The Cooperative Tube Guitar Amp Project

Basic Math for Tube Amp Geeks

Rev 06

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You don't have to be a rocket scientist to work on guitar amps, but understanding a few, simple mathematical formulas and when and how to use them is very helpful, and at times necessary. This paper will introduce the basic units, concepts, and formulas, with real life examples. This paper is *not* an introduction to electronics or tube amps. For a good introduction to tube amps, point your web browser at http://www.ax84.com/ and look for a Theory Document for the P1 or P1 eXtreme.

Example circuits generally come from the Kalamazoo Model One as that is a common amp I am familiar with and for which I had access to raw schematics. It is generally similar to a tweed Champ with a tone control. A full schematic is included at the end of this paper; you can find more details on this amp at http://www.rru.com/~meo/Guitar/Amps/Kalamazoo/ .

Contents

BASIC ALGEBRAIC OPERATIONS

Most of the math we need to know for home brewing amps, at least initially, is simple algebra. If algebra scares, you, fear not! We'll keep it simple, and stick with the basics we really need to know. The rest of this section is copied straight from Practical Algebra, 2d Courses.

Basic Algebra

The numerical value of a quantity is found by assigning certain values to the letters contained in it, and simplifying the result.

Order of Precedence of Operations

The order of performing operations in algebra is determined by certain rules.

1. In any term (§ 14), symbols of aggregation being absent, raising to powers and extracting roots must be performed before multiplications and divisions.
   Thus, $2x3^2 = 18$; $3x^2 = 3xx$; while $(3x)^2 = 9\ xx$.
2. Symbols of aggregation being absent, multiplications and divisions must be performed before additions and subtractions.
   Thus, $3 + 4 \text{ x } 5 = 23$; $5 \text{ x } 2^2 - 2^3 / 4 = 18$.
3. Operations inside symbols of aggregation are performed before those outside.
   Thus, $8(3 + 4) = 8 \text{ x } 7 = 56$. $(2 \text{ x } 3)^2 = 6^2 = 36$.
4. Otherwise, operations are performed left to right.

PREFIXES AND UNITS

Prefixes

A lot of the units we use cover many orders of magnitude (powers of 10, like from .000,001 to 1,000,000, or even lower and higher (especially lower). Rather than use scientific notation (e.g., 3.3x10^7) we use prefixes that designate multiples of 1/1000 or 1,000.

Symbol	Prefix	Multiplier
p	pico	1/1,000,000,000,000
n	nano	1/1,000,000,000
u	micro	1/1,000,000
m	milli	1/1,000
k	kilo	1,000
M	mega	1,000,000

There are others, but these cover the standard ranges of the components we use.

Units

We will only need to reference a handful of units of measurements.

Symbol	Unit	Meaning
E (or V)	Volt	electrical potential, a.k.a. electromotive force, often compared to pressure
I	Amp	electric current, often compared to flow rate
P	Watt	power
R, Ω	Ohm	Resistance to electron flow, measured in ohms
C	Farad	Capacitance, measured in farads (F)
L	Henry	Electromagnetic inductance, measured in henries (H)
Z	Ohm	opposition to AC electron flow
X		Reactance, or imaginary part of impedance, related to a circuit's capacitance and inductance

Yes, it seems confusing at first to use E and I to designate voltage and current in equations even though we use V and A in the values. But that's the standard and sticking with it will be less confusing in the long run.

Examples:

3kV is 3 kilovolts, or 3,000 volts.
1mV is 1 millivolt, or 1/1,000th of a volt.
1kΩ is 1 kilohm, or 1,000 ohms.
1μF is 1 microfarad, or 1/1,000,000th of a Farad.

Common Notation

Any of the prefixes can apply to any of the units in the right circumstances, but in the world of guitar amps, there's usually a certain subset of prefixes commonly applied to each unit.

Resistance and impedance ranges usually range from ohms through kilohms through megohms. The inductors used in guitar amps typically are in henries, though occasionally you will run across millihenries (mH).

People especially seem to get confused about capacitance, because most of us aren't used to thinking about such tiny fractions, and because of the various ways they are named. For instance, 0.001μF is the same as 1nF is the same as 1,000pF.

Older schematics typically used no symbol on the end of resistor values below 1k (1000), and used the decimal point as needed. The newer standard, implemented to increase readability, uses an R on the end of values below 1k, and uses an R or the prefix symbol instead of a decimal point. Capacitance values common to guitar amps used to be expressed almost exclusively in microfarads or in picofarads. Now they tend to be expressed in whatever magnitude uses the least digits without resorting to use of a decimal point.

Notation Examples					
Resistance			Capacitance		
Numeric Value	Old Method	New Method	Numeric Value	Old Method	New Method
2.2	2.2	2R2	0.0022	2200µF	2200µF
1	1	1R	0.001	1000µF	1000µF
10	10	10R	0.00022	220µF	220µF
22	22	22R	0.0001	100µF	100µF
100	100	100R	0.000022	22µF	22µF
1,000	1K	1K	0.00001	10µF	10µF
2,200	2.2K	2K2	0.0000022	2.2µF	2.2µF or 2200nF
10,000	10k	10k	0.000001	1µF	1µF
22,000	22k	22k	0.00000022	.22µF	220nF
100,000	100k	100k	0.0000001	.1µF	100nF
220,000	220k	220k	0.000000022	.022µF	22nF
1,000,000	1M	1M	0.00000001	.01µF	10nF
2,200,000	2.2M	2M2	0.0000000022	.0022µF	2.2nF or 2200pF
10,000,000	10M	10M	0.000000001	.001µF	1nF
22,000,000	22M	22M	0.00000000022	220pF	220pF
			0.0000000001	100pF	100pF

Voltages range from microvolts (µV) through millivolts (mV) through volts through (in rare cases) kilovolts (kV). µV will usually be referencing noise voltages. mV would include input signals, higher levels of noise, or power supply ripple. Volts might be used for the latter, or for most of the voltages encountered in an amp. kV would most likely only show up in terms of spikes, although a handful of really big, home brew amps based on higher powered transmitter tubes have been built.

Currents typically range from microamps (µA) through amps (A). µA is again probably noise. mA covers almost everything else in a typical guitar amp. Anything dealing with A (an amp or more) is probably either a fuse or on the wall voltage side of things. It's rare to find anything rated for more than a few amps in a guitar amplifier.

Voltage and current notation summary			
Name	**Notation**	**Meaning**	**Common Tube Guitar Amp Usages**
microvolts	µV	1/1,000,000ths of volts	Noise
millivolts	mV	1/1,000ths of volts	Input signal, noise, PSU ripple
volts	V	0-999 volts	Most voltages in a tube guitar amp
kilovolts	kV	1,000s of volts	A bad spike from the wall or in an output circuit

Voltage and current notation summary			
Name	**Notation**	**Meaning**	**Common Tube Guitar Amp Usages**
megavolts	MV	Miilllions and miilllions of volts	Lightning strike!
microamps	µA	1/1,000,000ths of an amp	Noise, control grids
Milliamps	mA	1/1,000ths of an amp	Most currents in a tube guitar amp
Amps	A	0-999 amps	Power wiring, bigger filament currents, output transformer secondaries
kiloamps	kA	Thousands of amps	You' don't even want this in your home, much less in your amp!

TUBE DATA SHEETS AND SPECS

Reading Data Sheets

Voltage Measurements

(all WRT cathode!)

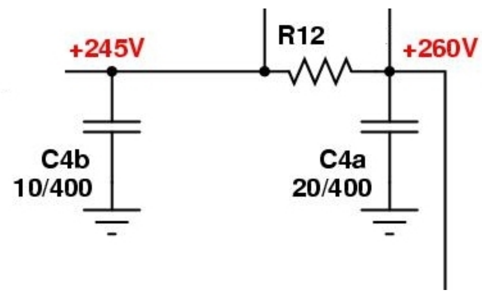
Symbols

OHMS LAW

The most important and commonly used of these formulas is known as Ohm's Law. Simply stated, the current through a resistor varies proportionately with the voltage difference across the resistor. The law can be expressed in three ways:

(1a) R = E / I
(1b) E = I * R
(1c) I = E / R

So long as we know any two of these values, we can determine the third. From **(1a)** it should be clear that if either the voltage or current in a circuit rises or falls, the other rises or falls in proportion.
Examples from common usage:

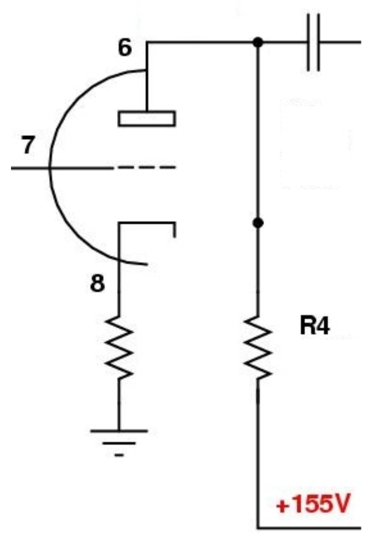


Ex. 1a) If you need to drop 15V after the first capacitor in a power supply, and the current draw after the resistor R12 is expected to be 7mA, what size resistor is needed?

