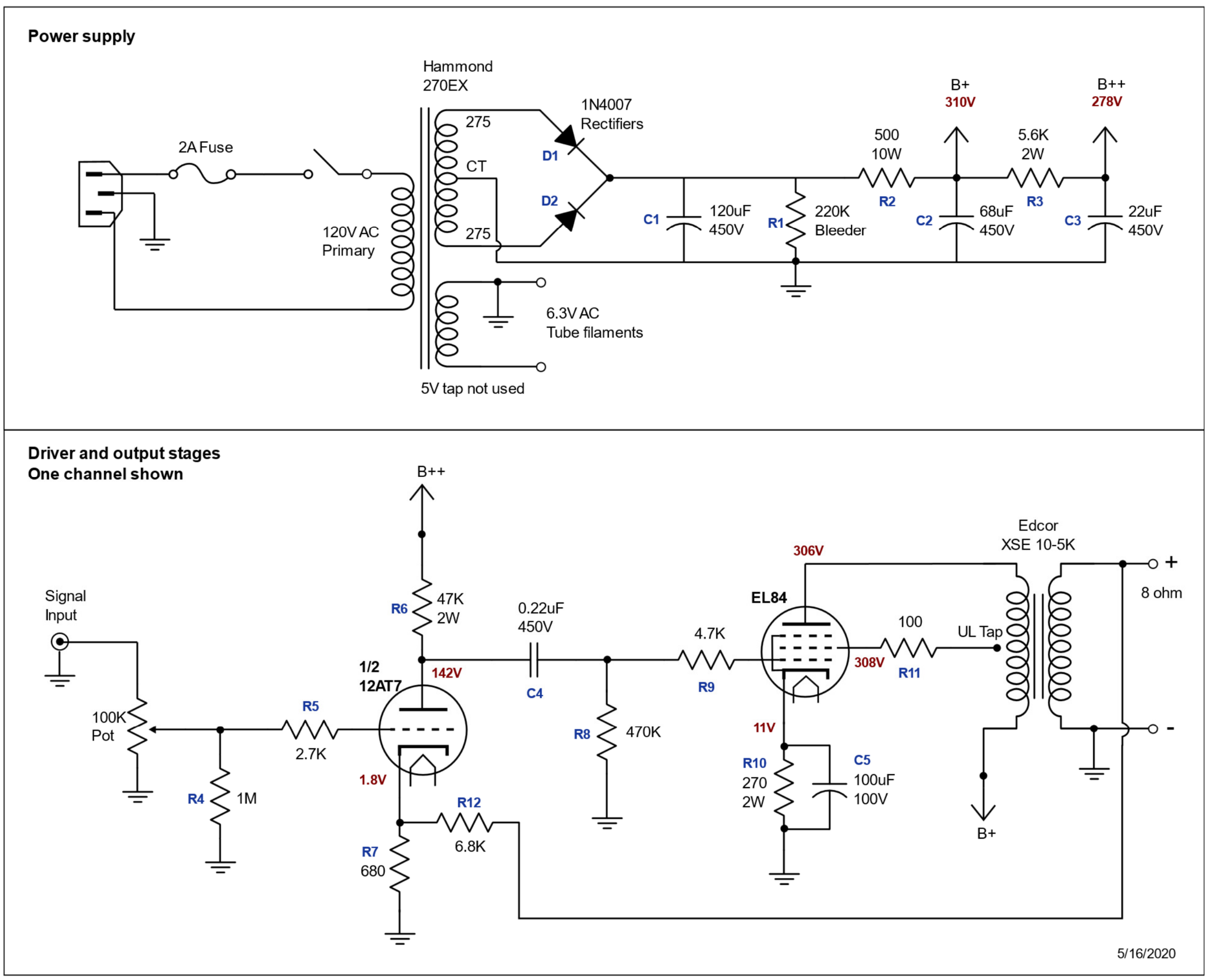
- A great album to play. I think Grateful Dead would be a good first listen.
- Comfy chair, preferably with cat in your lap.
- Celebratory drink. I recommend a gin & tonic with fresh lime.

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 commonly used 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.

Exordium Single-Ended Amplifier 12AT7 / EL84



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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: 4 watts per channel

Input Sensitivity: 825mV RMS

Total Harmonic Distortion: 1.8% @ 1W (1kHz)

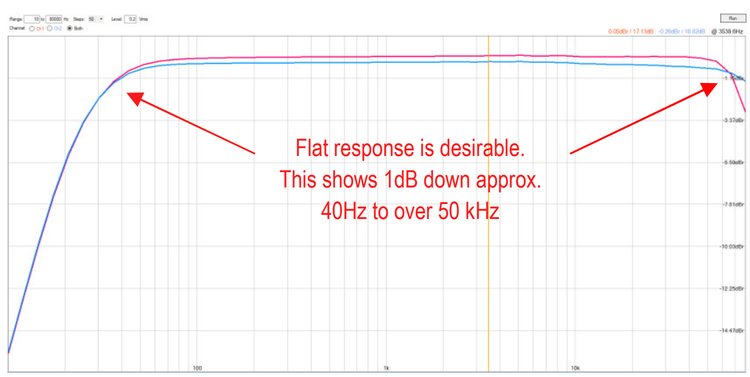
Frequency response: 40 Hz – 20 kHz

Detailed measurements

Frequency Response

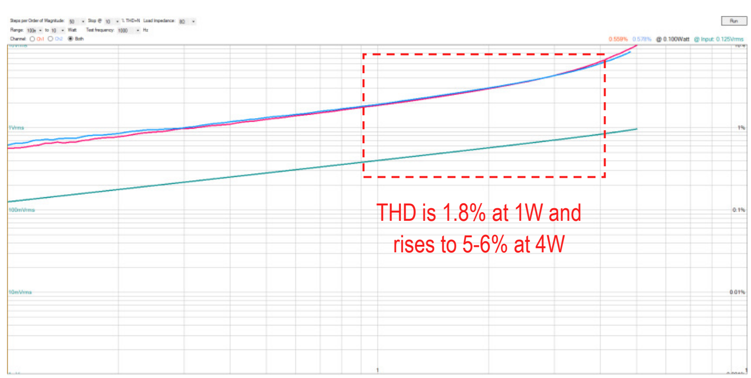
This shows a flat frequency response across a wide audio range. It is within 1dB from about 40Hz to over 50kHz. While very few speakers have response below 40Hz, and you typically can't hear to 20kHz, we want this to be as accurate as possible.

You can see here the two channels from my test in red and blue, illustrating one of my channels slightly different than the other. Not audibly noticeable, but typical that the tubes are not going to perform identically to one another, volume potentiometer may not be perfectly balanced, or other components can vary in small amounts within a tolerance



THD to Power

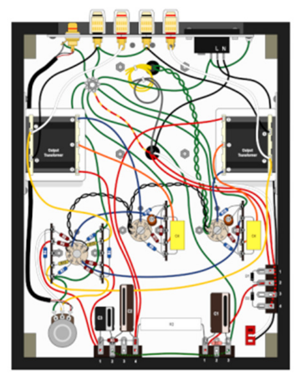
This chart shows how distortion (top line) is proportional to output power (bottom line). This is not a high-powered amplifier, but you can still get good sound with only one or two watts. With a sufficiently strong input signal you can run the amplifier up to about 4 watts before THD starts to rise to 5-6% or higher. Distortion would be higher at lower 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. 😊



Use layout diagram in the appendix

Read each instruction carefully and ensure yours matches exactly what you read and see. In the appendix is a **layout diagram** for your reference. Be sure to use this. 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).

If you have any questions, please send an e-mail or submit a question 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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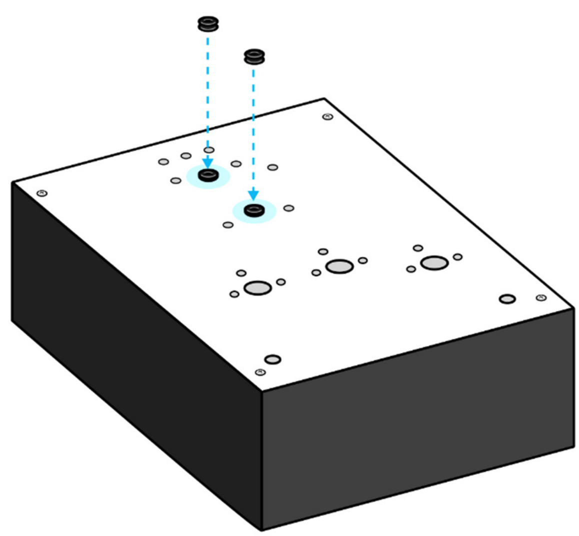
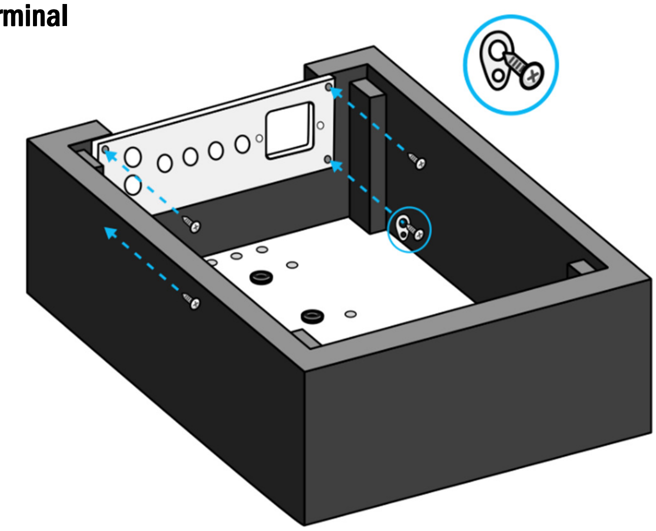
1 Insert the rubber grommets into the chassis

Insert the **two rubber grommets** into the large middle holes near the back of the chassis. This is where the power transformer will be mounted, and the wires will feed through these rubber grommets and be protected from scraping the edges of the aluminum panel. You will need to use your nimble raccoon-fingers to manipulate them into place.



2 Mount the aluminum back panel, including safety terminal

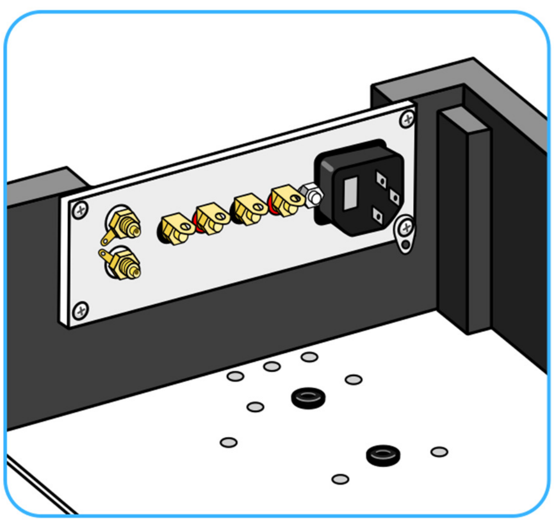


Turn the chassis upside down and attach the **aluminum back panel**, using **four ¼" pan head screws** in the predrilled holes. Make sure you put the smooth finished side of the panel facing the exterior and oriented with the square hole on the right as shown in the illustration here. Also, as you screw 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.

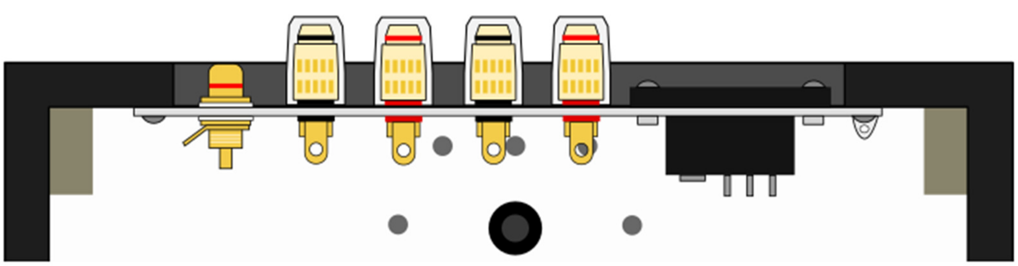
3 Mount the cable connectors onto the back panel

Next you will 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.

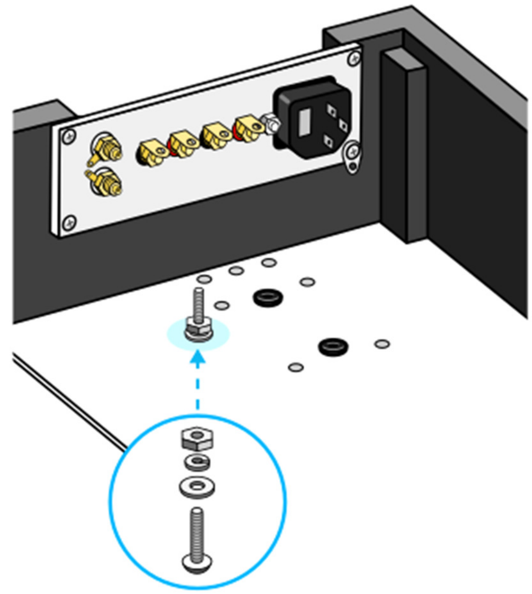


Finally, mount the **two RCA jacks** (red on top and black on bottom will match the wiring instructions later). Again, there are plastic washers that fit in the holes in the panel to insulate the input jacks. Orient the small metal tabs toward one another. These carry the input signal ground and we will 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!



4 Attach the ground bolt to the aluminum top panel

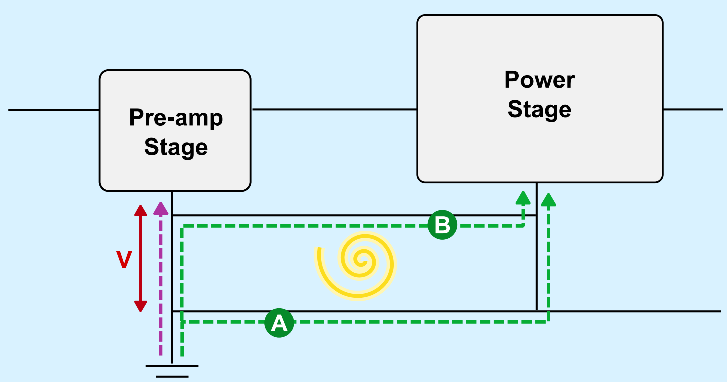
Attach the **7/8" ground bolt** with a flat washer, lock washer and nut in the hole on the aluminum top panel where shown, off to one side. We will use this as our star ground point and will be running wires with ring terminals to this point. Secure it very tightly. The aluminum panel scratches easily, so 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 these 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:

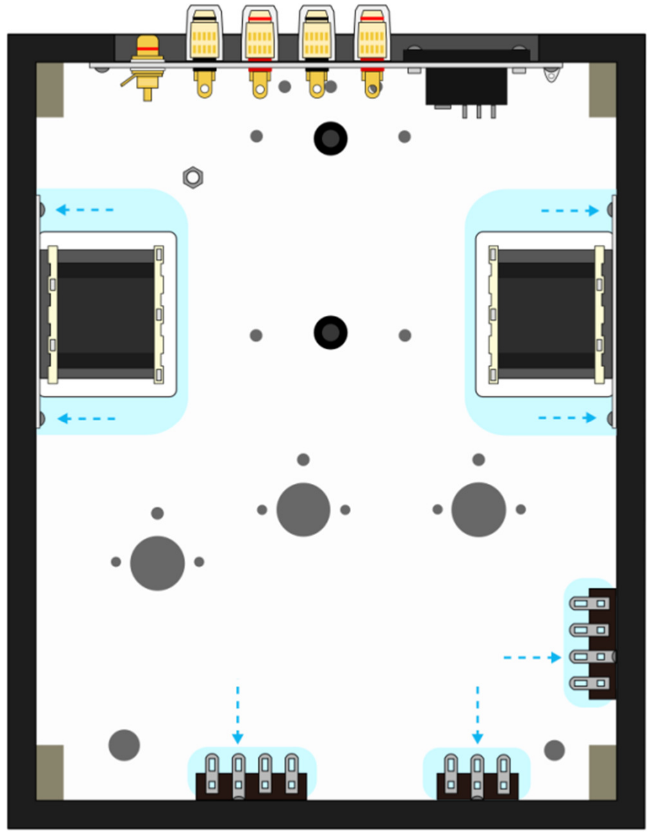


Here you see that the power stage has two paths to ground—one direct (A) and one that shares a ground wire with the input pre-amp stage (B) (the pre-amp also has a loop not highlighted). This forms a ground loop that will pick up interference or stray AC magnetic fields that are created elsewhere in 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.

5 Mount terminal strips and output transformers onto the walls of the chassis

Use ¼" pan head screws to attach **two 4-lug terminal strips** and one **3-lug terminal strip** to the walls as shown. The strip on the right hand side will be used for rectifier diodes, and the strips on the front of the amplifier will be used for power supply filter resistors and capacitors.

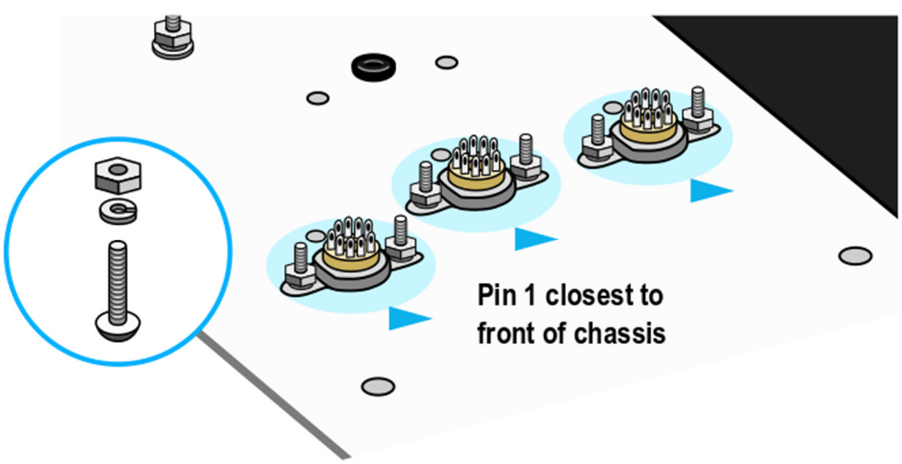


Also using ¼" pan head screws, attach the **two output transformers** to the walls of the chassis on each side, with the terminal lugs facing upward so you can solder wires to them later.

We are mounting these sideways and elevated slightly away from the top of the amplifier in order to reduce magnetic interference from the power transformer. Transformers create magnetic fields and if these are too close, there will be an induced hum in the output from the AC mains frequency (60 Hz in US). Altering the orientation of the transformer cores and maintaining a physical distance are ways to reduce this type of hum.

