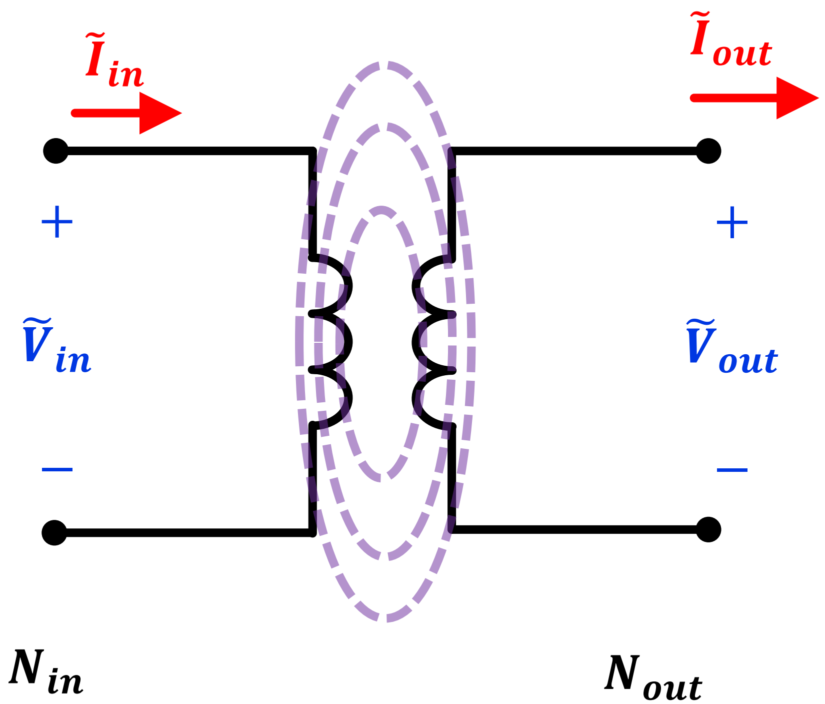
Lecture 4

Tube Electronics

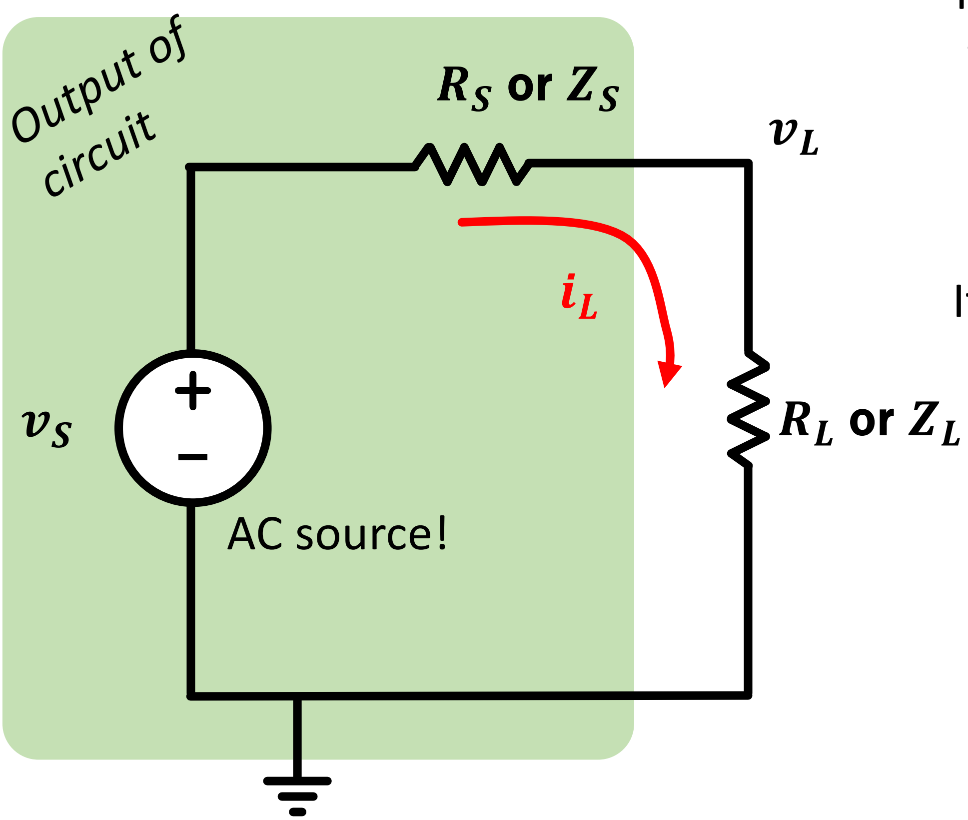
The Transformer

- OK, so what can we use the transformer for? We can't amplify
- Several big uses:
  - Power conversion
  - Electrical Isolation
  - **Impedance Matching**
  - Coupling Stages
  - Phase Inversion



Transformers: Impedance Matching

- We can always model the exchange of information and energy from one portion of a circuit to another with a Thevenin circuit driving a load:



If concerned about passing voltage onto load: focus on $R_L > R_S$ and ideally $R_L \gg R_S$

If concerned about passing max power into load:

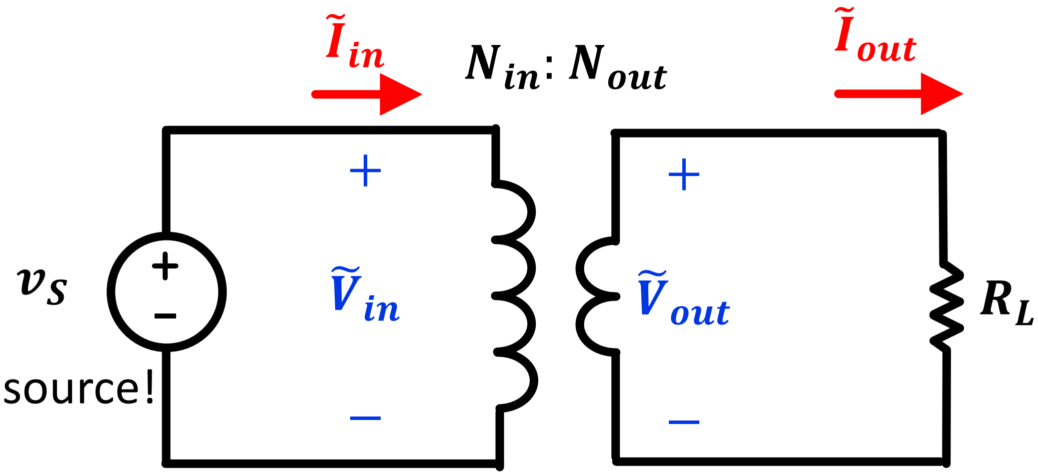
focus on trying to get as close as possible to $Z_L = Z_S^*$

Transformers: Impedance Matching

- We can always model the exchange of information and energy from one portion of a circuit to another with a Thevenin circuit driving a load:

Like before: $\frac{V_{out}}{V_{in}} = \frac{N_{out}}{N_{in}}$

$V_{in} \cdot I_{in} = V_{out} \cdot I_{out} \quad \therefore \frac{I_{out}}{I_{in}} = \frac{N_{in}}{N_{out}}$



But now: $I_{out} = \frac{V_{out}}{R_L}$

Therefore: $I_{in} = I_{out}\frac{N_{out}}{N_{in}} = \frac{V_{out}}{R_L}\frac{N_{out}}{N_{in}}$

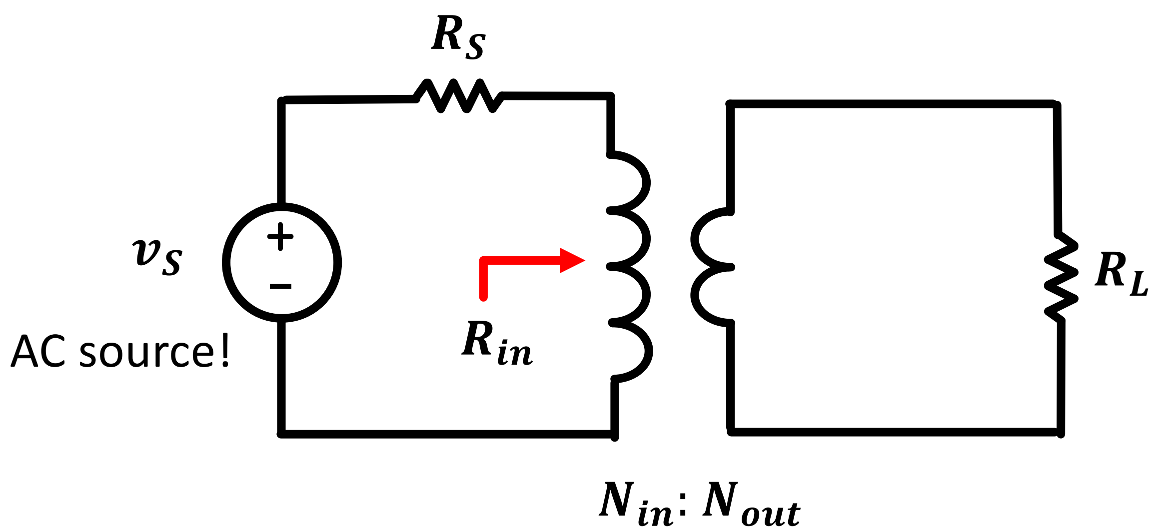
We could define $R_{in} = \frac{V_{in}}{I_{in}}$:

Or rewrite as: $I_{in} = \frac{\frac{N_{out}}{N_{in}}V_{in}}{R_L}\frac{N_{out}}{N_{in}}$

So therefore: $R_{in} = R_L\left(\frac{N_{in}}{N_{out}}\right)^2$

Transformers: Impedance Matching

- A transformer can change how a particular load "looks" to a source:



$$R_{in} = R_L \left(\frac{N_{in}}{N_{out}}\right)^2$$

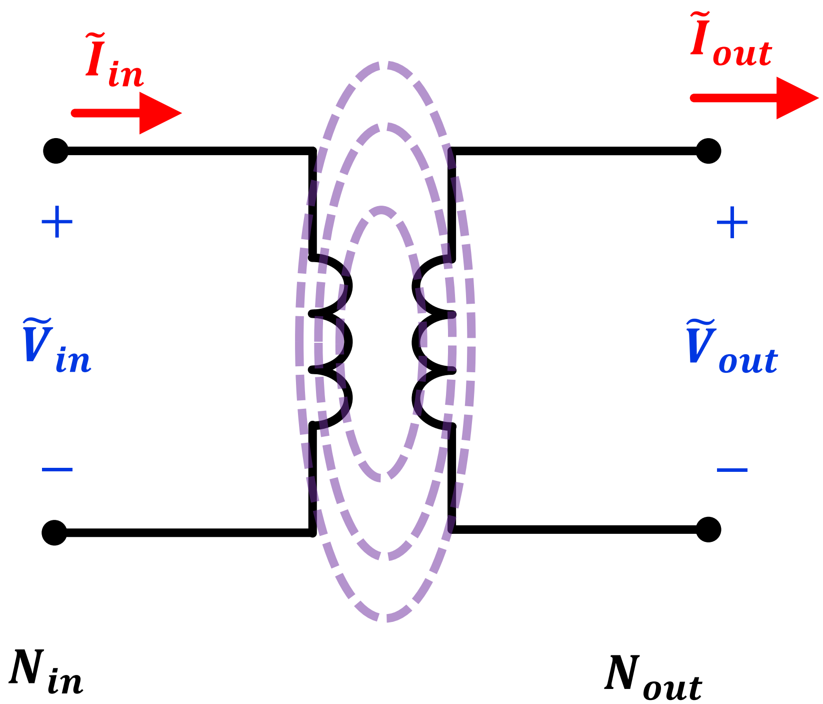
Works more generally for impedance too:

$$Z_{in} = Z_L \left(\frac{N_{in}}{N_{out}}\right)^2$$

- Is R_L too low (like might be the case in a speaker)? Use a step-down transformer to increase the resistance
- Is R_S too high (like is sometimes the case in an antenna)? Use a step-up transformer to decrease the resistance

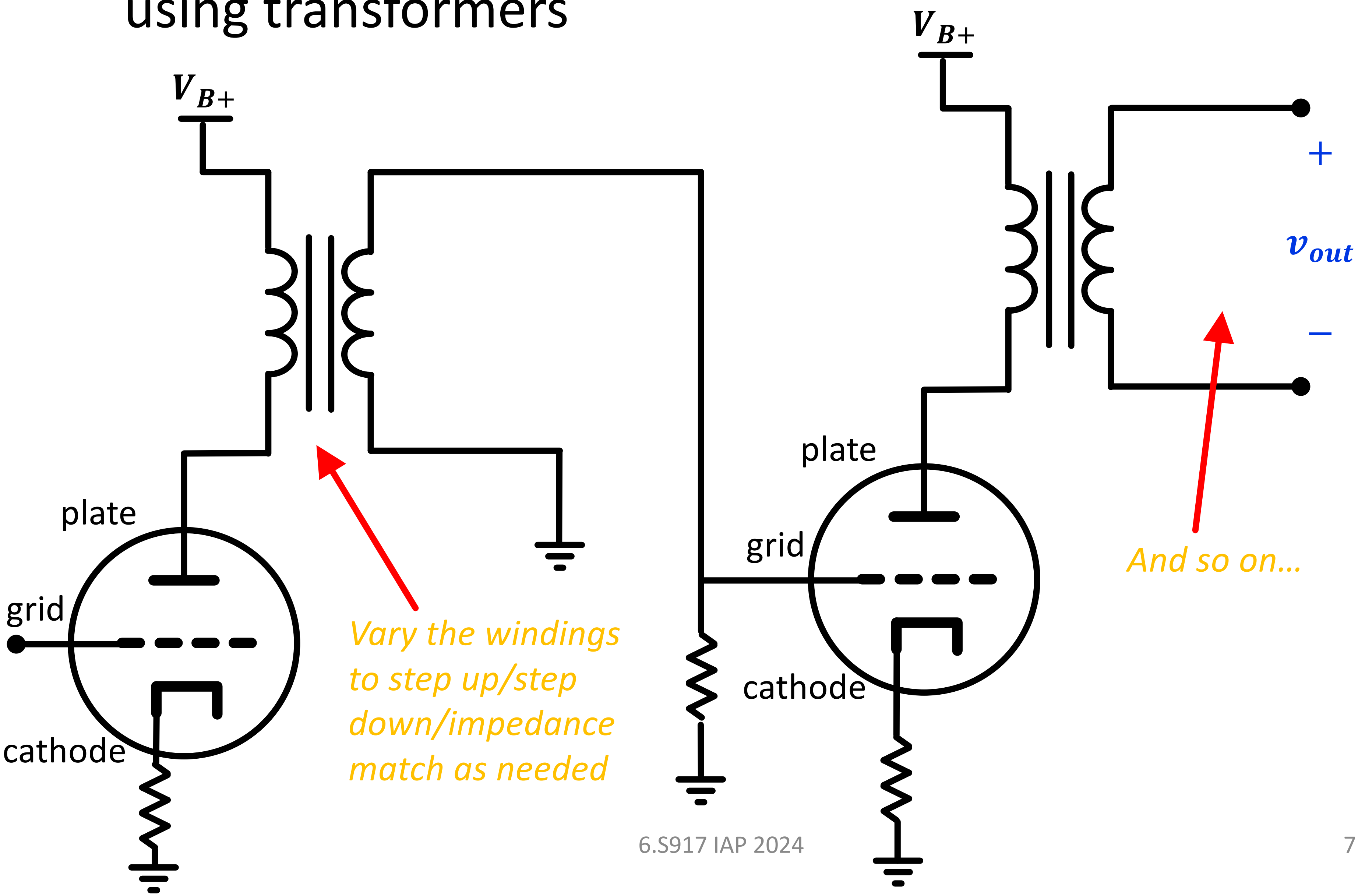
The Transformer

- OK, so what can we use the transformer for? We can't amplify
- Several big uses:
  - Power conversion
  - Electrical Isolation
  - Impedance Matching
  - **Coupling Stages**
  - Phase Inversion



Linking Tubes (Coupling)

- Many early tube circuits that had more than one tube would "couple" one stage of circuit to the next using transformers

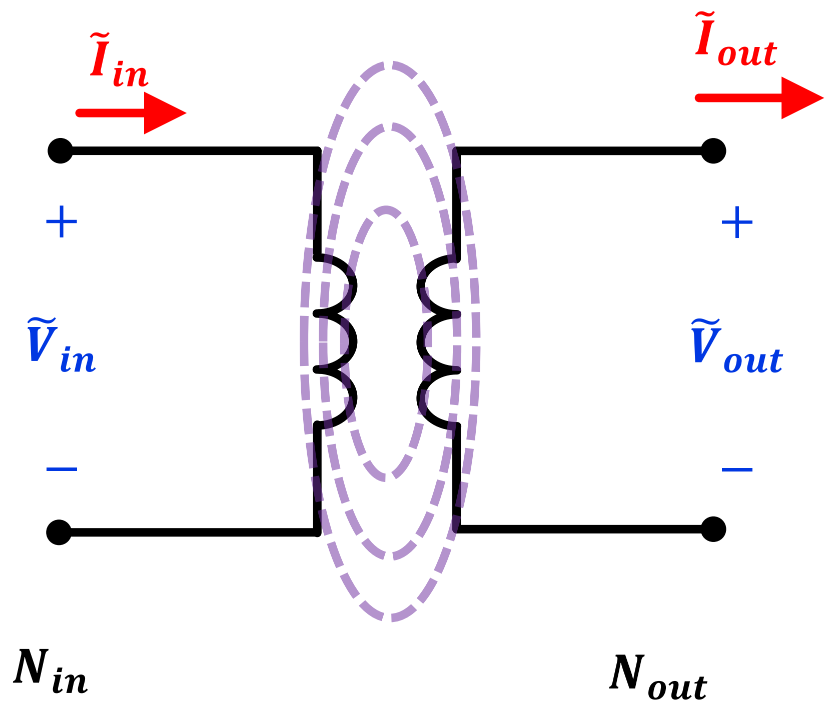


Transformer Coupling

- Expensive and with time disappeared from all but the most important stages (replace with resistive or capacitive coupling)

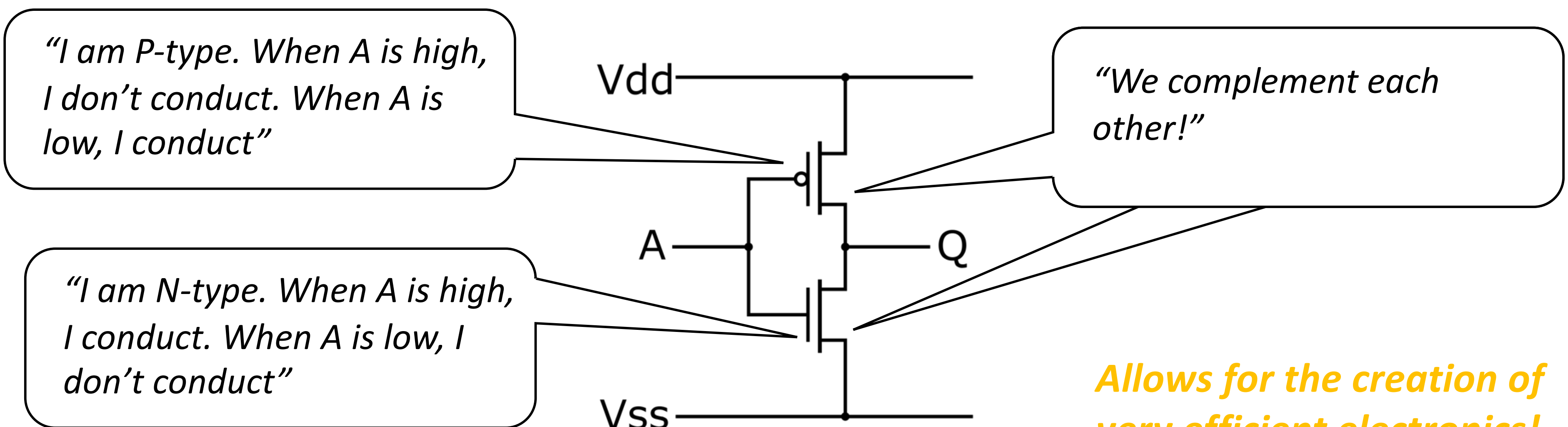
The Transformer

- OK, so what can we use the transformer for? We can't amplify
- Several big uses:
  - Power conversion
  - Electrical Isolation
  - Impedance Matching
  - Coupling Stages
  - **Phase Inversion**



Problem: Tubes only have one "type"

- In the future (>1950s) we'll have N-type and P-type devices, working off of electron and hole charge carriers, respectively
- Allows us to develop amplifiers that work in complementary fashion
- Consider a CMOS inverter for example

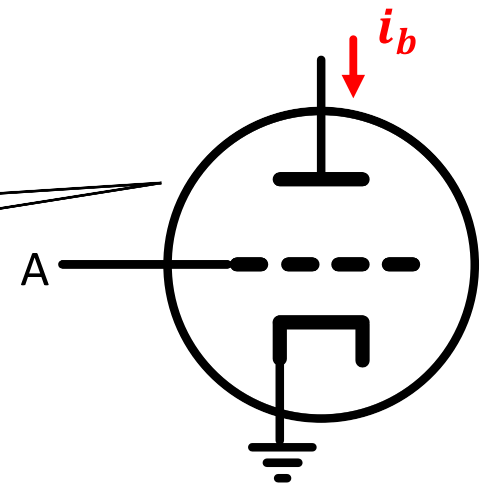


Allows for the creation of very efficient electronics!