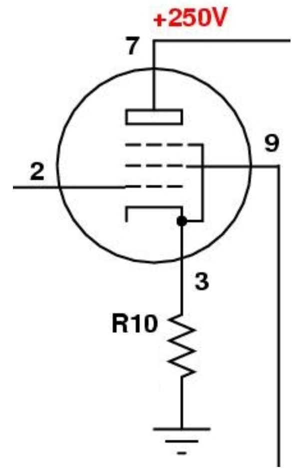
```
E = 15V
I = 7mA = 0.007A
R = E / I
R = 15 / 0.007 = 2142 =~ 2200 = 2.2k
```

Ex. 1b) If a 12AX7 preamp circuit has a 100k plate resistor, and plate current in a 12AX7 triode is typically 0.5mA, what is the voltage drop across the plate resistor?

```
I = 0.5mA = 0.0005A
R = 100k = 100,000
E = I * R
E = 0.0005 * 100,000 = 50V
```



This means that the voltage at the plate will be 50V less than the voltage coming into the resistor from the B+ supply. So if the preamp B+ is 155V, the plate voltage will be 105V. In reality the current draw varies between tubes and those tubes' operating points in any given circuit. In the Model One, typical drops across the preamp plate resistors are, indeed, in the 45V to 50V range.



Ex. 1c) If the power amp stage cathode resistor R10 measures 150 ohms and the voltage drop across that resistor measures 8.25V, how much current is the tube pulling?

```
R = 150R
E = 8.25V
I = E / R
I = 8.25V / 150R = ~0.055 = 55mA
```

(For future reference, in a 6BQ5/EL84 with the plate at 250V and the screen just below that, ~5mA of that 55mA is screen current.)

While technically resistance applies to DC voltages, the formulas here work identically for impedance (resistance to alternating current, see below).

As you use the formulas, pay attention to the relationships between the values. Over time you will get a feel for these and they will be very helpful. For instance **(1b)** tells us that for a constant voltage, as the resistance goes up, the current must come down, and as the resistance goes down, the current must come up. If we vary the current, the resistance likewise varies in an inverse manner. Look for the relationships in all things mathematical, not just here.

[Ohms Law Triangle]

JOULE'S LAW

Another very commonly used equation is Joule's Law, often termed the power equation:

(2a) `P = E * I`

One common use is to determine the static plate dissipation of a circuit, especially a power amp. If the plate voltage of a 6BQ5/EL84 is 250V and the plate current is 50mA, how much power is the plate dissipating?

Ex. 2a)
```
E = 250
I = 50mA = 0.05
P = E * I
P = 250 * 0.05 = 12.5 watts
```

Sometimes you don't know both the voltage and current, but you do know one of these and a resistance (or impedance, see below) value. In these cases, you could determine the missing value from the two values you have using the appropriate version of Ohms Law above. But if you don't need to know that value, you can always substitute for the missing value based on Ohms Law:

(2b) `P = E * I and E = I * R so P = (I * R) * I = I^2 * R`
(2c) `P = E * I and I = E / R so P = E * (E / R) = E^2 / R`

The “^” symbol designates “raised to the power of”. So E^2 is read as “E squared”.

For quick examples, let's use the numbers in the corresponding examples from Ohms Law (**1b** and **1c**):

Ex. 2b)
```
P = I^2 * R = 0.0005^2 * 100,000 = 0.025 watt = 25mW
P = E * I = 50 * 0.0005 = 0.025 watt = 25mW
```

Ex. 2c)
```
P = E^2 / R = 8.25^2 / 150 =~ 68 / 150 = ~0.45 watts
P = E * I = 8.25 * 0.055 = ~0.45W
```

resistors typically come in 1/4W, 1/2W, 1W, 2W, 3W, 5W and 10W ratings (there are larger ones as well). We need to pick resistors that can dissipate at least the power we calculated. It's a good idea to use something larger than the minimum you can get by with; otherwise surges, defects, and/or environmental issues such as heat buildup in a chassis can cause the resistor to exceed its rating and self-destruct. So in examples **2b** a 1/4W or 1/2W would be more than sufficient; a 1W should be enough for example **2c**, with a 2W having an even better safety margin.

The author has long speculated that part of the tonal “warmth” of classic tube amps is a function of how the components act as the amp heats up due to trapped heat from the tubes.

Standard engineering practice is to double the expected power due to the thermal coefficient of resistance. Resistance is a function of temperature, and by joule heating, a function of power dissipation.

[Ohms Law Wheel]

POWER: AREA UNDER THE CURVE

[DC vs AC power on plates]

AC VS DC AND RMS

The following discussion applies to voltage, current and power but we will focus on voltage for purposes of discussion. Voltages are typically described as DC voltages, AC Peak voltages (0 to peak), AC peak to peak voltages (negative peak to positive peak), or RMS (root-mean-square) voltages, which are a kind of average equivalent for AC voltages. The latter (RMS) is the most common method of referring to AC voltages. The calculations for converting between peak and RMS voltages below refer to sine waves only; the values for triangle, square and other wave shapes are different. Meters typically measure AC as RMS voltages.

Conversion between sine wave voltages is straight-forward. To convert from peak voltage (either side on an AC voltage from 0 to peak or the voltage out of an unfiltered, full wave rectifier) to RMS voltage we just multiply by $\frac{1}{\sqrt{2}}$ or 0.707:

(3a) `Erms = Ep * 0.707`

Ex. 3a) If we measure a 353V peak before the rectifier diodes, what is our RMS voltage?

`Erms = Ep * 0.707 = 353 * 0.707 = ~250V`

Conversion of peak to peak voltages is half that, which is the same as multiplying by $\frac{1}{2\sqrt{2}}$ or 0.354:

(3b) `Erms = Epp * 0.354`

Ex. 3b) If we measure a 705V peak to peak to peak sine wave before the rectifier diodes, what is our RMS voltage?

`Erms = Epp * 0.354 = 705 * 0.354 = ~250V`

To convert from RMS to either peak voltage, we can divide by the same constants or multiply by their reciprocals.

(3c) Ep = Erms / 0.707 or Erms * $\sqrt{2}$ = Erms * 1.414
(3d) Epp = Erms / 0.354 or Erms * $2\sqrt{2}$ = Erms * 2.828

Ex, 3c/3d) If we use an oscilloscope or meter capable of such measurements to observe the peak AC voltage from the wall, what would that voltage be? What about peak to peak?

Wall Voltage Conversions				
RMS	**Peak**		**Peak to Peak**	
120	Ep = 120 / 0.707	170V	Epp = 120 / 0.354	339V
240	Ep = 240 / 0.707	339V	Epp = 240 / 0.354	678V

RMS Details

The above formulas are great for sine waves, but they're really just shortcuts. They derive from the RMS (Root Mean Square) formula. RMS is really based on statistical sampling, so it will work for other wave forms as well. The general equation for RMS is:

(3e) $Erms=\sqrt{[E^2]}$ *where [] denotes the arithmetic mean.*

The arithmetic mean is a simple average, where you add up a list of numbers and divide by the number of numbers in the list:

(3f) $$x=\frac{x1+x2+x3\ldots+xn}{n}$$

so we may expand **(3e)** to

(3g) $$Erms=\sqrt{\frac{E1^2+E2^2+E3^2\ldots+En^2}{n}}$$

This formula in turn is really an approximation of a calculus function which we won't worry about.

Statistical sampling in this case would mean checking the voltage over time and saving the readings. For accuracy, you need to check the voltage very frequently. But there's no real reason to get into that level of detail in the work we're doing with amps. If you care about an RMS value, say, observed on a scope, you can always estimate based on the closest wave form type from the following table.

Conversion Multipliers for Wave Shapes			
Conversion	**Sine Wave**	**Square Wave**	**Triangle Wave (Isoceles)**
Peak to RMS	0.707	1.0	0.58
RMS to Peak	1.414	1.0	1.73

[Plates: AC vs DC voltage, how AC P-P swings to supply]

POWER SUPPLY RATINGS

The value of a DC voltage produced by a power supply will vary depending on the type and efficiency of the filters, as well as the load on the power supply.

[FILL IN WITH DRAWINGS OF TYPES OF RECTIFIERS AND FILTERS]

For the best tool around for learning about power supplies and how things work within them, download a copy of Duncan Munro's excellent PSU Designer at http://www.duncanamps.com/psud2/index.html . (This only works with Windows, sadly, but is good enough that I keep a Windows system around just to run this and Duncan's Tone Stack Calculator available at the same web site.)

RESISTANCE, REACTANCE AND IMPEDANCE

Resistance, per se, applies only to DC. The AC equivalent is impedance. While we typically refer to impedances in ohms, as if they were simple resistances, they really have two components, a resistive component and a reactive component, referred to as reactance, which arises from capacitance or inductance in a circuit.

Electrical resistance is defined as impeding the flow of electricity. Everything can be considered to have resistance, even conductors. The wires we use in building amps have resistance, albeit usually so little compared to everything else that we don't care.

An impedance, Z, is formally defined as

(4a) $Z = R + jX$

where j is the imaginary number $\sqrt{-1}$ and R and X are the resistive and reactive components.

At the frequencies used in guitar amps, given the values of the capacitors and inductors (chokes, transformers) we use, the resistive component is usually negligible, and we can pretend that the reactive component X is the actual impedance Z. (Actual resistive components tend to vary according to component construction details, as well.)

Capacitance and Impedance

Capacitive reactance Xc is inversely proportional to the signal frequency f and the capacitance C according to the formula:

(4b) $Zc \approx Xc = 1 / (2 * \pi * f * C)$

A capacitor is formed when two conductors parallel each other and an electrical charge forms across them. The ability to store a charge in this fashion is called capacitance. Technically, capacitance is the ratio of stored charge to voltage. Besides the components we call capacitors, any two parallel wires, leads, or other surfaces carrying electrical charges have a capacitance. There is even capacitance between the internal components in a tube, such as the plate and grid. These are very small but have a slight effect on tone as they form RC networks with both internal tube impedances and external circuit components.