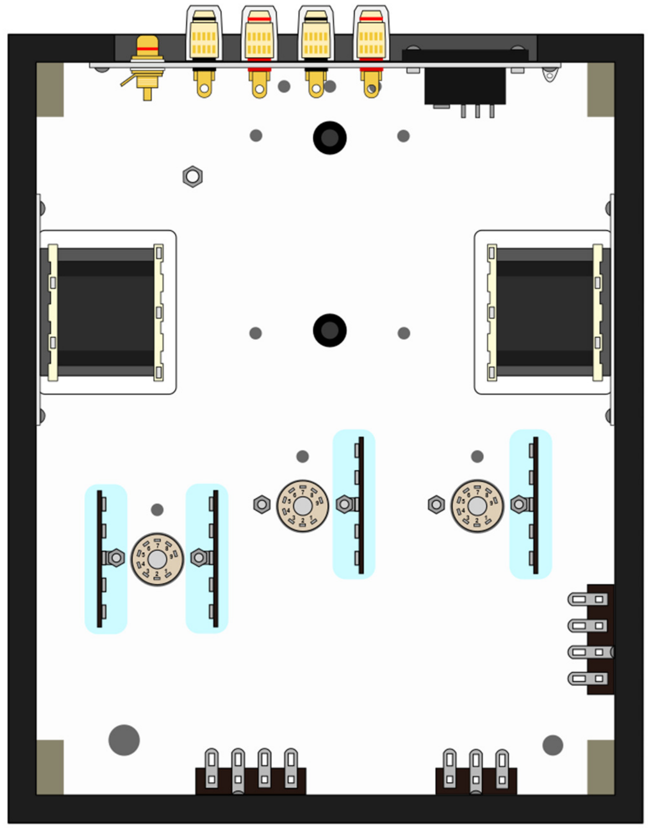
6 Mount the tube sockets onto the aluminum panel

Mount the **three 9-pin tube sockets** onto the aluminum panel of the chassis, placing the sockets on the inside of the chassis. Important: **the sockets must be oriented so that pin #1 is near the front of the chassis** (indicated with arrows in the illustration). Insert #4 screws from the outside, being careful not to scratch the top of the chassis and then tighten from the inside of the chassis with a lock washer and nut. There are some extra lock washers and nuts you will use in the next step.



7 Mount terminal strips onto the tube socket bolts

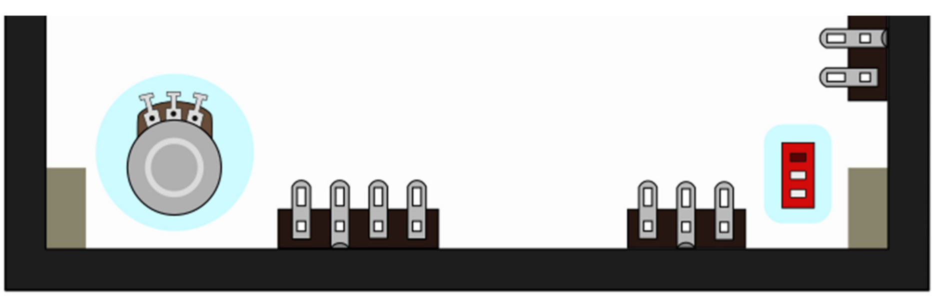
Using the extra lock washers and nuts from the previous step, mount a total of **four 5-lug terminal strips** onto the tube sockets as shown. The left hand socket will get two strips. This is where your dual-triode driver tube will go, and we will be placing resistors around this socket on both sides. The other two sockets are for the output tubes and we have fewer components to attach, so they only need a single strip on the right hand side. Place the strips on top of the protruding screws above the nuts you already tightened, then use additional lock washers and nuts to secure.



8 Mount the potentiometer and power switch onto the aluminum top panel

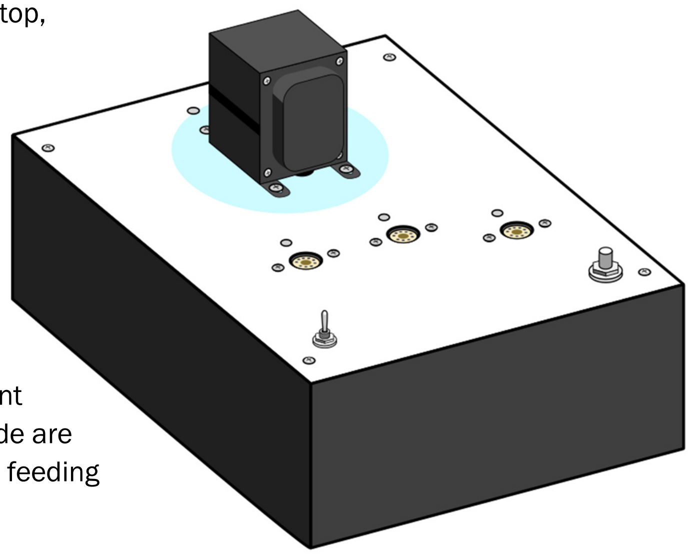
Mount the **potentiometer** and **power switch** in the holes near the front of the chassis. The potentiometer has a small anti-rotation tab that will not be used. Break it off using needle-nose pliers. I have included a toothed lock washer that holds the potentiometer in place when tightened (this washer goes on the inside of the amplifier, while the smooth one goes on the outside). This avoids an ugly hole drilled in the chassis for that tab, and unless you are the Incredible Hulk wanting to turn up your AC/DC song, you will not be turning your volume knob so hard that you cause the pot to slip.

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.



9 Mount the power transformer and tie off unused wires

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? You'll want the hardware to go like this: 5/8" #8 screws go through the power transformer bracket from the top, then through nylon washers, then through the aluminum chassis panel, then secured from the inside using a flat steel washer, lock washer, and nut. Got it? The nylon washers are just used to lift it up a bit to make room for the rubber grommets and also protect the chassis from scratches. Also, you might want to tape the wire ends 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 transformer so that the screws on its front side are facing forward (green and yellow wires should be feeding into the rear rubber grommet hole).



I find it works to put the nylon washers onto the chassis over the screw holes, put the screws into the transformer, feed the wires down through the grommet holes, and carefully lower the transformer down with screws going through their holes. Then try to hold the screws in place as you tilt the amp sideways and get the washers & nuts in place by hand, and finally tighten each one. 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.

We will use most of the transformer wires, but you will not need a few of them. The two yellow wires are a 5V supply typically used for a tube rectifier. And the gray wire is for a variation on the mains voltage for 115V (we will use the 125V white wire). Rather than cutting these off, I suggest you trim the ends 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**. That way if you in the future want to use this transformer in a different way, you still have access to the taps.

Power Transformer Lead Colors and Usage

black	In combination with the white lead, this is for the primary side of the transformer to receive mains voltage at 125V
gray	In combination with the white lead, this is for the primary side of the transformer to receive mains voltage at 115V
white	Combines with the black or gray lead for the primary side of the transformer mains voltage
2 red	These are the high voltage secondary AC (~550VAC, or +/- 275V relative to the center tap). We will rectify into DC.
red w/ 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.
2 green	These are the 6.3VAC secondary windings for the tube filament (heater) supply. This will go in parallel to each of the tube sockets.
2 yellow	These are a 5VAC secondary winding, typically used for the filaments of a rectifier tube. Our amplifier is using silicon diodes instead of a rectifier tube, so we will not need this 5V supply, and will tie this off.

10 Wire the tube filaments including ground reference

The next several steps will be running wires all over your amp. Do your best to be neat and trim wires relatively short, but not too short. Dog-leash length, not dental floss, if you know what I mean.

We will start with the tube filaments. These are also called “heaters” because they heat up the cathodes of the tubes to a very high temperature. We will twist the wires that supply their power. It’s a rite of passage for all tube amp builders. You will be awesome at this, I know it.

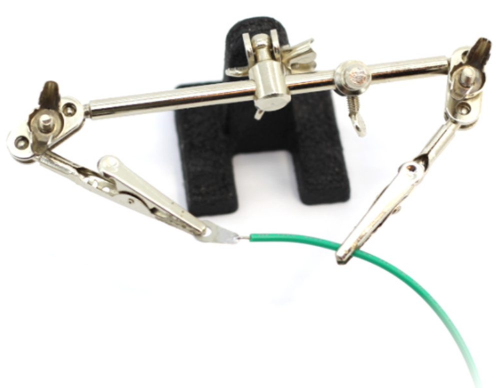
Start with the **two green wires from the transformer** that supply 6.3V. Twist these wires together, snug but not too tightly, and shape it to lead up to the right-hand socket. Trim and fit the leads up to pins 4 and 5, but don’t solder just yet.

We cannot just leave this supply floating with no DC voltage reference. There can be some leakage current in the transformer or in the tubes from cathode to heaters that could result in a hum. Some transformers include a center tap for the filament supply, allowing us to reference the tap to zero volts ground potential. Ours does not include a center tap, so we will simply reference one side of the supply to ground.

Cut a 7” length of **green hookup wire** and solder a ring terminal to one end of it. You will be soldering ring terminals on several wires throughout the instructions. I like to use a set of “helping hands” to hold the wire and terminal in place while I solder, but you can use any method that works best for you. This green wire will run from pin 5 of the right hand tube socket to our star ground bolt. This gives us the ground reference that we need for the heater supply. Prepare this wire, but don’t solder yet.

Creating an artificial center tap

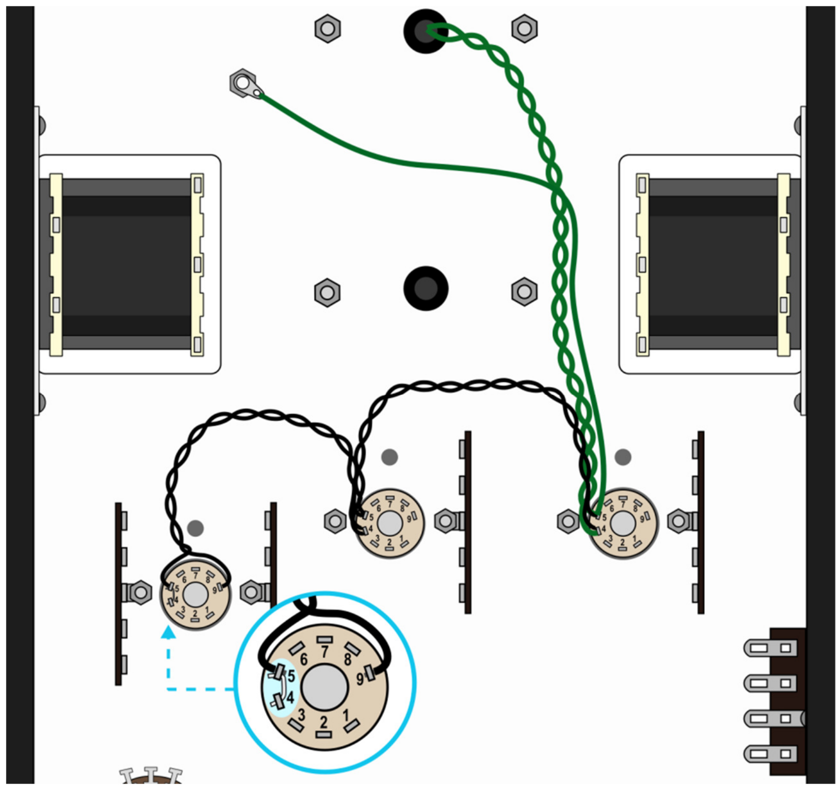
You could create an artificial center tap for the heater supply using two resistors as a voltage divider across the supply, and then reference the center point to ground. I have not found in tests that creating the center tap is significant enough to justify the added complexity in this particular amp but you could certainly do this as an enhancement by adding another terminal strip and two 100 or 220 ohm ½W resistors. It will draw a small amount of extra current that translates to additional heat.



Next, we will run parallel wires to supply the other tube sockets. Use the **black 20 awg “heater” hookup wire** (labeled in its own bag) and cut into four pieces about 6” long each. Note that the other hookup wire in this kit is 22 awg, so it’s important you use this heavier gauge wire. I like this type of polyolefin wire for heaters because the insulation is thin but strong, and it’s easy to twist and hold its shape. Twist these wires and arrange so you can run a parallel connection from the right tube socket to the middle one. Give some space around the tube socket like your heater wire wanted to walk on the other side of the street to avoid that one annoying neighbor who always just wants to complain about the homeowners association and dogs that bark too much. I mean, you can't be worrying about that stuff, life goes on, man. Shape and trim the wire carefully so it leads up to pins 4 and 5.

Do this again with another set of parallel black heater wires over to the left side driver tube socket. The 12AT7 tube has more than one voltage option; in our case you'll need to connect one of your wires to both pins 4 and 5, and the other wire to pin 9. The way we'll do this is to run one wire to pin 5, and then a bridge connector over to pin 4. Trim a little excess bit of one of the component leads from the big 120uF capacitor. The positive lead is longer and you would later be trimming it anyway. Bend this into a U-shape using needle nose pliers and fit across pins 4 and 5. Trim so it's not sticking out too far.

Now you are ready to solder these all up. Solder the green transformer wires, black wires in parallel, and ground wire on one side to the right tube socket pins 4 and 5. It's a lot to fit into those tiny pins but you can do it! After soldering, trim any excess leads and inspect carefully to make sure there are no little strands that might be loose or touching across these pins.



Solder the two pairs of black wires onto the middle tube socket pins 4 and 5. And then solder the left tube socket wires to pins 5 and 9, with the bridge connector from pin 4 to 5. You are doing a good job. I don't care what anybody says.

Why am I twisting wires?

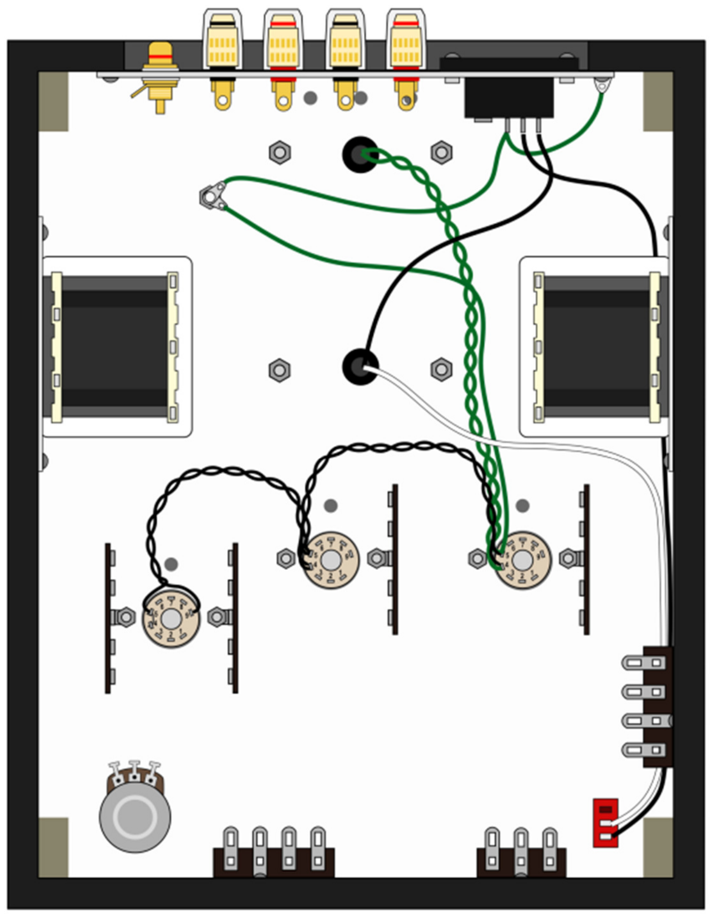
Tube filaments take high currents to heat up—EL84 tubes draw about 760mA each, and another 300mA for the 12AT7. This comes from the transformer at 6.3V AC at 60 cycles per second (US). If we aren't careful, this can create interference with sensitive audio signal wires, amplified and heard as a hum. 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 alongside signal wiring, crossing where needed, but trying to minimize the proximity.

11 Wire the power switch and safety grounds

Let's take care of the primary side of the power supply. Cut and strip an 11" length of **black 22 gauge hookup wire** and run this along the right side of the amp. You can tuck it underneath the output transformer. Solder it from the Live terminal of the IEC power inlet (after it crosses the fuse) to the power switch lug that is nearest the front of the amplifier. Route and trim the **white wire from the power transformer** so it runs along the edge of the amplifier and solder it to the middle lug on the power switch. Then route and trim the **black wire from the power transformer** and solder it to the Neutral lug of the AC power inlet.

See what's happening here? We have made a switched circuit from the incoming AC mains power to the primary side of the power transformer. Turn on the switch, and AC current will flow across the primary of the transformer, and we will then get our transformed voltages through other wires on the secondary side.

Now let's run an earth ground for safety. Any time you have mains or high voltage present, you want to ground the exterior metal chassis, just in case a wire were to somehow be loose and in contact with the surface, and you were to touch it. The safety ground puts the chassis at earth potential so current would be shorted instead of running through your body. Cut a 5" length of **green hookup wire** and solder a ring terminal on one end that will go over the star ground bolt. Cut and strip a 2" length of green hookup wire. Solder one end to the ring terminal you had attached to the lower right screw of the back panel. Now solder both of these wires to the middle safety ground lug of the IEC inlet. Cool? Both panels are now running to safety earth ground.

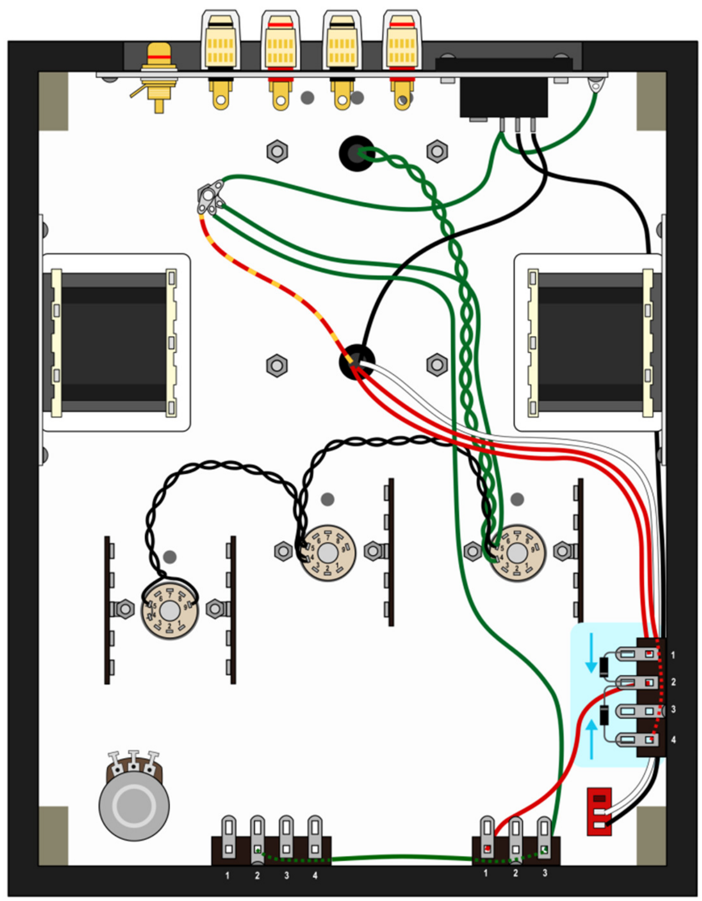


12 Wire the secondary power supply, ground and center tap, and rectifier diodes

The job of the transformer is to “transform” your household 120V mains into a higher voltage, in our case 550V AC. But the amplifier needs a clean DC voltage, not AC. So we will rectify and filter this power supply. We are using silicon diodes to rectify the AC to DC, and in a later step we will use capacitors and resistors to do the filtering. For now, let’s run some wires that we will need, and solder in the rectifiers.