Tubes only have one “type”

- Tubes only work off of electrons as carrier
- No “P-type” tube

“I am N-type. When A is high, I conduct. When A is low, I don’t conduct”

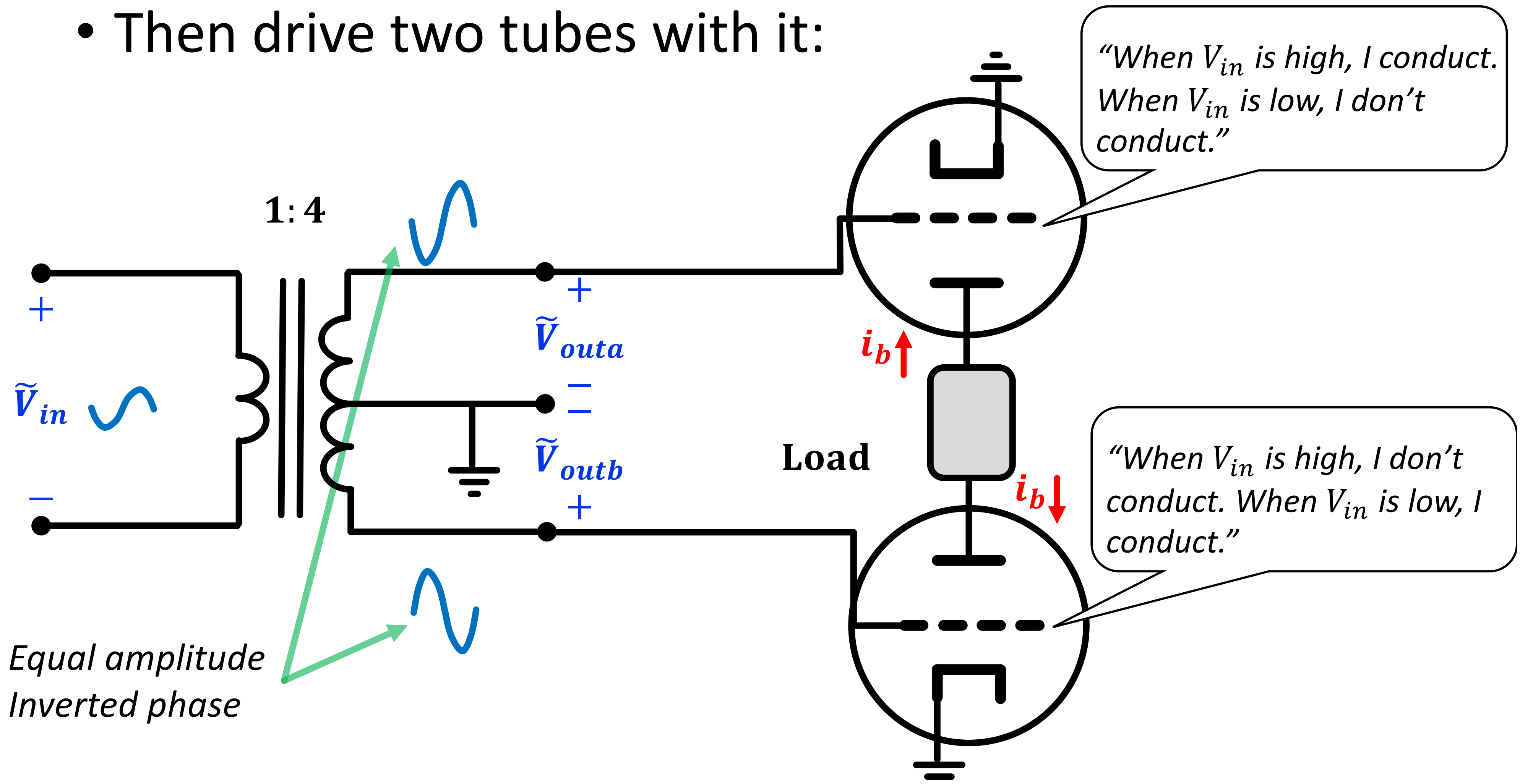


“I am P-type. When A is high, I don’t conduct. When A is low, I conduct”

Missing
☹

Solution: Use a Transformer

- Use a Center-tap to Ground to create two completely out-of-phase signals from input signal.
- Then drive two tubes with it:

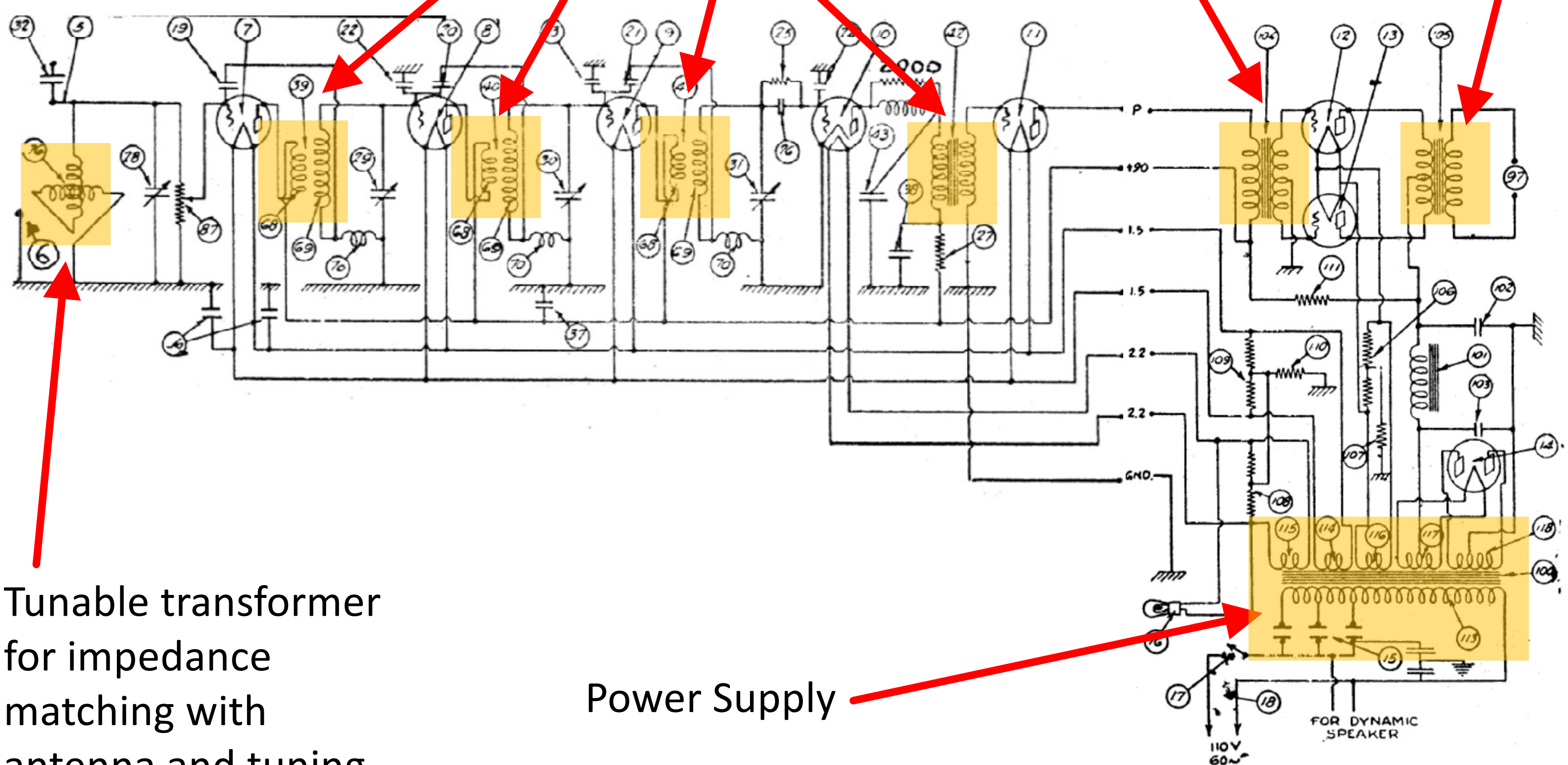


1928 Bosch Radio Receiver Schematic

Impedance Matching And/or coupling Transformers

Phase Inverting Transformer for push-pull amp

Impedance Matching Transformer for speaker



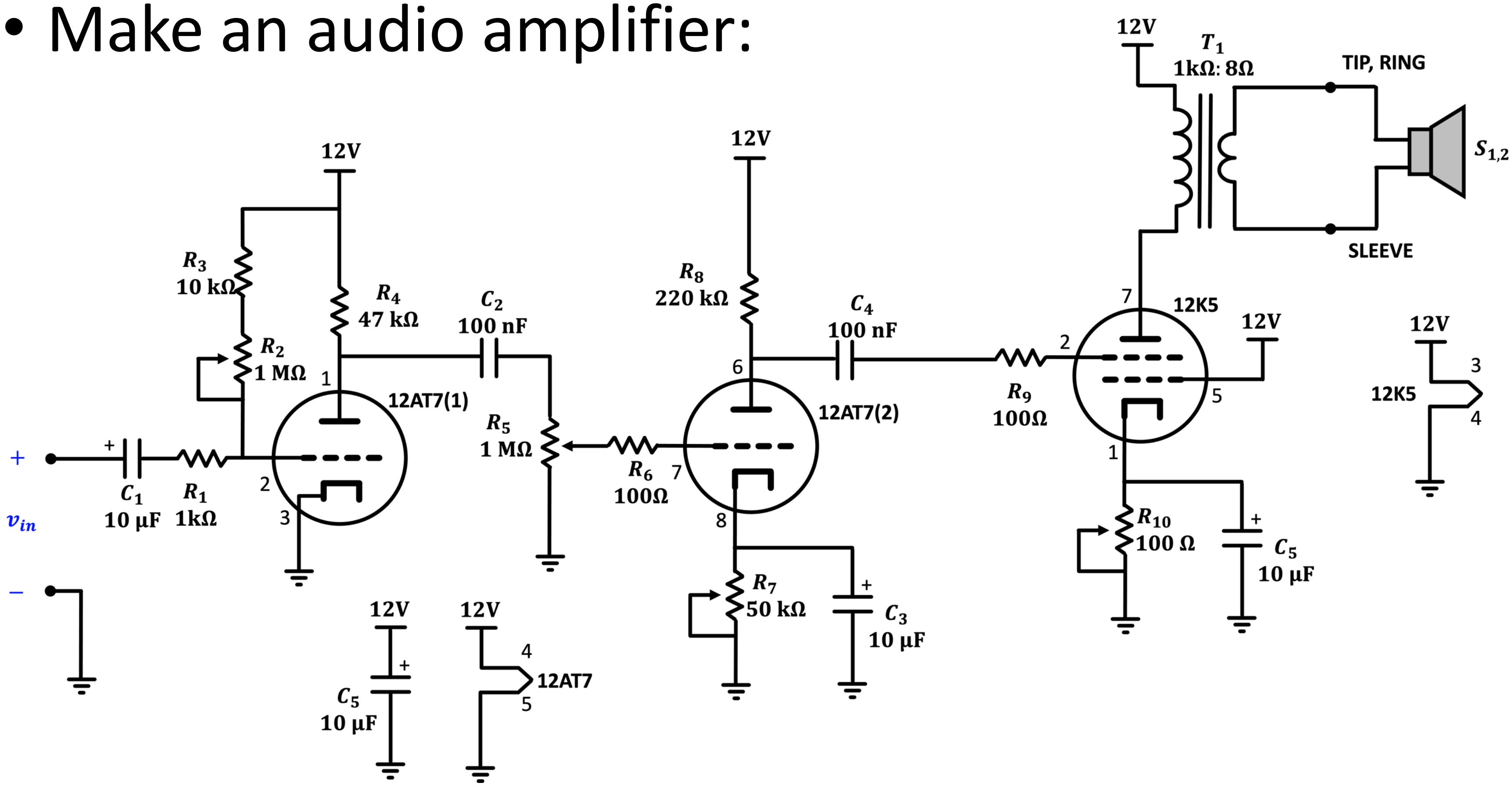
Tunable transformer for impedance matching with antenna and tuning

Power Supply

Designing with Tubes

Lab 2 (2023 version)

- Make an audio amplifier:

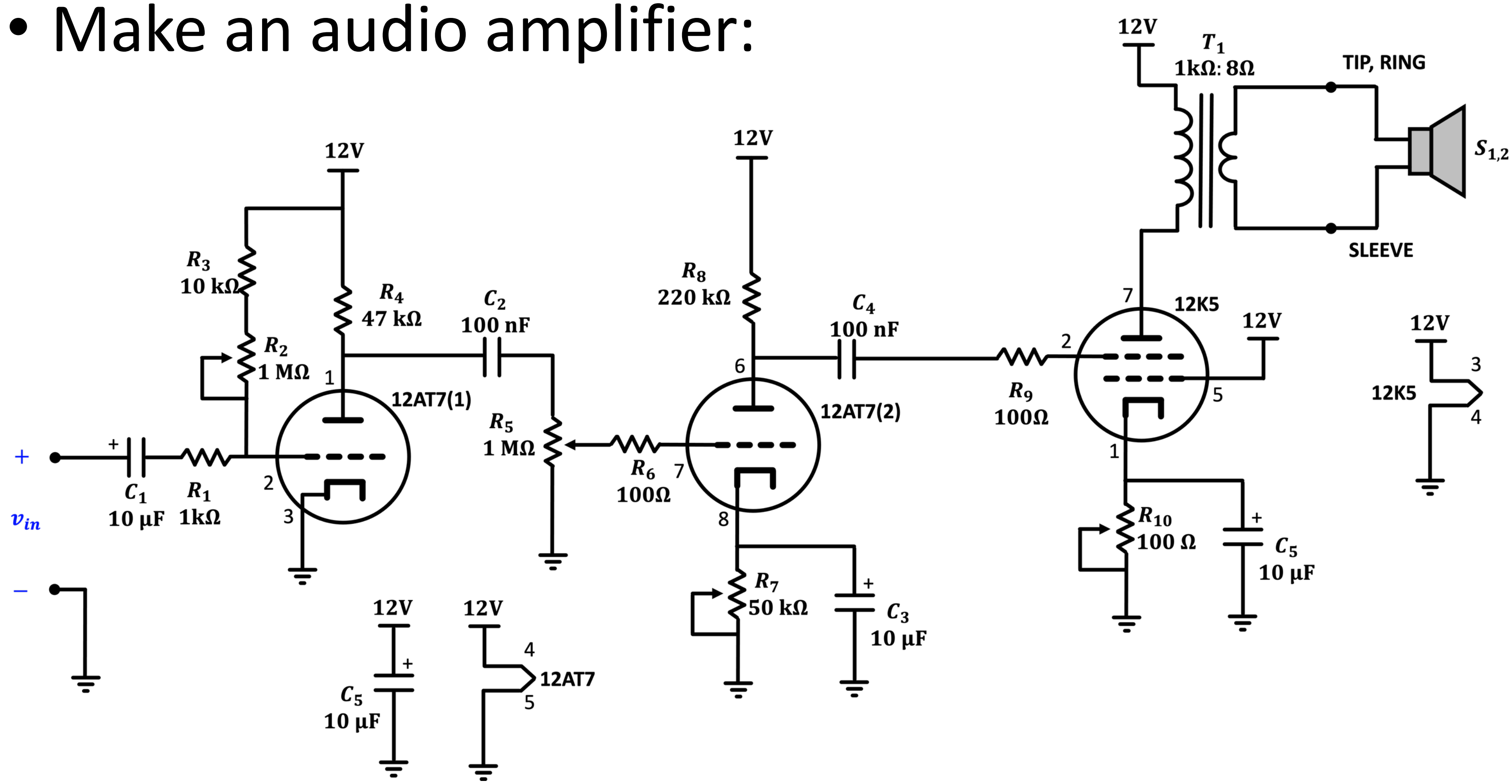


Lab 2 (2024 Version) Sorry

- Slightly different so we'll actually have two circuits to look at/think about with two different sets of tubes.

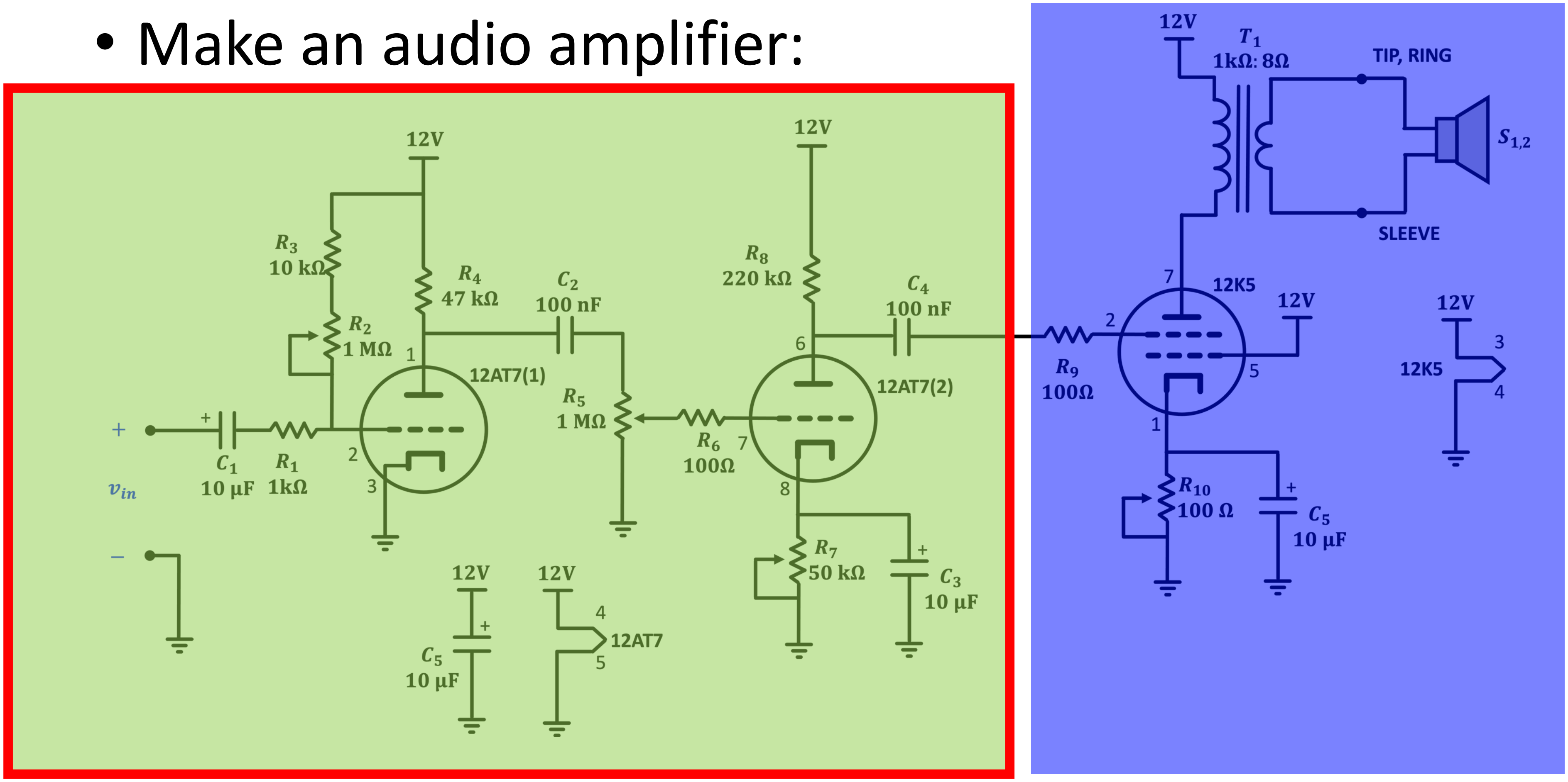
Lab 2 (2023 version)

- Make an audio amplifier:



Lab 2

- Make an audio amplifier:

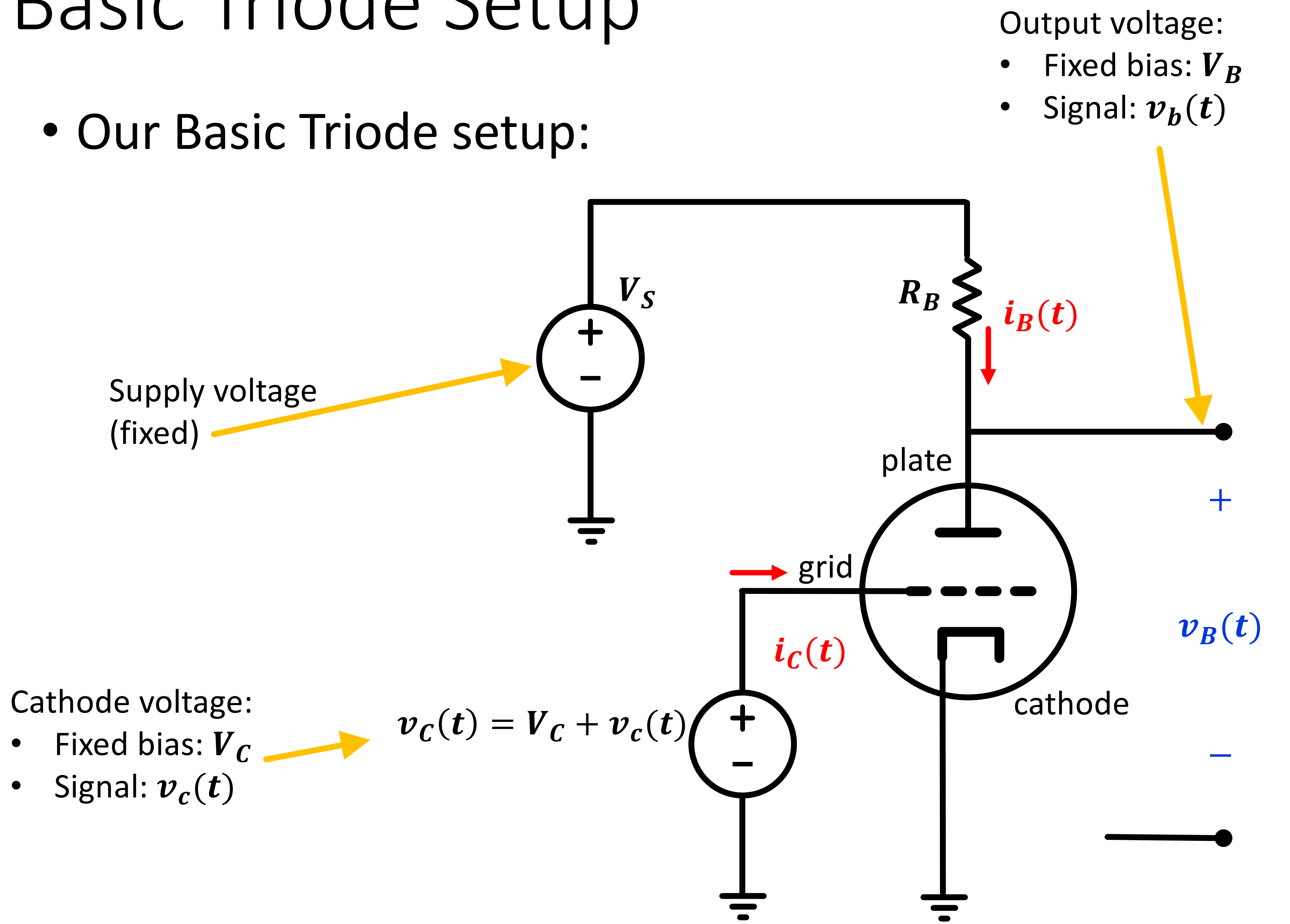


Preamplifier (largely concerned with increasing voltage of signal)

Power Amplifier (largely concerned with moving as much energy into the load as possible)

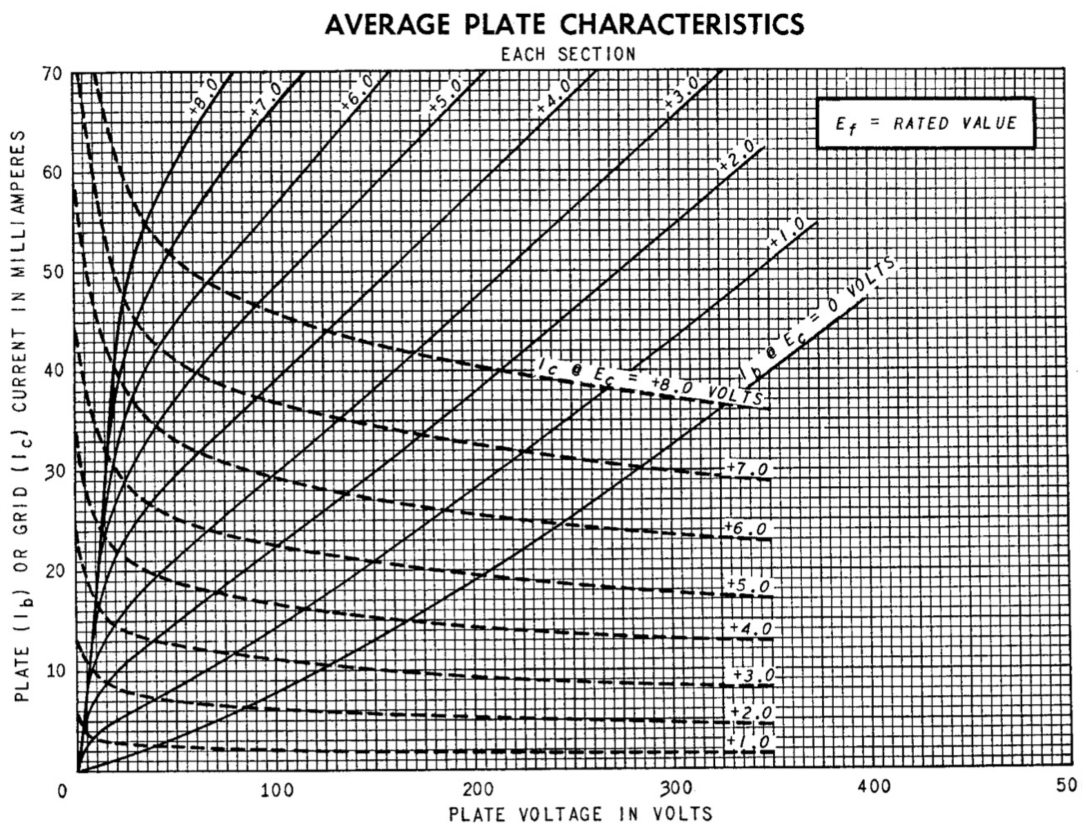
Basic Triode Setup

- Our Basic Triode setup:



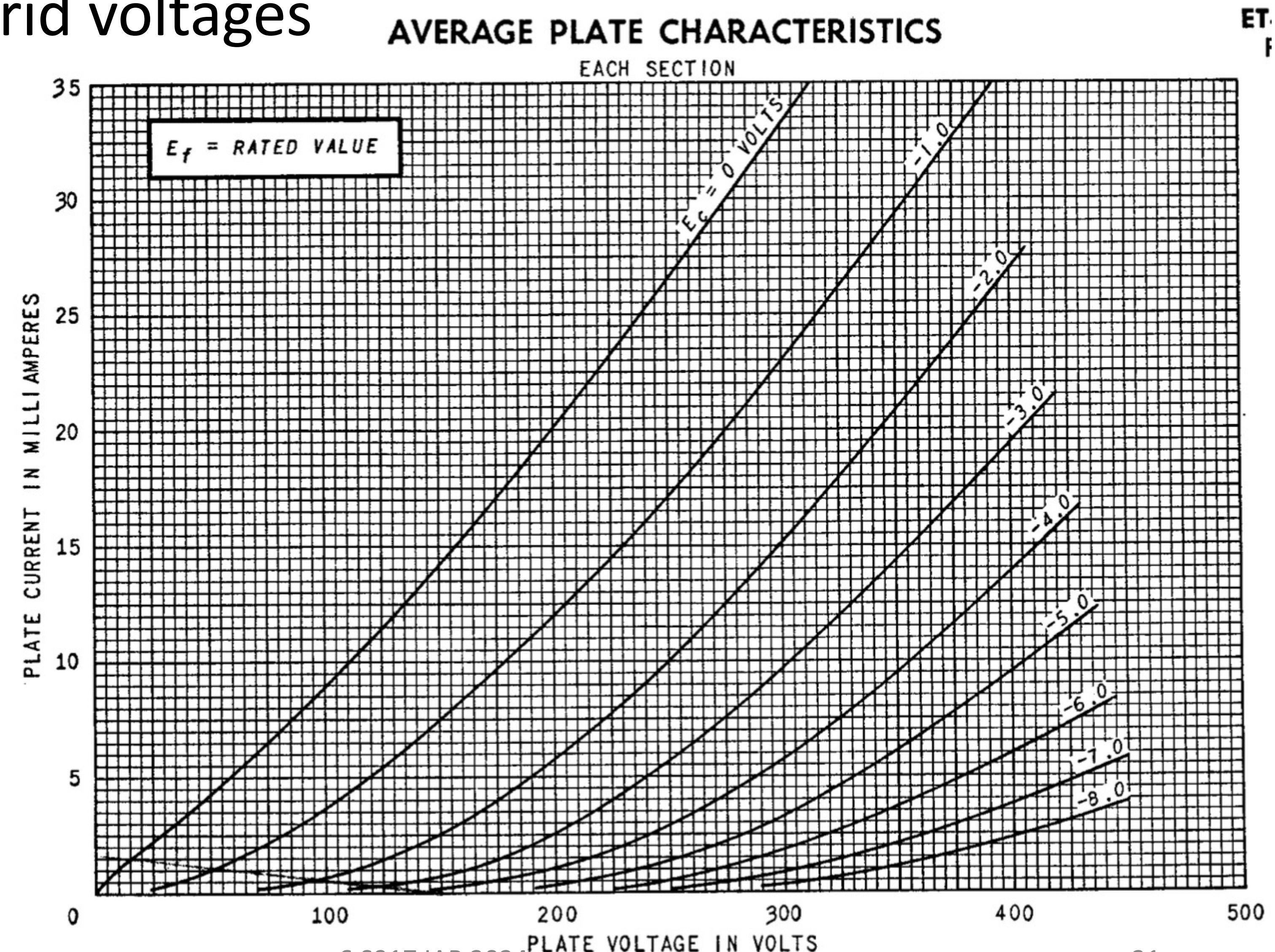
12AT7 Curve 1

- Plate Currents (and grid currents) for when the grid is at a positive voltage
- We won't use this much so ignore



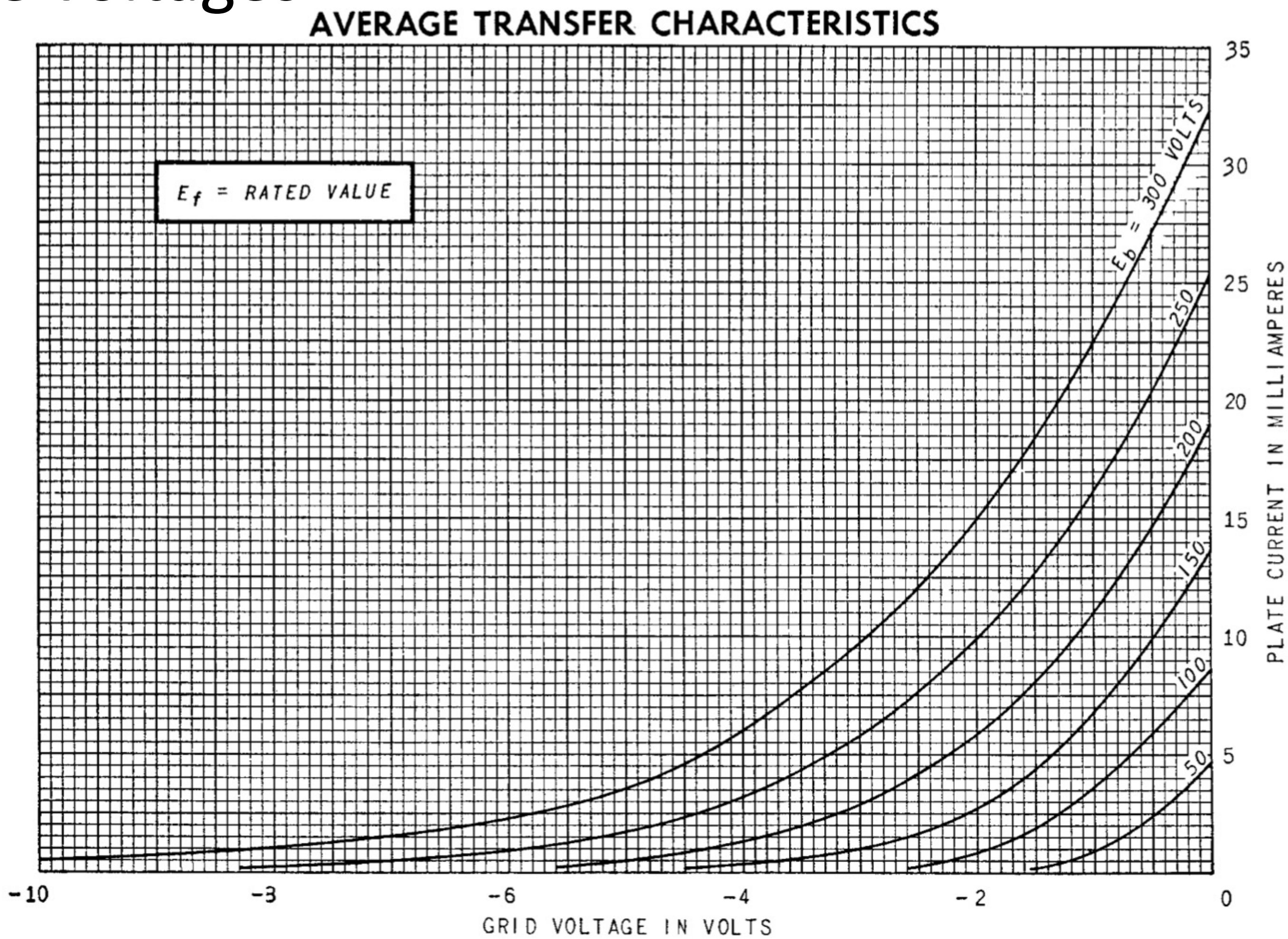
12AT7 Curve 2

- Plate current as a function of plate voltage for specific grid voltages



12AT7 Curve 3

- Plate current as a function of grid voltage for specific plate voltages

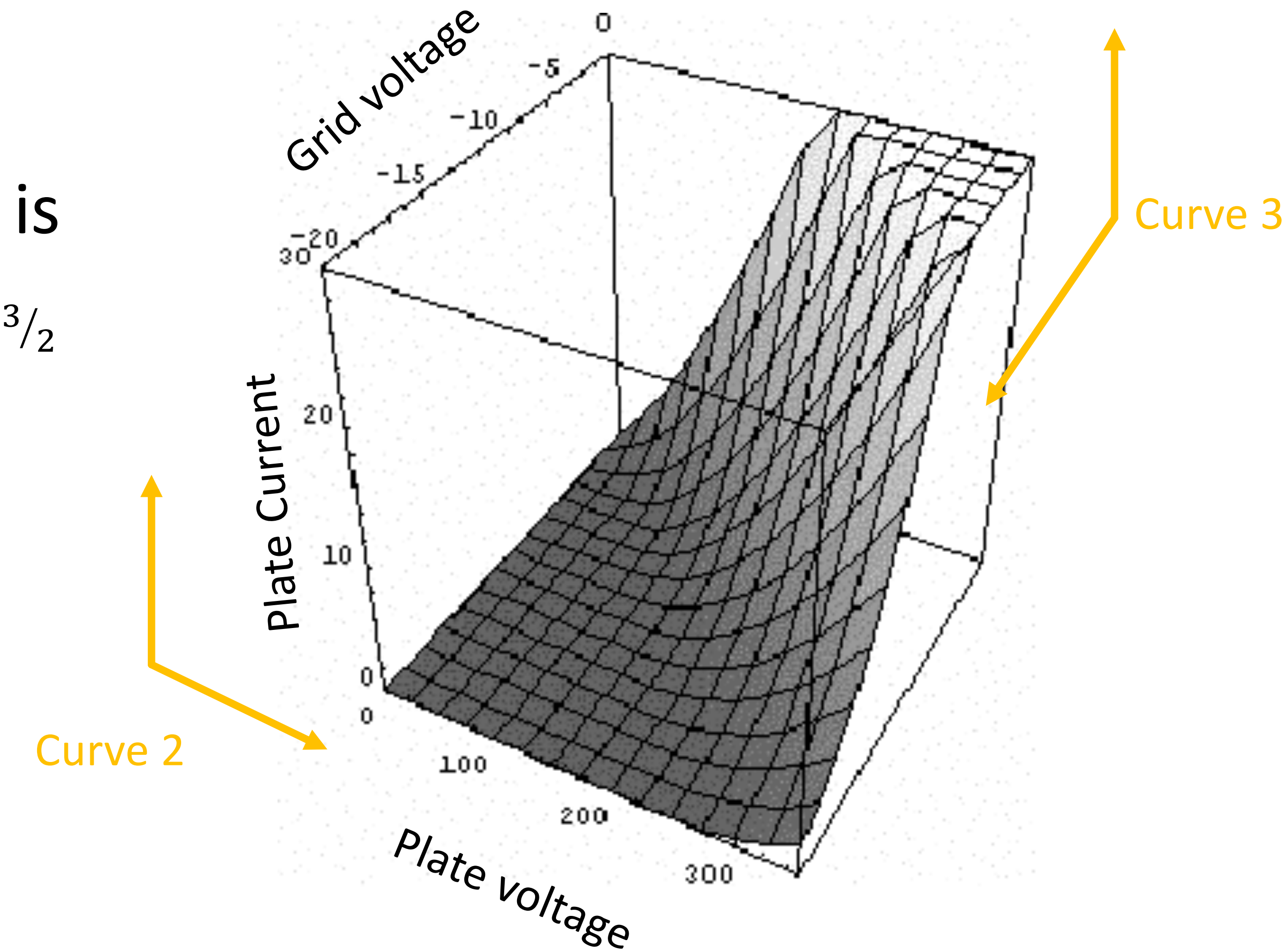


All together

- The two plots are slices across two of the three axes
- The general rough pattern is

$$I_B = P\left(V_C + \frac{V_B}{\mu}\right)^{3/2}$$

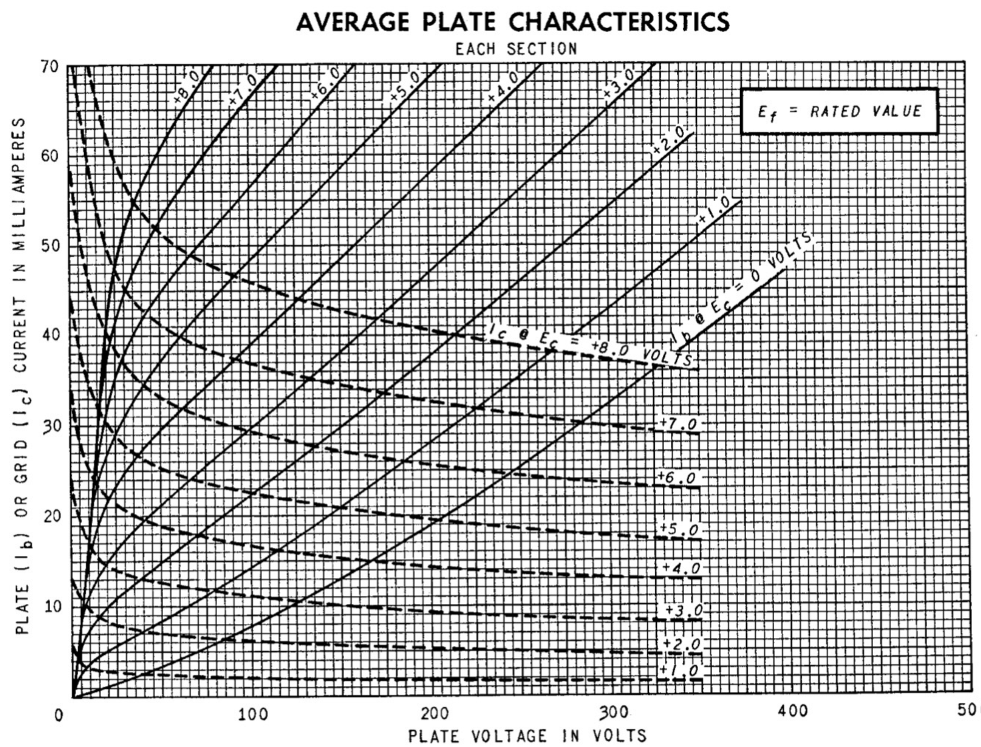
Whole mess of physical constants



https://www.john-a-harper.com/tubes201/

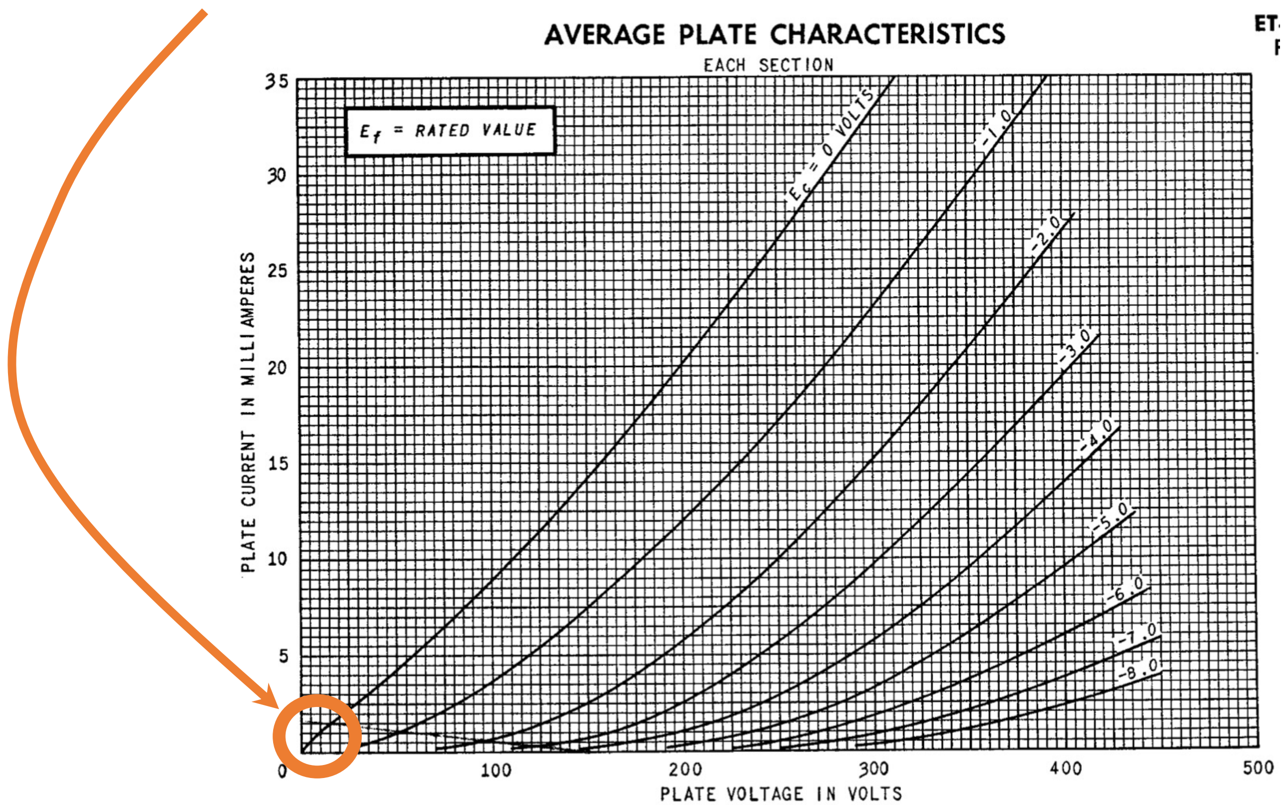
Running Tubes with Positive Grid

- There are times and places to do this, but generally we don't want to.
- This is especially true in our class where we're running at very low voltages



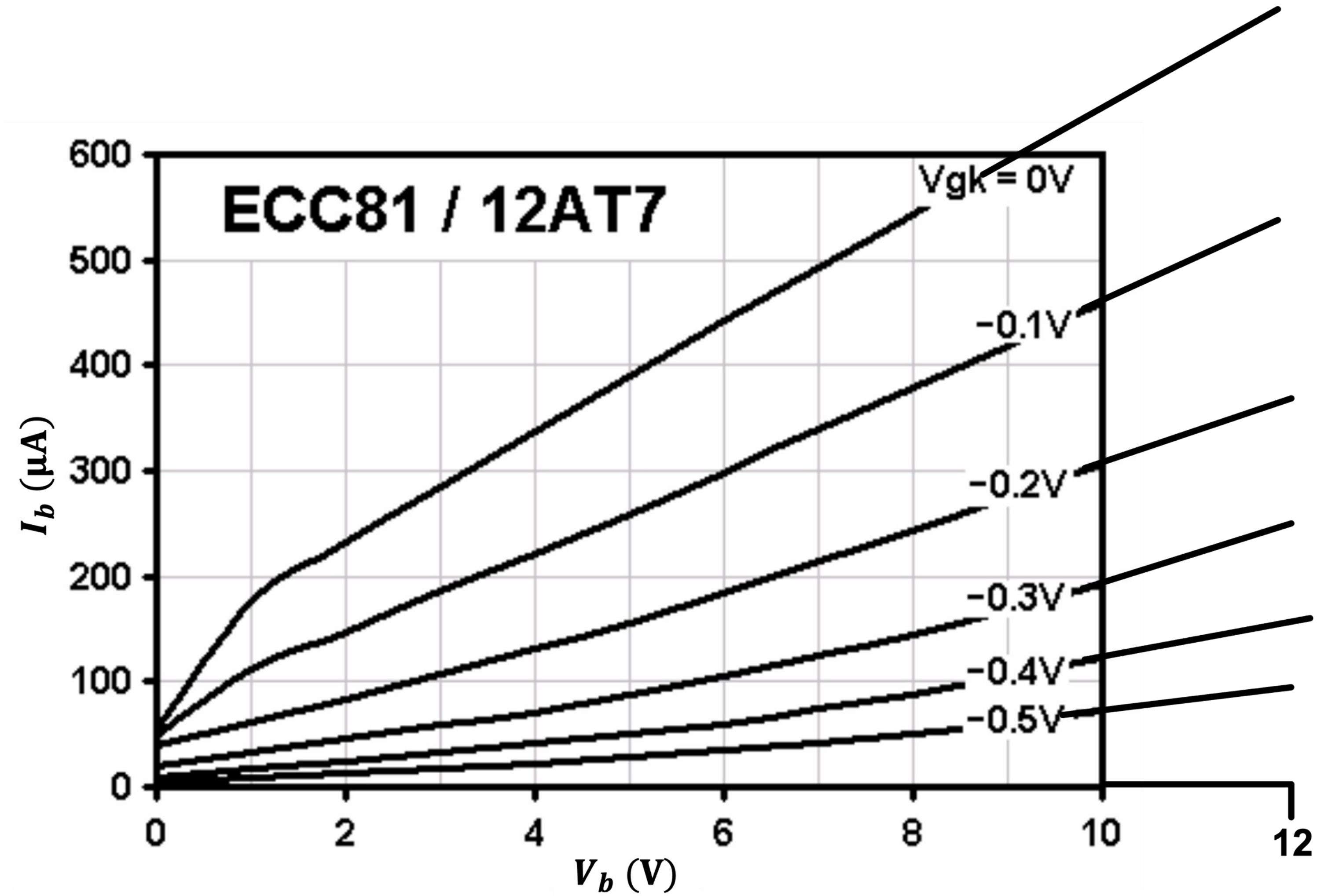
Problem with these plots…

- They're all way too zoomed out.
- We'll be running our tubes in "starvation" mode in this class for safety ($V_B \leq 12V$)



Thankfully Zoomed-in Plots exist

- We're not the first to starve our tubes



Taken and slightly extrapolated from here: http://www.valvewizard.co.uk/Triodes_at_low_voltages_Blencowe.pdf

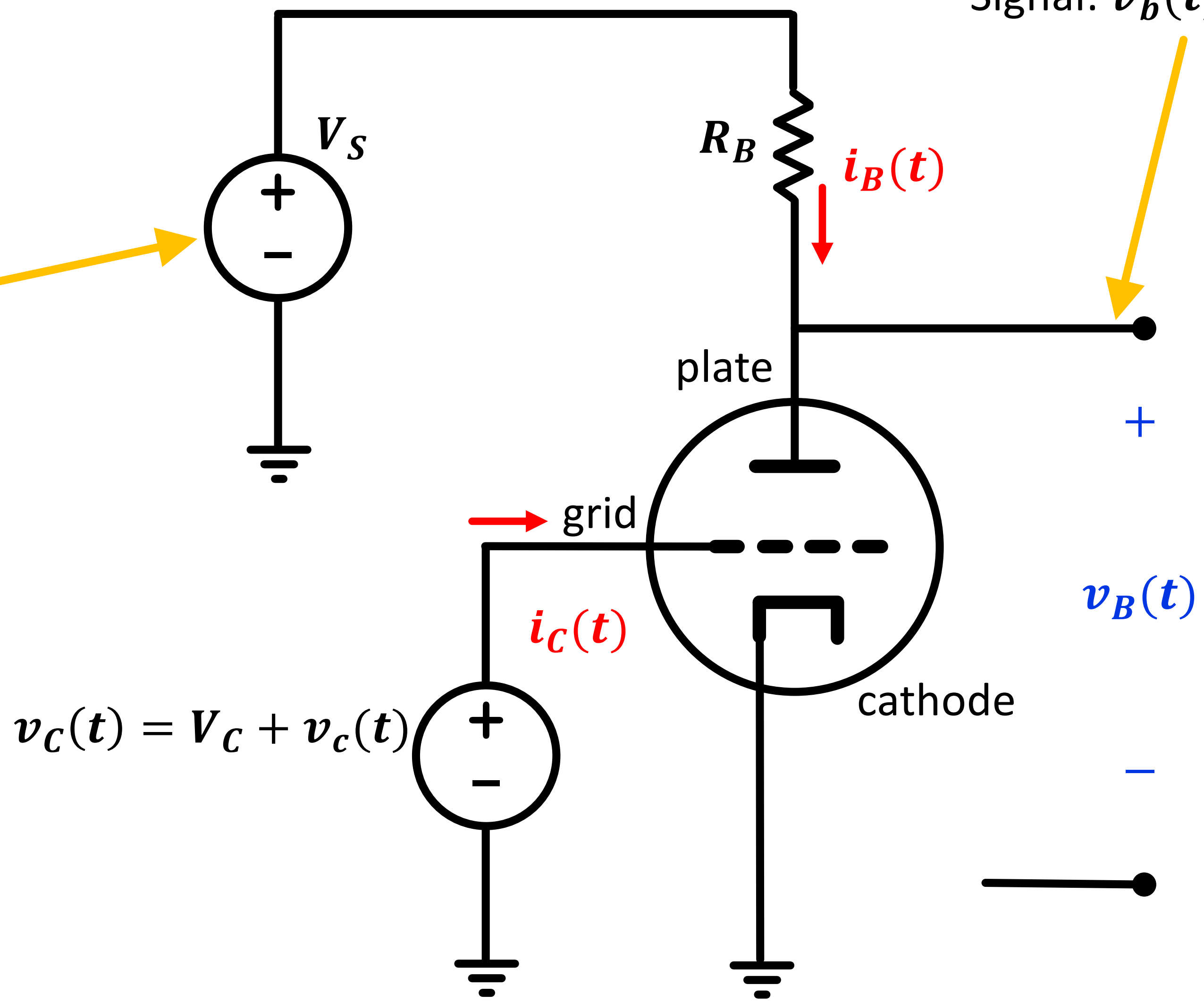
OK So How Do We Use that Plot?