At lower frequencies, a capacitor tends toward being an open circuit, at higher frequencies it tends toward being a short circuit. Capacitors block DC and pass AC, passing higher frequencies better than low.

To get a feel for how impedance changes with frequency and capacitance, let's look at how well various capacitors shunt standard power supply frequencies to ground. We'll evaluate at 100Hz and 120Hz (the doubled frequency rates of standard wall power frequencies, coming out of a full wave rectifier). Older amps typically had first filter caps of 10µF or 20µF. Today's solid state rectifiers are far more likely to use 47µF or 100µF caps, so we'll evaluate for all of these.

Ex. 4b) $Z = 1 / (2 * \pi * f * C)$

Frequency	10µF	20µF	47µF	100µF
100Hz	159Ω	79Ω	34Ω	16Ω
120Hz	132Ω	66Ω	28Ω	14Ω

A tenfold increase in capacitance is accompanied by a tenfold decrease in impedance at the same frequency. A basic inspection of the equation tells us that if the capacitance is invariant, a tenfold increase in frequency would likewise result in a tenfold decrease impedance.
NOTE: A properly functioning capacitor has an infinite resistance to DC since DC has a frequency of 0:

(4d) `Zdc = 1 / (2 * π * 0 * C) = 1 / 0`

Regardless of the capacitor value, you still end up dividing by 0, which gives an infinite result.

[Add example using Kalamazoo tone stack.]

Inductance and Impedance

Inductance is the ratio of a magnetic flux to the current causing it. At audio frequencies, this primarily occurs in coils of wire, especially those wound around an iron core. Inductive reactance Xl is directly proportional to the signal frequency f and the inductance L according to the formula:

Inductors found in tube guitar amps are primarily chokes, for power supply smoothing, and transformers, for changing voltage and current to values more appropriate, or for impedance matching. Some multi-band equalizers also include smaller inductors.

(4e) `Zl =~ Xl = 2 * π * f * L`

At lower frequencies, an inductor tends toward being a short circuit, at higher frequencies it tends toward being an open circuit. Thus inductors pass DC and tend to resist AC, passing lower frequencies better than high frequencies.

To get a feel for how impedance changes with frequency and inductance, let's look at how well various inductors shunt standard power supply frequencies to ground. We'll evaluate at 100Hz and 120Hz (the doubled frequency rates of standard wall power frequencies, coming out of a full wave rectifier). We'll try some common values of 1H, 4H, 10H and 12H.

Ex. 4e) `Z = 2 * π * f * L`

Frequency	1H	4H	10H	12H
100Hz	628Ω	2.5k	6.3k	7.5k
120Hz	754Ω	3k	7.5k	9k

A tenfold increase in inductance is accompanied by a tenfold increase in impedance at the same frequency. A basic inspection of the equation tells us that if the inductance is invariant, a tenfold increase in frequency would likewise result in a tenfold increase in impedance.

NOTE: A properly functioning inductor has a 0 resistance to DC since DC has a frequency of 0:

(4d) $Zdc = 2 * \pi * 0 * L$

Regardless of the inductor value, you still end up multiplying by 0, which gives a 0 result.

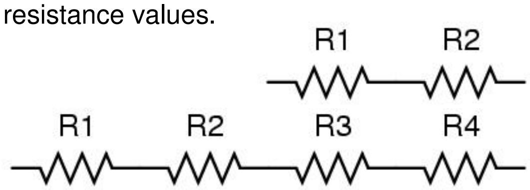
[Markus recommends a practical example.]

SERIES AND PARALLEL RESISTANCE

NOTE: The following applies equally to impedances.

Resistances in Series

To determine the resistance of resistors in series, you just add the resistance values.



(5a) $R = R1 + R2$

This applies no matter how many resistors you have in series.

(5b) $R = R1 + R2 + R3 + R4 \ldots$

For instance, if you connect a 100K resistor and a 220K resistor in series, you get 320K.

Ex. 5a1) $R = 100k + 220k = 320k$

If you need a value you don't have, you can put smaller values in series to get it. For instance, if you need a 200k resistor, you can use two 100k resistors:

Ex. 5a2) $100k + 100k = 200k$

You could also use four 47k resistors as an approximation (or four 47k resistors and a 10k resistor to get closer):

Ex. 5b) $47k + 47k + 47k + 47k = 188k$
$47k + 47k + 47k + 47k + 10k = 198k$

Each resistor will have the same current through it, but each resistor's voltage drop will be proportional to its share of the resistance.

(5c) $Er1 = Er * (R1 / R)$ *where R is the total resistance from* ***(5a)***
$Er2 = Er * (R2 / R)$

For example, if you have 300V going through a 100k resistor (R1) and a 220k resistor (R2) connected in series

Ex. 5c1) $Er1 = 300 * (100k / 320k) = 300 * 0.3125 = 93.75V$
$Er2 = 300 * (220k / 320k) = 300 * 0.6875 = 206.25V$

The sum of the voltages thus equals the original voltage, just as the sum of the resistances equals the overall resistance:

Ex. 5c2) `93.75V + 206.25V = 300V`

From **(5c)** we know the ratio of voltages across resistors in series is proportional to the ratio of the resistances:

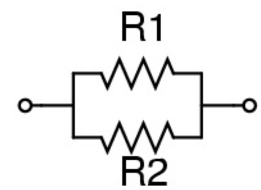
(5d) $$\frac{E1}{R1}=\frac{E2}{R2} \quad \text{and} \quad \frac{E1}{E2}=\frac{R1}{R2}$$

This applies whether R1 and R2 are two resistors, or one resistor and a total resistance value. The same applies to the voltages.

For any number of resistances, if the values are the same, we can just multiply:

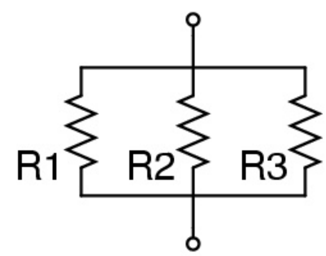
(5e) `R = R1 * N`

Resistances in Parallel



This is a bit more complex. The general equation for paralleled resistors is the reciprocal of the sum of the reciprocals of the resistances. If that sounds complicated, just remember what the formula looks like:

(5f) $$R=\frac{1}{\frac{1}{R1}+\frac{1}{R2}+\frac{1}{R3}}$$



This works regardless of how many resistances you are paralleling.

Let's say you want to parallel three 6BQ5 output tubes for a souped up Model One, and you want to know the total plate resistance if each tube's plate resistance at 250V is 38K:

Ex. 5f) $$R=\frac{1}{\frac{1}{R1}+\frac{1}{R2}+\frac{1}{R3}}=\frac{1}{\frac{1}{38\text{k}}+\frac{1}{38\text{k}}+\frac{1}{38\text{k}}}=\frac{1}{0.000026+0.000026+0.000026}=12667$$

When you are just paralleling two resistances, you can simplify this to

(5g) $$R=\frac{R1\times R2}{R1+R2}$$

If, for instance, you want to run parallel preamp triodes, you could give each triode its own plate resistor of 100k, or you could connect the plates and use one resistor with a value equivalent to two 100k resistors in parallel:

Ex. 5g1) $$R=\frac{100\text{k}\times100\text{k}}{100\text{k}+100\text{k}}=\frac{10000\text{M}}{200\text{k}}=50\text{k}$$ *(47k is the closest standard value)*

(Just remember that you have now doubled the current through this resistor, and recalculate the resistor's wattage rating.)

The formulas apply with unequal resistances as well. For instance, if we want to drop the value of a cathode resistor just a little from 1.5K, we might see what effect paralleling a 10K resistor has:

Ex. 5g2) $$R=\frac{1.5\text{k}\times10\text{k}}{1.5\text{k}+10\text{k}}=\frac{15\text{M}}{11.5\text{k}}=1300\text{R}$$

If we wanted a specific value near this one, we could also try the equation with the nearest, standard value resistors above and below the 10K to see what we came up with. How does changing any of these values change the overall value in relation to the other resistor *(more relationships!)* ?

- Going higher on either value raises the overall value.
- Going lower on either value lowers the overall value.
- Changing the smaller value impacts the overall value the most.
- Changing the larger value impacts the overall value the least.
- The greater the difference in values, the more the lower value dominates the overall result, and vice versa.
- The greater the difference in values, the more changing the lower value dominates the overall change, and vice versa.

Each resistor will have the same voltage through it, but each resistor will carry current proportional to its resistance per Ohms law.

When the values of all the resistances in parallel are the same, the result simplifies to the value of one resistor divided by the number of resistors paralleled:

(5h) $$R=\frac{R1}{N}$$ *where N is the number of resistors in parallel*

Let's rework example **5g1** using this formula:

Ex. 5h) $$R=\frac{100\text{k}}{2}=50\text{k}$$

The standard symbol for two resistances or impedances in parallel is two vertical bars. So if we wanted to reference “R2 paralleled with R3” in an equation, we would write R2||R3 .

Wattage in Series and Parallel

Until now, we have looked only at the resistance, But how does this affect wattage? It doesn't really; the wattage per resistor is computed using Joule's law. But there are times we need a specific wattage rating in a resistor and don't have it; what do we do then?

The simplest thing is to build a resistor pack with the appropriate rating from similar resistors. For instance, if we need a 100K resistor with at least a 3W rating, but only have 2W resistors available, what can we do?