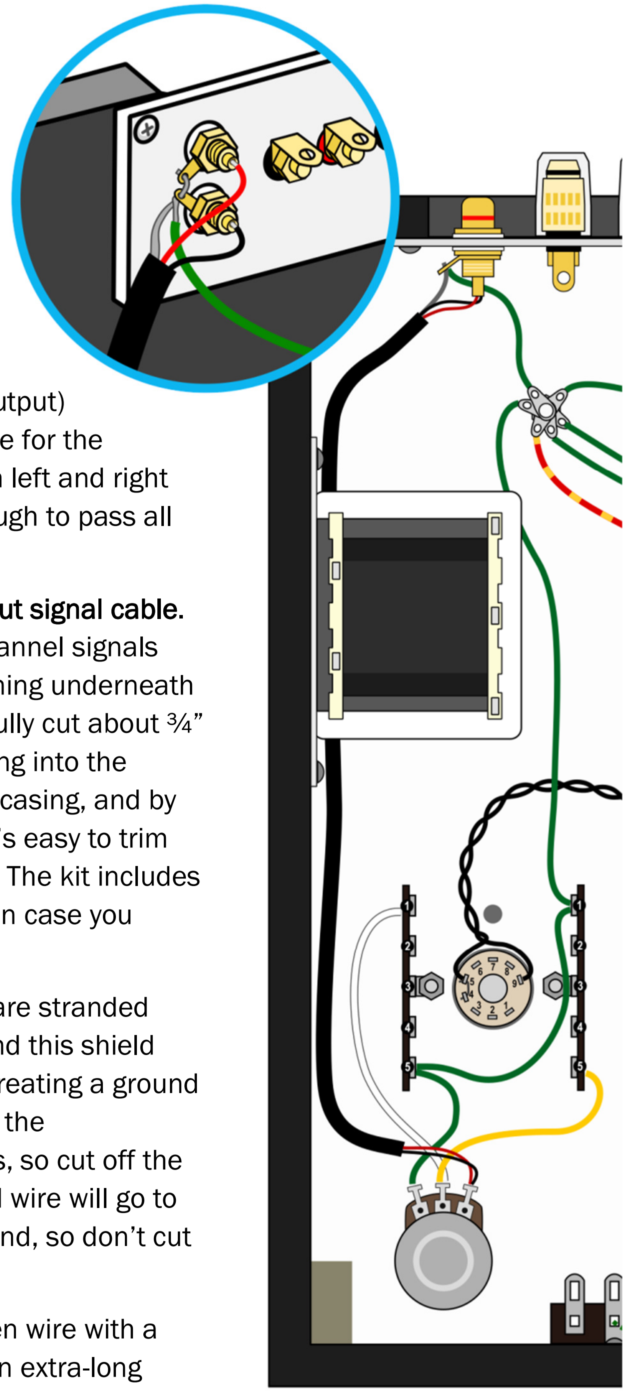
Route the **two red leads** from the power transformer to lugs 1 and 4 of the terminal strip on the side wall. I find it best to run the wire lead up from the bottom and solder into the hole nearest the wall. Cut a 5” length of **red hookup wire** and solder from lug 2 of this terminal strip over to lug 1 of the 3-lug terminal strip on the front of the amplifier.

Now you are ready to solder the **two rectifier diodes** onto the bracket from lug 1 to lug 2, and from lug 4 to lug 2 (skipping over lug 3). These take the AC from the power transformer and send the rectified DC output to the capacitor and the choke for smoothing. Diodes allow current only in one direction, so you need to <u>solder them in the correct orientation</u>. The stripe (cathode end) needs to be facing the second terminal lug. Bend the leads of the diode and trim to length to fit neatly in place. Solder, trim any excess, and inspect for a clean connection. There will be 550V AC across these exposed leads and terminal lugs, so you don’t want stray wires or bits of solder anywhere (and further reason to be careful and not poke your fingers around in the amplifier when it’s powered up!)



Finally, we will need a few wires running to ground. Trim the **red-and-yellow-stripe wire** from the power supply and solder a ring terminal to it. Put this on the star ground bolt. This is the center tap of the secondary high voltage supply, and will represent our zero voltage potential point. Trim and strip two lengths of **green hookup wire**, one 11” and one 5”. Solder a ring terminal on one end of the 11” wire. This goes to star ground. Now solder both wires to lug 3 of the 3-lug terminal strip on the front of the chassis. Solder the other end of the 5” wire to lug 2 of the 4-lug strip on the front of the chassis. These two terminal strips will later have some capacitors that need to have one side grounded and these wires will carry those grounds back to our star.

13 Wire the potentiometer and input grounds



Cut **four lengths of green hookup wire at 2", 3", 3" and 6"**. Solder a **ring terminal** to one end of the 3" piece and another to one end of the 6" piece. You'll also need a length of **4" white** and **3" yellow wire.**

You have a dual-gang potentiometer that attenuates both channels of the input signal using a single volume knob. The yellow and white will be your left and right signal wires that go from the middle lugs of the potentiometer (attenuated output) to the driver tube. The 2" green wire is a ground wire for the potentiometer, and we'll use the <u>same wire</u> for both left and right channels. Strip one end to have bare wire long enough to pass all the way through one lug and onto the other.

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 (running underneath the output transformer). You will need to very carefully cut about ¾" or 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 12" 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 other end of the shielded wire will go to the RCA input jacks. You'll need the shield on this end, so don't cut it off! Twist it so it's like a wire.

Let's start with the RCA input jacks. Use the 3" green wire with a ring terminal on one end. Strip the other end with an extra-long exposed wire and solder it to <u>both</u> of the RCA jack outer terminals. We'll just use one ground wire for both channels. Then line up the shielded wires. Connect the bare shield wire to the ground wire by soldering it anywhere on the wire or lugs. Solder the black and red wires to the respective inner connectors. See what's happening here? We ground the common (outer) wires of the input, ground one end of the cable shield, and run the audio signals to the potentiometer.

It's important to wire up the potentiometer correctly so that it will attenuate the channel signals in the expected way. Solder the shielded input signals to the right hand lugs, black on top and red on bottom. Solder the yellow wire to the middle top lug and the white wire to the middle bottom lug. And solder the 2" ground wire to both of the lugs on the left side. Trim any excess.

Now solder the other end of the white wire to lug 1 of the left terminal strip of the input stage tube socket. And the yellow wire to lug 5 of the right strip. Any time we run wires to the terminal strips, try to use the holes in the bottom. We will add resistors to run these inputs to the tube socket in a later step, using the upper parts of the terminal lugs.

This potentiometer ground will share the ground wire that our input tube stage will need, so wire the other end of the 2" green wire to the bottom hole of lug 5 of the left side terminal strip. At the same time you can solder a 3" green wire from this same hole over to the bottom hole of lug 1 of the right hand terminal strip. And wire the 6" green wire to that same hole, where it will then go to the star ground. We will then end up with three things all grounded here: the potentiometer, and the left and right input stage for the dual-triode tube.

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 home, and you don't live next door to a radio tower.

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. Skeptics may also question carrying both signals in this two-conductor cable, risking some level of cross-talk between the channels. I've used this method multiple times without any issue. Some cross-talk will exist in this amplifier, but it's due to having both channels pre-amplified using a dual-triode tube and is not likely to be noticeable.

14 Wire the tube sockets and transformers

You'll notice we are sort of working in layers. Most of these wires are down on the bottom, near the aluminum panel. Soon we will be adding wires or components above these. It will get harder to reach these wires later, so make sure they are neat and as you expect.

The diagram may start to look complex with wires running all over, but you should be following what each one is doing. To keep this step organized, follow this list of remaining wires to be run:

- **6" and 7" green wires** with ring terminals on one end of each, run from star ground to each of the power output tube socket terminal strips, lug 1
- **4" and 3" red wires** to run B++ power from lug 1 of the front left terminal strip to lug 2 of the left strip and lug 4 of the right strip on the driver tube socket

- **9” and 11” red wires** to run B+ power from lug 4 of the front left terminal strip to lug 5 of each output transformer (notice the output transformers are facing opposite directions, so lugs are in different positions; it’s easy to accidentally wire them incorrectly as a mirror image)
- **5” and 4” blue wires** to run plate voltage from output transformers lug 1 to output tube sockets pin 7
- **4” and 6” blue wires** to run pre-amplified signal from input tube socket pins 6 and 1 to lug 2 of each output tube terminal strips, but solder only the output tube side (we will be soldering a resistor to pins 6 and 1 of the input tube socket in a later step and will finish this wire then)
- **Two 7” orange wires** to run screen voltage from output transformers lug 3 to output tube strips lug 4
- **7” and 12” yellow wires** to run feedback from output transformers lug 7 to input tube strips lug 2 and lug 4 (look at the diagram to ensure each transformer goes to the correct strip)
- **6” and 7” white wires** for positive output of transformers lug 7 to red speaker binding posts
- **Two 6” black wires** for common from output transformer lug 9 to black speaker binding posts
- **2” green wire** to connect the two common black speaker binding posts to one another
- **3” green wire** with ring terminal on one end to connect nearest black speaker binding post to star ground

Wow, pretty good.

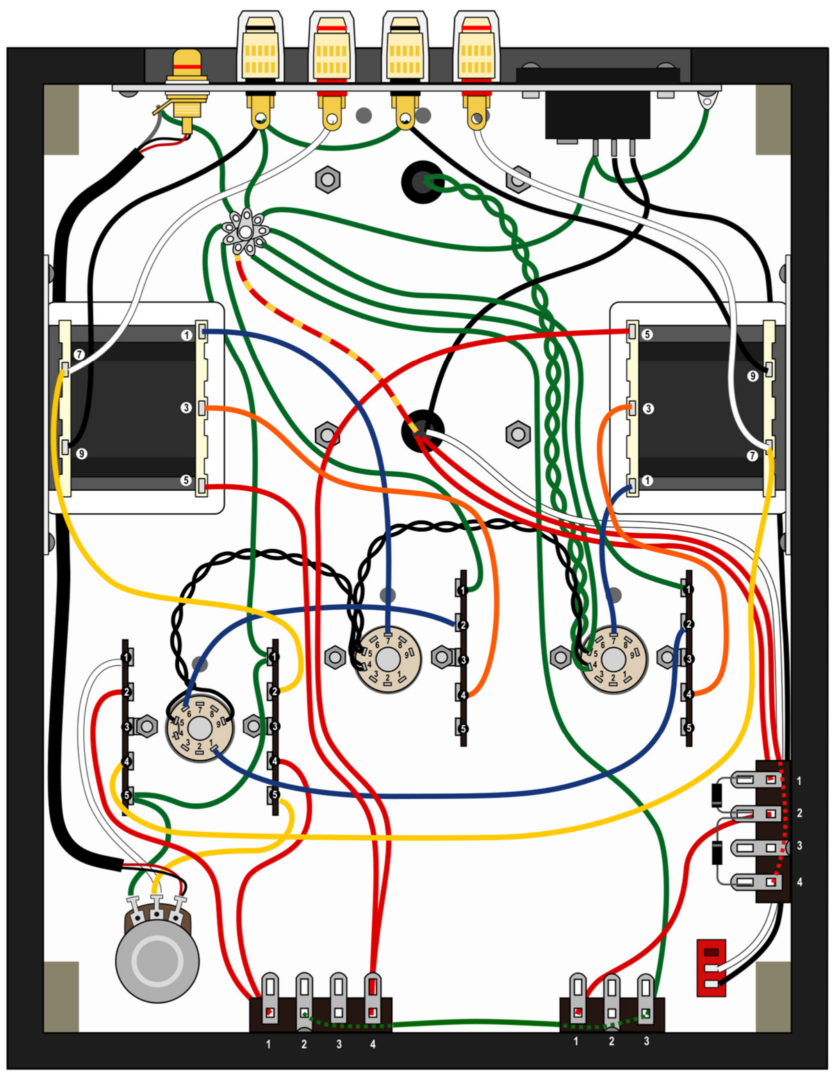
CHECKPOINT

It’s a good time to do a check before moving on. It will be harder to reach these wires later and it’s always best to catch a mistake now!

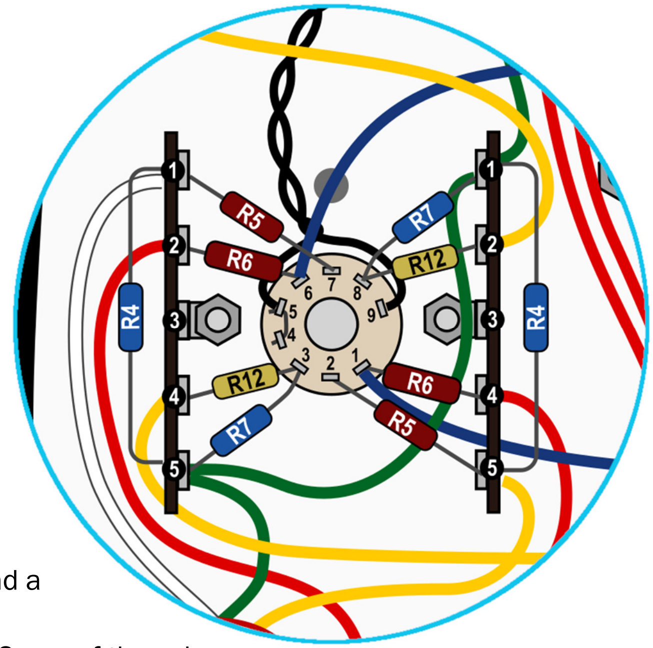
Go back over the entire wiring diagram and make sure you have everything connected in the right place and didn’t miss any wires.

In particular be careful you didn’t mix up left and right channel or positive and common of output transformers. It won’t matter in some places, such as the input jacks. But in others it matters very much because we are using feedback that must be the right polarity and connect output to input of the same channel.

Looking good? I knew you were pretty awesome.



15 Solder the driver tube resistors



Now for my favorite part. I just love resistors and capacitors, don't you? Let's get started with some resistors on the input tube socket.

It's easy to get resistors mixed up. They're little, with colored stripes like those candies your aunt had in a jar just as a decoration, and you might set one down for a moment, and then—wait, was that the 4.7k or the 470k? So get out your multimeter, and check these before you solder them in place just to make sure you've got the right one.

The 12AT7 tube is a dual triode in a small size, so there are several resistors that all need to go around a small physical space. Take your time, shape your components carefully, and you'll have no problem! Some of these have multiple components in a single lug or tube socket pin so you may find it easier to solder at the same time, or tack in place on one end to hold steady.

- 2.7k grid stopper resistor (R5) on pin 7 grid to left terminal lug 1
- 2.7k grid stopper resistor (R5) on pin 2 grid to right terminal lug 5
- 1M grid leak resistor (R4) on left terminal lug 1 (with grid stopper) to lug 5
- 1M grid leak resistor (R4) on right terminal lug 5 (with grid stopper) to lug 1
- 47k anode load resistor (R6) <u>and</u> blue signal wire on pin 6 to left terminal lug 2
- 47k anode load resistor (R6) <u>and</u> blue signal wire on pin 1 to right terminal lug 4
- 6.8k feedback resistor (R12) from pin 3 to left terminal lug 4
- 6.8k feedback resistor (R12) from pin 8 to right terminal lug 2
- 680 ohm cathode bias resistor (R7) from pin 3 (with feedback resistor) to left terminal lug 5
- 680 ohm cathode bias resistor (R7) from pin 8 (with feedback resistor) to right terminal lug 1

Boom. Good job. You are a rockstar. Inspect closely, trim any excess leads and make sure no components or leads are touching each other or wires. Go get a snack and flip your album to side B.

Point-to-point soldering

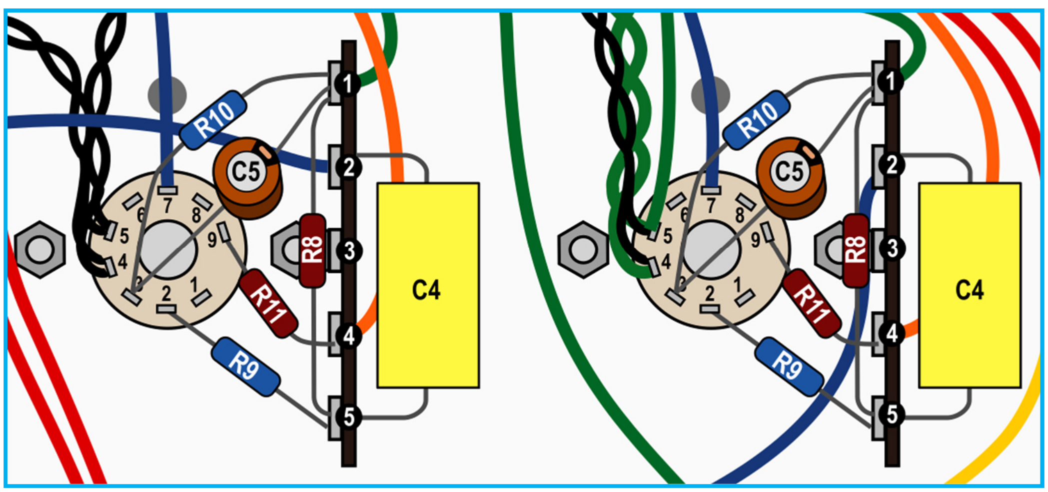
Some people are masters of neat and tidy point-to-point soldering—perfect straight angles, flawless lead shaping, impeccable solder joints. The first few amplifiers I built, mine looked terrible—wiggly leads and crooked components all over the place. We're all on a journey, right? Maybe you are already awesome, but if not, just give it your best. Keep leads relatively short, nothing touching other things, no loose joints or big solder blobs or excess leads poking out.

I like to trim and shape the leads with needle-nose pliers and test-fit a few at a time to see how they will fit next to each other. A little bend on the end can ensure it's got a good physical connection. Sometimes I'll put a little solder on the tip of my iron, hold the component with one hand and tack one side to get it to hold steady. Then I can use both hands to solder the other side and go back and neaten up the first one. It's important that the component doesn't move while the solder cools and hardens; if it moves you end up with a "cold solder" joint which may not be a good enough connection. Inspect each one after soldering to ensure it's a solid joint. Always trim your leads afterward and pick up the clippings.

16 Solder the output tube components

Now you'll do the output tube sockets. They both are the same, so repeat these steps for each one.

- 100 ohm screen resistor (R11) from lug 4 to pin 9
- 4.7k grid stopper resistor (R9) from lug 5 to pin 2. In this case, I like to solder from the hole on the bottom of the terminal strip because you will have more working room for the coupling capacitor on the top of the lug
- 0.22 uF coupling capacitor (C4) from lug 2 to lug 5. This is a film capacitor, and orientation does not matter.
- 470k grid leak resistor from lug 1 to lug 5. Note that you will have two other things to also solder to lug 1 in the next step.
- 270 ohm cathode bias resistor (R10) from lug 1 all the way over to pin 3, and also the 100uF cathode bypass capacitor (C5) across the same points. This is a polarized electrolytic capacitor, so it's very important that you put the negative side on lug 1 (ground). The negative side is marked with a stripe. Shape and fit these components so they are not too close to each other. They can sort of arch across the socket with clearance above the other pins. We could have used another terminal strip on the other side to be closer to pin 3, but a single strip can do the job here. The cathode resistor can get warm and it's best to keep your electrolytic capacitor with some breathing room around it.