- Our Basic Triode setup:

Output voltage:

- Fixed bias: $\boldsymbol{V_B}$
- Signal: $\boldsymbol{v_b(t)}$

Supply voltage (fixed)



Cathode voltage:

- Fixed bias: $\boldsymbol{V_C}$
- Signal: $\boldsymbol{v_c(t)}$

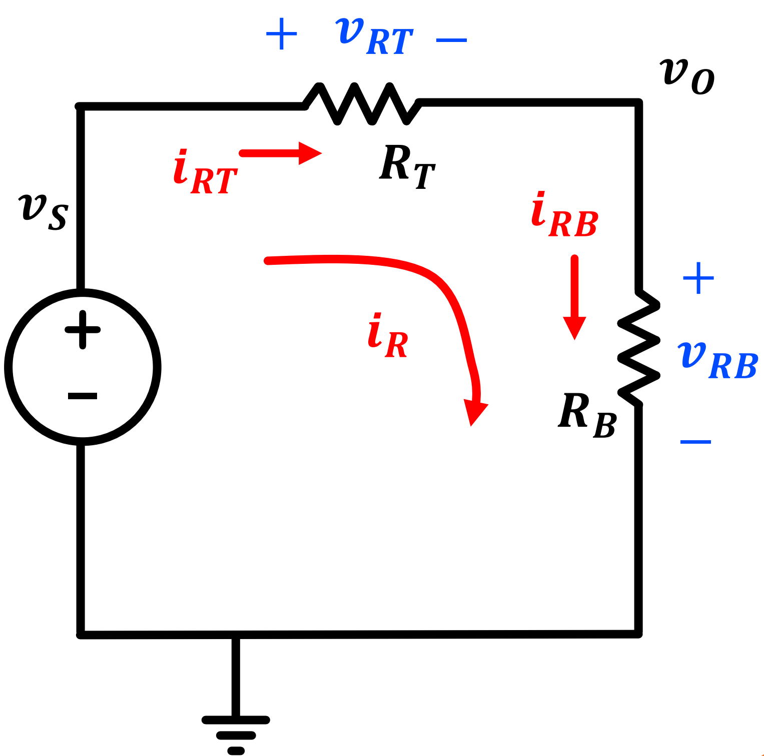
We need to find out where to bias the tube

- Biasing a device is “positioning” it electrically speaking so that it will respond from that point to incoming signals
- Where we position it will affect things like its:
    - Gain
    - Frequency response
    - Input and output impedances
- It is a complicated choice to make so you have to be comfortable just rolling with things and assuming you might have to change it.

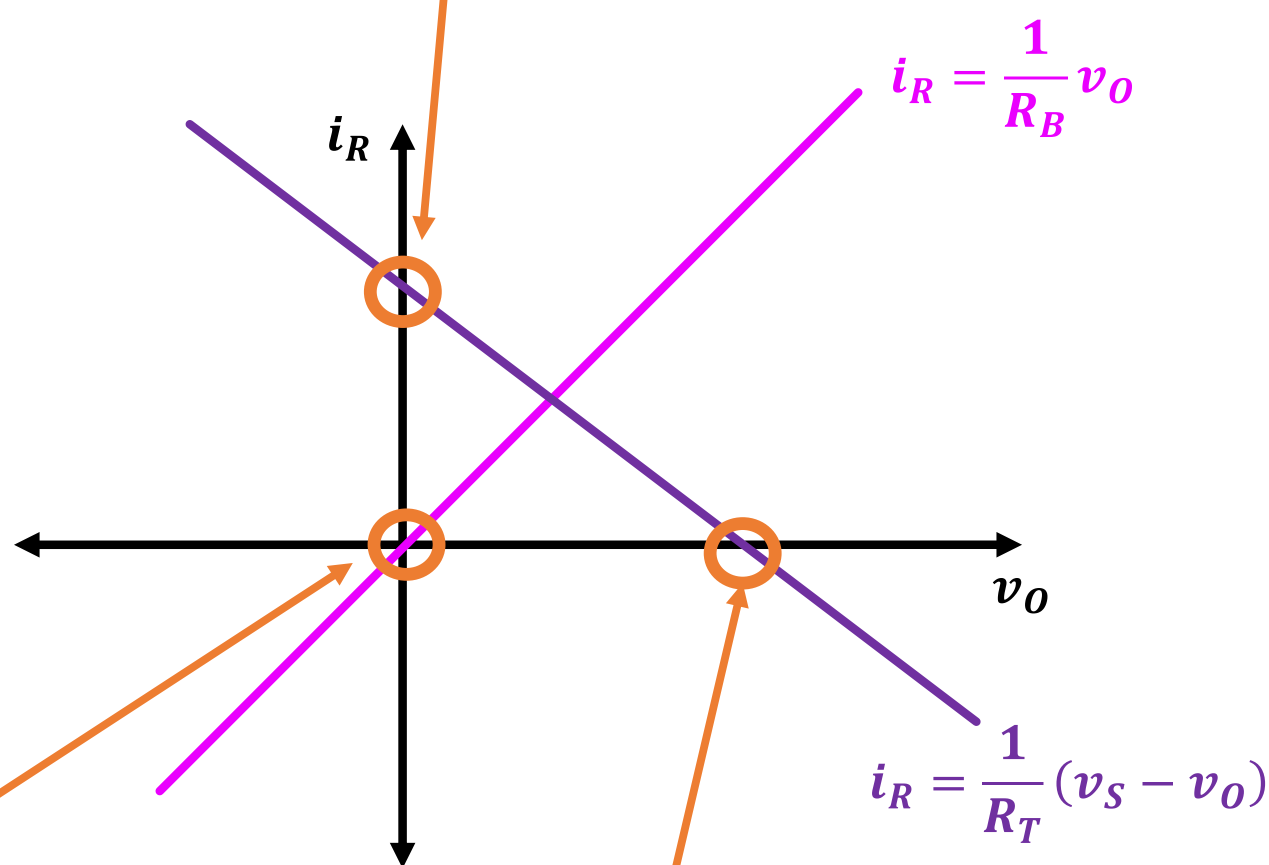
To Start We pick an R_B

- What value? I don't know. I give up.
- It comes with practice/time/experience. Let's pick two different values and see how they will "land" on the I-V characteristics:
  - 24Kohm
  - 47Kohm
  - 240 Kohm

Remember the Load Line!



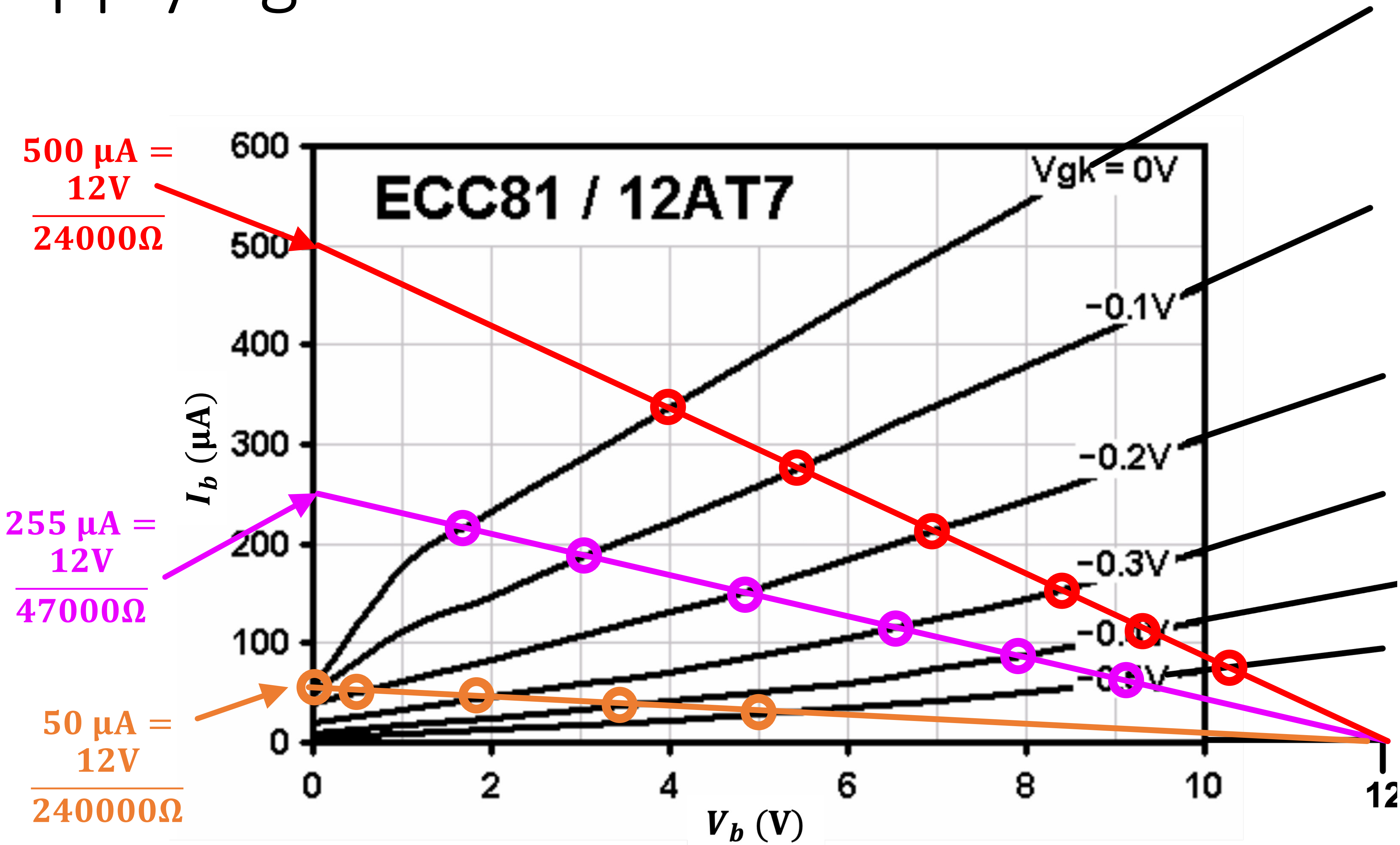
What i_R would be if v_O=0 according to R_T (answer: $\frac{v_S}{R_T}$)



What i_R would be if v_O=0 according to R_B (answer: 0)

What v_O would be if i_R=0 according to R_T (answer: v_S)

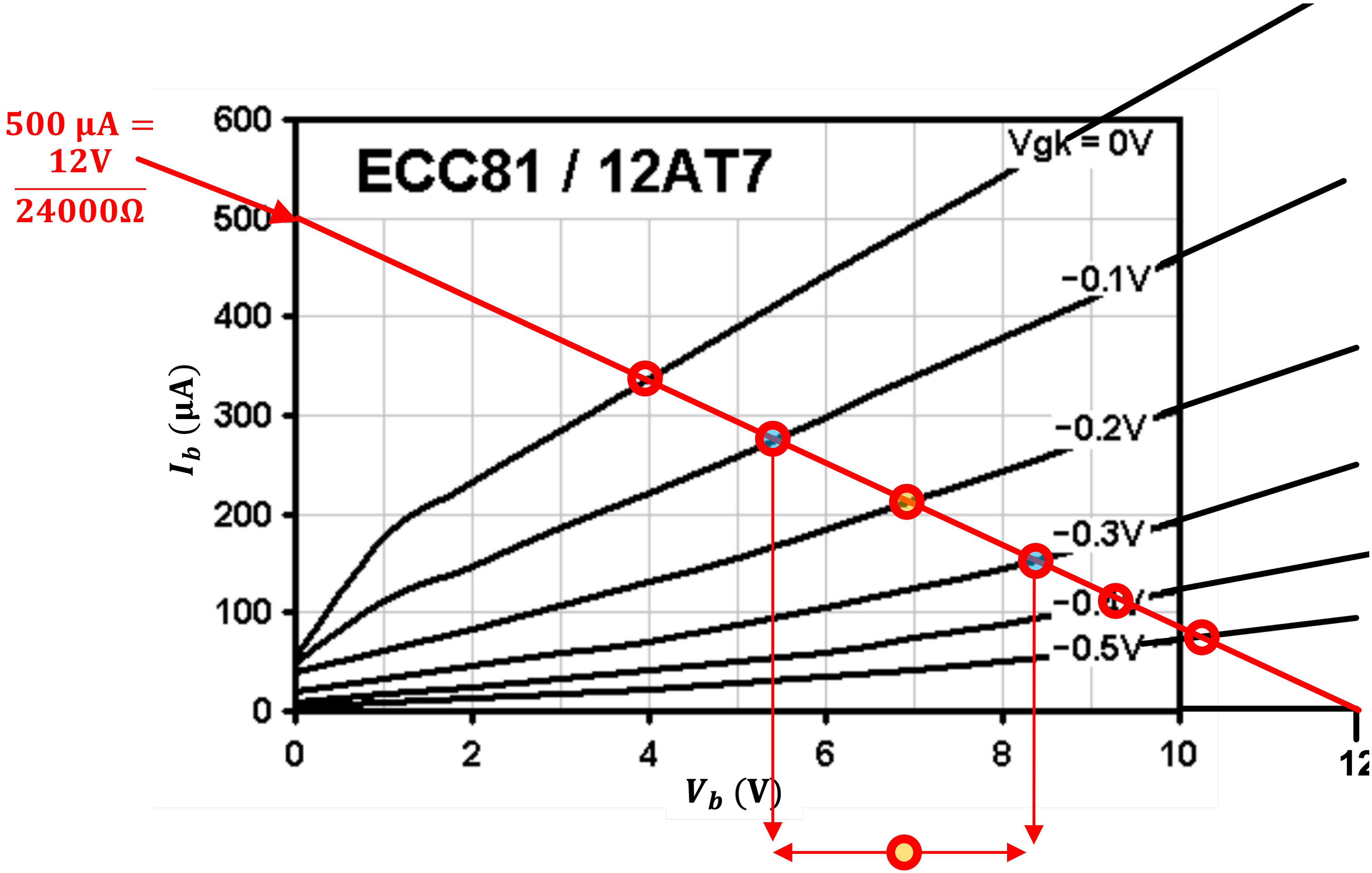
Applying that here:



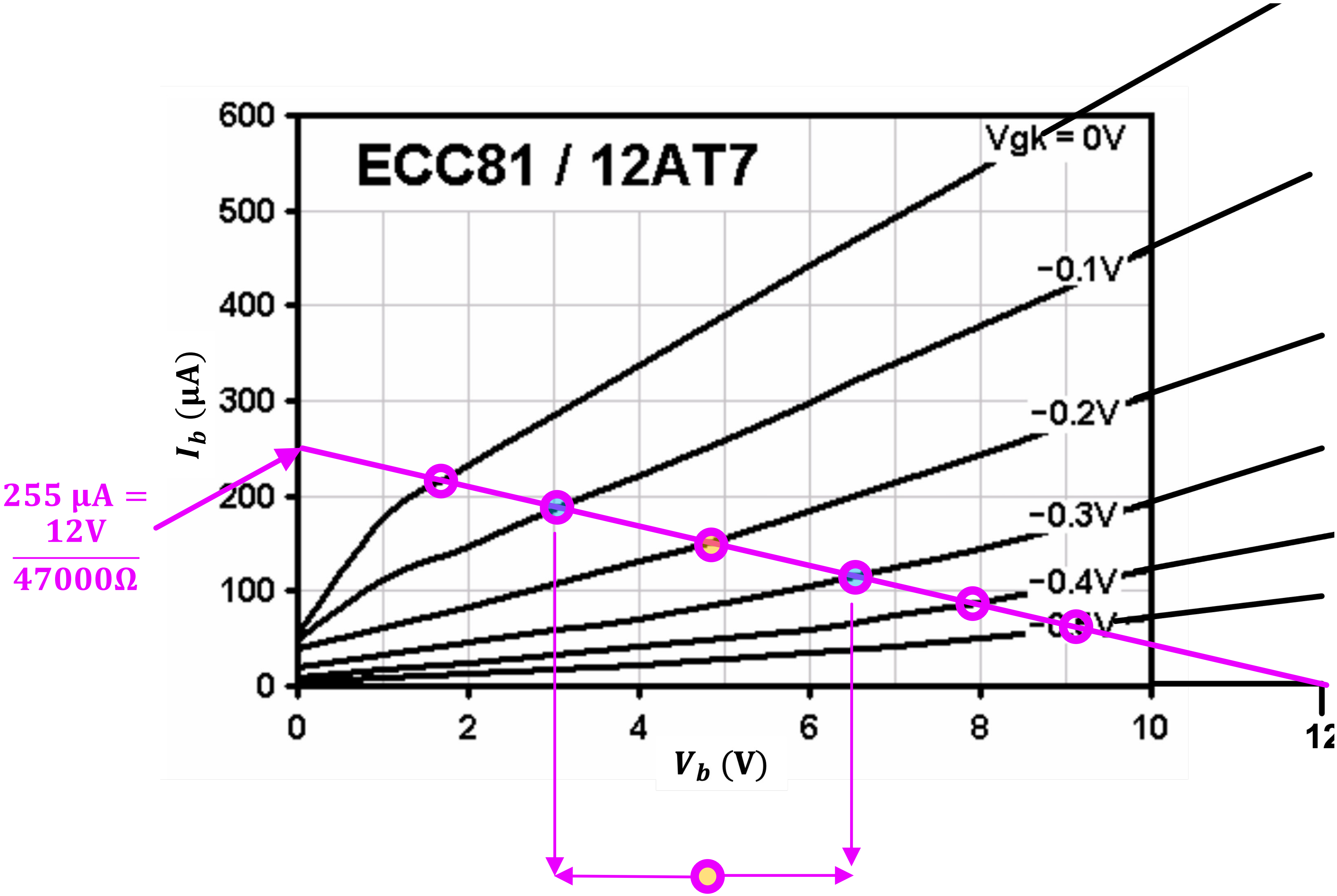
Taken and slightly extrapolated from here: http://www.valvewizard.co.uk/Triodes_at_low_voltages_Blencowe.pdf

The next step is to pick an operating point

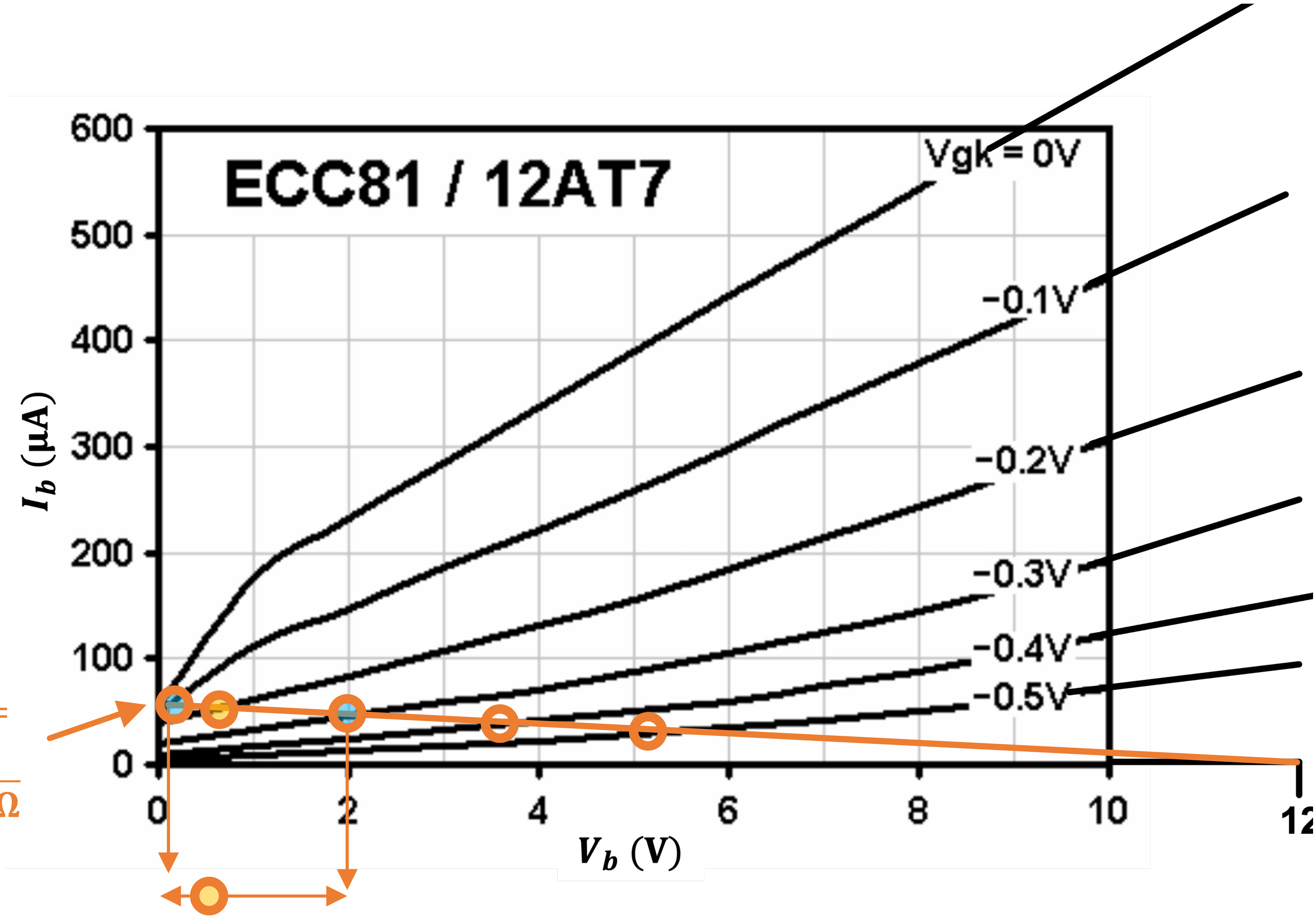
- This is a “Solution” on each load line that you want to analyze around
- Eventually we would bias the triode to sit there when no signal is present, and any signal coming in would deviate from that point, moving you up and down the load line
- We could then analyze how the output would look



$$A_v = \frac{\Delta V_b}{\Delta V_{gk}} \frac{8.25\text{V} - 5.25\text{V}}{-0.3\text{V} - -0.1\text{V}} = -15$$



$$A_v = \frac{\Delta V_b}{\Delta V_{gk}} \frac{6.5\text{V} - 3\text{V}}{-0.3\text{V} - -0.1\text{V}} = -17.5$$



$$\frac{50\ \mu A = 12V}{240000\Omega}$$

$$A_v = \frac{\Delta V_b}{\Delta V_{gk}} \frac{2V - 0V}{-0.3V - -0.1V} = -10$$

For an Amplifier we Want:

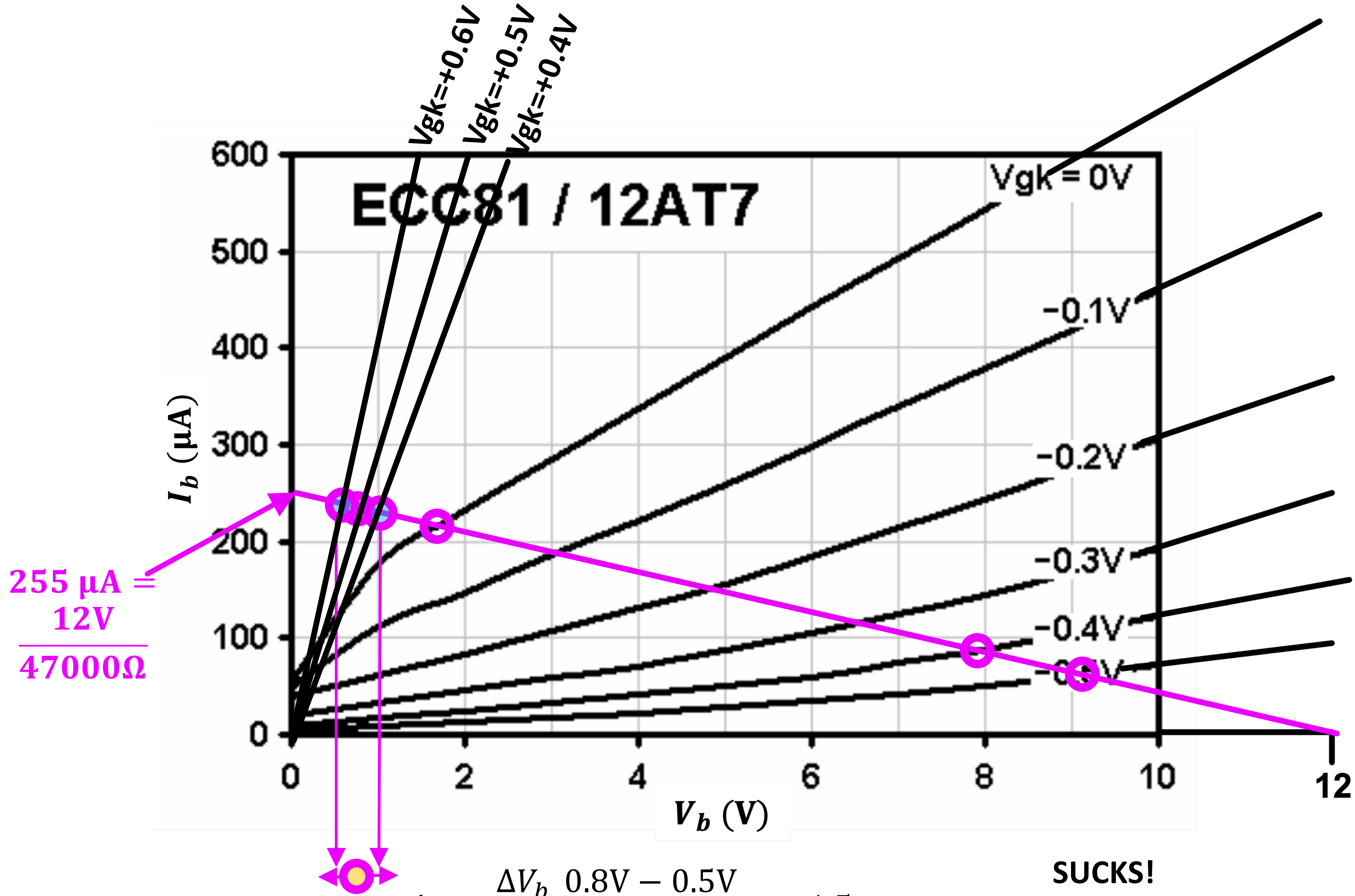
- We want a good gain (small input wiggle makes large output wiggle)
- We want a symmetric, linear behavior (we want a clean sine wave in to make a clean sine wave out…not a smushed one)

Results?