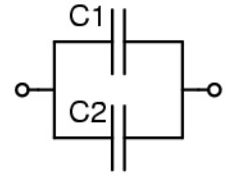
We know that if we have two resistors of the same value, then putting them in series doubles that value, and putting them in parallel halves that value. So we start by seeing if we have two 50K 2W resistors (probably 47K or 56K) to use in series, or if we have two 200K resistors to use in parallel. In either case since the resistors have the same value, they will have the same voltage drop across them. Since the same current will flow through each resistor, the wattage dissipated will be the same. In either case it will be half of what we would see with a single resistor, so we can use whichever we have the resistors for as each will dissipate ½ of 3W, or 1.5W.

If we do not have identical resistors, we can try to find values we can put in series or parallel to make the value we want. Just recall that in series they will have the same current but different voltages across them, but in parallel the voltages are the same but the current varies. We can then apply equation **(2a)**, **(2b)** or **(2c)** based on the values we have available, and determine the power each resistor must dissipate.

SERIES AND PARALLEL CAPACITANCE

While the formulas above work for impedance as well as resistance, sometimes we just want to know the value of capacitors in series or parallel.

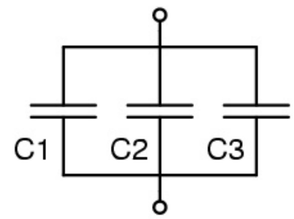
Capacitors in Parallel



When you put capacitors in parallel, you just add the capacitance values.

(6a) $C = C1 + C2$

For instance, we might want to double up or triple up the second stage capacitance in a Kalamazoo power supply to reduce hum:

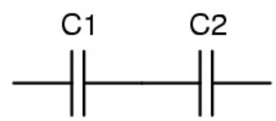


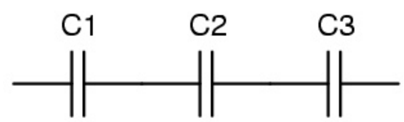
Ex. 6a) $C = 10\mu F + 10\mu F = 20\mu F$
$C = 10\mu F + 10\mu F + 10\mu F = 30\mu F$

Each capacitor will have the same voltage across it. Since there is no actual current flowing in a properly operating capacitor, we don't usually worry about that. The one place we may care is in power supplies. A large capacitor can look reasonably close to a short circuit at low frequencies, so we may need to deal with the current flowing in and out of the capacitor as if it were flowing through the capacitor. The current increases proportionally with the size of the capacitor, and inversely proportionally to frequency. You can work this out for yourself with ohms law.

Capacitors in Series

The capacitance of capacitors in series is computed using the same approach as for paralleling resistors. The general equation for series capacitance is the reciprocal of the sum of the reciprocals of the capacitances:





(6b)
$$\frac{1}{\frac{1}{C1}+\frac{1}{C2}+\frac{1}{C3}}$$

This works regardless of how many capacitors you are paralleling.

Each capacitor in series should see the same voltage potential across it. The most common use of series capacitors in guitar amps is to provide a higher working voltage, usually in a power supply.

For instance, if you need a 600V cap, but all you have are 500V caps, you can use two or more of these in series to get the voltage rating you need. For instance, if you want ~47µF/300V on the first PS stage, but all you have are

200V caps, can you use them? The answer is yes, if you have 100µF caps:

Ex. 6b1) $$C=\frac{1}{\frac{1}{100u}+\frac{1}{100u}}=\frac{1}{0.01+0.01}=\frac{1}{0.02}=50uF$$

Note that we did this using consistent units, µF (microFarads). We can as easily do this with decimal numbers, after determining that 100µF is the same as 0.0001F:

Ex. 6b2) $$C=\frac{1}{\frac{1}{0.0001}+\frac{1}{0.0001}}=\frac{1}{10k+10k}=\frac{1}{20k}=.00005=50uF$$

Since each of these gets an equal share of the voltage, we can easily compute the voltage per capacitor Ec:

(6c) $$Ec=\frac{E}{N}$$ *where E = total voltage, N = number of caps*

Applying this to example **6b1**, we get:

Ex. 6c) $$Ec=\frac{300}{2}=150V$$ *150V / capacitor is well within the 200V ratings*

This would remain true even if each capacitor had a different voltage rating! In that case you would need to make sure that Ec did not exceed the voltage of the lower rated capacitor.

In this case, it's a good idea to place a resistor in parallel with each capacitor to help equalize the voltage. In power supplies (the main place this happens in guitar amps), 220k is is a good value to start with if you aren't sure what to use. If the caps are of different voltage ratings you should probably use resistors of different sizes, in direct proportion to the voltage ratings of the caps. For instance, if you were putting a 200V cap and a 350V cap in series, you might use 220K and 330K resistors.

When you are just using two capacitors in series, you can simplify equation **6b** to

(6d) $$C=\frac{C1*C2}{C1+C2}$$

Let's rework example **(6b1)** using this equation:

Ex. 6d) $$C = \frac{100u * 100u}{100u + 100u} = \frac{10000u}{200u} = 50u$$ *(47µ is the closest standard value)*

When the values of all the capacitances in series are the same, the result simplifies to the value of one capacitor divided by the number of capacitors in series:

(6e) $$C = \frac{C1}{N}$$ *where N is the number of capacitors in series*

Let's prove that this works for the previous example:

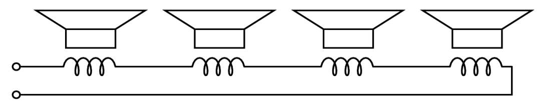
Ex. 6e) $$C = \frac{100u}{2} = 50u$$

While we used examples with identical capacitances, the formulas apply with unequal capacitances as well.
See the final example under "Resistances in parallel" for an example.

SERIES-PARALLEL AND PARALLEL-SERIES

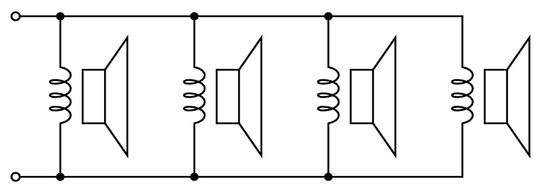
Sometimes we have a network of components involving both parallel and series connections. The most common case we care about involves speaker cabinets. With just two speakers, they must be in either parallel or series. When more than two speakers are involved, there are more possibilities for wiring them. These extra possibilities are series-parallel and parallel-series.

We will start with the common problem of connecting four speakers. First, let's revisit what happens if we connect them all in series or parallel.



Resistances in series simply add (or we can multiply by the number of resistances if the values are the same). If we put four 4Ω speakers in series we get a 16Ω load.

Ex. 8a) $R = 4 * 4 = 16$

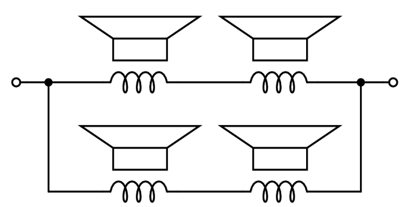


If we put those four 4Ω speakers in parallel, we get 1 ohm.

Ex. 8b) $R = 4 / 4 = 1$

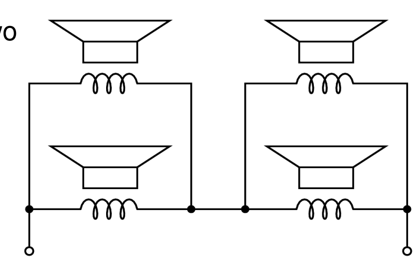
The first example might be useful, but the second almost certainly wouldn't be. There are plenty of amps looking for a 16Ω load, but I've never run across a guitar amp expecting a 1Ω load. A possible exception would be a requirement for an impedance mismatch (see *Transformer ratios* below).

Is there any other load we can get with these speakers? Yes, we can get a 4 ohm load by using either series-parallel or parallel series.



In the first example, we hook two speakers in series, then hook the other two in series, then wire the two sets in parallel.

Ex. 8c)
$$R = (R1 + R2) \,||\, (R3 + R4)$$
$$R = (4 + 4) \,||\, (4 + 4) = (8 \,||\, 8)$$
$$= 8 / 2 = 4\Omega$$



We can also hook the speakers up in parallel-series. In this case we hook two speakers in parallel, hook the other two speakers in parallel, then wire both sets in series. The resulting impedance is identical.

Ex. 8d)
$$R = (R1 \,||\, R2) + (R3 \,||\, R4)$$
$$R = (4 \,||\, 4) + (4 \,||\, 4) = (4 / 2) + (4 / 2)$$
$$= 2 + 2 = 4\Omega$$

Both configurations have the same result- the impedance of a single speaker.

Summary impedance table for 4 speakers	
Configuration	**Impedance**
Series	Z * 4
Parallel	Z / 4
Series-Parallel	Z
Parallel-Series	Z

We must also consider the wattage. If all four speakers can handle the same wattage, then the total wattage is 4x the wattage of one speaker. This is because each speaker dissipates the same wattage. The ugly corollary is that if the speakers cannot handle the same wattage, the total wattage the set can handle is 4x the *lowest* wattage rating. This means that if you have 4 100W speakers, you can connect them any of these four ways and they will handle 400W (`4 x 100W`). But if three of them are 100W and one is 25W, the set can only handle 100W (`4 x 25W`) regardless of which way they are wired. If you doubt this, I encourage you to do the math yourself, using any voltage, current and impedance values you choose. *(Personally, I'd use 10V, 1A and 10Ω just to keep the math simple.)*

If the impedance of all the speakers is not the same, the math is more complex. You'll need to do the math for each set of parallel or series speakers, then compute the series or parallel results respectively. You wouldn't normally do this but it can be useful in some cases, such as when:

- the only speakers available are mismatched
- it helps match speaker wattage to usage
- you want to use an odd number of speakers

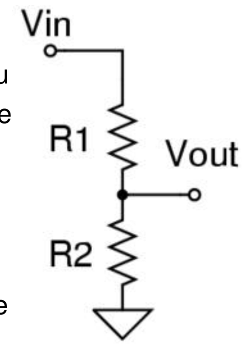
In each case, draw out the configuration, determine the parallel and series segments, and do the math.