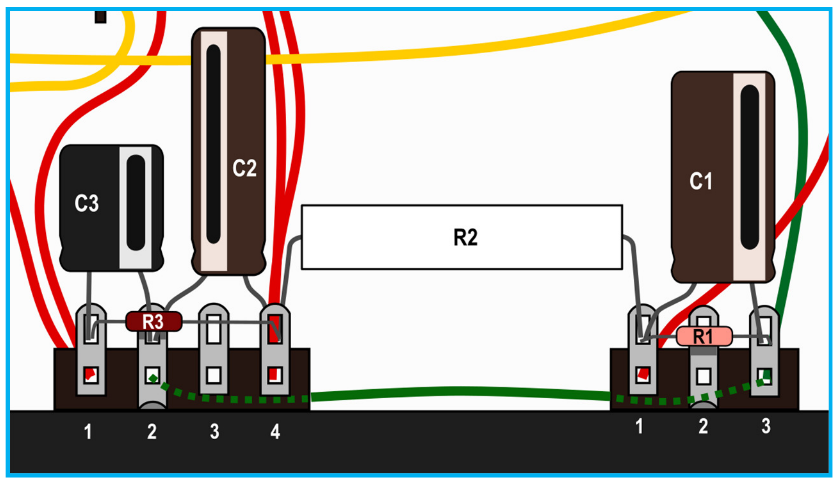


17 Solder the power supply filter components and bleeder resistor

We saved these for nearly last because they are kind of big and hard to work around once in place. I'll sort of walk you through from right to left to follow a bit of logical flow of our power supply filtering. I suggest you trim all of the component leads first and fit them roughly in place to see how they all look. Then solder.

- Solder the 120uF 450V electrolytic capacitor from lug 1 to lug 3 on the right side terminal strip in the front of the chassis. Ensure the negative lead (stripe side) is on lug 3 (ground). This is our primary reservoir capacitor to filter and supply high voltage.

- Solder the 500 ohm 10W resistor bridging across lug 4 of the left side terminal to lug 1 of the right side terminal.
- Solder the 68 uF 450V capacitor on lugs 2 and 4, ensuring the negative lead (stripe) is on lug 2 (ground). I like to solder this one at the same time as the next one.
- Solder the 22 uF 450V capacitor on lugs 1 and 2, with negative lead (stripe) on lug 2 (ground)
- Trim and shape the 5.6k resistor (R3) so it reaches over between lug 1 and 4 of the left terminal strip (above and over the other lugs) and solder in place
- Trim and shape the 220k bleeder resistor (R1) so it fits across lugs 1 and 3 of the right terminal strip and solder in place. This is a safety measure to ensure the capacitors are drained after several seconds when the amplifier is turned off. With no bleeder method, your capacitors could store energy for a long time, and there's a risk you'd turn off the amplifier, unplug it, thinking it's all safe, but if you touched the wrong spots—POW! Know what I mean? Don't skip this step.

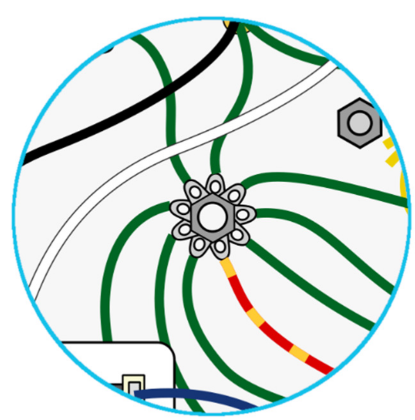


Lug 3 is unused and simply provides space for the capacitors to fit nicely. This big power resistor will get very hot, dissipating around 5W of power. Make sure your capacitors are not too close to it, and it's not touching any wires nearby.

If you notice what's happening here we have a 120uF reservoir capacitor taking our rectified DC voltage, then we have two RC filters (Resistor-Capacitor) that are reducing the ripple voltage and we take high voltage off of these two places to go to the output or driver stages. The driver stage needs more filtering, and can operate on lower voltage, so it goes through two filters.

18 Secure the star ground bolt

We are almost there! Important step to not forget! Put on the final **lock washer and nut** on the star ground bolt that you saved from step 4. Arrange all 9 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.

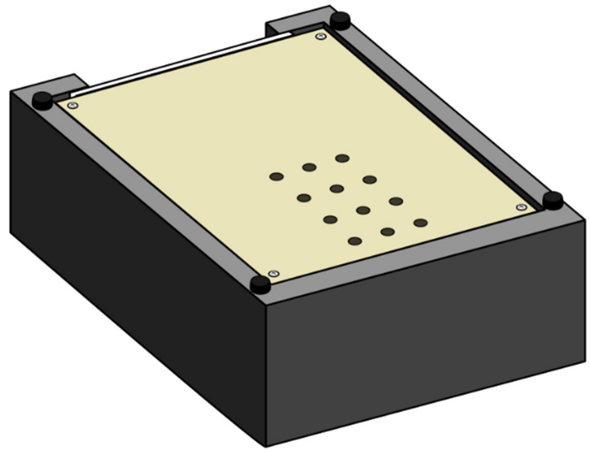


FINAL CHECK POINT

You are very close! Before final steps to close up the amplifier, it's time for a double-check of all your work. Use the layout diagram in the appendix and trace through every wire and component. You can also go back over the steps to re-read if necessary. There are a lot of steps, and anyone can make mistakes. Now is the best time to find them, rather than after you turn on the power and something goes wrong and causes damage to a component. Here's a checklist:

- ☐ Trace the circuit of your mains voltage coming from the power inlet, through the power switch and closing a loop with the primary wires of the power transformer.
- ☐ Use a multimeter to confirm that you wired the power switch properly: no continuity between leads in the off position; continuity in the on position. (No power cord connected.)
- ☐ Check the heater wiring coming out of the power transformer and going in parallel to correct pins on each tube socket, with wires neat and not touching other things, one side ground referenced.
- ☐ Check the wiring of the power supply, including high voltage secondary wires from the power transformer, diodes, capacitors and resistors of the filtering stages.
- ☐ Verify the diodes are oriented with correct polarity, and all electrolytic capacitors oriented with correct polarity.
- ☐ Check the output transformer wiring all going to the correct places and no mix-up between which ones go to the left channel and which to the right.
- ☐ Check that tube sockets are oriented with the correct pin numbers, and components or wires to those pins are correct
- ☐ Verify 9 wires going to the star ground point from where they should, including the center tap of the power transformer for high voltage.
- ☐ Use your finger to press on all solder connections and components to ensure solid connections.
- ☐ Check that you have tightened down the transformers, power switch, potentiometer, RCA jacks and speaker jacks so that none are loose
- ☐ Check that no wires are touching the cathode resistors on the power tube sockets, and no wires are touching the big 10W power resistor. These will heat up.
- ☐ Check that all leads are trimmed short. Verify there are no stray strands of wire or anything touching the aluminum top and back panels or leads of other components or tube sockets.
- ☐ Turn the amplifier to the side or upside down and ensure no loose wire clippings are rattling around. Find them and remove.
- ☐ Use a multimeter to touch anywhere on the aluminum top and back panels to verify continuity to the earth ground on the IEC inlet (middle prong)
- ☐ If you are unsure about anything, re-read. Send an e-mail or check online if you have questions. If your spider-sense is tingling, it's worth checking on it!
- ☐ Tell yourself how great you are!

19 Attach bottom panel and rubber feet



Blow a magical wish into your amplifier and place the perforated bottom panel on the chassis, ensuring the holes are near the front of the amplifier where the most heat will be generated. Screw in place using **four 3/8" truss head screws** into the predrilled holes.

Attach the **four adhesive rubber feet** in the corners. Place the amplifier upright and ensure it sits properly. It's important that the amplifier be raised up on these feet so that airflow can enter the perforations at the bottom and keep the interior cool.

20 Attach the volume knob and pretend you are listening to heavy metal

Yeah, you almost forgot about the **volume knob,** didn't you? Rotate the potentiometer to one extreme or the other so you can position the knob at the right place to reflect where you'd expect to have zero volume or full volume. Place the knob on the potentiometer post and tighten the set screw using a tiny flathead screwdriver. 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.

21 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.

Let's get the tubes into the right spots. Insert the 12AT7 tube into the tube socket that is on the right side closer to the volume knob (remember we have it turned upright now, not aligned like the layout diagram). The pins will only align in one orientation due to the layout of the holes. Insert the two EL84 tubes into the other tube sockets. 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, output from a mobile device, a source from a preamplifier, etc. You will need your own RCA interconnect cables.

Connect 8 ohm speakers to the speaker binding posts. Do not run the amplifier without speakers connected (or 8 ohm dummy load resistor rated 10 watts or more).

Ensure the power switch is in the off position and plug in the AC power cord.

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.

Now… I suggest you queue up a first-try song. I think for this amp, Grateful Dead Ripple might be just perfect. But choose your own, whatever you like. Diana Krall. John Denver. Ozzy. Beatles. You know, whatever.

With the volume at about ½ and an input signal playing, 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
- Sparks, smoke or strong burning smells. (Some heat smells are normal as the tubes and components get to operating temperatures.)

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 relax 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 will get very hot over a longer time period (maybe an hour or so). 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 sufficient listening levels, depending on your source signal. But do not overdrive the amplifier with a pre-amp. If you hear distortion, turn it down!
- 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 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 tube works.

Troubleshooting:

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

- Your AC cord and connection all ok and definitely providing power?
- Did the fuse blow? Take it out and check continuity. 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)
- 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 diodes are not 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, and signal coming out of it to the driver tube?
- 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 only inclusive of the assembly instructions necessary 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 and components such as resistors and capacitors. 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!

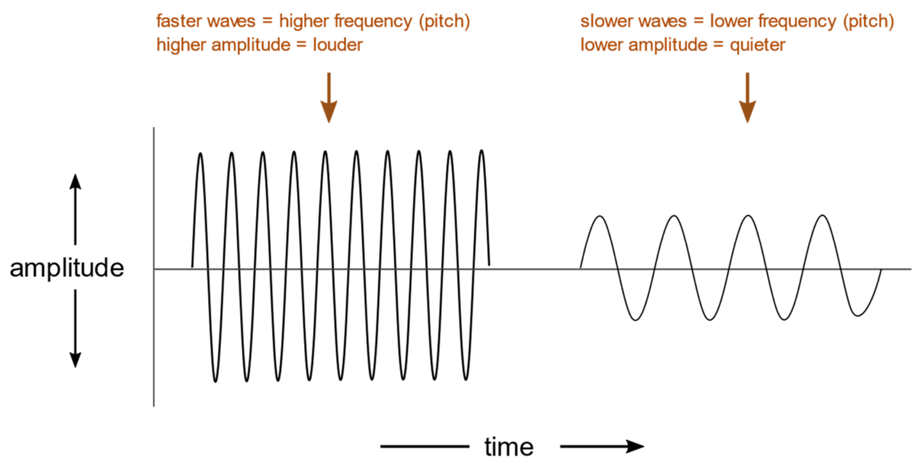
The EL84 (6BQ5) tube was originally introduced by Mullard in 1954. There are relatively few manufacturers of vacuum tubes around the world now, mostly in Russia, China, and Slovakia—where JJ Electronic acquired fabrication equipment from the original TESLA company.

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.



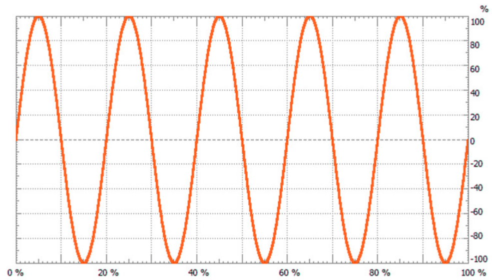
Electronic audio recording equipment converts actual sound waves moving through the air into electric signals using a microphone that reacts to the sound waves creating a voltage at a frequency and level corresponding to the sound. A recording device can capture this stream of varying voltage information, 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 spacial 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).

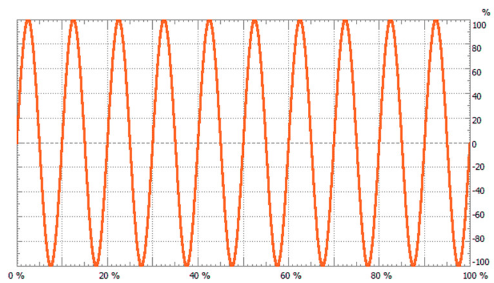
Pure cycles of rising and falling amplitude over time are **sine waves** and can be described with math formulas that I won't introduce here. But you could think about sine waves as a type of building block that, in complex combinations of frequency, duration and amplitude, can make up music or other 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

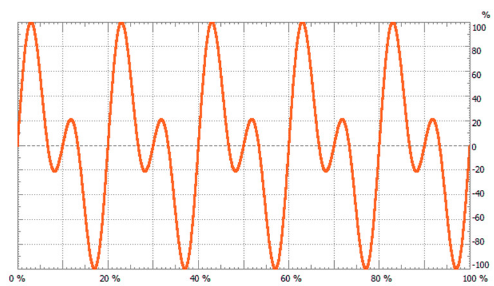
sine wave



160 Hz sine wave



resultant waveform when combined

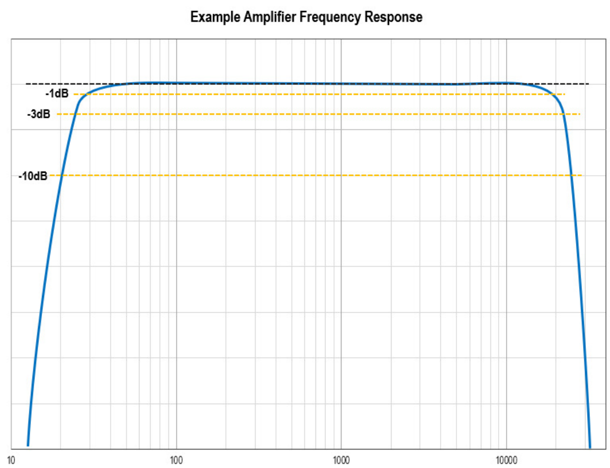


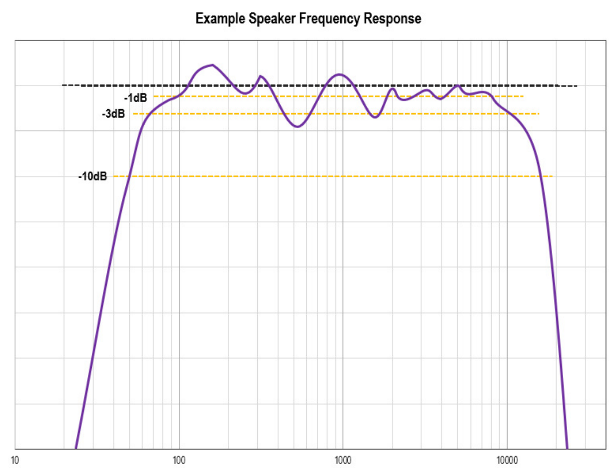
Humans can hear sound only within certain frequencies. To cover human hearing adequately, most audio equipment is designed or evaluated in the range between 20Hz and 20,000Hz. Hertz (Hz) is a measure of the number of wave cycles per second. A vibration at 20 cycles per second is very slow, and we would 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.

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 commonly used 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 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.





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.

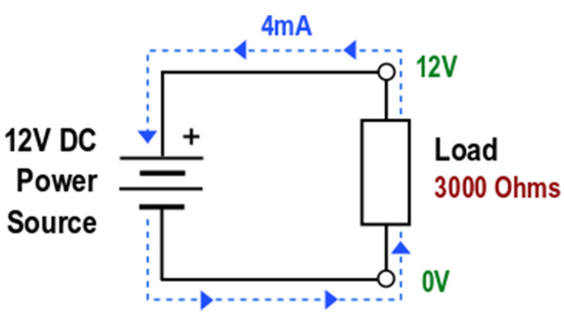
We can use one of the greatest magical formulas ever, **Ohm's Law**, which describes the relationship between these three (and we can solve for the third if we ever know the other two):

$V = IR$

$I = V/R$

$R = V/I$

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 4mA of current ($I = V/R$).



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.

Direction of current

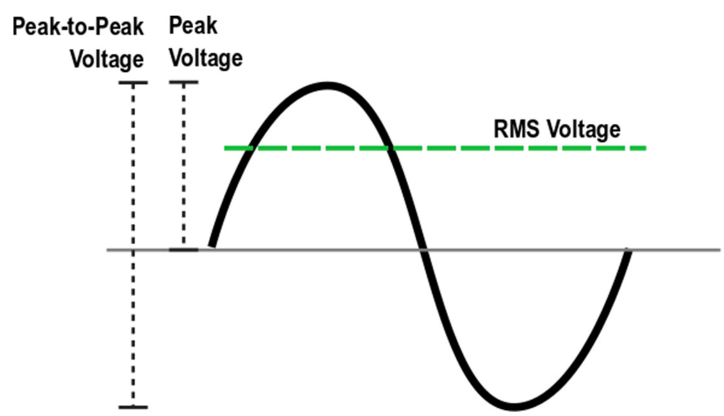
You will notice I drew arrows in the direction from negative to positive to represent the current. Don't worry about direction. There is a history and convention of thinking about current flowing from positive to negative, and we often refer to a "voltage drop" that happens across the load that makes 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.

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

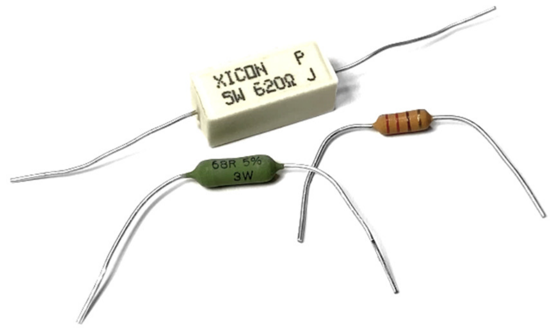
Finally, while we are on the subject of Ohm's law and the voltage and current through a resistive load: **power (P)** represents the rate that energy is produced or used in a circuit. It is measured in Watts and is the product of current times voltage (P = IV). Or, knowing Ohm's law, you could calculate 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.