- The three different resistors have different behaviors when operating around a bias voltage of -0.2V on the grid:
  - 24K will oscillate back and forth symmetrically with gain of -15
  - 47K will oscillate back and forth symmetrically with gain of -17.5
  - 240K will oscillate back and forth asymmetrically with gain of -10
- Resistor #2 seemed to be the "best"…clean output…biggest gain. Others less asymmetric and/or less gain

Why Bias at -0.2V for grid?

- Because that was a guess. We could choose others. And in combination with other resistors we will get other behaviors.
- What if we biased at +0.5 V on the grid instead and used that “winning” 47K resistor?

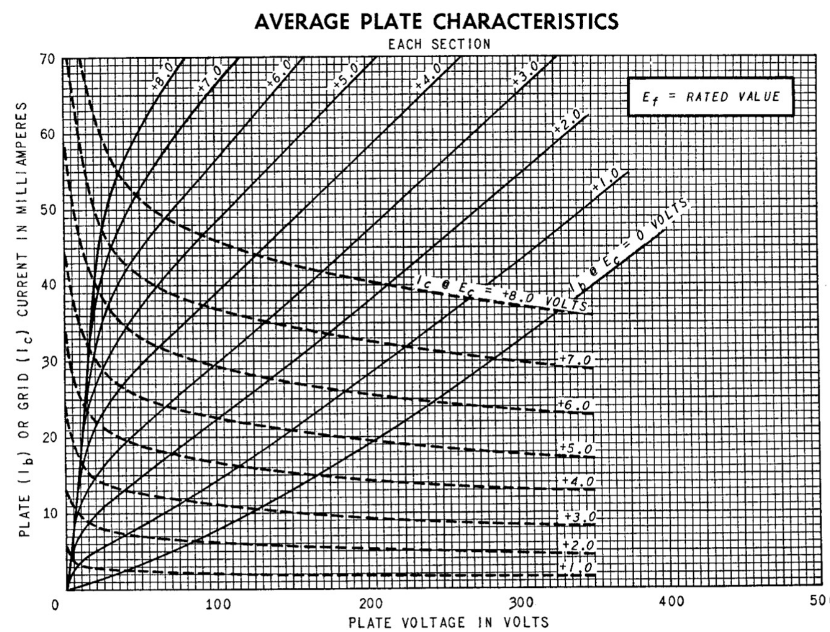


$$A_v = \frac{\Delta V_b}{\Delta V_{gk}} \frac{0.8V - 0.5V}{0.4V - 0.6V} = -1.5$$

SUCKS!

Also Though…

- At positive grid voltages, current starts to flow into the grid (electrons escape to grid rather than plate…kinda makes sense)
- This is a huge problem for low-voltage tube circuits (and also higher ones too)



So you pick something…

- And you may need to go back and change it later. Design is iterative!
- But let’s say for the first stage of our pre-amp we want to operate around a grid bias of -0.2V
- How *DO* we bias?

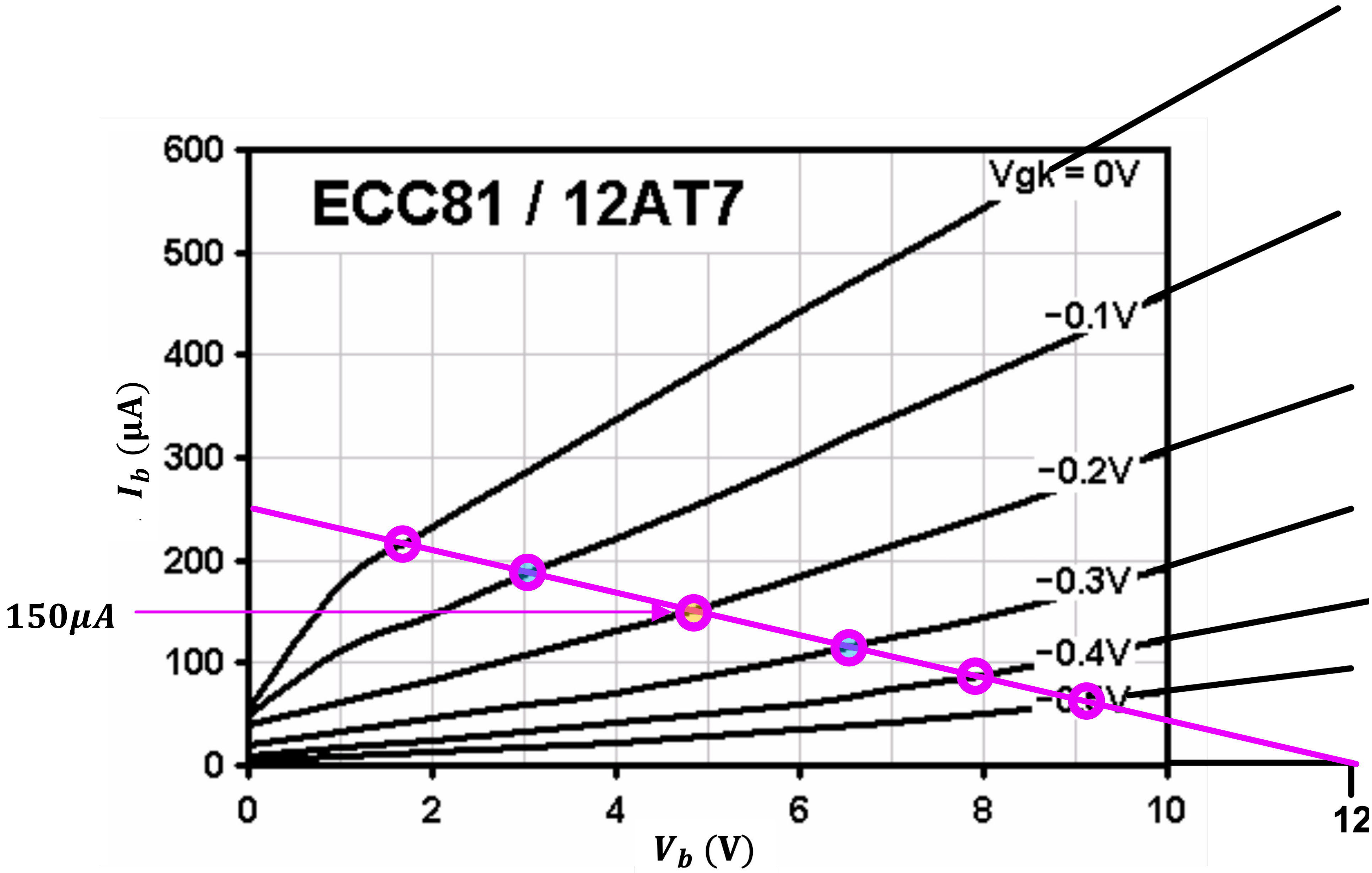
Grid Leak or Cathode Bias

- We almost always want our Grid voltage to be negative compared to our cathode. You get this two ways:
  - Make cathode ground, make grid below ground
  - Make grid ground, make cathode above ground
- In both cases $V_{grid} - V_{cat} < 0$ and we'll be in the good region of our I-V relationship

Method 1: Cathode Bias

- Determine at rest what current will be going through cathode.
- Use that current to estimate a resistor needed below it to generate a voltage drop equivalent to the bias we want.

Method 1: Cathode Bias



Method 1: Cathode Bias

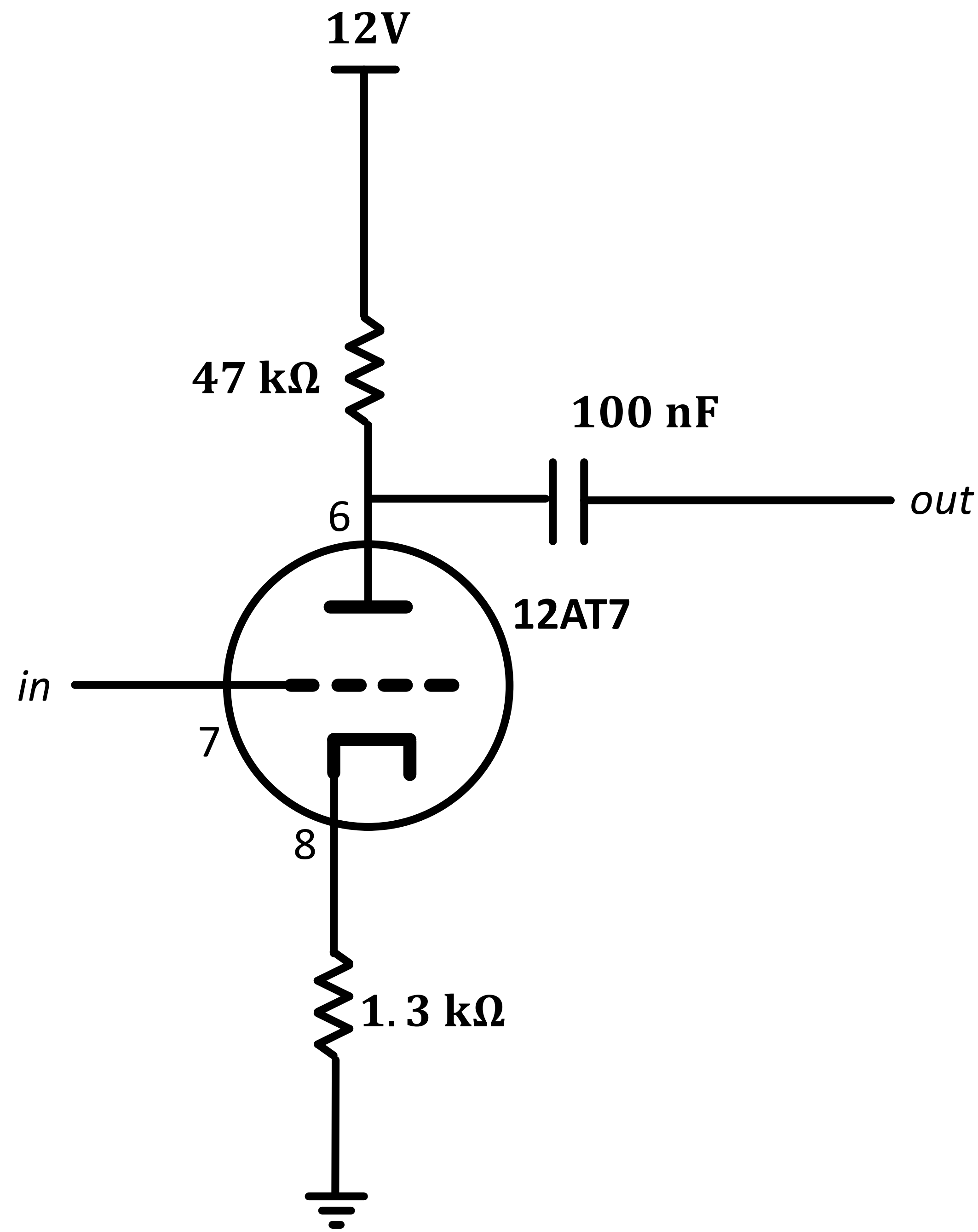
- Assuming grid is at Ground, we need a resistor to turn 150 uA into 0.2V
- Thank you Ohm's Law!

$$R_{bias} = \frac{0.2\text{V}}{150\mu A} = 1300\Omega$$

- So let's build our circuit:

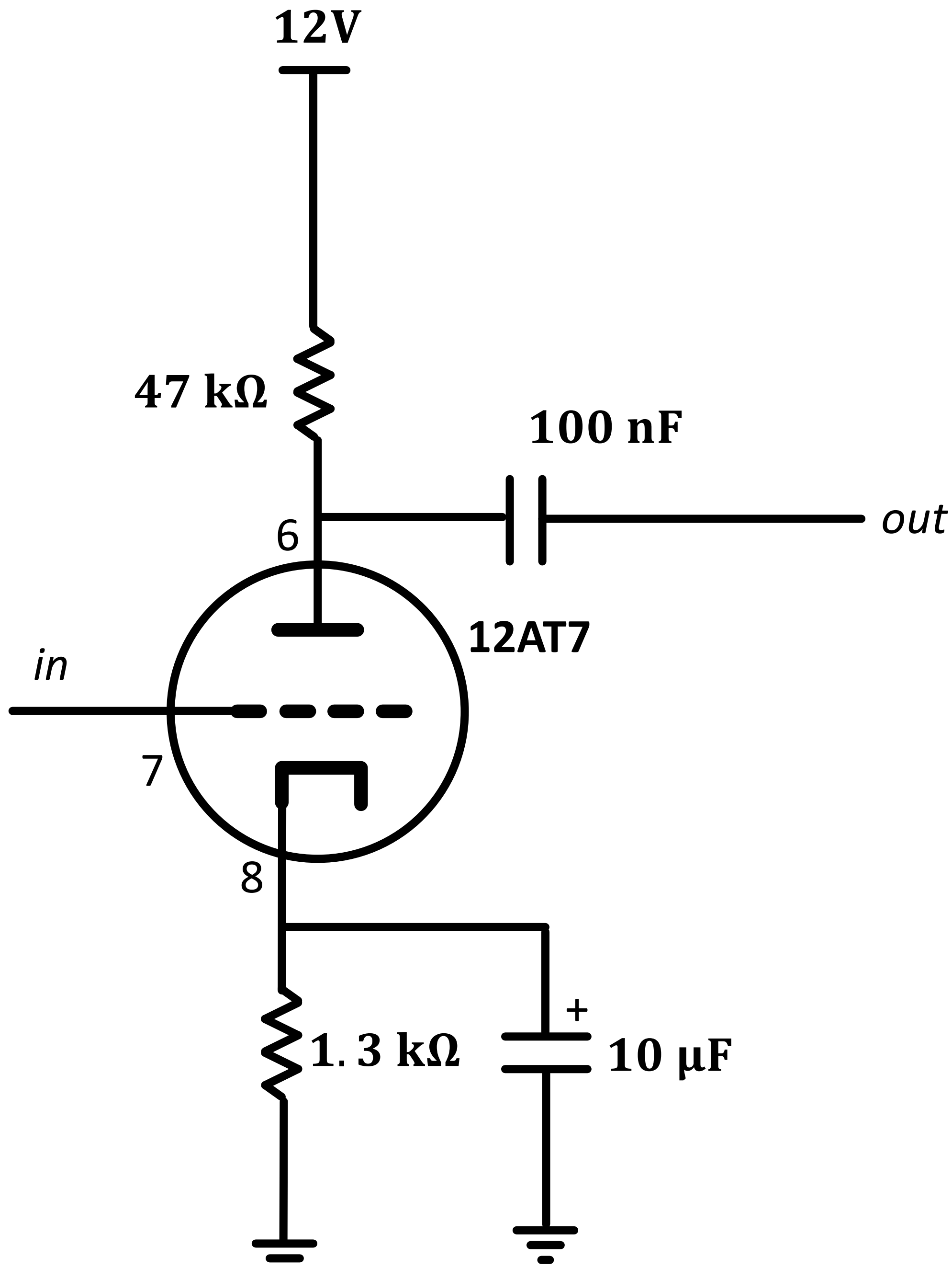
Cathode Bias

- Noice
- But…
- At audio frequencies the presence of that cathode resistor can eat into our ability to swing up and down…it will essentially modify our load line and bias point



Cathode Bias

- Solution is to put a capacitor in parallel with the bias resistor
- At DC it is invisible and our biasing is fine
- At AC (audio or whatevs), it shorts the resistor out and we don't get the "cathode degeneration"

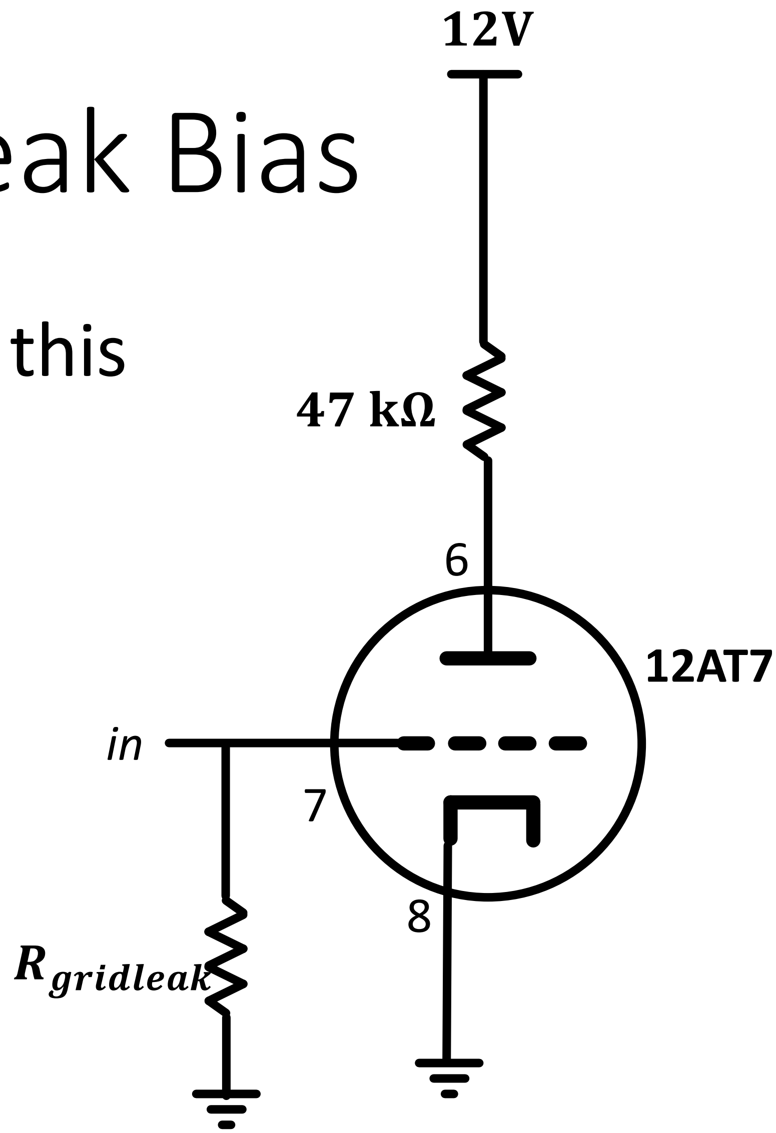


Method 2: Grid Leak

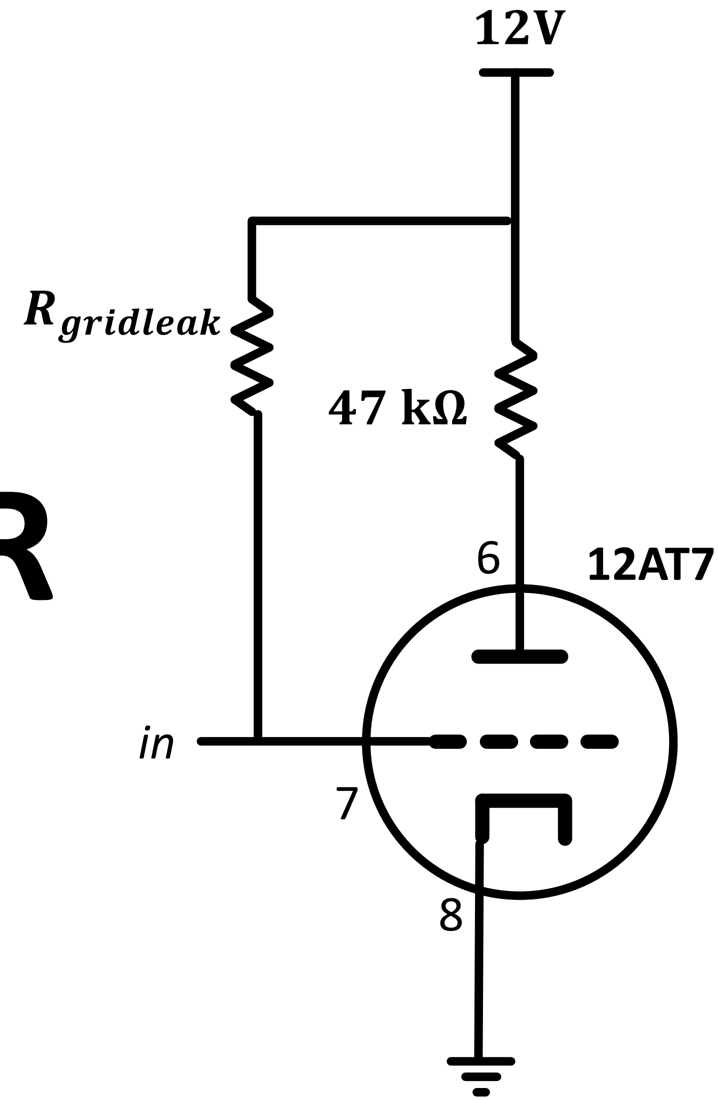
- Ground the cathode and then…connect the grid to either ground or (in low volt tube cases) Vcc
- This will make the grid a negative voltage
- …
- …
- …
- That doesn’t make sense.