Speaker Efficiency

[efficiency vs wattage]

VOLTAGE DIVIDERS

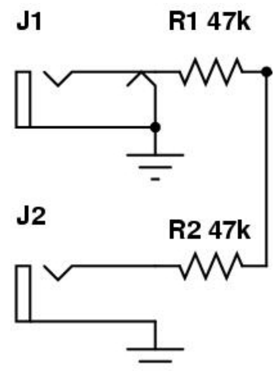
[Intermission with application of several things we've learned]



One common form of series resistances used in guitar amplifiers is the voltage divider. You should recall that the voltage drop across resistors in series is proportional to the ratio of the resistances. We can use this to determine a voltage at a divider midpoint, or to design a divider to get a certain voltage (assuming a constant current load).

Input dividers (a simple example)

First, let's determine a voltage based on the values of two resistances. A common example comes from the way most guitar amp inputs are wired. Typically these are wired so that one input provides full voltage, but plugging into a different input might utilize a voltage divider for a lowered input voltage.



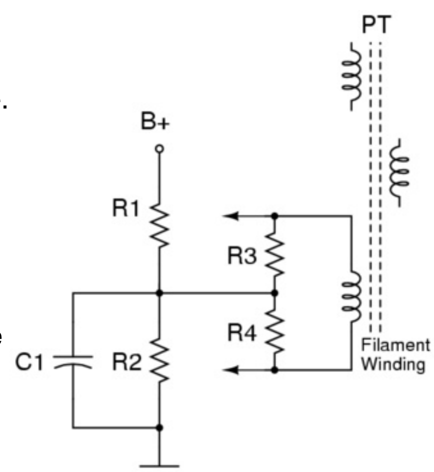
Consider the Model One's inputs; plugging into input one gives you full voltage. The resistor attached to input two is not in the circuit as it's not grounded. But plugging into just input two sends the voltage through R2 and R1 to ground, with a tap in the middle feeding the preamp. How does this affect the input voltage?

The voltage across either resistor is proportional to that resistor's percentage of the total resistance. Since we don't know the actual voltages, we'll just use the percentages for now. (We'll use E in the equation, but still reference percentages.)

Ex. 7a)
$$R = R1 + R2 = 47k + 47k = 94k$$
$$Er1 = E * (R1 / R) = 100\% * (47k / 94k) = 100\% * 0.5 = 50\%$$

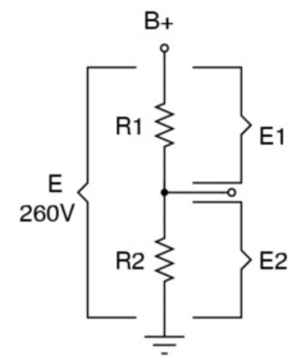
So whatever the input voltage is, we end up with 50%, or 1/2 of it, going to the grid of the preamp. A typical guitar pickup signal is 100mV; 50% of 100mV would be 50mV.

Heater Bias Divider (a thorough example)



We can also use this to design a voltage divider to give us a certain voltage. One common example is to provide a DC elevation for a heater circuit for hum reduction. The best hum reduction is often found with DC elevation over 50V. Where can we get 50V? We can use a voltage divider to get it anywhere we have a higher voltage! A common place to get this voltage is off the first B+ tap. In the Model One that is around 260V. Let's say you want to use a 75VDC heater elevation (more than 50V, but safely within the 100V maximum difference between cathode and heater of a 6BQ5/EL84.

The voltage divider in question is comprised of resistors R1 and R2. (C1 is there just to make things as hum free as possible, and doesn't really affect the voltage value.) The 75V will therefore be across R2 so let's call it E2. So long as the ratio between the resistors corresponds to the ratio between the voltages we want, any values of resistors will do. The limiting factor is current; if we make the resistors too small, the circuit approaches a short circuit. We don't want much current to flow, so we arbitrarily plan for 1mA through these resistors as it makes the calculations easier. Ohms law gives us the total resistance R (R1 + R2) across the divider:



Ex. 7b) R = E / I = 260V / .001 = 260,000 = 260K

From this total resistance we can determine the individual resistances using the total voltage (260V) and then the voltage ratio of the desired voltage (75V) to the total voltage (260V):

Ex. 7c) R2 = R * (E2 / E) = 260k * (75 / 260)
= 260,000 * 0.288 = ~74,880 = ~75k

Using the series resistance equation **(5a)** we can determine the other resistor's value:

Ex. 7d) R = R1 + R2 so R1 = R - R2 = 260k - 75k = 185k

75k is a common resistor value (yay!) but 185k is not. In fact the closest value is 200k. What would that do to our voltage?

Ex. 7e) R = R1 + R2 = 75k + 200k = 275k
E2 = E * (R2 / R) = 260 * (75k / 275k) = 260 * 0.27 = 70V
which is close enough (especially since we picked the voltage arbitrarily from a range!)

If we want to bring that voltage back up a bit, how can we do it? Since the voltages are proportional to the resistance values, we can increase the bottom voltage by either increasing the bottom resistor value or decreasing the top resistor value. Let's try increasing the bottom value first. The next common value up is 82k.

Ex. 7f) R = R1 + R2 = 82k + 200k = 282k
E2 = E * (R2 / R) = 260 * (82k / 282k) = 260 * .29 = 75V - *Bingo!*

Alternatively what happens if we lower the value of the top resistor to the next lowest, common value (150k)?

Ex. 7g) R = R1 + R2 = 75k + 150k = 225k
E2 = E * (R2 / R) = 260 * (75k / 225k) = 260 * .33 = 86V

This is still OK, especially since the cathode is really elevated by 7V to 8V, which reduces the potential difference (which we've ignored until now). The only downside is that by reducing the overall resistance we upped the current slightly.

Ex. 7h) I = E / R = 260V / 225k = 260 / 225,000 = 0.00116 =~ 1.2mA

This difference is negligible.

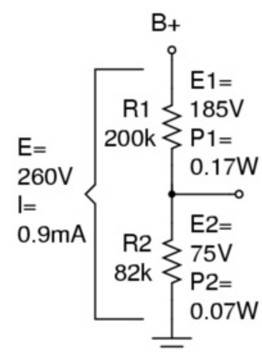
We can pick any of these, but let's pick the 82k/200k version. (Why? Why not?)

We also need to consider what power rating these resistors need. We can get the current and we know most of the voltages, so we can easily get the missing voltage. Remember from example **7f** that these resistances give us 75V for E2.

The current will be the same through both resistors, so we only need to compute it once:

Ex. 7i)

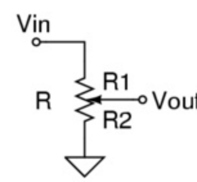
```
I = E / R = 260 / 282k = 0.0009 = 0.9mA
E1 = E * (R1 / R) = 260 * (200k / 282k) = 260 * 0.71 =~ 185V
P1 = E1 * I = 185V * 0.9mA = 185 * 0.0009 =~ 0.17W
P2 = E2 * I = 75V * 0.9mA = 75 * 0.0009 =~ 0.07W
```



So we can get by with 1/4W resistors, but 1/2W or 1W are more common in the tube amp world and provide an extra safety margin against surges.

Pots as Voltage Dividers

A potentiometer, or pot, is a variable resistor. In most cases, it is wired as some form of voltage divider. A volume control is typical of this. The resistance across the end terminal of the pot R is divided into two resistors R1 and R2 by the wiper. As you can see in the schematic to the right, a typical volume control looks similar to the voltage divider from the previous example.



Ratios and Percentages

When referring to a voltage divider, we often refer to the ratio between the resistors or voltages. For the voltage divider biasing the filament circuit, we get:

Ex. 7j) $$\frac{E1}{E2}=\frac{185}{75}=\frac{2.5}{1}=2.5:1$$

We also refer to voltage dividers as ratios compared to their wholes, or as percentages. In the above example, what is the output voltage Eo expressed as a ratio or percentage of the input voltage Ei (the whole)?

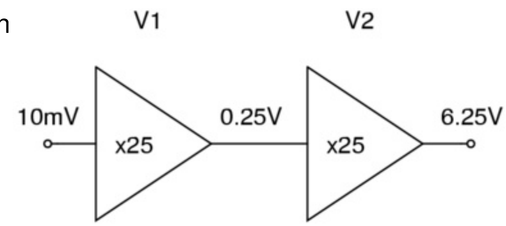
Ex. 7k) $Eo=\frac{75}{260}=\frac{2}{7}=0.29$ = 29% of Ei (For Ei of 260, Eo = 0.29 * 260 = ~75V.)

CIRCUIT GAIN

Voltage gains in series multiply. So if you have one preamp circuit following another preamp circuit, the total voltage gain A will be the gain of the first stage ($A1$) times the gain of the second stage ($A2$). If there are more than two stages, the gain continues to multiply.

(8a) $A = A1 * A2$
(8b) $A = A1 * A2 * A3 \ldots$

Each of the preamp stages in the Model One has a fairly modest gain of 25, so the total preamp gain is 625.