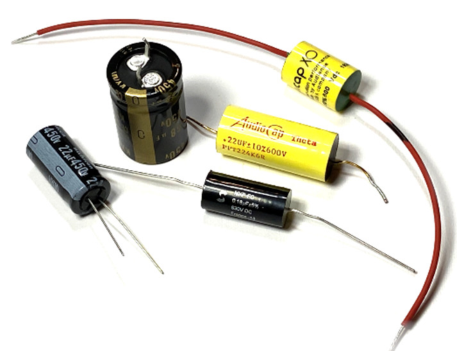


Note that wirewound resistors are generally available in relatively lower resistances due to their method of construction. I use them sometimes for power filtering or cathode bias resistors, which are often less than 1 kOhm. Wirewound resistors can be inductive, but in this application, it will not have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

Capacitors

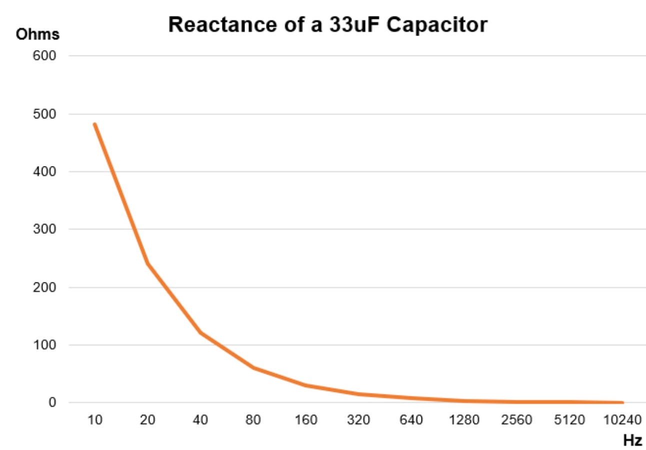
A capacitor stores energy in an electric field. It can be created in various ways, but commonly is done using two conductors (or plates) separated in some way, such as by a film or ceramic material or dielectric. There is no electrical connection between the two conductors, but because they are physically 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:

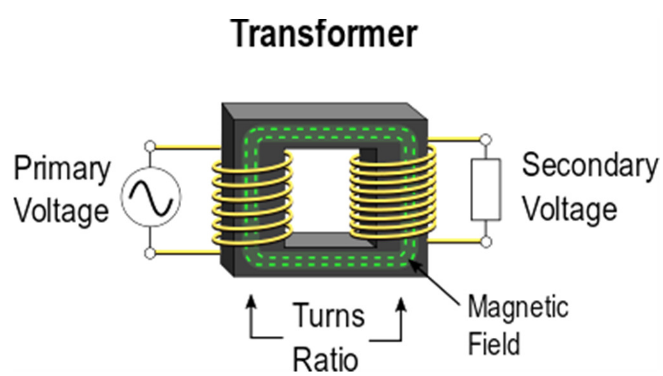
$$\boldsymbol{X_L = 2\pi f L}$$

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.



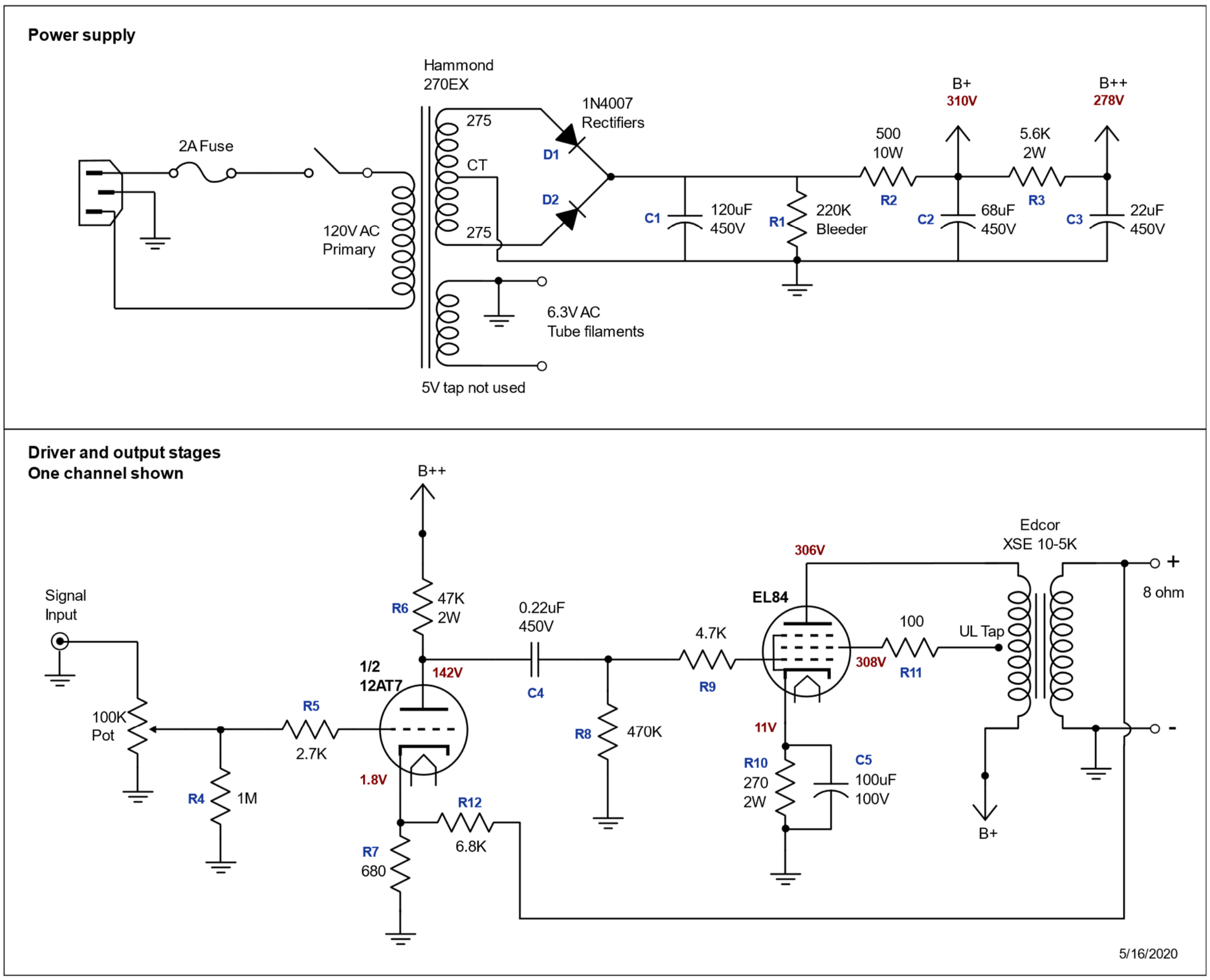
Keep in mind that this is a passive electrical activity (unlike an amplification process). We are putting the circuit load on the secondary side of the transformer where there is going to be a voltage, load resistance and resulting current draw. On the primary side, that load will appear differently 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.

Exordium Single-Ended Amplifier 12AT7 / EL84



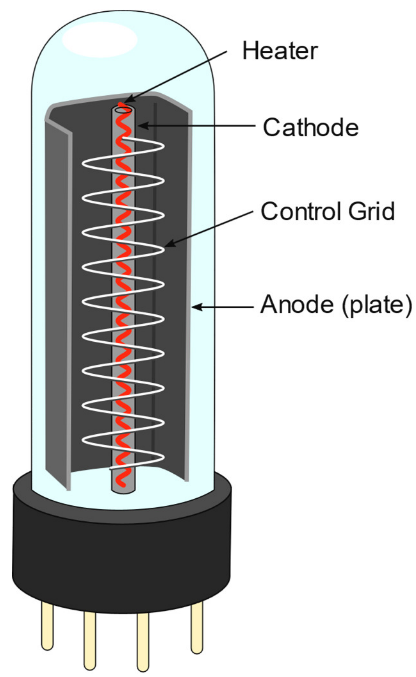
A later section will go over the power supply in detail, but for now, just know that the purpose of this portion of the circuit is to take AC voltage from your wall outlet ("mains" voltage) and convert it to high voltage DC, referred to as "B+". This is a historical term from when batteries were used 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 310V DC. You'll see later why we need this high of voltage.

The arrows on the right-hand side illustrates that the B+ is an output of the power supply circuit, or actually two outputs—one referred to as B+ and the other as B++ because there are two different voltages used. Similar arrows are shown in two places in the amplification part of the circuit (driver and output stages), indicating that the B+ or 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 stage, you can see the schematic flows from left to right, with the input signal entering on the left, the 12AT7 tube is a **triode** vacuum tube that performs a first level of amplification ("driver"), then the EL84 is a **pentode** vacuum tube that performs a larger ("power" or "output") amplification. We will also go over the details of these tube types 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 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 some types of tubes, the cathode is directly heated by running current through it, but in most modern triodes (including the tubes in this kit) 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.

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.

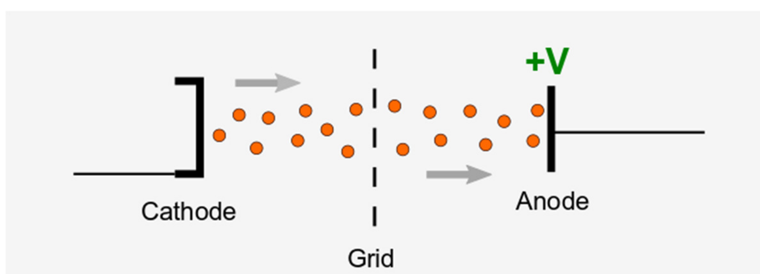
The anode is referred to as a plate because it's a metal plate surrounding the cathode, and we can put on the anode a juicy and delicious positive voltage with respect to the cathode. You will soon start to see why we need high voltage in a tube amplifier. If you just put a few volts on the anode, the 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 miles 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 miles 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.

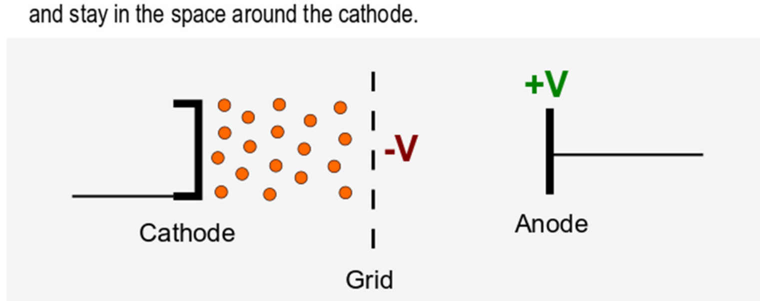
Alright, so an operating tube is allowing current flow (the "valve is open"). Now, there's one more component to make this a triode: the control grid. This is a wire mesh in between the cathode and anode that is spaced wide enough to allow the electrons to pass through. But what might happen if you applied 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 less negative charge? Electrons and current flows (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).

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



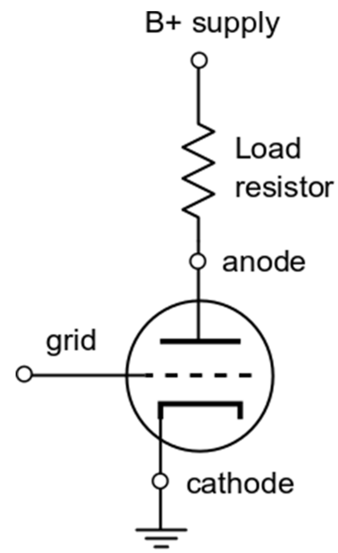
By altering the voltage of the grid, we can "open and close the valve," allowing current to flow more or less. Awesome! This is why a tube amplifier is sometimes referred to as a "valve amplifier." If we were to put an audio signal on that control grid, then the changing voltage over time of the audio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

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



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 to put the tube in context of a circuit. 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, 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

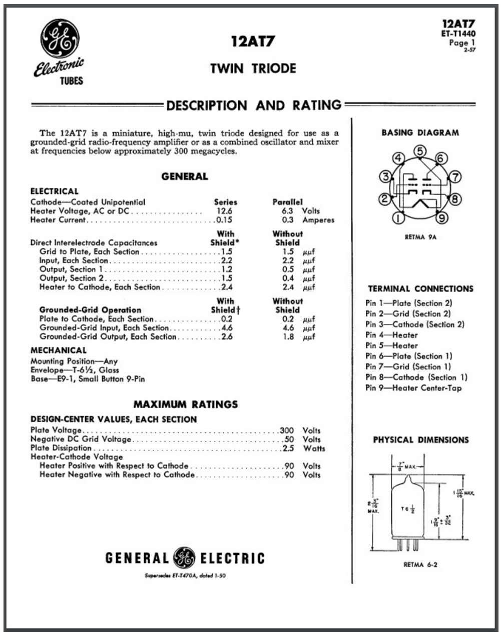
So in this made-up example, -2V volts on the grid is allowing 5mA of current to flow. All we are doing here is using an easy technique to calculate current using a known resistance and measured voltages, using Ohm's law. But I want you to have the load resistor and Ohm's law in mind as we get a step 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 12AT7 tube and take a look at an example datasheet:

12AT7 Datasheet (example pages)



12AT7
ET-T1440
Page 1
2-57

Electronic TUBES

12AT7

TWIN TRIODE

DESCRIPTION AND RATING

The 12AT7 is a miniature, high-mu, twin triode designed for use as a grounded-grid radio-frequency amplifier or as a combined oscillator and mixer at frequencies below approximately 300 megacycles.

GENERAL

ELECTRICAL

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

Direct Interelectrode Capacitances	With Shield*	Without Shield	
Grid to Plate, Each Section	1.5	1.5	μμf
Input, Each Section	2.2	2.2	μμf
Output, Section 1	1.2	0.5	μμf
Output, Section 2	1.5	0.4	μμf
Heater to Cathode, Each Section	2.4	2.4	μμf

Grounded-Grid Operation	With Shield†	Without Shield	
Plate to Cathode, Each Section	0.2	0.2	μμf
Grounded-Grid Input, Each Section	4.6	4.6	μμf
Grounded-Grid Output, Each Section	2.6	1.8	μμf

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
Negative DC Grid Voltage	50	Volts
Plate Dissipation	2.5	Watts
Heater-Cathode Voltage		
Heater Positive with Respect to Cathode	90	Volts
Heater Negative with Respect to Cathode	90	Volts

BASING DIAGRAM

RETMA 9A

TERMINAL CONNECTIONS

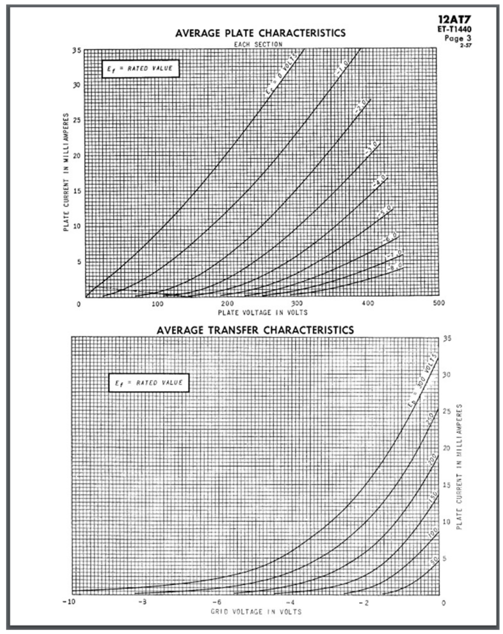
Pin 1—Plate (Section 2)
Pin 2—Grid (Section 2)
Pin 3—Cathode (Section 2)
Pin 4—Heater
Pin 5—Heater
Pin 6—Plate (Section 1)
Pin 7—Grid (Section 1)
Pin 8—Cathode (Section 1)
Pin 9—Heater Center-Tap

PHYSICAL DIMENSIONS

RETMA 6-2

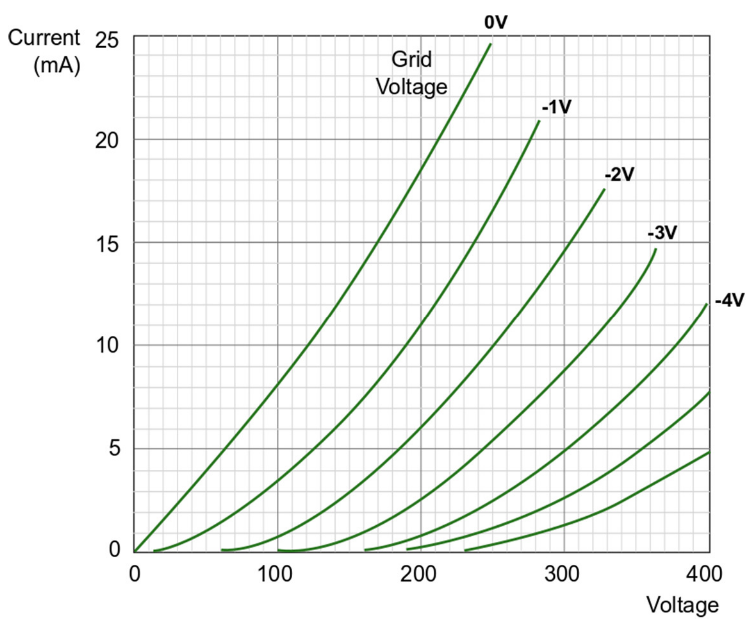
GENERAL ELECTRIC

Supersedes ET-T470A, dated 1-50

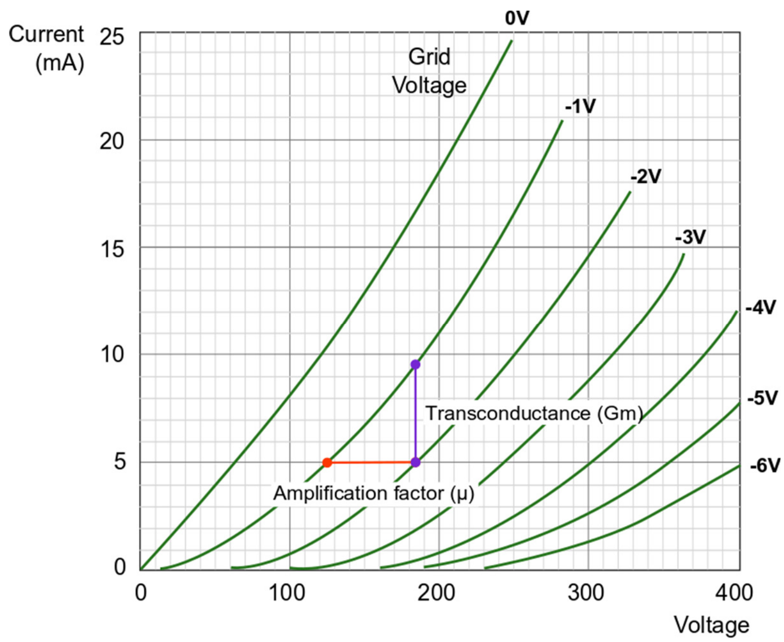


Go search for one of these online (e.g. “12AT7 datasheet”) and pull one up for reference. We won’t go into all of the details, but you’ll find some useful information and I always keep these handy especially for the pin diagrams to tell you which pin number is the anode, grid, etc., or to know how much 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. Using the chart below, if you had the grid at -2V and you put 200V on the anode, then the tube (valve) will allow about 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 4-5mA of current change. 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 12AT7 datasheet and you see transconductance of 4,000 – 5,500 (depending on operating conditions), which would match 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 60V (blue line above). Aha! Here is the leverage that we have been looking to understand. We could swing 60 volts of anode voltage for every one volt on the grid. Powerful, yah? So the μ of the 12AT7 is 60 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 of the amplifier, you'll see that we won't expect to get this full factor of amplification in our 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 50k Ohms and we supplied 350V B+ (we will actually use a lower voltage in our circuit, but this is just to illustrate). 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 350V. Let's plot a point at zero mA and 350V 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 350V were to drop

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

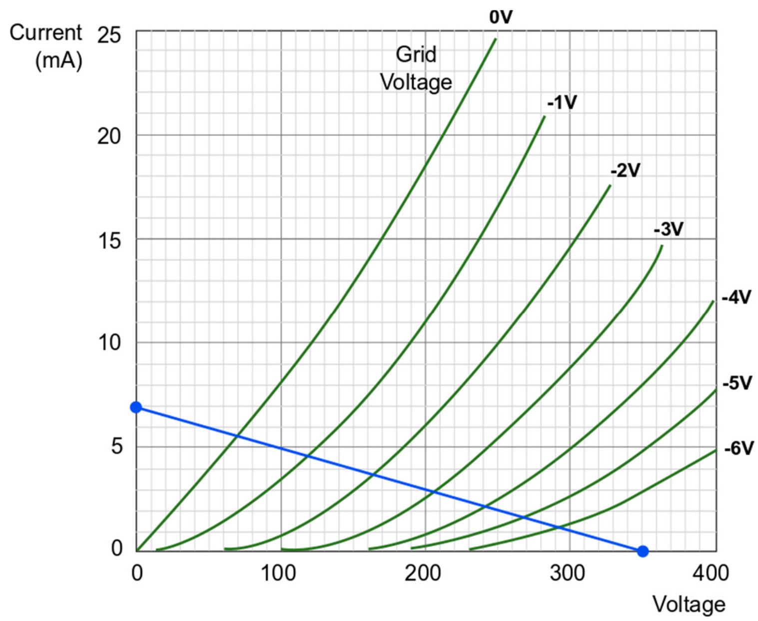
across that resistor, and there was zero volts on the anode. Ohms law in this case to solve for current:

I = V/R

I = 350 / 50,000

I = 0.007A or 7mA

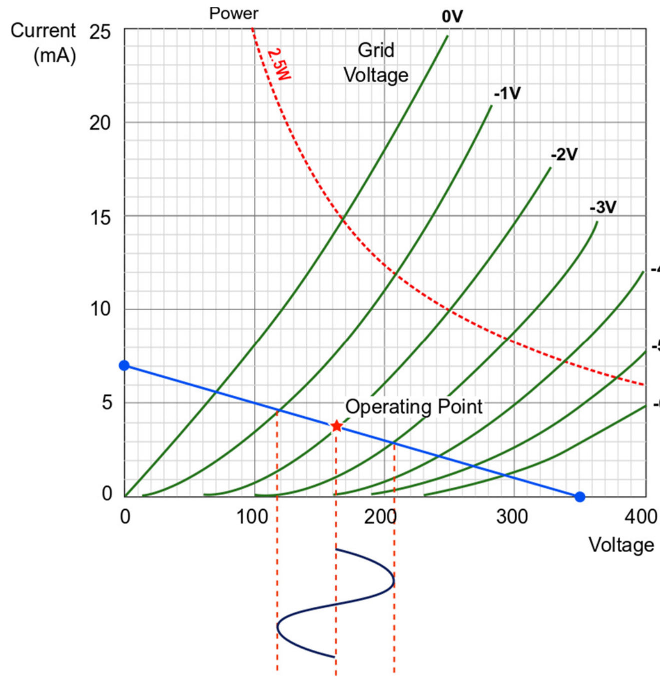
So let's plot another point at 7mA current and 0 volts on the anode. Ohms law is a linear relationship, so this is all we need to draw a load line between these two points.