Gridleak Bias

- Just do this



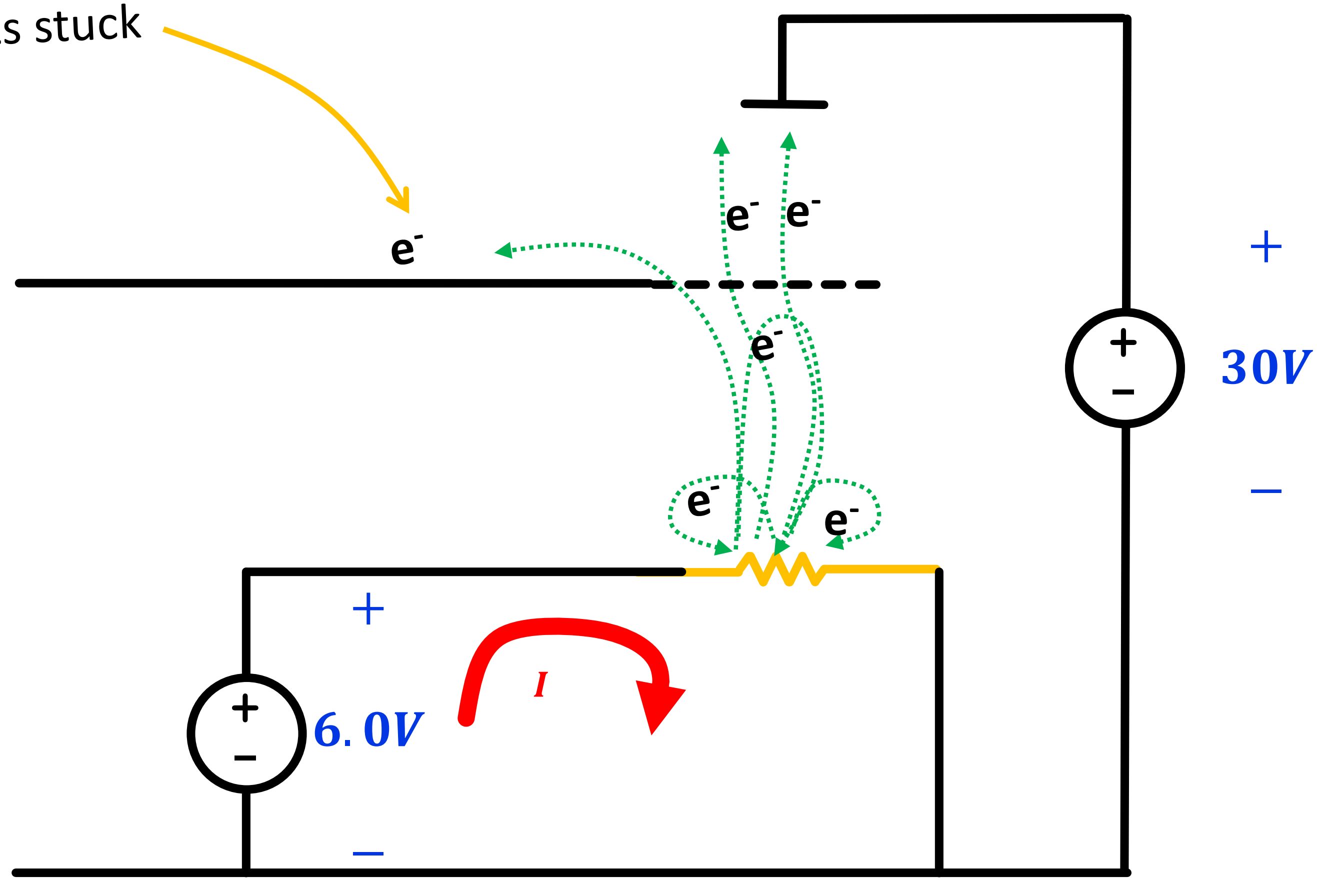
OR



- And you'll get a negative voltage (depends on value of resistor) at the grid but will be negative!

Remember the "physics"

Occasionally an electron lands on the grid, cools off, and gets stuck



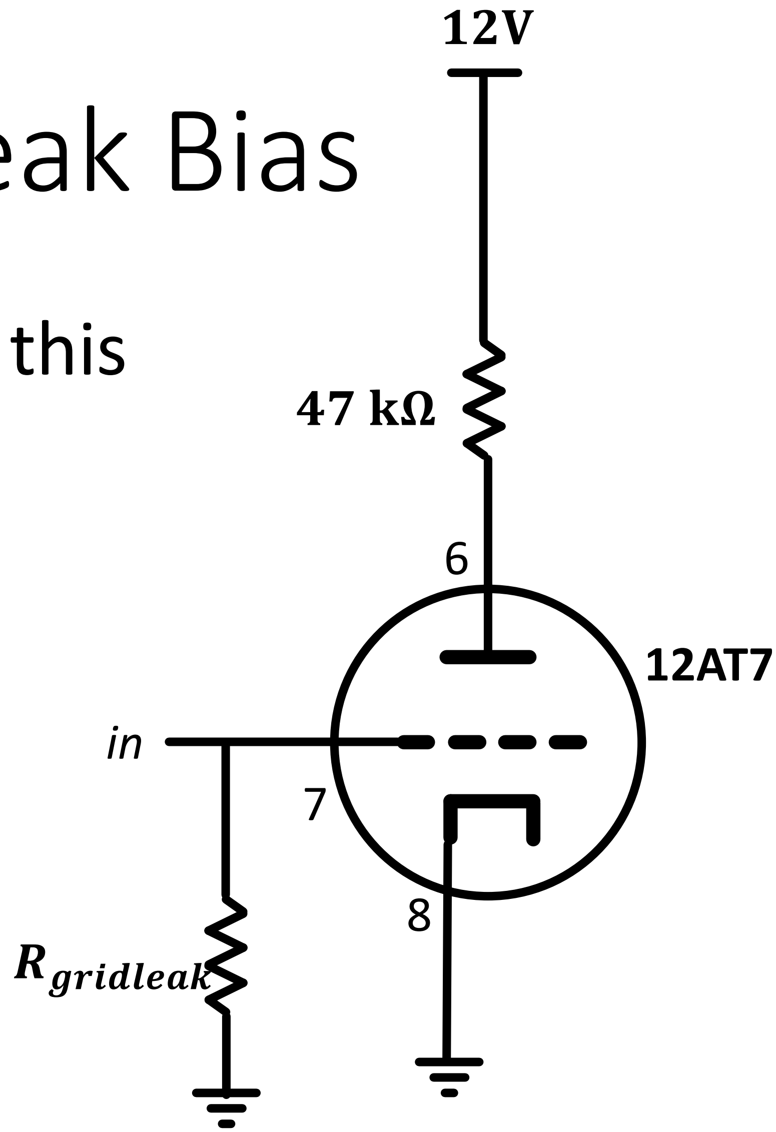
Nice Drip*

- If left alone, eventually enough electrons get stuck on the grid that they make it more and more negative negative to the point that they shut the tube off.
- If we give them an escape route (to anywhere more positive which can either be ground or Vcc), and you pick the right resistor, you can develop a tuned balance of leaking electrons and a steady negative voltage can be maintained.

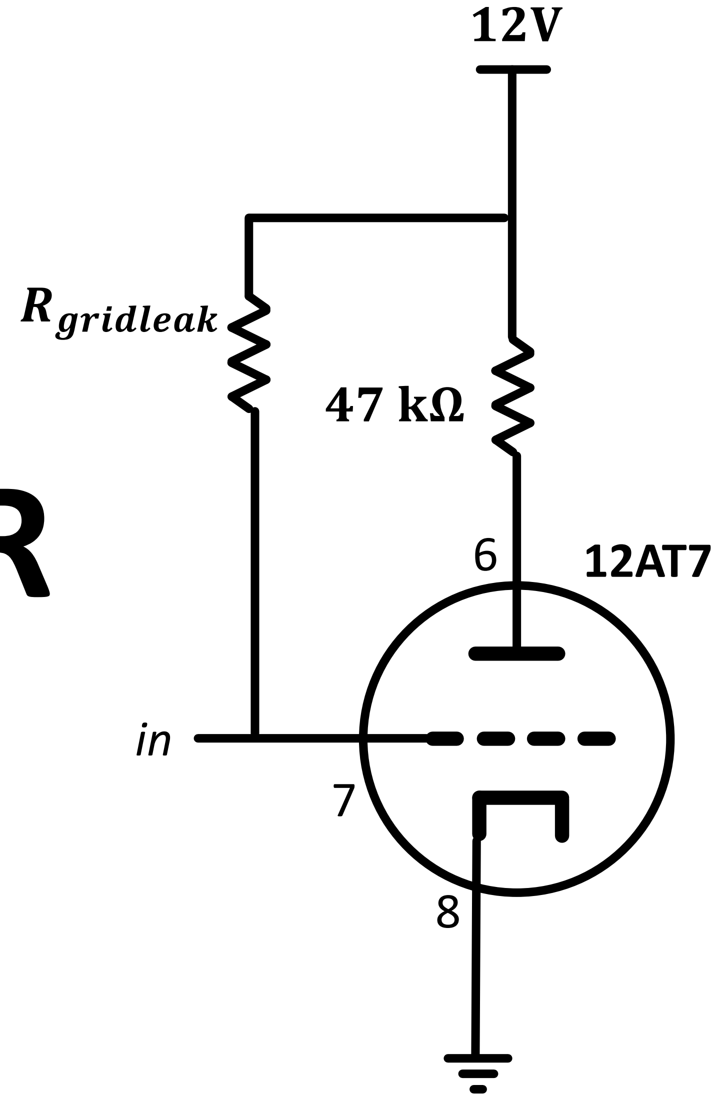
* did I say that right?

Gridleak Bias

- Just do this



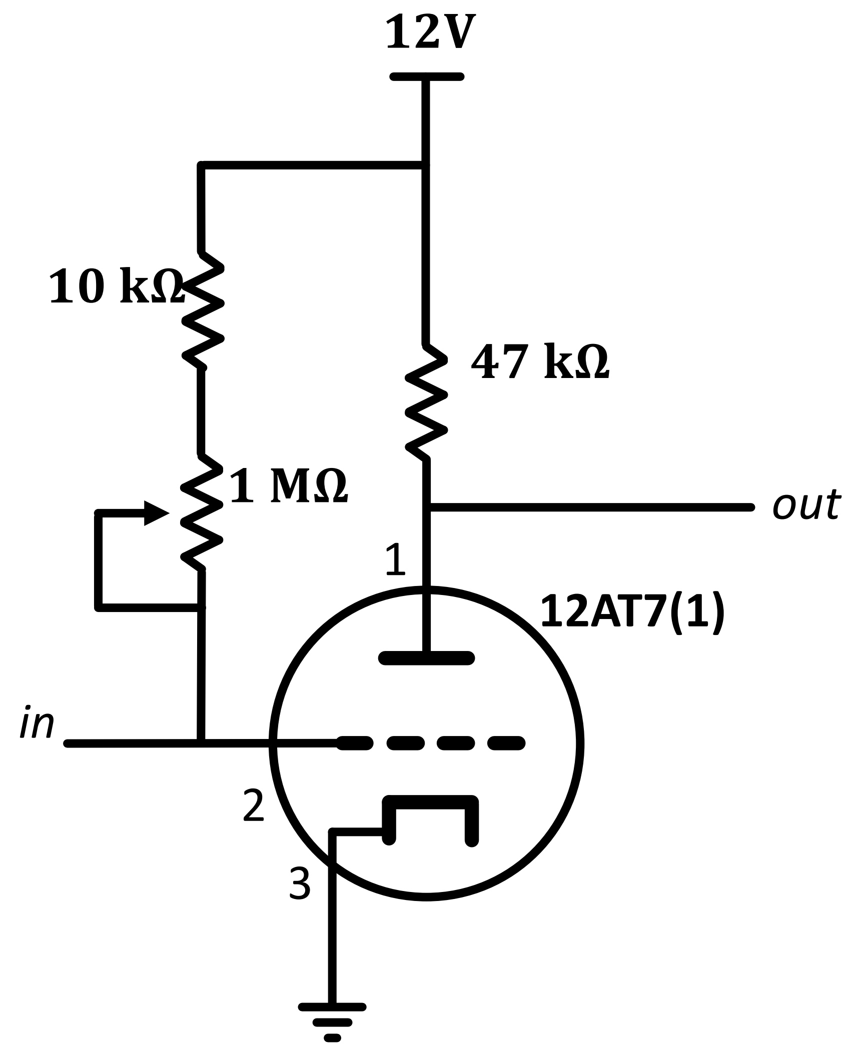
OR



- And you'll get a negative voltage (depends on value of resistor) at the grid!

So grid leak bias:

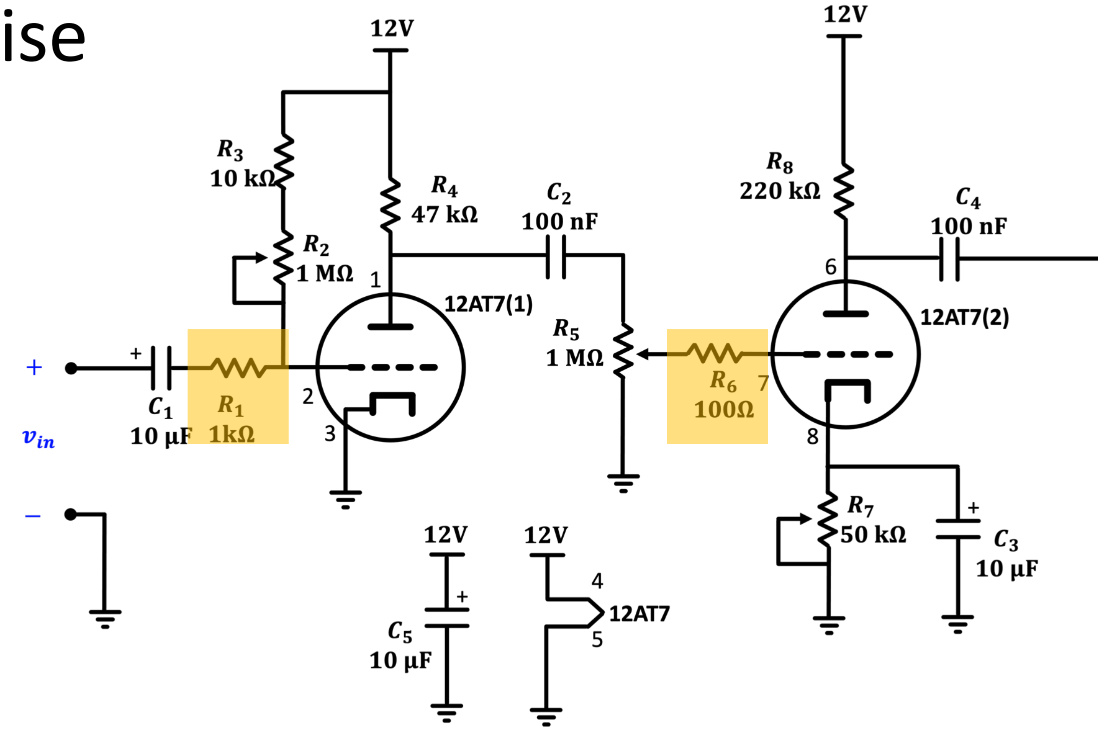
- Sometimes needs tuning
- But it works.
- It can be unstable, though so often cathode bias is a first choice, but early tube circuits used this a lot
- Also low-voltage sets really benefit from this



Could also grid leak to ground, but in a starved circuit like ours
The resistor would need to be much smaller and that would lower input impedance.
We'll grid-leak to ground on our input stage where impedance doesn't matter as much in 2024

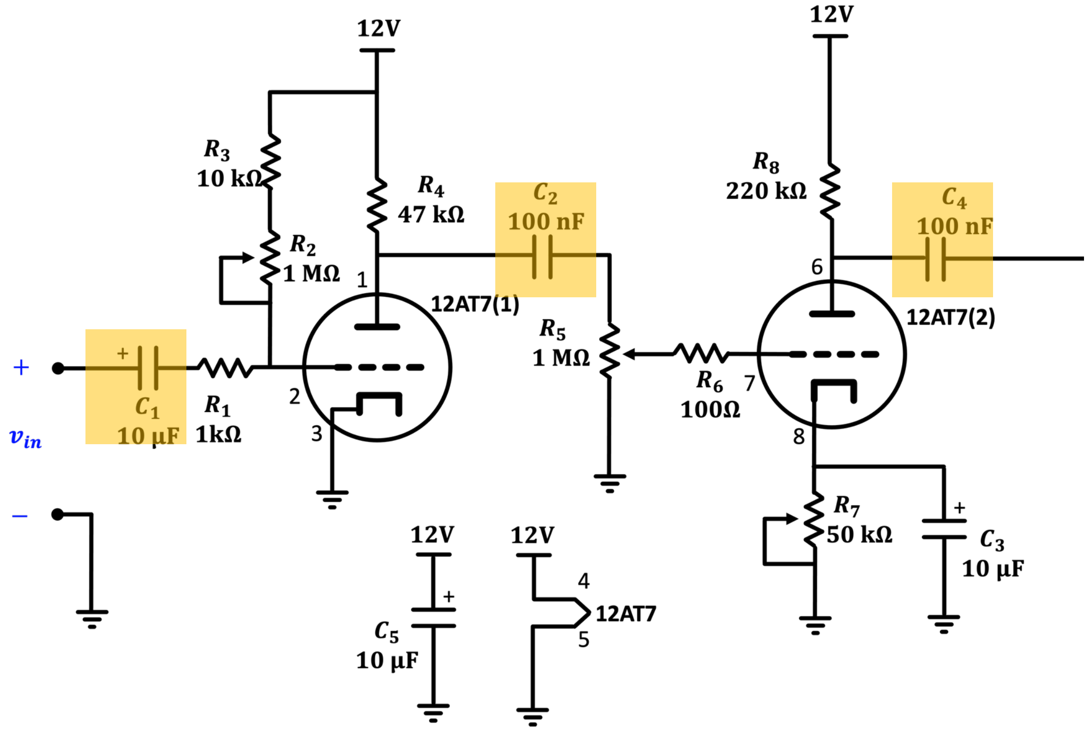
Grid Stoppers

- More next Tuesday, but rarely connect directly to a tube grid. Instead go through some sort of resistor…maybe 100 to 1000 Ohms.
- Call this a “grid stopper”
- Cuts down on noise



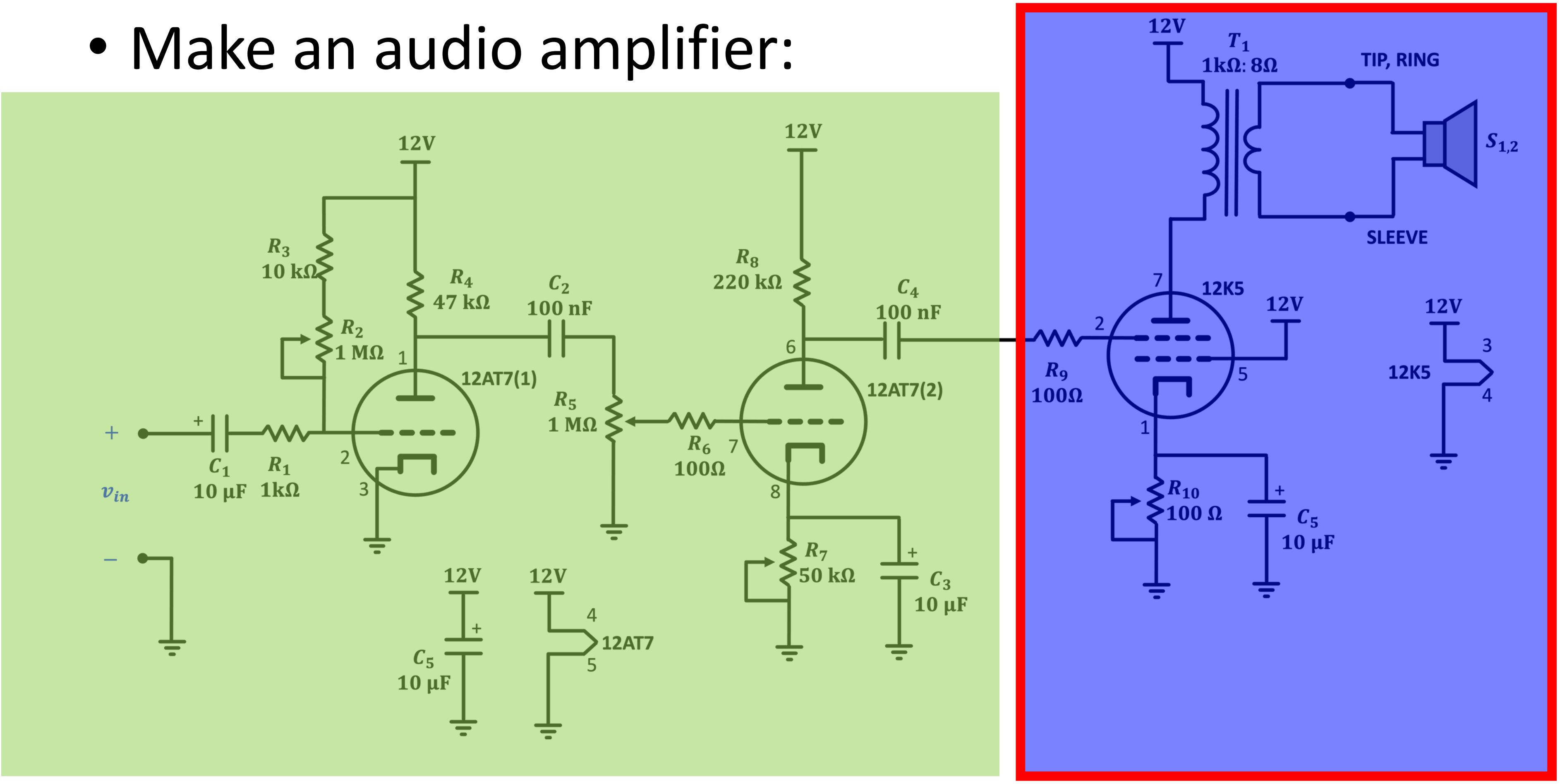
Capacitive Coupling

- While Early Tube circuits used a lot of transformers or even resistive coupling, capacitive coupling can also be fine
- There’s downsides, but as a first intro, they are easy to use
- Let’s signals through while preventing the biasing of one stage (DC) affecting the other



Lab 2

- Make an audio amplifier:

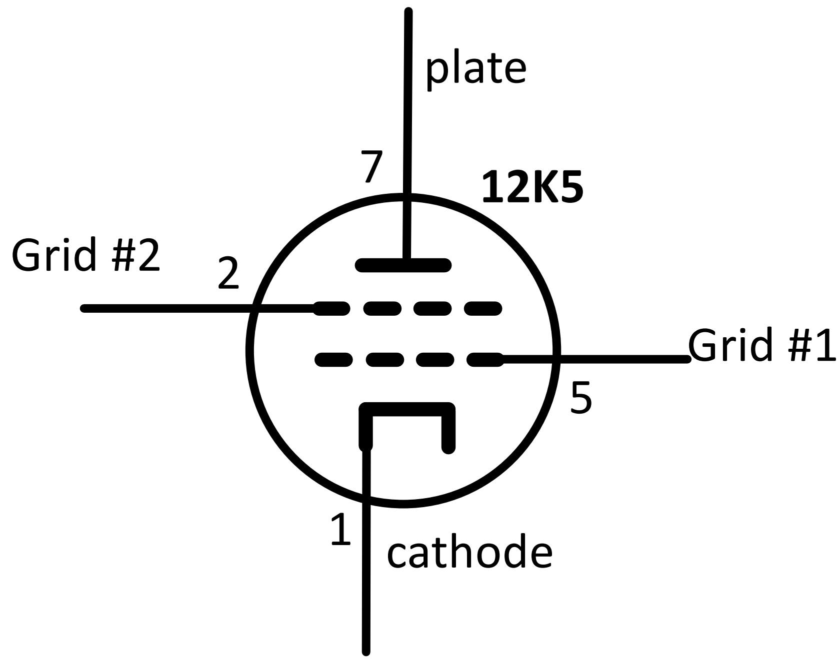


Preamplifier (largely concerned with increasing voltage of signal)

Power Amplifier (largely concerned with moving as much energy into the load as possible)

Another Tube?…the 12K5

- Space-Charge Tetrode
  - Tet is something for ”four”…so four electrodes
- Plate still plate
- Cathode still cathode
- Grid 2 is like our regular triode grid
- Grid 1 can be thought of as an accelerator grid. Attach it to high voltage (12V) and this will let us accelerate the cloud of electrons that builds up near the cathode more effectively towards the plate



This is kind of a weird tube and not used very often

Aside Car Electronics with Tubes

- Cars had radios and electronics in them as early as the 1930s.
- Tubes run on high voltages (100's of volts)
- Car batteries have been 12V or 6V for long time
- How did we get high voltage from low voltage batteries?