Ex. 8a) $A = 25 * 25 = 625$

As seen in the block diagram of the circuit, we can thus calculate the actual signal voltage at any stage if we know the input voltage. A modest signal from a single note or lightly played chord might only produce 10mV from the guitar pickup. After the first stage this becomes 250mV.

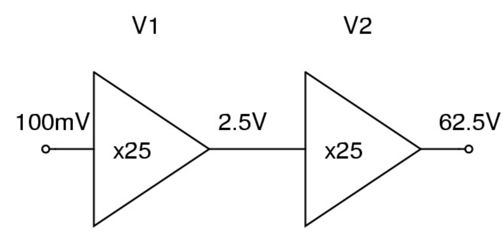
> *V1 and V2 represent tubes in schematics. I don't know why V is used for that; perhaps it stands for "vacuum tube".*

Ex. 8a1) $Vo = Vi * A1 = 10mV * 25 = 250mV$

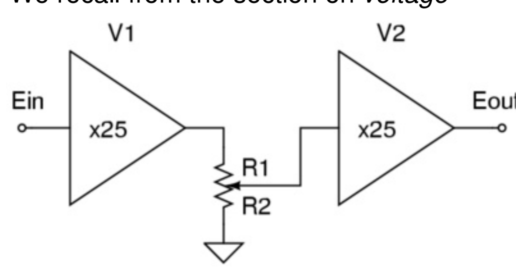
After the second stage this is 6.25V.

Ex. 8a2) $Vo = Vi * A2 = 250mV * 25 = 6250mV = 6.25V$

This turns out to be the maximum signal for the 6BQ5 grid at our operating point (conveniently the default given in every 6BQ5 data sheet on the planet!) to drive the tube to full power without appreciable distortion. Since most guitars today are capable of well over 100mV output, it should be clear why the Model One can produce lots of crunchy attitude!



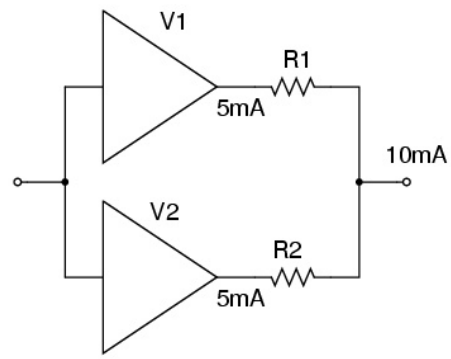
In reality there is some loss between stages; the coupling cap and grid reference resistors act as frequency dependent voltage dividers. We'll come back to that briefly in the section on *high and low pass filters*. Additionally, we can add voltage dividers between the gain stages. We recall from the section on *voltage dividers* that a volume control is a voltage divider. How does the volume control affect the overall gain?



At its minimum setting, the volume control lets 0% of the signal through. At maximum, it lets 100% through. At its measured midpoint, it lets 50% through. To see the impact of these settings on overall gain we convert each percentage back to a decimal number (this is done by dividing the percentage by 100) and multiply that by the previous stage. Let's call this the reduction factor.

(8c) $A = A1 * R\%/100 * A2$

Gain 1	Reduction Factor	Gain 2	Overall Gain
25	0	25	0
25	0.5	25	312.5
25	1.0	25	625



Current gains in series multiply as well, but in general a guitar amp is a voltage multiplier; exceptions are generally driver stages, including the power amplifier, reverb drivers, and cathode followers. If you ever cascade current amplifiers, just remember the concepts are the same as for voltage multipliers.

Voltage gain stages in parallel don't multiply or even add; the signals superimpose on one another. In this case, however, current *does* add. If you have two stages in parallel with the same signals, each producing 5mA, you will have 10mA driving the next stage. But the voltage gain will be exactly the same as if you had only one stage.

TRANSFORMER RATIOS

Transformers are named so because they transform the values of an AC current. They transform voltage, current and impedance, though we are typically only thinking of one or two of these at a time. A given transformer does these things at a specific ratio, which is dependent on the number of turns in each winding.

A ratio is just a way to look at how two numbers relate proportionately. A 10 to 1 ratio (written as 10:1 or 10/1) means 10 of something versus 1 of something. A transformer with a 25:1 winding ratio has 25 times as many windings on the primary as it has on the secondary.

With a power transformer (a.k.a. mains transformer), we are primarily concerned with transforming voltage. With a driver (output or reverb) transformer we are mainly concerned with the impedance ratio. (In reality, they all interact.)

For our purposes, the only electrical parameters that are fixed are the maximum voltage and current each winding can handle. When we speak of a 120V power transformer (PT), we simply mean a transformer designed to handle 120V into the primary. The term doesn't mean anything else; we still have no idea how much current it can handle, or what voltages come out of the secondaries. It's a handy label, not a real definition of the transformer. People often ask what impedance their output transformer (OT) has, but a transformer doesn't have an impedance, per se. It has an impedance ratio.

Voltage Ratios

The voltage ratio of a transformer is directly proportional to the turns ratio. A transformer with 1,000 turns on the primary side and 200 turns on the secondary side has a turns ratio of 5 to 1, which we write as 5:1. This tells us that the voltage ratio is also 5:1 since they are proportional.

(9a) $$\frac{Ein}{Eout}=\frac{Nin}{Nout} \quad \text{or} \quad \frac{Ein}{Nin}=\frac{Eout}{Nout}$$

So if we know the input voltage we can determine the output voltage, and if we want a specific output voltage we can determine what the input voltage needs to be.

(9b1) $$Ein=Eout*\frac{Nin}{Nout}$$

(9b2) $$Eout=Ein*\frac{Nout}{Nin}$$

Conversely if we know the turns on one side, and both voltages, we can determine the turns on the other side.

(9b3) $$Nin = \frac{Nout * Eout}{Ein}$$

(9b4) $$Nout = \frac{Nin * Eout}{Ein}$$

It may seem like we don't really care about this unless we are winding our own transformers, but sometimes we do. For instance, people are often confused as to why their heater voltages are higher than they expect (at least in the USA). But applying these principles to the PT based on old and new wall (mains)voltages, it suddenly makes sense.

Older tube amps were designed and built when USA wall voltages were lower than they are today. Most amps from the "Golden Era" were designed around a wall voltage of 117VAC. Today's wall voltage is typically 125VAC. What effect does this have on the filament voltage? We could convert the voltage ratio to a whole number winding ratio, then convert that to a new voltage ratio, but let's just skip the intermediate step: we can go directly from one voltage ratio to a second the same way:

(9c) $$\frac{Ein1}{Eout1} = \frac{Ein2}{Eout2}$$

The same set of variants derive for this as for **(9a)**.

Let's start by coming up with the wall to filament turns ratio for a PT. The old wall voltage was 117, the new wall voltage is 125. The original filament voltage was 6.3 so what should we see today?

Ex. 9b1) $$\frac{117}{6.3} = \frac{125}{E} \quad \text{so} \quad E = 6.3 * 125/117 = 6.3 * 1.068 = 6.7\text{V}$$

Even older transformers were designed when many areas only had 110VAC, resulting in a higher ratio and higher filament voltage today.

Ex. 9b2) $$\frac{110}{6.3} = \frac{125}{E} \quad \text{so} \quad E = 6.3 * 125/110 = 6.3 * 1.136 = 7.1\text{V}$$

These formulas work for any voltages; they apply equally to high voltage windings and to voltages in driver transformers such as OTs.

Current Ratios

Current ratios work just like voltage ratios, only they are inversely proportional to winding ratios. This means they are also inversely proportional to voltage ratios. (If this seems odd just remember that the amount of power out equals the amount of power in (ignoring any losses). Since P = E * I, if P remains the same, I must go down if E goes up, and vice versa.

(9d) $$\frac{Iin}{Iout}=\frac{Nout}{Nin}$$

(9e) $$\frac{Iin}{Iout}=\frac{Eout}{Ein}$$

Part of picking a power transformer is knowing how much current it will have to handle. If we know the current loads of the secondaries, we can determine the current the primary must carry. The Model one has three tubes wired for 6.3V filaments:

Tube	Filament Current
6X4	0.6A
6BQ5/EL84	0.76A
12AX7/ECC83	0.3A

The sum of these currents is 1.66A at 6.3VAC. Measured and derived currents in the amp work out to about 57mA on the high voltage secondary at 500VAC . The pilot lamp is negligible since it's a neon lamp and we'll ignore any losses. So how much current will this amp pull from the wall?

Ex. 9e1) $$Iin=\frac{1.66\mathrm{A}*6.3\mathrm{V}}{117\mathrm{V}}=1.66\mathrm{A}*0.054=0.09\mathrm{A}=90\mathrm{mA}$$

Ex. 9e2) $$Iin=\frac{0.057\mathrm{A}*250\mathrm{V}}{117\mathrm{V}}=0.057\mathrm{A}*2.137=0.122\mathrm{A}=122\mathrm{mA}$$

Adding these together, we get 212mA current drawn from the wall.

One might expect to pull slightly less current at today's wall voltages, but that would assume that filaments behave linearly with voltage changes, and that tubes do as well. Neither is necessarily true, plus we fudged a little; the current draw on the secondaries was measured at today's wall voltage and the filament current assumed the standard filament voltage. The data sheets don't tell us how filament current varies with voltage.

*Just for completeness, we can apply Joule's equation **(2a)** to determine that the Model One pulls ~25W from the wall, even though it only produces 5W to 6W of audio power.*

Remember that voltage ratios and current ratios are inverse. So if you have twice the voltage on the secondary you will have half the current, and vice versa.