So what we see here is the linear relationship between voltage and current for a 50kOhm load resistance and 350V 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 4mA of current and 160V on the anode. If we change the grid to -1V (less negative), then we will have 4.5mA of current and 120V. Notice that this is a change of 1V on the grid and a change of 40V on the anode—not the full 60 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, this puts us roughly in the middle of the load line and there will be a steady-state current of around 4mA, and 160V 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 120V to 210V. 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 uses one tube to produce an output, as opposed to other options such as a push-pull tube amplifier that would use two tubes amplifying portions of the signal.

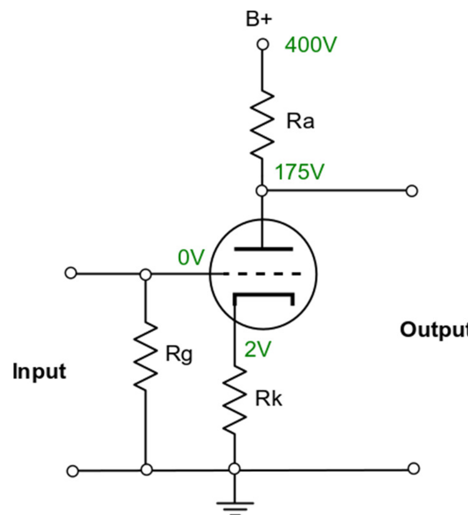
One more consideration regarding load line and operating point. The tube will have maximum rated limits of operation. In the case of the 12AT7, the datasheet tells us that the anode cannot be higher than 300V in steady operation[3]. So our operating point must be left of that point. And the tube is rated for maximum power dissipation of 2.5 watts. The red dotted line on the chart shows where current and voltage would exceed 2.5W of power dissipation on the anode, so our load line and operating point needs to be below that line. (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 4.5mA, then Ohm's law will tell us that we need a value of:

R = V/I

R = 2 / 0.0045

R = 444 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 50k Ohm so we won't worry about it, or you could re-calculate the load line with this larger value of 50,444 Ohms. (And of course 444 is an unusual number and we could round this cathode resistor value to one that is typically available.)

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 12AT7.

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.

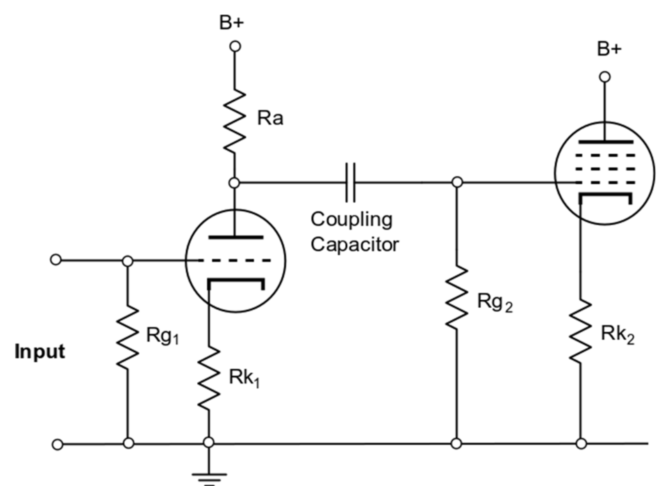
Coupling, AC load line, and cathode bypass capacitor

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 in our amplifier 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 160V 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 an EL84 power tube—for further amplification, but we can't put 160V 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 the entire B+ because the tube takes time to warm up before any current flows, so the full voltage will appear on the anode, at least for a few seconds at startup.

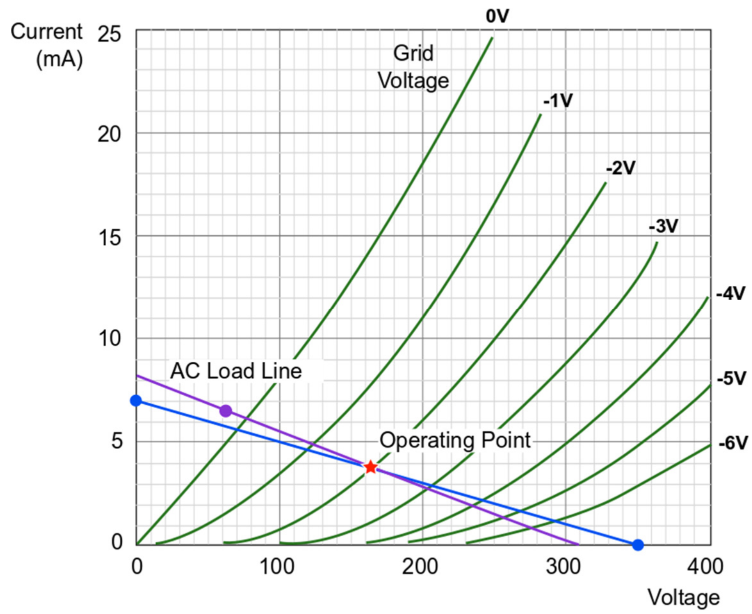


We will get into the output stage soon, but we need to go back now and consider a few things with our driver stage. Our load line was fine for defining an operating point when there is DC voltage without audio (AC) on the grid, but since we are allowing AC voltage to pass on to the next stage through 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 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:

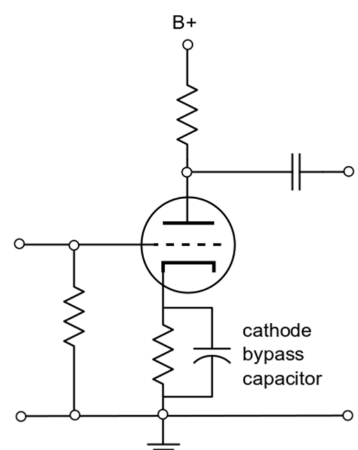
$$R = \frac{R_a \times R_{g2}}{R_a + R_{g2}}$$

Solving this with 50,000 and 470,000 as our Ra and Rg2 values tells us that the AC resistance would be about 45.2k 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 45.2k Ohms, then the current difference for this voltage drop is 2.2mA. So we can plot a point that is 100V lower than our operating point, and 2.2mA 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 5mA. Remember how we solved to find our cathode resistor value and came to 444 ohms so our cathode would be at 2V. Well, 5mA across 444 ohms in Ohm's law is about 2.2V, 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. You'll see in our circuit we will allow it in our 12AT7 stage, but will use a solution in the output stage: a **cathode bypass capacitor**. It's best to illustrate now, so you understand it. 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, say 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.

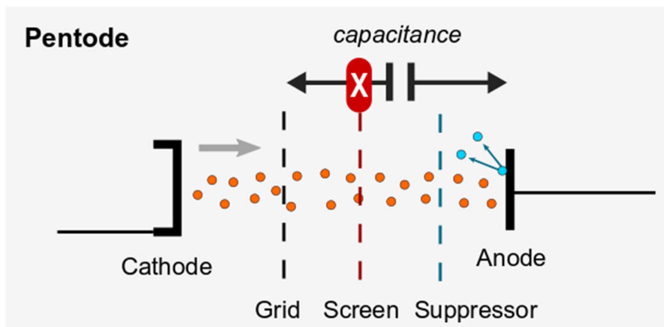
Output stage and pentode tubes

The tube used in our driver stage is a triode, which has great qualities, but also some limitations. You can read further material I reference in the appendix to understand at a greater level, but I will summarize.

A triode has a small amount of undesirable 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 introduces a new complication in our 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 general principle of the power stage pentode tube is similar to the driver triode tube: put high voltage on the anode and screen, 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.

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 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.

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

In our circuit, we are using one type of pentode tube, the EL84. Notice on the schematic the bottom dotted line is the grid, the next one is the screen, and the top one is the suppressor. Note that a pentode tube could be made to operate in triode mode by simply connecting the screen to the anode so they are always at the same voltage. Some amplifier designs do this and we will discuss soon some choices of how we will actually use the screen in ultralinear mode versus pentode or triode mode.

On the schematic, you can see again some familiar components: we have another grid-leak resistor, we have a cathode resistor with bypass capacitor, and we have an anode load—oh, 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 and size of the output transformer is very important in maintaining a flat frequency response across a wide bandwidth at our desired output power. The kit includes an Edcor brand transformer, made in the USA, that I believe is good quality relative to the cost and size of this particular amplifier kit. 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 with lower distortion at 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.

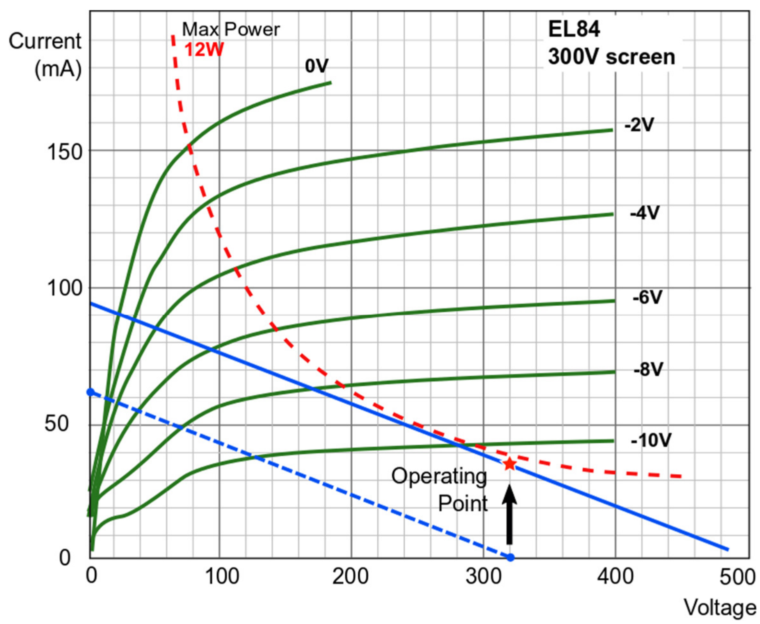
So if the speaker is the load on the power tube, how big of a load is it and can we calculate the load line again? This amplifier is designed to work with an 8 ohm speaker impedance, but the windings ratio of the transformer will make this impedance look much larger to the tube which is what we need 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 5,000 ohms on the primary side of the transformer for an

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.

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 5k ohms gives us a load that will work effectively for our supply voltage and characteristics of the EL84 tube.

Let's say in our example that B+ voltage is 310V (you'll see why I chose this in a minute) and we have a 5,000 ohm load, we can start to work on a load line and operating point. Like the triode tube in our driver stage, we can look at the tube characteristics provided by the manufacturer. The process will be a bit different because this is a pentode tube and because of our output transformer and speaker load. One challenge is that the load lines will vary depending on the screen voltage. Sometimes the datasheet will have multiple charts for different screen voltages. Below is one for 300V. Sometimes you might find one for 250V or something else. It's ok if this isn't perfect, 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 anyway.



In the chart shown, the blue dotted line is the initial load line for 310V and 5,000 ohms (62mA 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 so small 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 310V. 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 310V operating point. To maximize our power from this tube, let's pick a level just below the maximum rating, shown with the red dotted line. The 12W maximum would be at approximately 40mA of current. So we shift our load line up, keeping the same slope until we reach an operating point that is 310V and around 40mA. Finding the nearest grid line, this is pretty close to -10V. See that? But it's a bit below, so let's pick -11V. Now, if we need -11V 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 +11V. Using Ohm's law, if we are estimating 40mA of current dropping across 11V, this gives us a resistance of 275 ohms, or let's pick 270 which is a common resistor value. This will dissipate about 440mA of power, so we would choose a resistor rated at least double for a margin of safety, 1W or higher. (Some power tubes will dissipate much more power, so you should always calculate this!) We will bypass this capacitor with a 100uF electrolytic capacitor. I use 100V here, which is obviously more than necessary but I use the same type with other tubes that have higher cathode voltages.

Are you still with me? I know it's a lot, but you are getting it, right? Summarizing for a moment… we put 310V on the anode and because there is little resistive load under DC conditions, this is our operating point voltage. We elevate the cathode to 11V and our tube will be dissipating 40mA of current in its quiescent state, shifting our load line up. Now under AC conditions the signal will vary the voltage of the grid by say 8 volts or so depending on input level and amplification in the driver stage, and this will swing the anode voltage very widely, up to a few hundred volts. And importantly, it will put this alternating current across the transformer, 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. Also, you may be wondering why I chose 310V but the maximum rating for the tube is 300V. This is actually a maximum voltage relative to the cathode, which we have elevated to 11V, so should be safe.

At this time, we know enough about the operating point of the circuit to have our initial design and can modify if needed. We also need to get back to that screen. You thought I forgot, didn't you? Take a break, get a snack. Almost there!

Screen voltage and Ultralinear mode

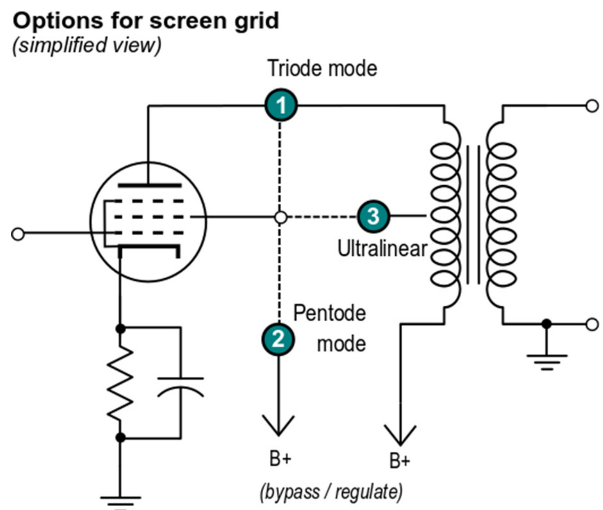
There are several options for how a pentode tube can be operated. This kit is designed for **ultralinear mode**, and so I will not go over a circuit for a standard pentode design in much detail. But I will cover a few basics so you understand the options and how ultralinear mode fits into those options.

First, and simply, you can take any pentode tube and operate it like a triode ("triode mode" or "triode strapped") by simply connecting the screen to the anode, and the voltage of each will always be identical. Both the anode and screen will swing together in voltage across the output load as a signal is applied and current passes through both of them. Output power will be lower, and the tube characteristics will generally have more lower order harmonic distortion—some consider this a desirable "sound" for a tube amplifier, though obviously perception of sound is highly subjective. The grid-curve chart shown earlier for the EL84 is not in triode mode and would look different if the tube were triode-strapped.

Second, to operate in pentode mode, you would put a DC voltage on the screen at around the B+ level or somewhat lower, and then you would also bypass the AC by using a capacitor to ground (not shown) so that your screen stays at a constant voltage. Only the anode will swing in voltage as the signal is applied. Pentode mode will have more power output possible, and generally produces more higher order harmonic distortion—some would consider a less pleasing sound, but again a subjective generalization. (I know I have just mentioned a few types of distortion and have not discussed this topic much yet; we will come back to it soon in more detail.)

Ok, these are two fine options. But some clever folks in the 1950s made a discovery of a third option that has very interesting results. You could think about triode mode and pentode mode as two ends of an extreme with respect to the screen voltage. On the triode end, the screen voltage is entirely determined by the anode (plate) voltage which means it changes with the audio signal, and on the pentode end the anode voltage is completely independent and the screen voltage is held at a constant level.

Each of these modes has their own form of non-linear distortion, but they tend to curve in opposite directions. If we were to take a position part-way in between these two extremes and put that on the screen, there's a sort of magic that happens at the right spot where we can get a more linear operation (less distortion) and still get most of the benefits of pentode mode for power. By putting a special tap on the output transformer, we can vary the screen voltage in proportion to the anode but not as much as in triode mode. It was found that a tap around 40-45% of the primary is the ideal spot. This was called "Ultralinear." It could be considered a form of negative feedback.



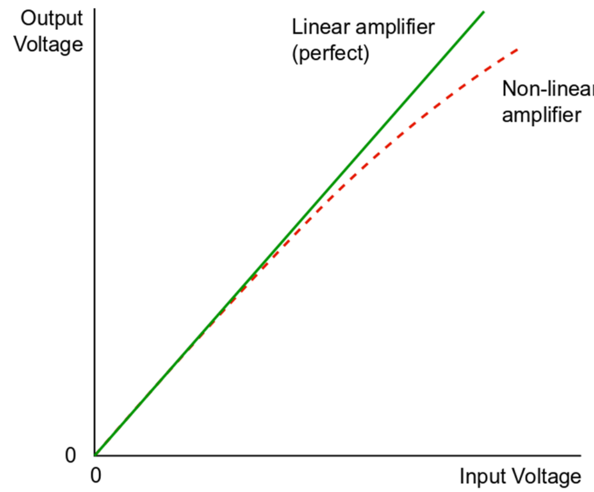
There is deeper theory of ultralinear operation you can study elsewhere. It's used in our case to have optimized performance: good power output and low distortion. Critics of ultralinear might believe triode mode sounds better or pentode performs better, but in my opinion this is a good option given design objectives of low distortion, reasonable cost and sufficient power output from the selected components.