Vibrator Power Supplies

- Use a electromechanical switch oscillator.
    1. Coil would charge up, causing relay to close
    2. Closed relay would break current, causing relay to release
    3. Released relay switch would let current start to flow again
- Rumbled while it ran hence name
- Make AC (square wave) from DC…and then run through step-up transformer

https://hackaday.com/2016/07/04/retrotechtacular-dc-to-dc-conversion-by-vibrator/ https://www.nonstopsystems.com/radio/pdf-hell/article-zerhacker-repair.pdf

Vibrator Power Supplies

- Simple example:

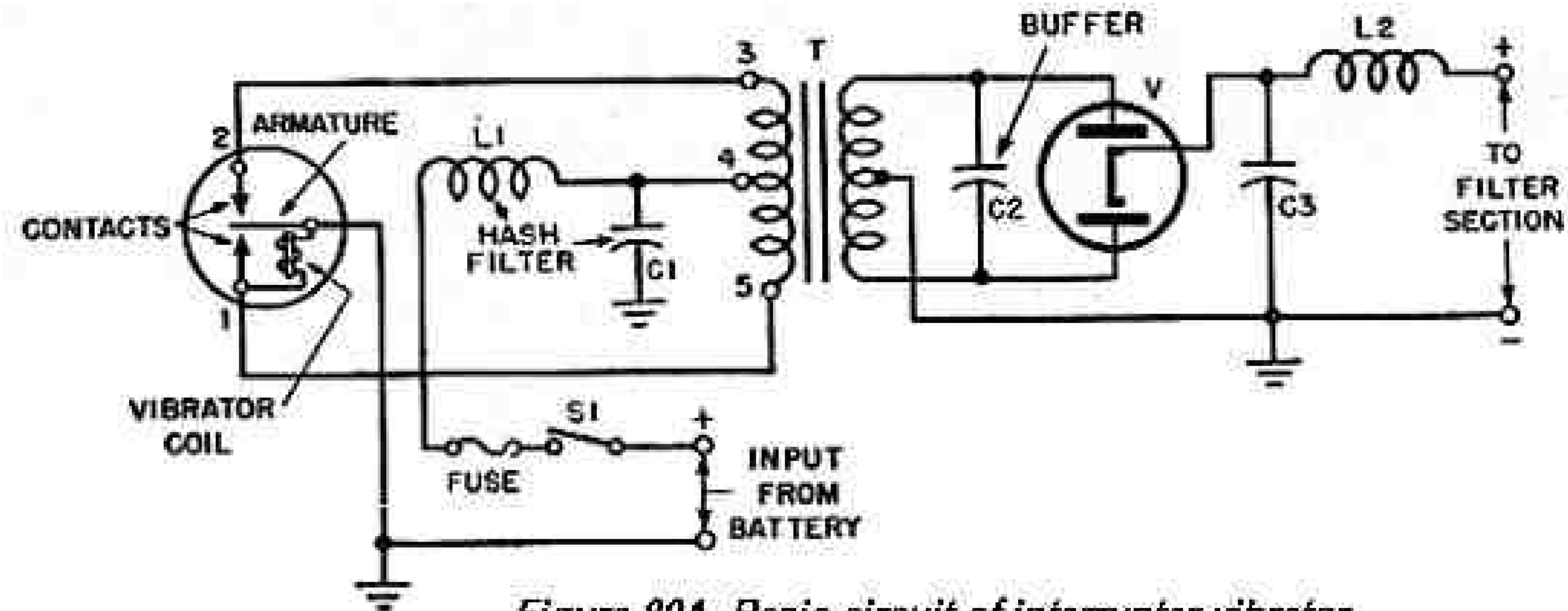


Figure 80A. Basic circuit of interrupter vibrator.

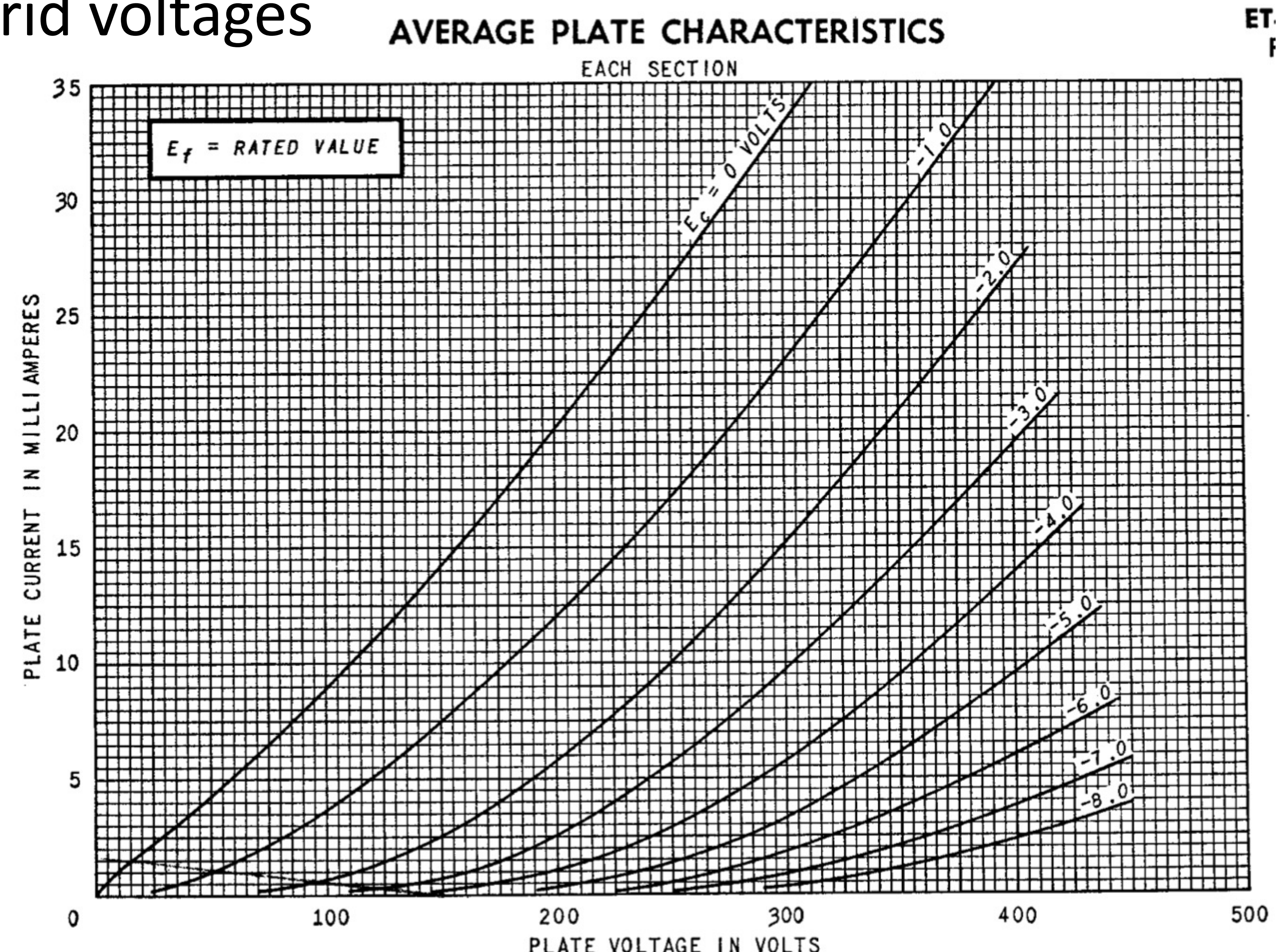
https://hackaday.com/2016/07/04/retrotechtacular-dc-to-dc-conversion-by-vibrator/ https://www.nonstopsystems.com/radio/pdf-hell/article-zerhacker-repair.pdf

Anyways… About this 12K5 Tube…

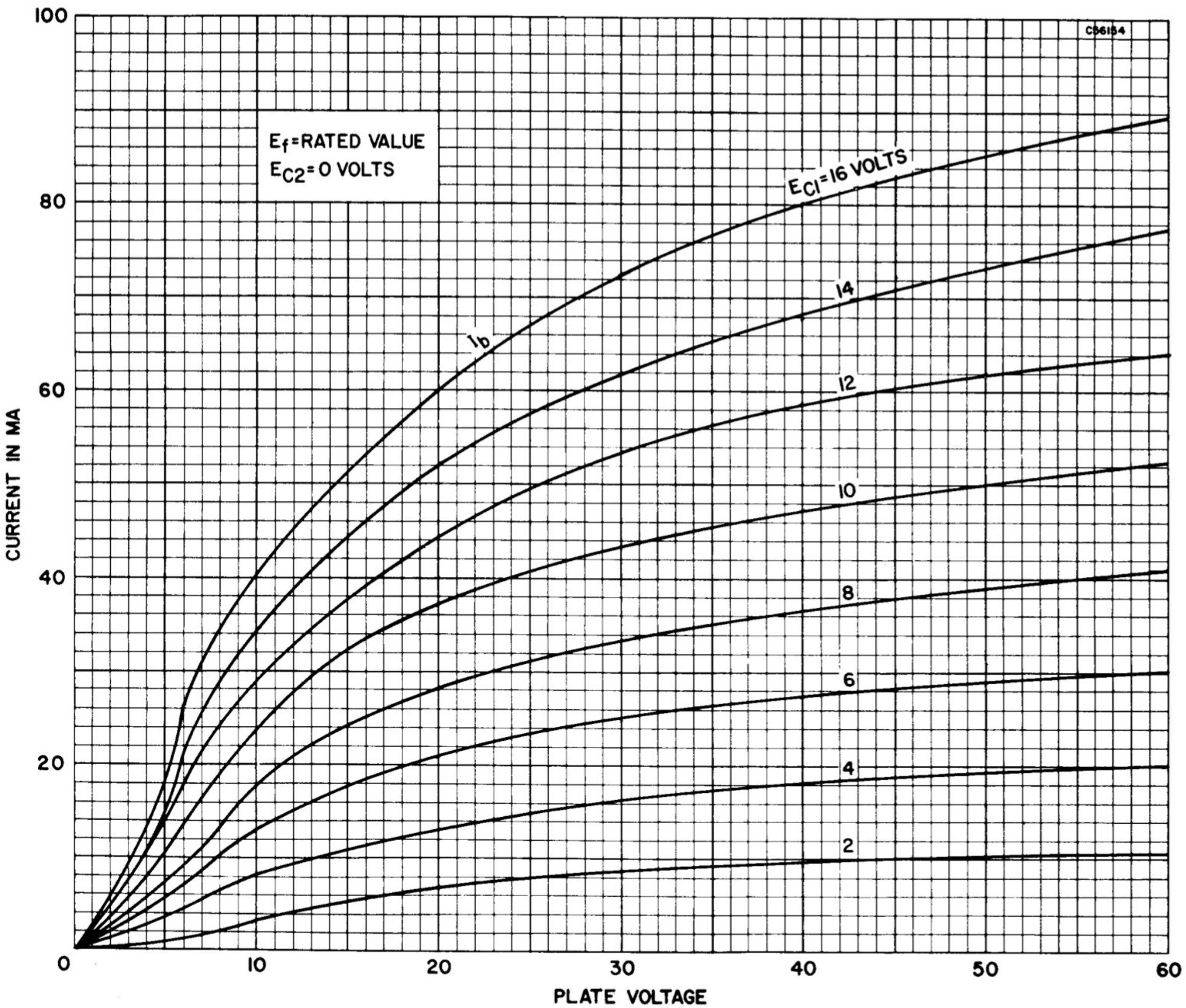
- Vibrator power supplies broke a lot (they were mechanical after all and the MechE’s are always the ones who fail us)
- So in late 1950’s research was done into making vacuum tubes that could actually work sorta well at 12V
- None of these tubes could produce much power, but they could do voltage gain and RF work at a time when newly appearing semiconductors just couldn’t
- The 12K5 was meant to be a audio amplifier **driver** for what would likely be an early germanium or silicon power transistor or something…not meant to drive a speaker directly

Remember the Triode Curve…

- Plate current as a function of plate voltage for specific grid voltages

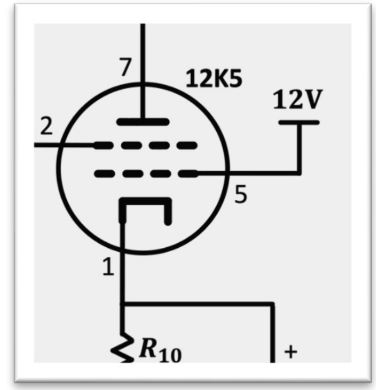


The Space-Charge Tube is different

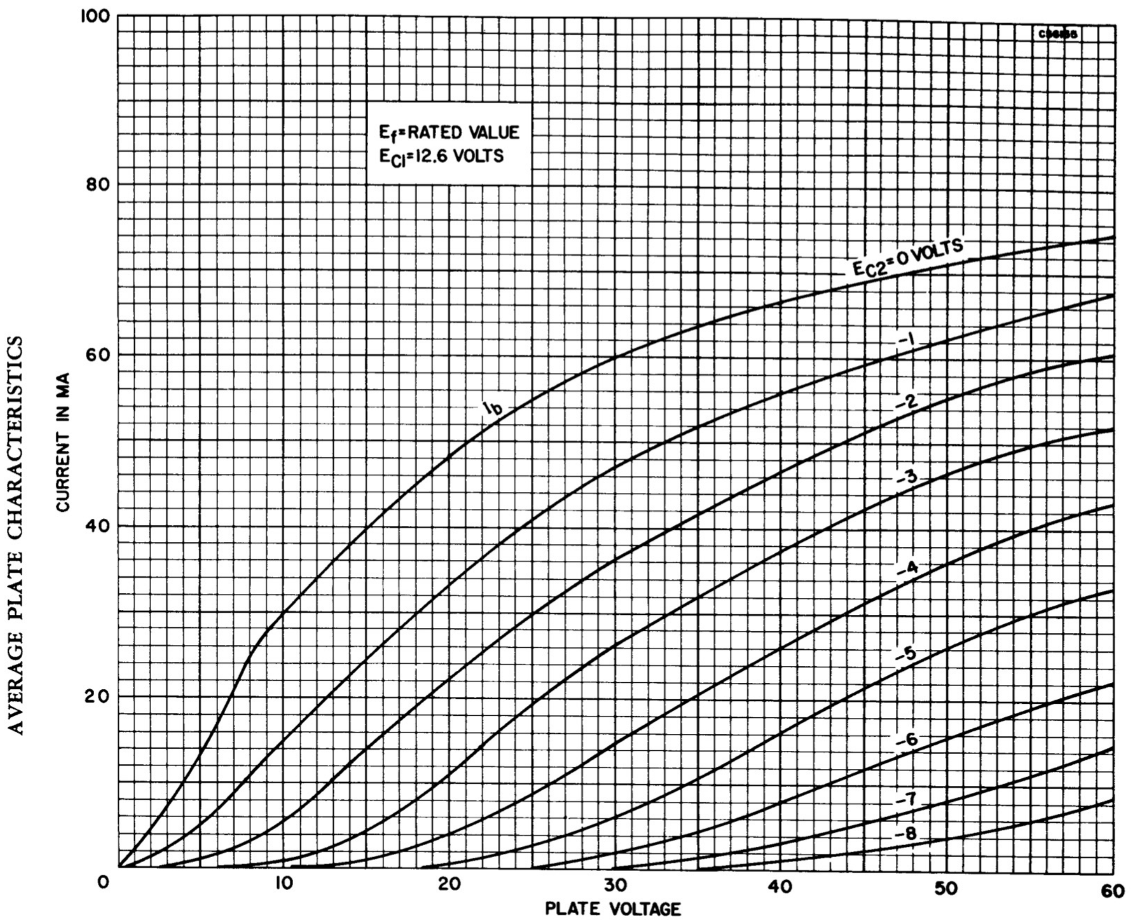


For a given control grid (C_2) value (here 0V), increasing the space charge grid voltage (C_1) in the positive direction accelerates the electrons! Increasing the current!

Just Tie C_1 to 12V



- We'll just tie the accelerator grid to 12V since that's easiest. Also there is a nearby (12.6V) plot in the datasheet that we can study then.



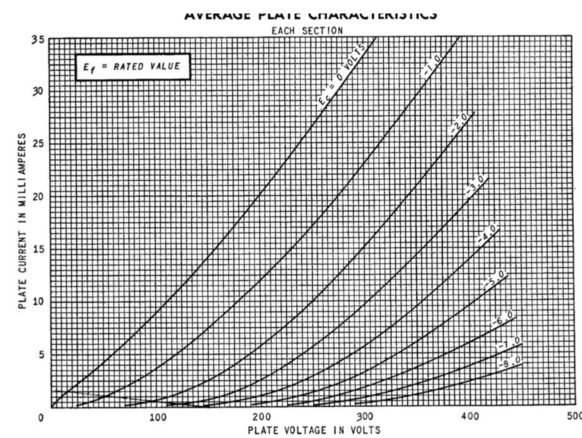
Given the space charge grid is set to 12.6V, plots of plate current I_B as functions of control grid voltage V_{C_2} and plate voltage V_B are shown here

Control grid voltage V_{C_2} is still negative relative to cathode! Just like in triode!

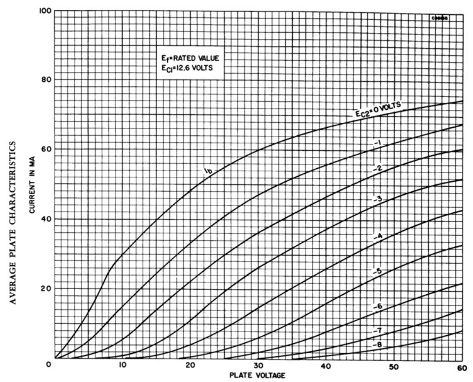
Qualitative Check…

- The 12K5's characteristics look a lot more "transistor-like" than the triode

12AT7 triode:

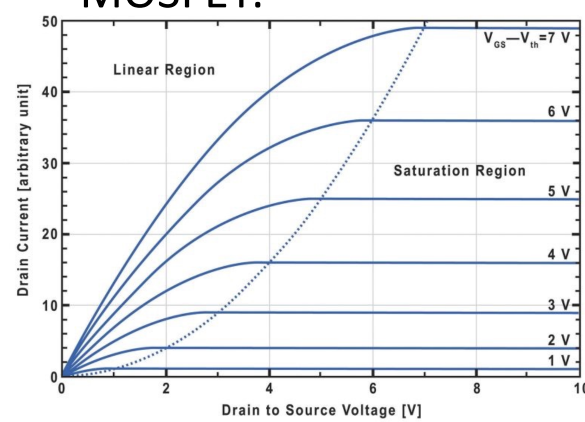


12K5 tetrode:



This looks more like this than this

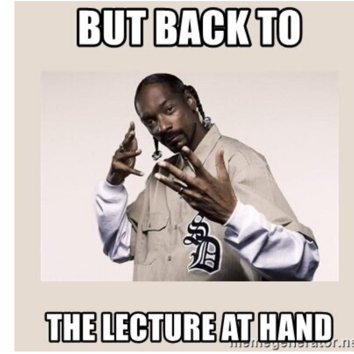
MOSFET:



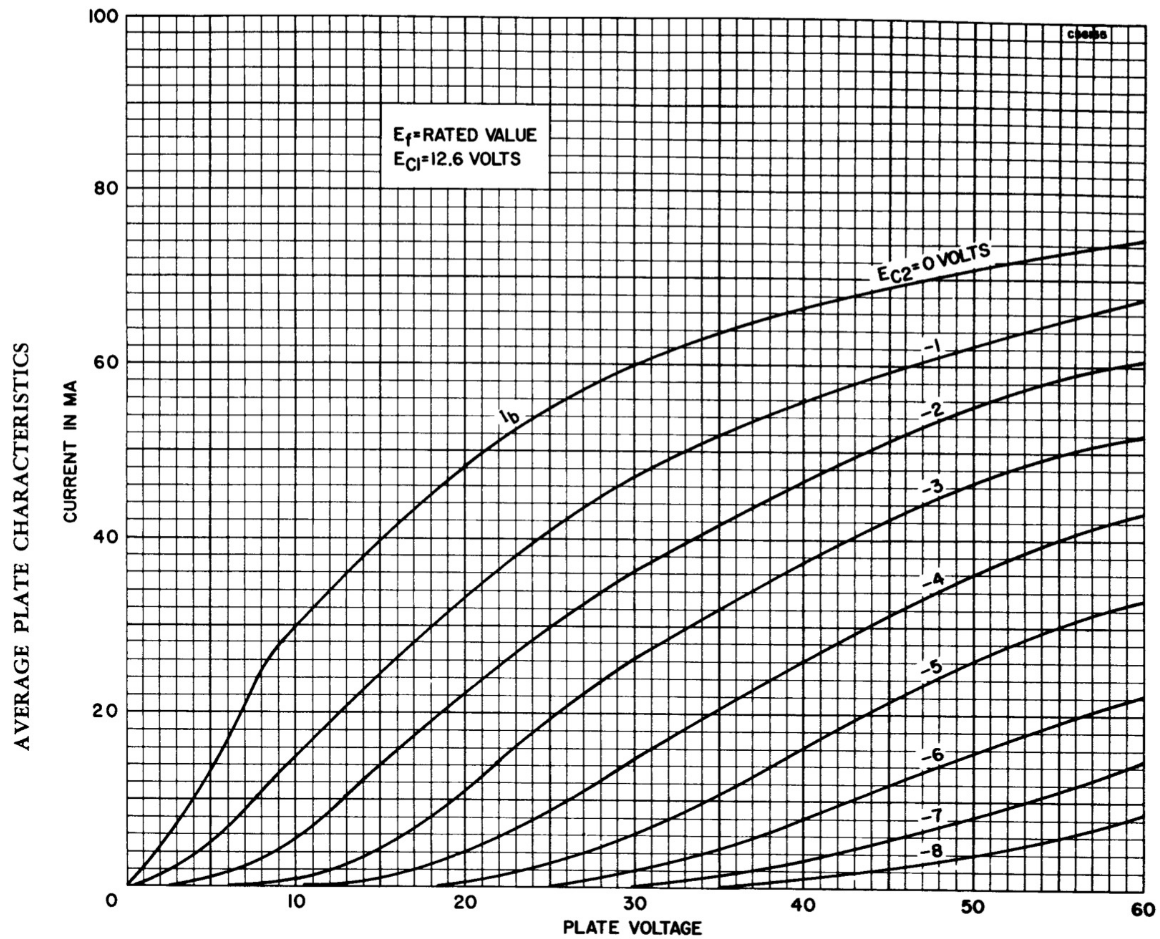
Sign of things to come (future classes) As more electrodes are added, the triode curve disappears and the "pentode/transistor" curve shows up

https://www.mks.com/n/mosfet-physics

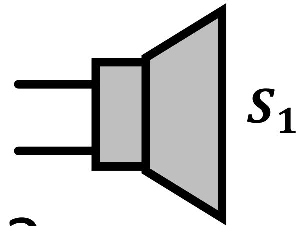
But Back to the Lecture At Hand



- Where should our load line go?
- We know the x (v_B)-intercept: 12V
- What is our slope or y-intercept?
- What is our Load?



12K5 is Driving a speaker.