Impedance Ratios

If we treat the numbers in a ratio as a division problem, we can always reduce it to N:1. For instance, a 10:5 ratio is 2:1. and a 10:3 ratio is 3.3:1. Remembering this will make the following a bit easier.

Output transformers are the primary place we care about impedance ratios. (A reverb driver transformer is essentially a lower power version of an output transformer. Some Gibson amps used transformers for phase inverters; impedance matching comes into play there as well.) An output transformer (OT) matches the impedance required to properly load the output tubes (typically a few thousand ohms) to the real world load of a speaker or group of speakers (typically between 2 and 16 ohms).

A 6BQ5 at 250V and 50mA on the plate and something close to 250V on the screen should have a load of about 4500 ohms, as specified in the data sheets. This is extremely typical of the Model One, the AX84 P1, and most single-ended 6BQ5 amps. These amps also typically use an 8 ohm speaker. So we know the impedance ratio we need is 4500:8 or 562.5:1 .

If we use a different speaker impedance, it reflects a different load back to the primary in a proportional manner. The reflected ratio is the same; the ratios have to be equivalent. So we just solve by setting one ratio equal to the other.

(9f) $$\frac{Zp1}{Zs1}=\frac{Zp2}{Zs2}$$

Let's say we want to use a 4 ohm speaker on our 4500:8 transformer. Applying equation **(9f)** we get

Ex. 9f) $$\frac{4500}{8}=\frac{N}{4} \quad \text{so} \quad N=\frac{4*4500}{8}=\frac{4}{8}*4500=2250$$

So the impedance ratio is now 2250:4. Yes, this is really the same ratio, but the numbers reflect the impedances the amp “sees” under these conditions. So the load on the 6BQ5 plate with a 4 ohm speaker and this transformer is 2250 ohms. While this is low and will stress the tube a bit, it's still safe. (It's always better to mismatch low with tubes, but high with transistors. With tube amps an open output may be fatal to the amp; with transistors a short circuit across the output is inevitably fatal to the amp.) This is why many builders like to use transformers with multiple output taps; this allows us to use any (standard) speaker impedance we like and keep the correct load on the output tube(s).

Determining a transformer's impedance ratio

The impedance ratio of a transformer is always the square of its winding ratio.

(9g) $$\frac{Zp}{Zs}=\left(\frac{Np}{Ns}\right)^2 \quad \text{or} \quad \frac{Np}{Ns}=\sqrt{\frac{Zp}{Zs}}$$ *where N is number of windings.*

A common problem is determining the impedance ratio of a transformer from a donor amp, or simply one that sat in a drawer or parts box so long we've lost or forgotten the specs. How can we determine this?

1. Induce a known voltage into one winding of the transformer.
2. Measure the voltage induced on the other winding.
3. Write these voltages down as the voltage ratio.
4. Apply equation **(9g)** to get the impedance ratio.

Ex. 9g) We find an amp chassis someone has thrown out. It has no tubes and no markings. The transformer looks big enough to handle maybe 8 to 10 watts, based on others we've seen. We hook the secondary of this OT to the filament winding of a power transformer we have laying around. Using our meter, we measure 6.7V going into the secondary of the mystery OT. Then we measure the output on the primary; we get 201V. The voltage and winding ratios are thus both 201:6.7 or 30:1. We have several speaker cabinets handy; what would be the impedance ratio for each? Using the first form of **(9g)** we get a base impedance ratio of

$$\frac{Z}{1}=\frac{30^2}{1}$$

or 900:1. We can multiple this by each speaker impedance to show the ratio with the corresponding primary impedance. For instance with an 8 ohm speaker, we would

$$\frac{900}{1}=\frac{N}{8} \quad \text{so} \quad N=\frac{900*8}{8}=\frac{7200}{8}$$

or 7200:8 .

2Ω	4Ω	8Ω	16Ω
1800:2	3600:4	7200:8	14400:16

You would then look through tube data sheets to see what this might fit, or you could plot load lines for tubes you want to use and see if they fit with this transformer. For the record, you could probably use this with either a 6BQ5 or 6V6 with the 4 or 8 ohm speaker, though the impedance would be a little high for the 6BQ5. You could probably use a 6L6 with the 2 or 4 ohm cabinets. The rule of thumb is that you can always go up 100% or down 50% safely *so long as you aren't pushing either the tube or OT too hard.*

HIGH, LOW AND BAND PASS FILTERS

- general makeup
- 3db points
- slopes vs components, graphing
- miller capacitance with grid resistors

BIAS

Build on example 1c:

- bias voltage and current
- plate voltage WRT cathode voltage
- wattage across cathode resistor
- tube, plate and screen dissipation
- applying ohm's & joule's laws to cathode resistors in series (w/ pots)

There are several ways to determine bias for a stage:

1. measure / calculate the plate and grid currents
2. measure / calculate the cathode and grid currents
3. the oscilloscope method

We will ignore the third method here as it doesn't really require any math.[1]

Plate and Screen, Current and Power

While you can insert an ammeter and measure DC current directly, most of the time we measure a voltage drop and apply Ohm's Law. For instance, in a stage with a plate load resistor, you measure the drop across the resistor and compute the current from the resistance and voltage. Control grids in these stages typically don't draw enough current to worry about.

In a stage driving a transformer, you can measure the static DC current from a plate to the B+ tap; no math is involved. Do not try to measure AC current this way. Do not play the amp or run a signal through it when measuring the current this way.

In a pentode stage you also measure the screen grid current, typically by measuring the voltage drop across the screen stopper and computing from there. In each case you should compare the measured or calculated current against the specs, then compute the static dissipation and compare that to the specs.

Always start with the published specifications in the data sheets. As you gain experience or grow to trust the experience of others, you may rely on such "experiential specs" as well.

For instance, standard 6BQ5/EL84 data sheets include the following specifications:

- Max plate voltage (300V)
- Max Grid No. 2 (screen grid) voltage (300V)
- Max Grid No. 2 input power (2W)

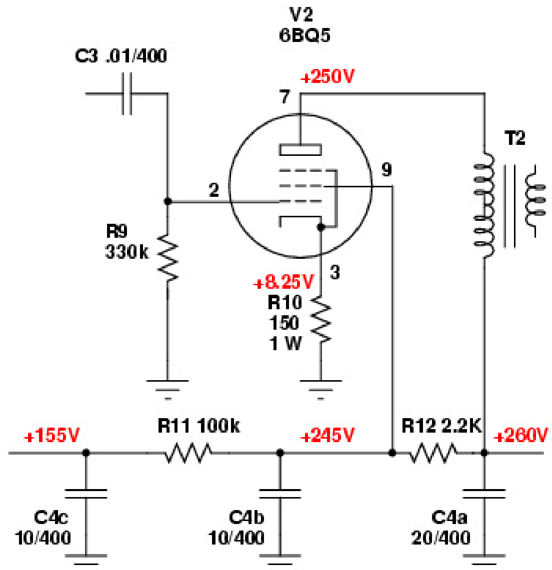
1 Nevermind that the author believes it useless!

- Max cathode current (65mA)
- Plate dissipation (12W)

Note: most other tubes' data sheets do not include a maximum cathode current.

The cathode current is equal to the sum of the plate and screen grid currents (you may safely ignore control grid current unless running well into class AB2.)

Let's do the math for our Model One.



We could measure the plate current directly, but that requires inserting an ammeter into the circuit. Since we have a cathode resistor, we can easily compute the cathode current:

Ex. 15a) $Ik = Ek / Rk = 8.25\text{V} / 150 = 55\text{mA}$

That's less than the max cathode current, so we're off to a good start. We know that plate current is cathode current less screen current, but since we don't have a screen stopper, how can we get the screen current? We can compute it from the difference in currents through R12 and R11. R12 carries the current for the screen plus the preamp stages, but R11 carries the current only for the preamp stages. Therefore the difference between the two is the screen current.

Ex. 15b)

$$Ir12 = Er12 / R12 = 15\text{V} / 2200 = 0.0068$$
$$Ir11 = Er11 / R11 = 90\text{V} / 100000 = 0.0009$$
$$Igs = Ir12 - Ir11 = 0.0068 - 0.0009 = 0.0059$$
$$Igs = 6\text{mA}$$

There's no published spec for max screen current, so we move on to screen power.

Ex. 15c)

$$Egs = E - Ek = 245\text{V} - 8.25\text{V} = 236.75\text{V}$$
$$Pgs = Egs * Igs = 236.75\text{V} * 6\text{mA} = 236.75 * 0.006 = 1.4\text{W}$$

This is less than 2W, so we're still OK.

There's no published spec for maximum plate current, but we still need the current to compute the static dissipation (wattage). Once we have that and the plate voltage with respect to the cathode, we can compute the plate power.

Ex. 15d)

$$Ip = Ik - Igs = 55\text{mA} - 6\text{mA} = 49\text{mA}$$
$$Ep = Epp - Ik = 250 - 8.25 = 241.75$$
$$Pp = Ep * Ip = 241.75\text{V} * 49\text{mA} = 241.75 * 0.049 = 11.8\text{W}$$

Plate power is just under 12W. Some people are nervous running this close to the stated maximum, but this really isn't a problem. First off, this isn't an Absolute Maximum, but a Design Center Maximum, so there's some wiggle room. Secondly, it's a well known fact that NOS 6BQ5s and most recent 6BQ5s can handle more than 12W static dissipation.[2]

One last thing to check in a cathode biased amp is the power through the cathode resistor.