You can re-wire this kit to operate in triode mode by connecting the screen to the plate. You would still want a resistor on the screen pin (not illustrated here) for stability reasons to prevent oscillation, similar to a grid stopper resistor we will also put on the control grids. The screen is a sensitive part of the tube, and the datasheet will tell you the maximum voltage and power dissipation of the screen. EL84 tubes are rated for 300V on the screen and about 2W of power—notice that there is some current passing through the screen as some electrons will be hitting it, even while most are passing through and on to the anode.

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: $V_{out} = V_{in} * \text{gain}$, 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.

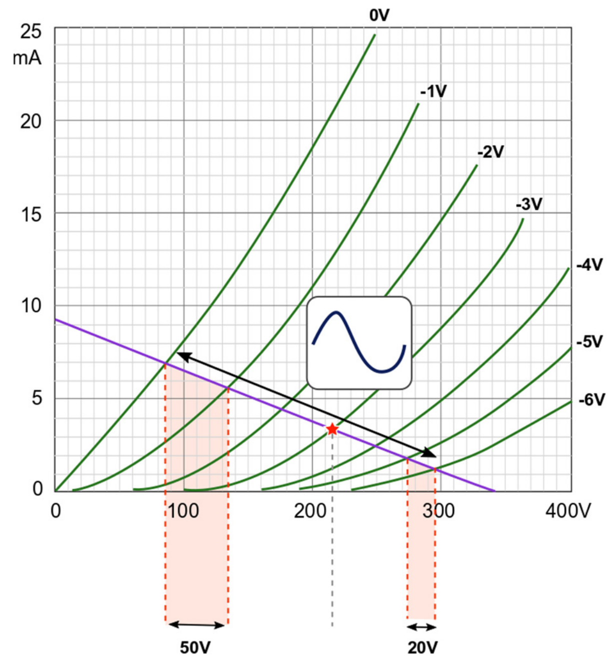
This non-linearity of the range of output voltages relative to the range of input voltages is distortion. This is an attribute of all tube amplifiers, and some might argue part of their "tube sound." In that respect, zero distortion might not actually be the goal, but certainly we want the output to 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.

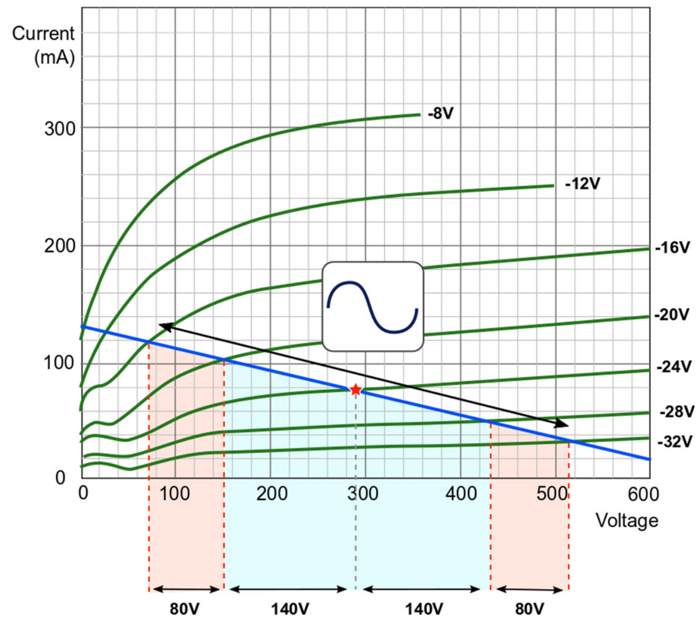
Now let's reintroduce the concept of time and consider a sine wave as a voltage changing over time, and the output voltage isn't perfectly identical in shape to the input sine wave. Remember how we drew a straight load line, expecting that variation of the grid voltage would cause the anode voltage to 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.

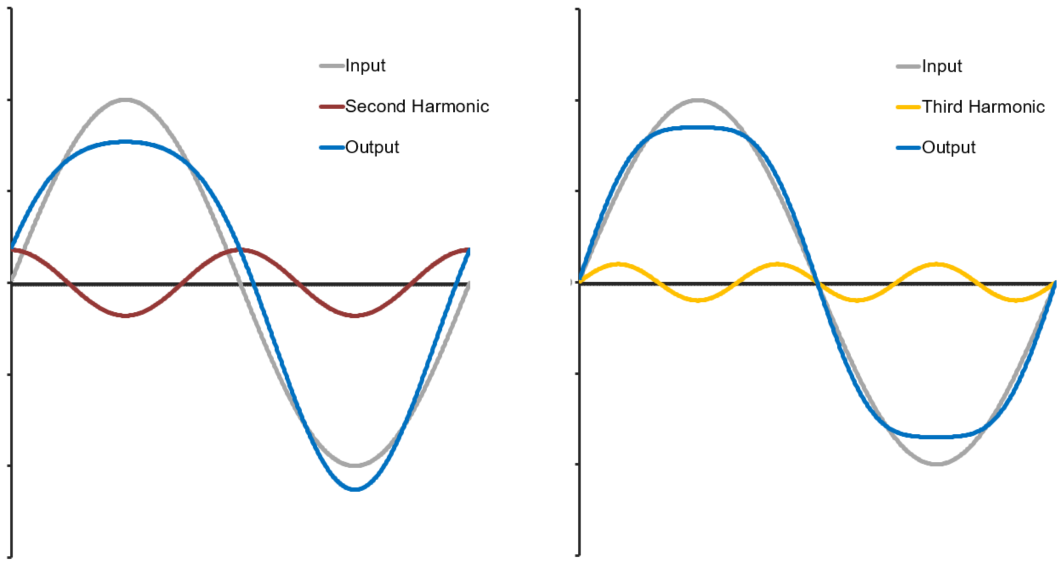
Now, we're ready to look at harmonic distortion another way to visualize these even and odd-order harmonics! I love this part, because the natural world, physics and math are sometimes like magic.

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).



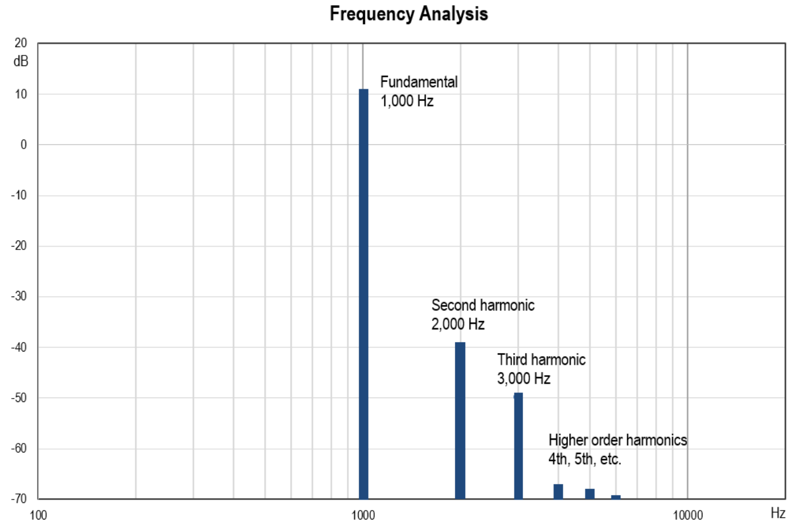
Are you getting it? The distorted waveform is **the same** as multiple sine waves at different frequencies and amplitudes added together.[5] Going back to our amplifier, it's important to re-emphasize: the output waveform is distorted due to various causes, and this is equivalent to a fundamental frequency 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 frequency. A frequency analyzer can do this for us. Below is an illustrative chart demonstrating measurements of harmonic distortion on the frequency spectrum.

[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.

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

Measure or Listen?

I believe in measurements to help understand performance of the amplifier or speakers. I've learned too often my ears 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. Also remember, at the end of the day, if you can play a system and it sounds good to you, you win!

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

If we believe an excess of distortion is not ideal, then the real question remaining to ask is: how can we limit it?

There is a technique we will review in a moment, but first I'll just mention that the component selection and design of the circuit is the most important starting point. This kit uses a 12AT7 driver tube and EL84 output tube, and is designed with a certain operating point, power supply and filtering, load lines, output transformer, etc. All of these choices result in a certain performance and level of distortion. There are many types of tubes, each with different characteristics for amplification factor, transconductance, grid curves. There are also many other circuit design choices more complex than ours, possibly involving multiple tubes or stages before the output. A push-pull is also another design, very different from single-ended and with different implications for power and distortion. All that to say, we start with components and a circuit designed as best we can for our intended performance, size or cost objectives, and then we can consider one more tool in our toolbelt: **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 or purity of design. Certainly if the circuit design 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 an absolutely beneficial technique.

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:

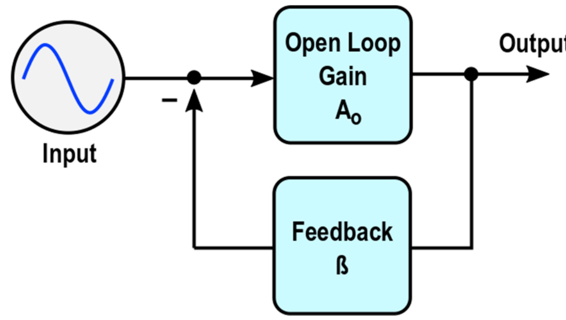
- A thermostat detects the room is too cold and turns on the furnace until the temperature meets an expected level and then the thermostat turns it off.
- Your car's cruise control measures how fast the car is going and modulates the gas to the engine if the car is going too slow or fast relative to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

[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.

(meaning there is no feedback loop) and we know this gain is not perfectly uniform for all input voltages. It is sort of “out of control,” so to speak.

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.

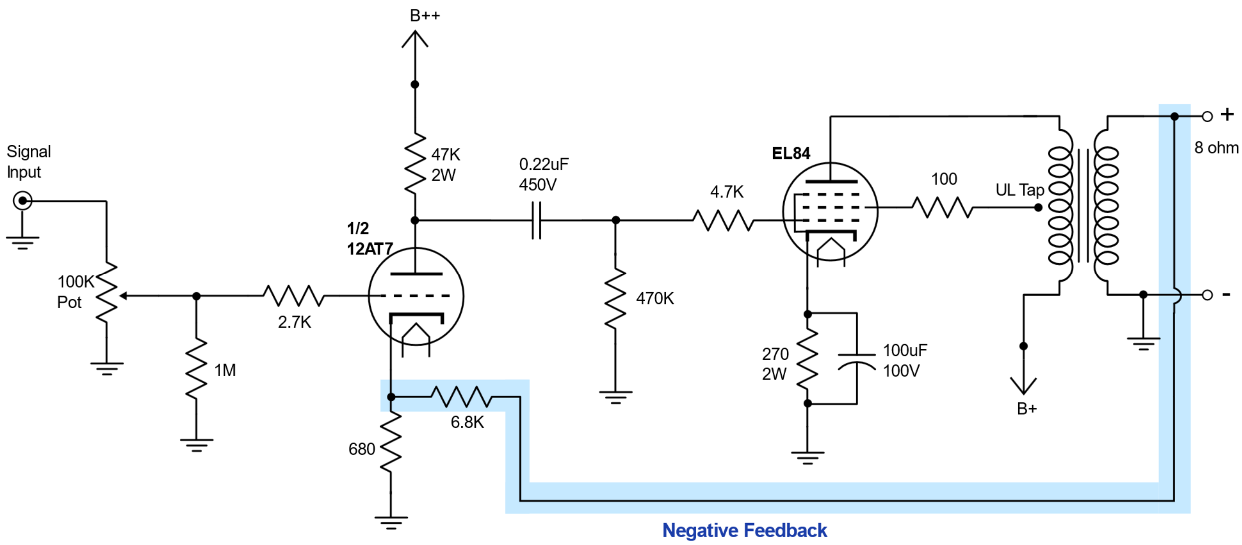


Taking a portion of the output and subtracting it from the input will attenuate the control voltage, lowering overall gain. This is a small sacrifice we make to use negative feedback, and presumes we have a substantial amount of gain to begin with. We have now tied the input to the output at a certain relationship, and the actual gain of the amplified signal is now 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 we need to deal with non-linearity and is why it will reduce harmonic distortion.

Before we look at our actual circuit again, I want to address one more mental trap that is easy to fall into. It is easy to trace a circuit at our slow and methodic human pace: “Ok, our input signal is coming in here… [finger pointing on schematic] …and then the tube amplifies the signal and it comes out over here… and then the feedback loop sends it down here where it comes back over to the input… and then, um, it goes through the tube again a second time? And over and over?” This is not the right way to think about it. There is not an iterative process happening over time, it is an almost instantaneous influence on the control voltage when we add in the feedback loop[7]. If there were an imbalance based on the feedback, the voltages would compensate faster than any audio frequency that we care about.

Negative feedback can be implemented in various ways: local feedback around one tube, global feedback around an entire circuit, etc. Let’s take another look at our schematic and see how it is using negative feedback. Notice that we have a connection from the 8 ohm output of the transformer all the way back, through a 6.8k resistor and to the cathode of the 12AT7 tube. This is one type of feedback, using a portion of that output signal and applying it to the cathode. Remember we chose not to bypass our cathode resistor, so any variance in the cathode is going to impact the voltage difference to grid and affect our gain. So we now have the feedback relationship established with some of the output signal being effectively subtracted from the input stage. The choice of 6.8k is the amount of feedback—we could increase or decrease this resistor, and will have more or less feedback, controlling distortion. The tradeoff is that we give up gain. Because this kit uses rather small output transformers that tend to have higher distortion at low frequencies, I chose to use a bit more feedback, but at the expense of some output power.

[7] This subject is obviously more complicated than I’m describing here, and time can play a factor in various ways, but the intent is to explain feedback for very basic understanding, not a detailed technical description.



How do we know this is negative feedback, subtracting instead of adding? If you have ever hooked up feedback the wrong way, you would know it! Positive feedback creates oscillation as a portion of the output is added to the input, and this can eventually run away and destroy stuff. By adding the positive side of our amplifier output to the cathode of the tube, an increase in this voltage would make the cathode less negative with respect to the grid than it otherwise would be, acting effectively as a subtraction to the voltage that is applied to the grid.[8]

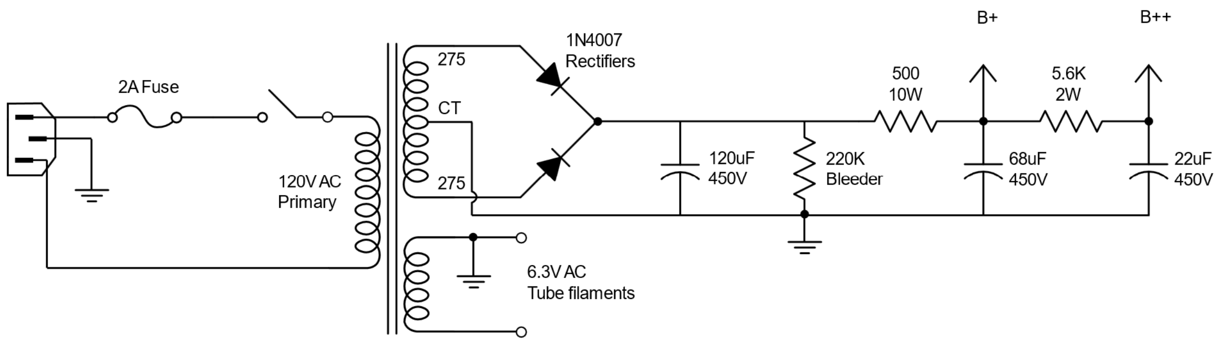
I know I've only barely described this, and poorly! Although we could look at other types of feedback or use some equations, I think I'm going to stop here and not try to go further than this general overview. But I hope you get the general concept: using the output as an influence on the input to achieve 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.

Power supply, rectification and filtering

We have covered all 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 electrical outlet and we have a few components the hot side passes through in series.

[8] There are actually multiple inversions of phase of the signal. If you look back at the load line, a positive change in the grid causes a negative change in the anode voltage. This means the output signal taken from the anode of the tube is inverted relative to the input. But we have two stages of amplification, each of which is inverting the phase before finally reaching the output of the amplifier.



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 and capacitors are charged up.

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 two 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 using a transformer that will take 120V AC (U.S. mains voltage) on the primary, and we will get 550V AC on the secondary. This transformer is commonly used in tube amplifiers and it has two additional windings on the secondary side. One will provide 6.3V as the power for the tube filaments (heaters) of driver or power tubes. The other is 5V, which is commonly used for rectifier tube filaments. In our case, we are not using a tube rectifier, so this winding is not used or shown in the schematic. It is also common to not show the heater wiring in the schematic because it is relatively straightforward and is otherwise isolated from the rest of the amplification circuit.

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 275V end 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 slightly different type of rectifier 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. 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.

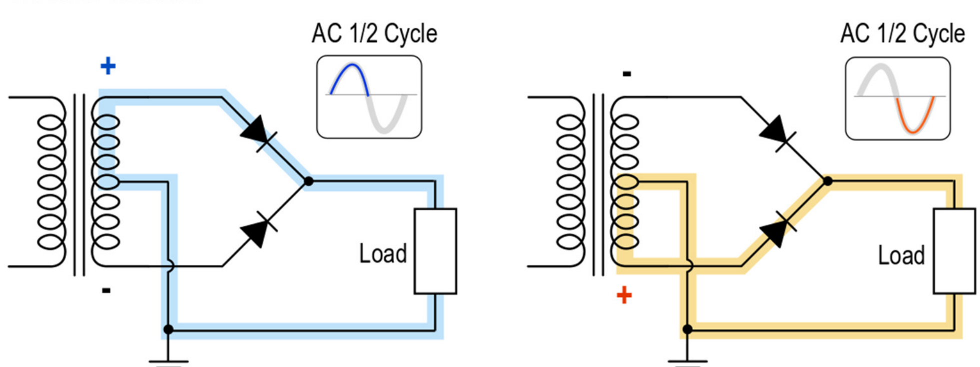
To convert AC to DC, we need a rectifier—something that will allow current to flow only in one direction, so we have only positive current. Amplifiers historically used a tube rectifier. From our earlier topic, you understand how a vacuum tube works—with a cathode emitting electrons and an anode pulling 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. Rectifier tubes drop a significant amount of voltage, require current to heat the filament, and add cost and physical space required in the amplifier. We have a better and cheaper solution now: silicon rectifier diodes. Once again, there may be debates about whether a tube rectifier is better: does it have a desirable "sag" under current loads impacting the sound and do guitar players prefer it in their amps, is it better to bring up the DC voltage slowly due to the heater warm-up time, what about switching noise of a 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 ideal for this amplifier kit, intended to be simple, high quality, and reasonable in cost. Using silicon diodes to rectify the power supply is very common in tube amplifiers and does not compromise the sound or make this a solid-state or hybrid amplifier in any way.

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. Diodes allow current to flow in one direction only and switch off when current goes the reverse direction. By connecting diodes on each secondary terminal, we create a two-phase rectifier. On the first half of the cycle when voltage swings positive on one terminal (with respect to center tap), that diode switches on and conducts current while the other terminal is now negative and that diode switches off. On the second half of the cycle, the opposite occurs and the other diode will conduct.

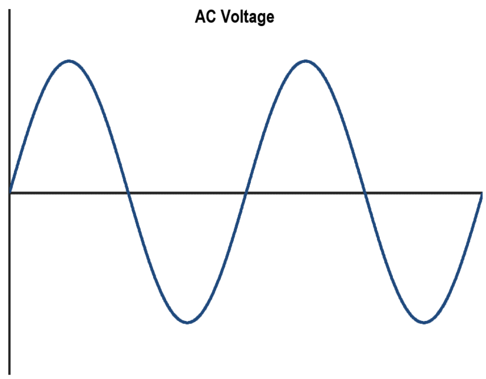
Tube vs. diode rectification and B+

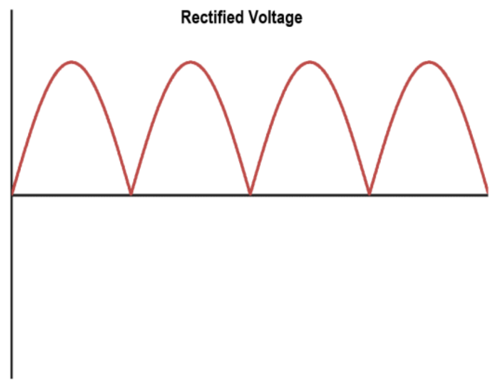
One criticism of silicon diode rectification is that it immediately allows the full B+ voltage to appear on the tube plates before they are warmed up and passing any current. The theory is that this high voltage damages the tubes. A tube rectifier warms up at a similar rate to the driver and output tubes, so the B+ would come up slowly, perhaps extending tube life. I'm not sure there is proof one way or the other, but I have seen experts argue both, and I generally believe that diode rectification and a few seconds of immediate B+ on the plates is not a risk to worry about.

2 Phase Rectifier



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 diode for the first half-cycle, and then from current flowing through the other diode for the second half-cycle. The rectified voltage now looks like the graph below.

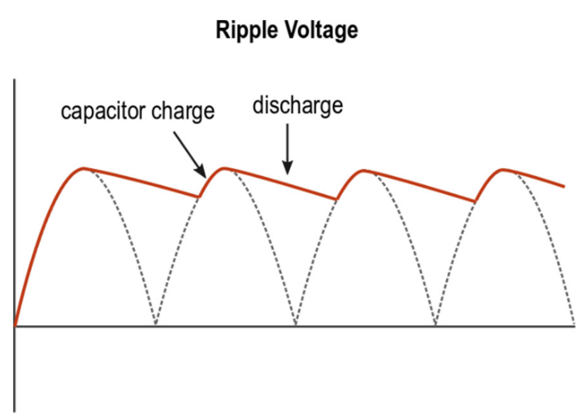




We are making progress, but our intention is to have smooth DC voltage, not large peaks and voids like this. We need to filter this power supply to smooth this out. There are various ways to do this, but the two main components to use are capacitors and chokes (inductors).

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. You could 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.

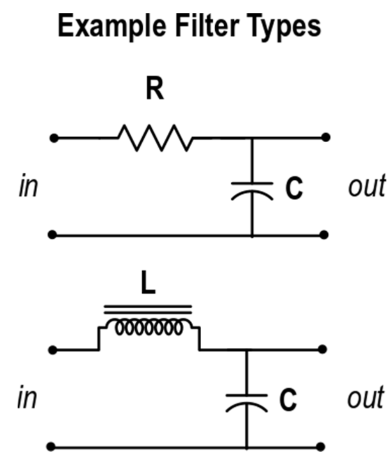
A reservoir capacitor will make our DC voltage look like the chart here. Note that we still have some ripple voltage as the capacitor is discharged, but it’s certainly better than the peaks we had previously. In our circuit we are using a 120uF capacitor as our reservoir capacitor. You could use a lower or higher capacitance. I will not try to describe the calculations of 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 small 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 any 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 the frequency of this ripple—think of it like AC at 120Hz riding on top of the DC current. 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. Downsides of chokes are that they can be expensive and physically large when they have enough inductance to do adequate filtering, and low enough DC resistance to not drop much voltage (all wires have some resistance).

In this kit, I was aiming for small physical size and lower relative cost, so I did not use a choke. The EL84 tubes also run on relatively lower B+ voltage compared to some tubes, so dropping voltage is actually not a problem. We use a 500 ohm resister followed by a second capacitor, this time a lower value of 68 uF. The resistor drops about 50 volts and dissipates around 5W of power.

So looking again at our schematic, we have our rectified power supply going through a capacitor/resistor/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 550V center-tapped (usually labeled 275-0-275), meaning 275V 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 275V RMS is actually a voltage that could reach nearly 390V at the peaks, and this is what our reservoir capacitor is being charged up with. Our resistor drops more than 50V and each diode will typically drop a small amount of voltage, too. So our final B+ supply turns out to be around 310-320V.

You will see there is filtered B+ that goes to the output stage, but there is also one more RC filter, using a 5.6k resistor and 22uF capacitor. This provides a bit 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. As an easy convention, we can refer to the second, lower voltage and more filtered power supply as B++.

A few notes on component ratings. First, the diodes used in the kit are 1N4007, frequently used rectifiers rated for reverse voltage up to 1000V. The peak to peak voltage from 390V charging capacitor to negative 390V on the reverse cycle of the diode would total 780V, and there can easily be some plus/minus variation in mains voltage or in the transformer, so 1000V gives us some extra room to be safe. Also, the capacitors are rated to 450V. Although our final B+ is just over 300V, at startup with no load and as the capacitors first charge, they can easily reach close to 400V.

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 144mA. If we add up the demand of our expected circuit based on our load lines, we would have approximately 40 mA per channel for the power tubes and 3 mA each for the driver stage, totaling close to 90mA or so.

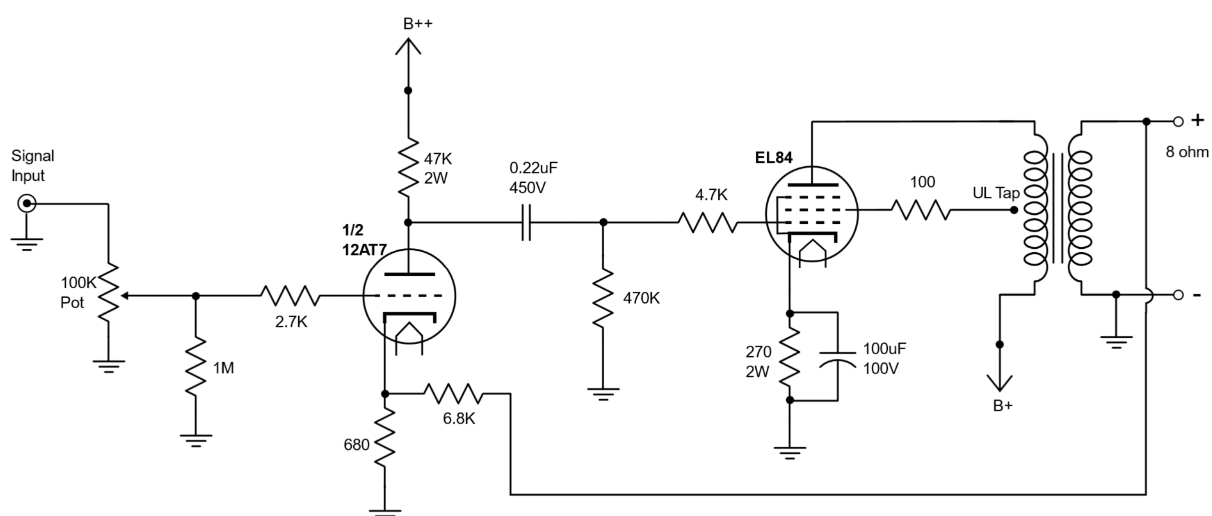
There is also a current demand of the heaters. Each EL84 requires about 760mA and the 12AT7 requires 300mA, for a total of 1.82A. This is rated separately on the transformer, and ours can supply up to 4A of current at 6.3V.

There is one final component on the power supply we haven't touched on, the 220k bleeder resistor. This is 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. A very small amount of wasted current through this bleeder is worth the safety of not having a surprise shock.

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.



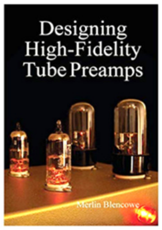
There is a 2.7k resistor leading into the grid of the 12AT7 tube, and a 4.7k resistor on the grid of the EL84. These are “grid-stopper” resistors and are used to help avoid stability problems. It combines with the internal capacitance of the tube from grid to cathode to act as an RC filter, small enough 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 these resistors—they might typically range from 1k to 5k or so. Some designs do not even use them, but I think it’s a good idea.

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.

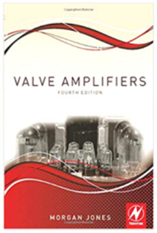


Designing High-Fidelity Tube Preamps

Merlin Blencowe

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

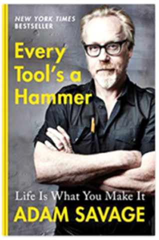
Excellent information and well-written for understanding.



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.

The Valve Museum website

www.r-type.org

A great collection of information and articles

Online communities:

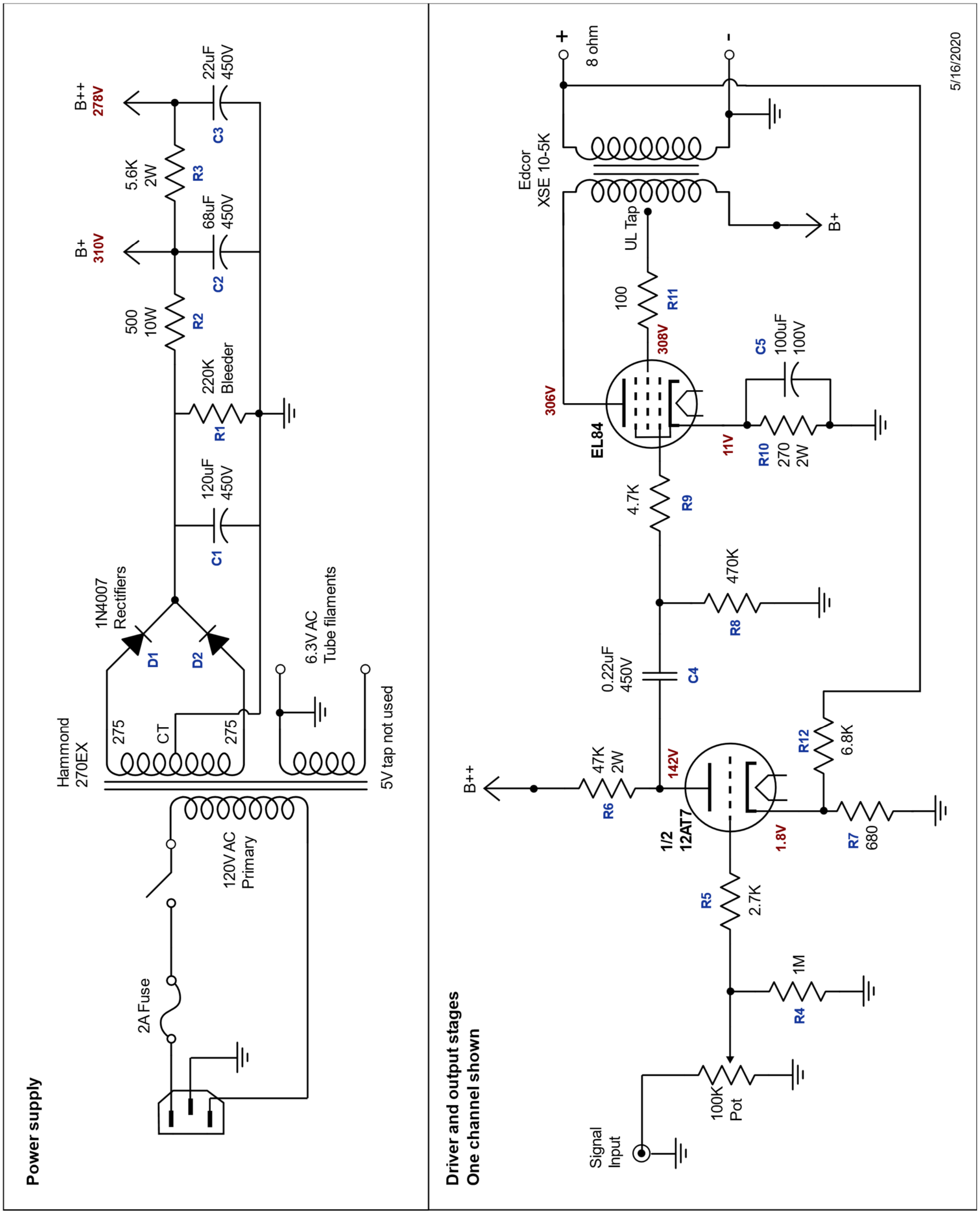
www.audiokarma.org

www.diyaudio.com

Facebook group: *Tube Amp Builders (DIY)*

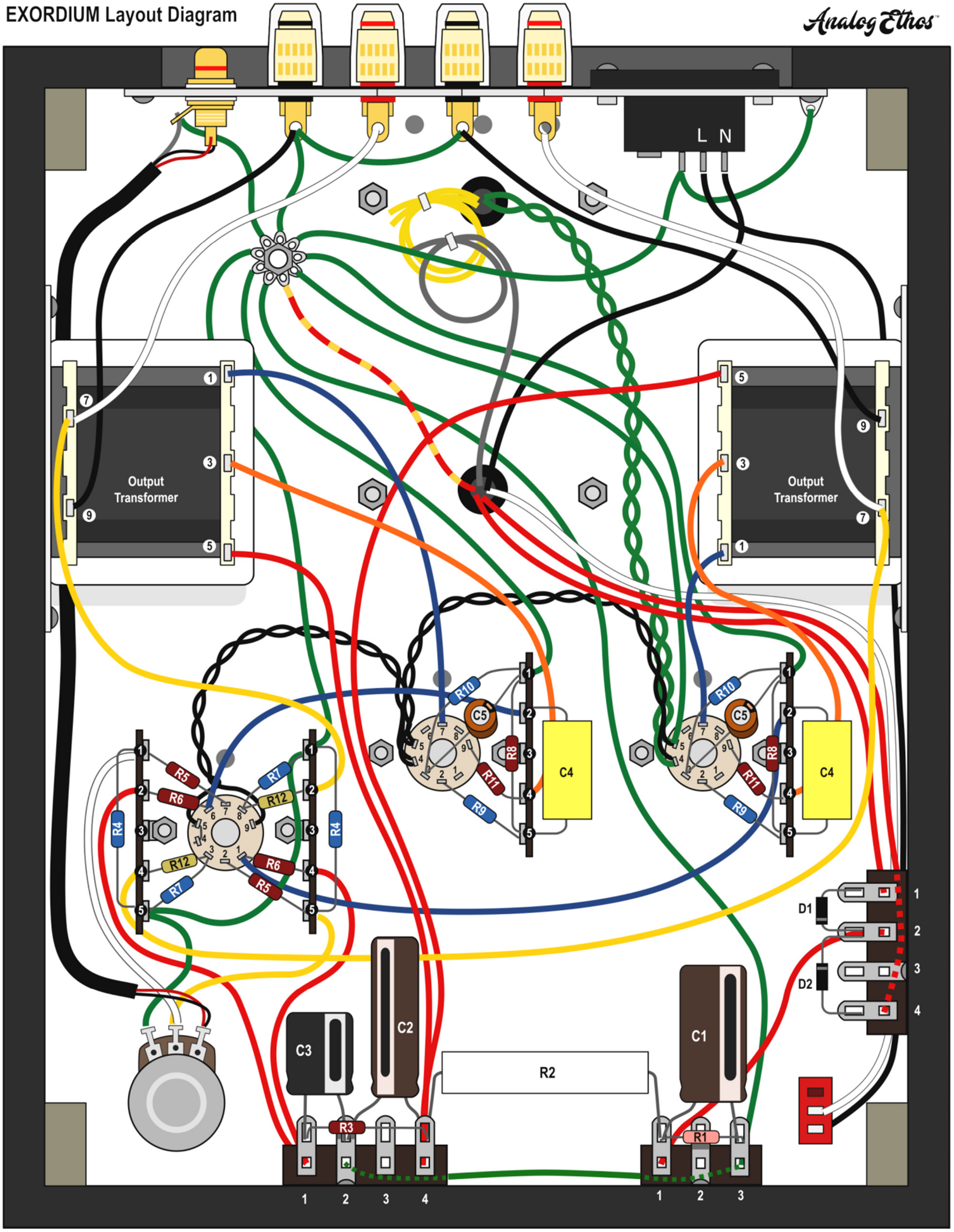
Appendix

Exordium Single-Ended Amplifier 12AT7 / EL84



Appendix

EXORDIUM Layout Diagram



Appendix

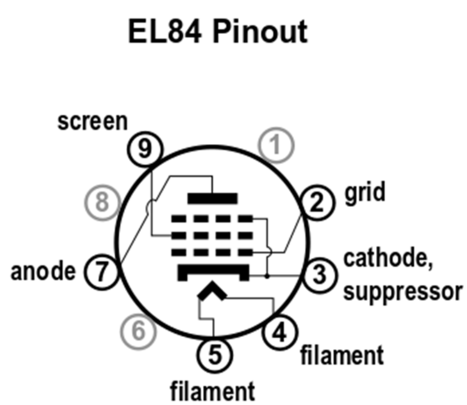
Component Number Reference:

D1, D2	1N4007 rectifier diodes
C1	120uF 450V electrolytic capacitor
C2	68uF 450V electrolytic capacitor
C3	22uF 450V electrolytic capacitor
C4	0.22uF film coupling capacitor
C5	100uF 100V electrolytic capacitor
R1	220k ohm 2W bleeder
R2	500 ohm 10W
R3	5.6k ohm 2W

R4	1M ohm
R5	2.7k ohm
R6	47k ohm 2W
R7	680 ohm
R8	470k ohm
R9	4.7k ohm
R10	270 ohm 2W
R11	100 ohm 2W
R12	6.8k ohm

Tube Reference:

Pinouts and some commonly used values are listed below. You can reference actual datasheets for individual tubes for more information.

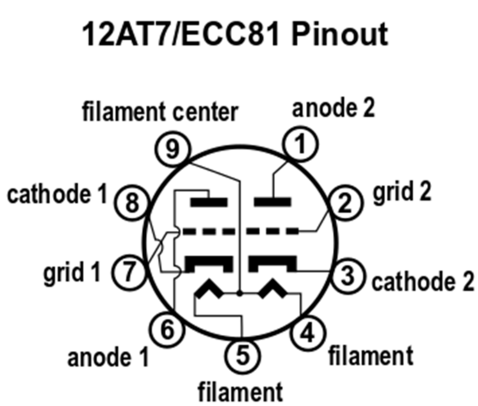


EL84 Pentode Typical Values

Filament voltage: 6.3V
Filament current: 760mA

Maximum plate voltage: 300V
Maximum plate dissipation: 12W

Maximum screen voltage: 300V
Maximum screen dissipation: 2W



12AT7 Dual-Triode Typical Values

Filament voltage: 6.3V parallel or 12.6V series
Filament current: 300mA

Maximum plate voltage: 300V
Maximum plate dissipation: 2.5W