Ex. 15e) $Pk = Ek * Ik = 8.25\text{V} * 55\text{mA} = 8.25 * 0.055 = 0.45\text{W}$

A 1/2W resistor might be adequate here, but that would be pushing things. A 1W or 2W resistor has more room for surges; this means less drift, longer life, and less likelihood of a blown resistor in the event of a partial short or mild current spikes. At the same time a dead short in the tube would have a reasonable chance of blowing the resistor before the OT died.

Fixed Bias Differences

There are no real computational differences with fixed bias, but there are shortcuts.

In a fixed bias amp, the cathode is at 0V, so the plate and screen voltages with respect to ground are the same as the plate and screen voltages with respect to the cathode. That's one less calculation for each of these.

To more readily measure the plate current, you could insert a 1Ω resistor between the plate and OT. Then you could measure the voltage drop there and compute the current. But most people insert a 1Ω resistor between cathode and ground, measure that voltage, and do the calculations from there. The voltage difference at the cathode is trivial enough to ignore in all common guitar amp circuits. The main advantage here is that you are measuring a lower voltage; since most test points are exposed, this reduces the risk of dangerous shocks under normal operating conditions. It also means you can use a lower wattage resistor!

Let's pretend we rebuild a Model One with a fixed bias supply and a 1Ω cathode resistor. Let's further assume that we still see 250V from plate to ground, and we measure 55mV across that 1Ω resistor.

Ex. 15f) $Ik = Ek / Rk = 55\text{mV} / 1\text{R} = 0.055 / 1 = 0.055\text{A} = 55\text{mA}$

The cool thing about this is that the current is the same as the voltage, so we can skip another step. You might want to add a 1Ω resistor in series with the cathode resistor in a cathode biased amp just to simplify the math!

Screen Stoppers and Other Current Limiting Resistors

If there's no screen stopper you can usually do the math as above. But some amps run the screen off the same tap as the plate. In this case there is no way besides ammeter insertion to get the screen current. Adding a screen stopper solves this problem since you can then use Ohm's Law to determine the screen current. You could use a 1Ω resistor here, but a bigger resistor is a good idea so long as it doesn't alter the tone too much. That's because a larger screen stopper can act as a current limiting resistor.

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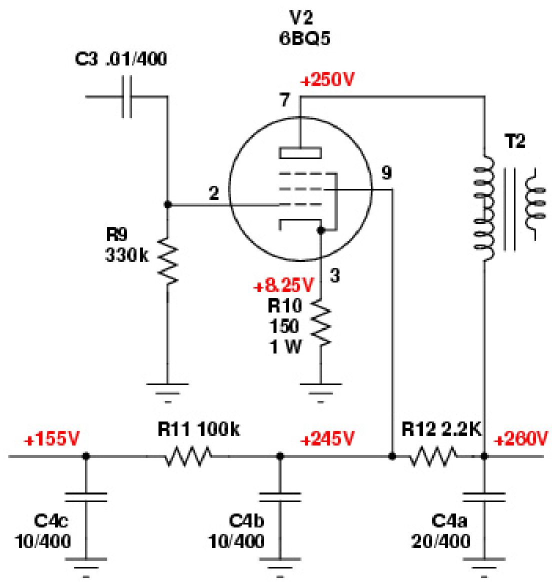
2 The author routinely runs these tubes at 13W to 14W with no problems and long lifetimes. You'll have to consider tube lifetime and cost and decide for yourself how hot you are comfortable running them.

How does that work?

In general, it works because the voltage must vary with the current to satisfy Ohm's Law.

Consider the screen supply resistor R12 in the Model One schematic. What would happen if the screen tried to draw twice the current? We know from **Ex. 15b** that the current through R12 is 7mA, of which 6mA is screen current. If the screen draws twice the current, or 12mA, we would have 13mA through R12. By Ohm's Law this would change the voltage.



Ex. 15g

$$Er12 = Ir12 * R12 = 13\text{mA} * 2.2\text{k}$$
$$Er12 = 0.013 * 2200 = 28.6\text{V}\,(27\text{V})$$

This lowers the screen voltage from 245V to 233V.

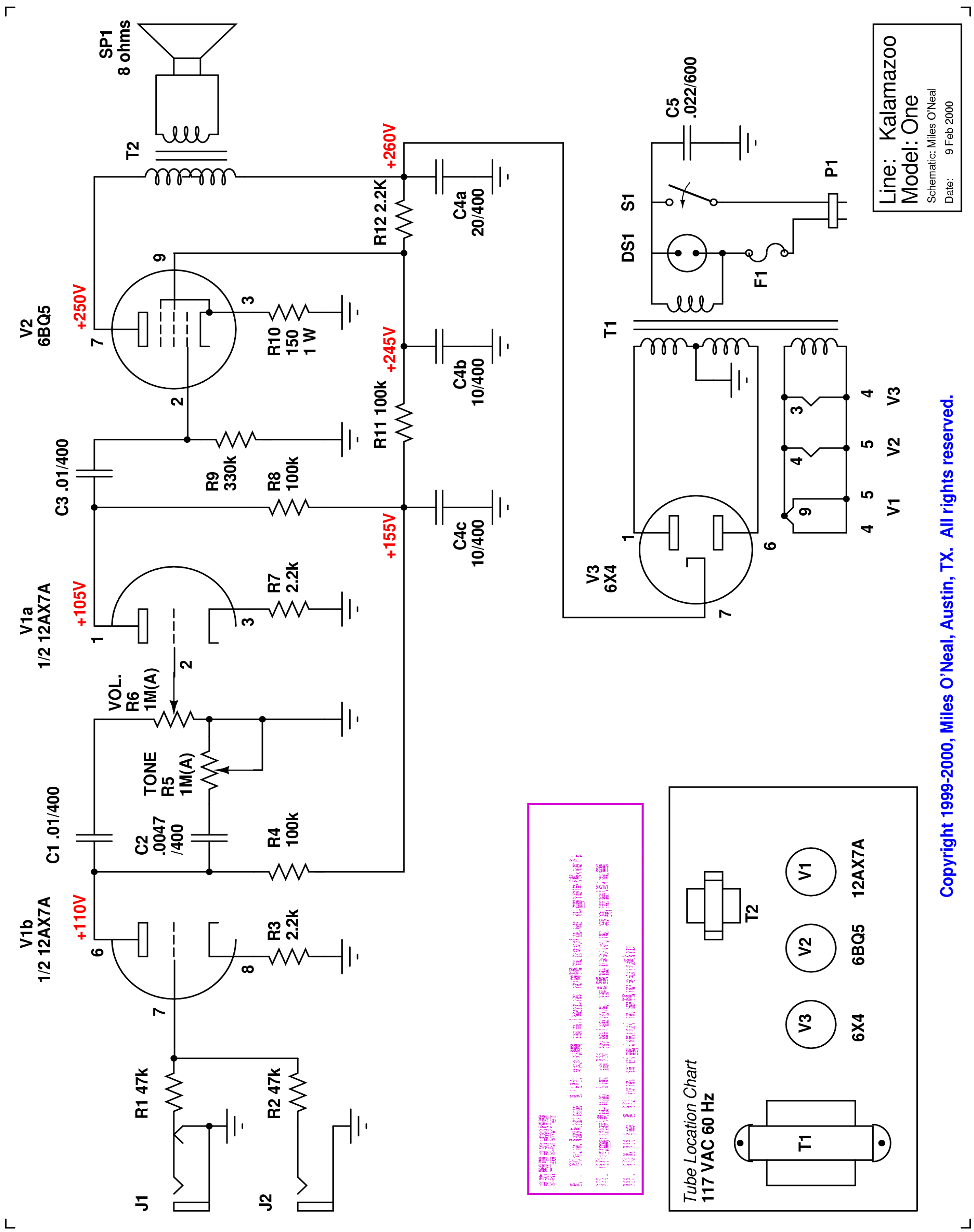
Ex. 15h $$E = 260\text{V} - 27\text{V} = 233\text{V}$$

Since the screen voltage is now lower with respect to the plate voltage than it was, it attracts less electrons, which means less current flows, so the screen current drops and the plate voltage rises back up until a happy medium is reached. This is going to be at a lower voltage and higher current than before, but it won't be as drastic as initially expected (2x the current).

LOAD LINES

Borrow from Stephen Keller and whoever had the other intro doc started

KALAMAZOO MODEL ONE SCHEMATIC



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CREDITS and THANKS

Reviewers

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Encouragement and Direction

Chris Hurley, Stephen Keller

LEGAL STUFF

``I can spell, but I can't type.'' (author)

WHERE DO IT GO?

Both from Alan Olson:

1. Explain how "standard" resistor values are calculated. Experienced amp builders know standard values for 10% and maybe 5% tolerance resistors, but inexperienced builders probably do not. The calculation of resistor values is not too hard - geometrically spaced values over each decade. The number of steps per decade depends on the tolerance: 1% - 96 steps, 2% - 48, 5% - 24, 10% - 12, and 20% - 6 steps. The multiplicative factor is 10^(1/steps). For example, 10% tolerance - 12 steps, the multiplicative factor is 10^(1/12) = 1.21153. The standard 10% values are then:

10x(1.21153)^k, k=0..11, or [10,12,15,18,22,27,33,39,47,56,68,82].

Explain audio tapered potentiometers. The resistance tape is logarithmic, but there are different kinds of tapers. You can also simulate a log taper using a linear taper pot and a shunt resistor – a good example of series-parallel resistor combinations.

Have not added ideas from Mark L yet!