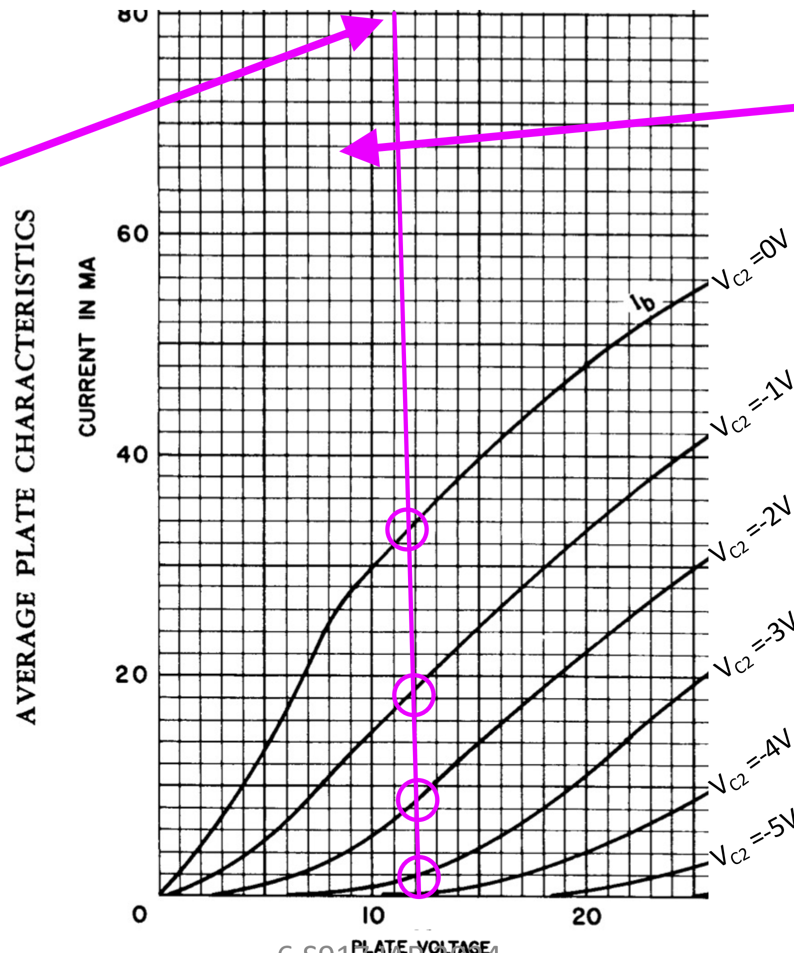


- What is the impedance of a speaker?
- Generally Very Low:
  - 8 Ohms, for example. What will that give us for a load line?

y (i_B)-intercept will be:

$1500\text{ mA} = \frac{12\text{V}}{8\Omega}$

Waaaaaay up there



Slope is $-\frac{1}{R_{speaker}}$

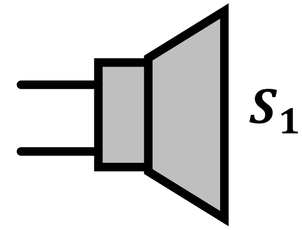
This thing is essentially vertical

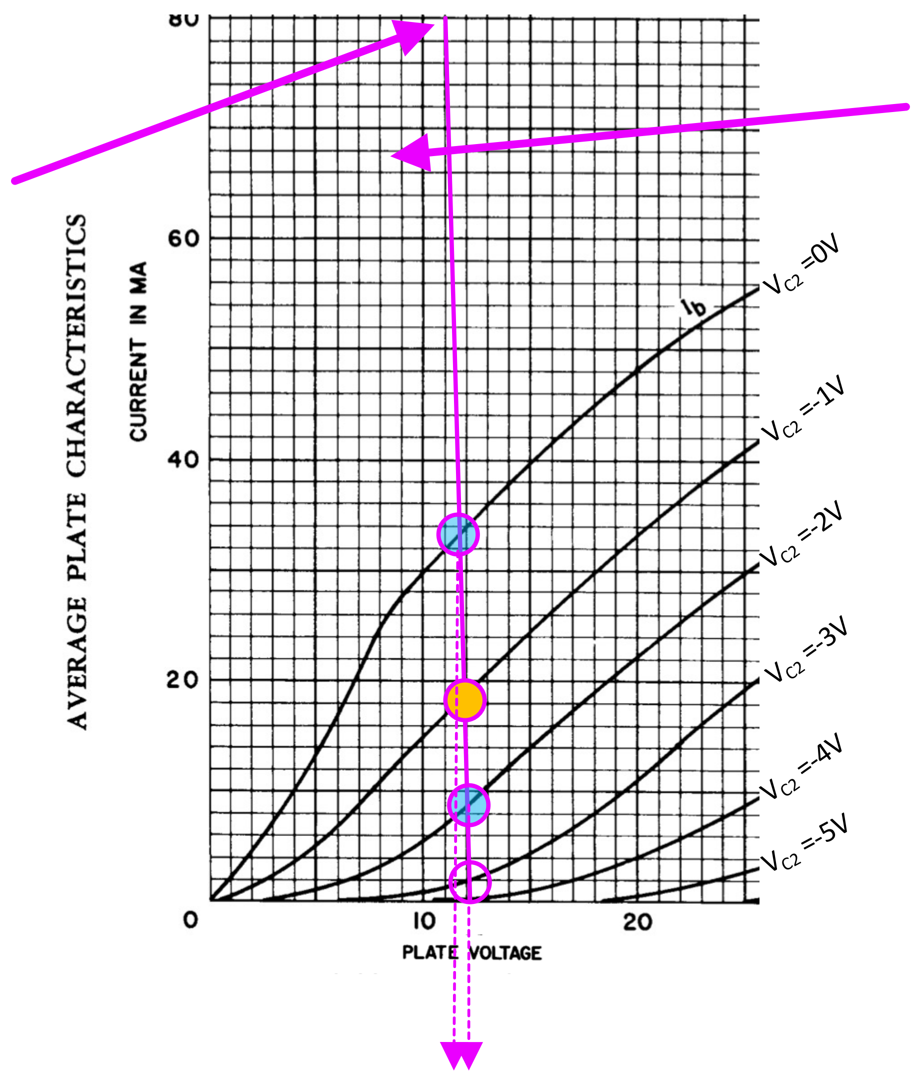
IS THIS OK?

Iunno this is just a line

Well let's think…

- If the input voltage is biased at -1V and we wiggle back and forth by +/- 1V what do we get?





$$A_v = \frac{\Delta V_b}{\Delta V_{C2}} \frac{11.938\text{V} - 11.736\text{V}}{-3\text{V} - -1\text{V}} = -0.1$$

$$\Delta V_b \approx 11.938\text{V} - 11.736\text{V}$$

IS THIS OK?

Voltage gain isn't really what we care about

How much power is delivered to load?

- For a 2V_{pp} input sine wave, we get out a 200 mV_{pp} sine wave into an 8 Ohm Load
- A 200 mV_{pp} sine wave has an amplitude of 100 mV
- A sine wave with amplitude 100 mV has an V_{RMS} of 70.7mV
- Power delivered to 8 Ohm load from this signal is $P_L = \frac{V_{RMS}^2}{R_L} = \frac{0.0707^2}{8\Omega} \approx 620\mu W$

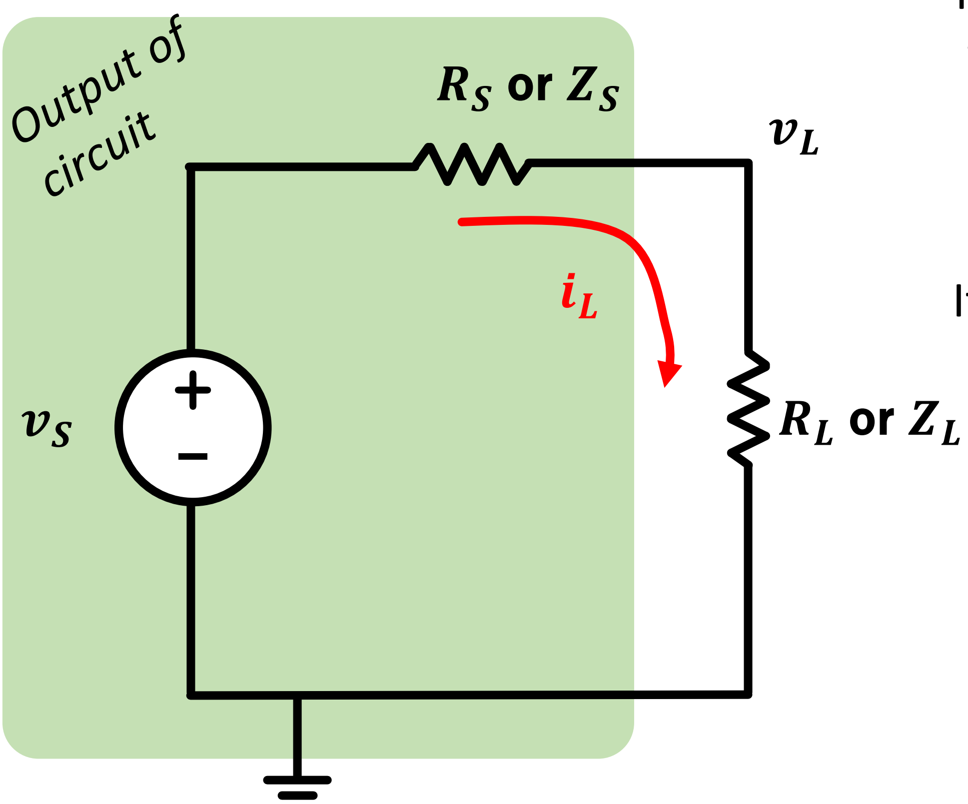
IS THIS OK?

This is not a lot of power…

So no, this sucks

We need a better impedance

- We can always model the exchange of information and energy from one portion of a circuit to another with a Thevenin circuit driving a load:



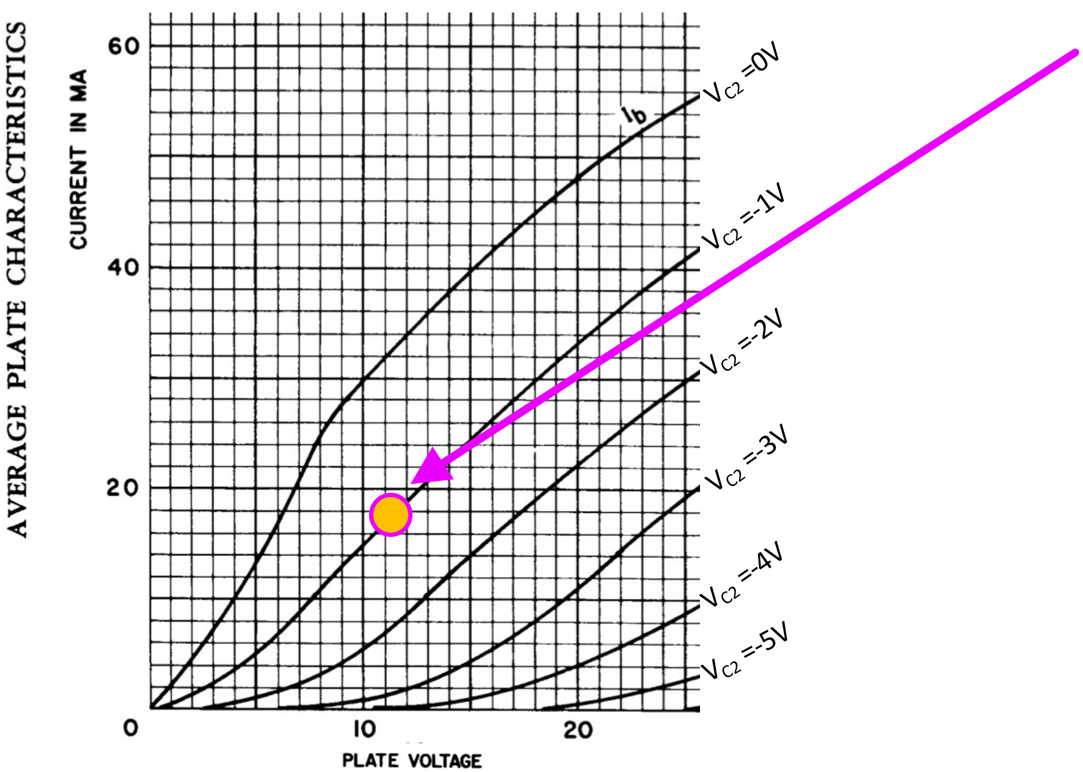
If concerned about passing voltage onto load: focus on $R_L > R_S$ and ideally $R_L \gg R_S$

If concerned about passing max power into load:

focus on trying to get as close as possible to $Z_L = Z_S^*$

What is our Output Impedance?

- That is the same as our Plate resistance r_P we could use the estimated numbers from the data sheet but those are for a particular point in operation. Let's go to the truth (the curves!)

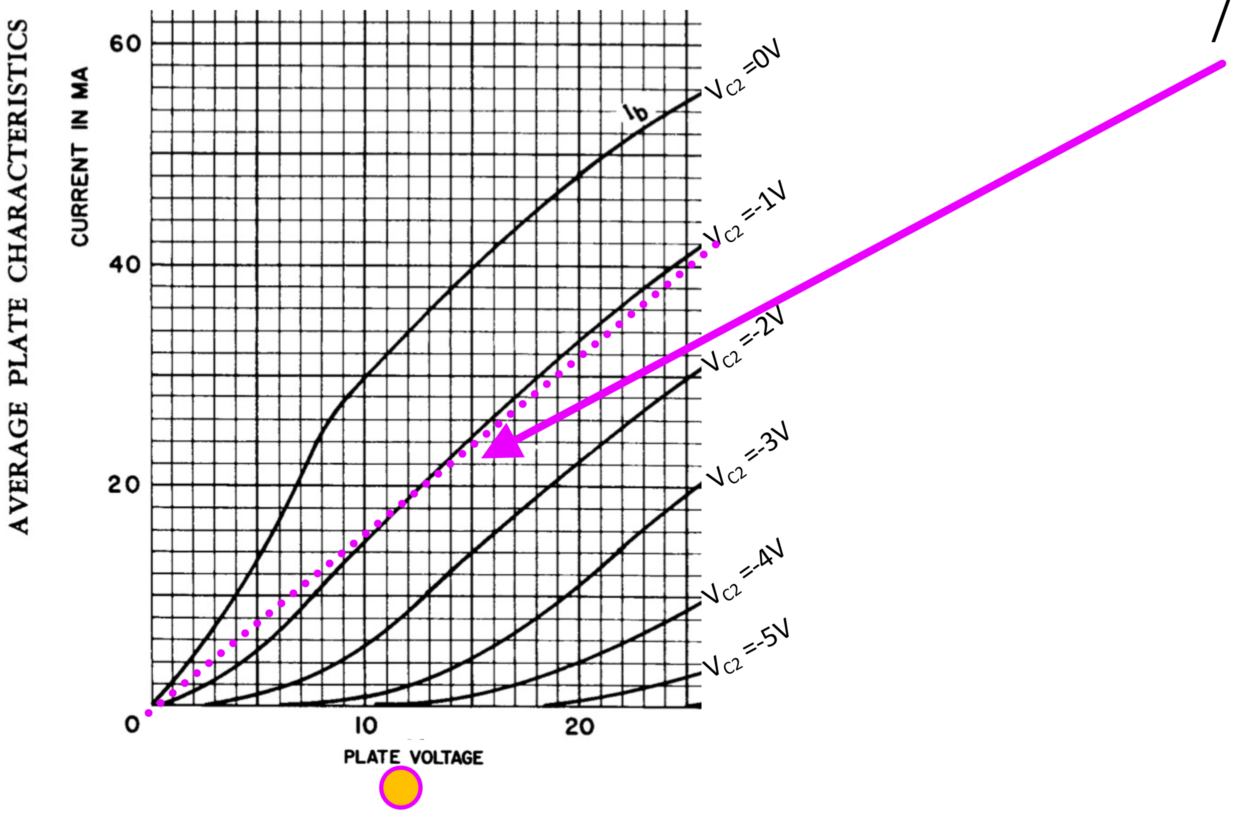


- At whatever point we operate at, the slope will give us our output impedance (or the inverse or it)

What is our Output Impedance?

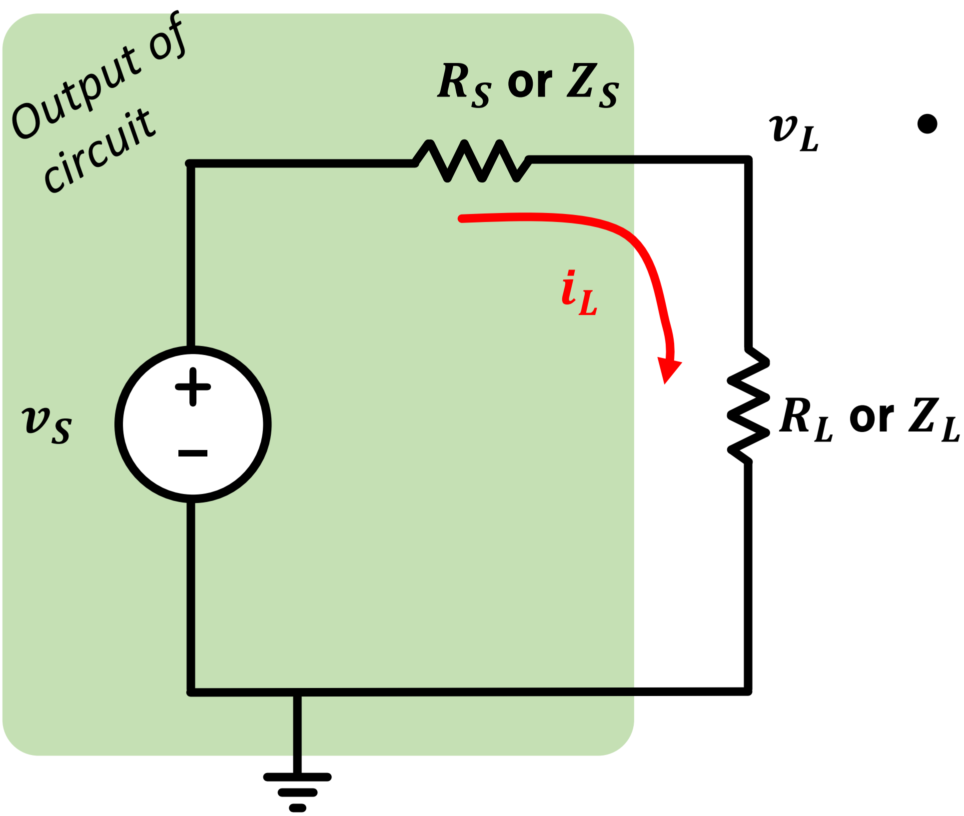
- It is varying but a rough estimate in this area of curves:

$$R_S = {}^{1}\!\Big/\frac{\Delta I_b}{\Delta V_b} = \frac{25\text{V}}{40\text{mA}} = 625\Omega$$



We need a better impedance

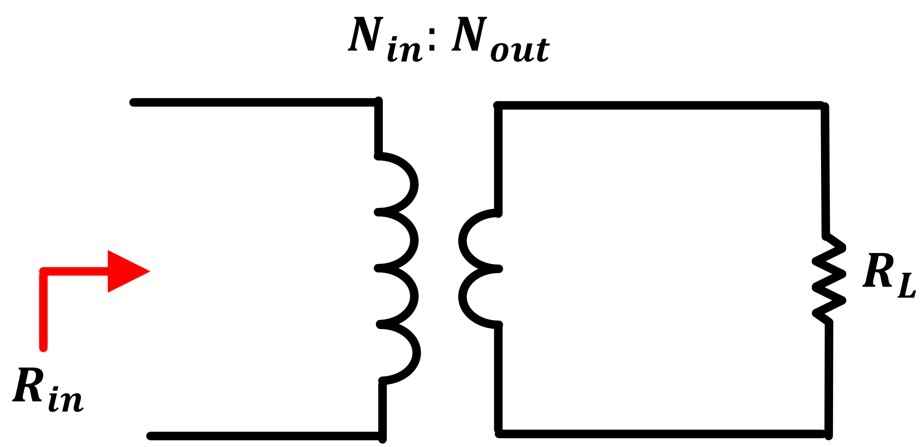
- So currently $R_S = 625\Omega$ and $R_S = 8\Omega$
- That is quite a mismatch



- If only there resolve this conflict.
- We need an ombuds component

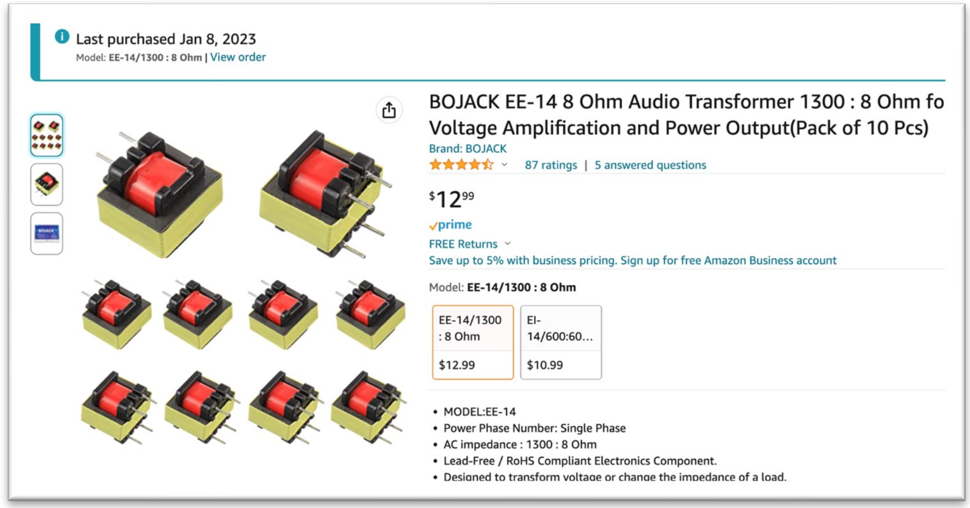
Use a transformer to **Impedance Match**

- We've already seen that a transformer can alter the effective impedance seen by a device.
- Let's use one here. We want to make a low-Ohm speaker look like a higher-Ohm device. How to do



So therefore: $R_{in} = R_L\left(\frac{N_{in}}{N_{out}}\right)^2$

A common problem

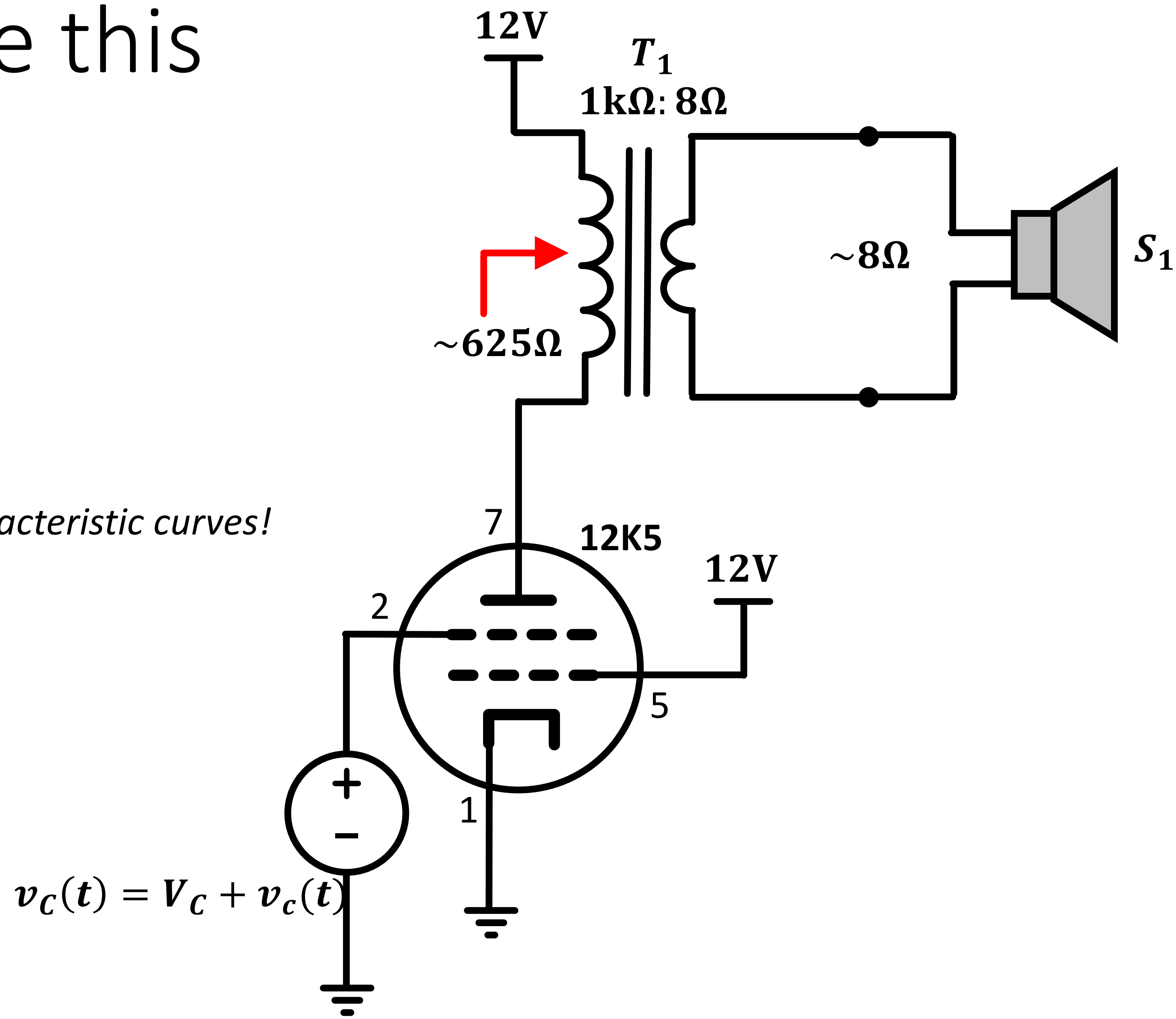


- This is needed quite a bit
- So I tracked down some transformers that are advertised to have a coil winding ratio such that it can make an 8 ohm look like a 1300 ohm
- Not exactly what we need, but not awful and gets us closer… (the load and source are same orders of mag now)
- For sake of argument, let's say this is really a 8ohm:1000 ohm transformer…which is another common model you'll see

They don't even list the winding ratio since that's not what we care about and we're lazy…they just do the math for us, but it could be backed out…roughly a 13:1 ratio

So we have this

Let's go back to our characteristic curves!

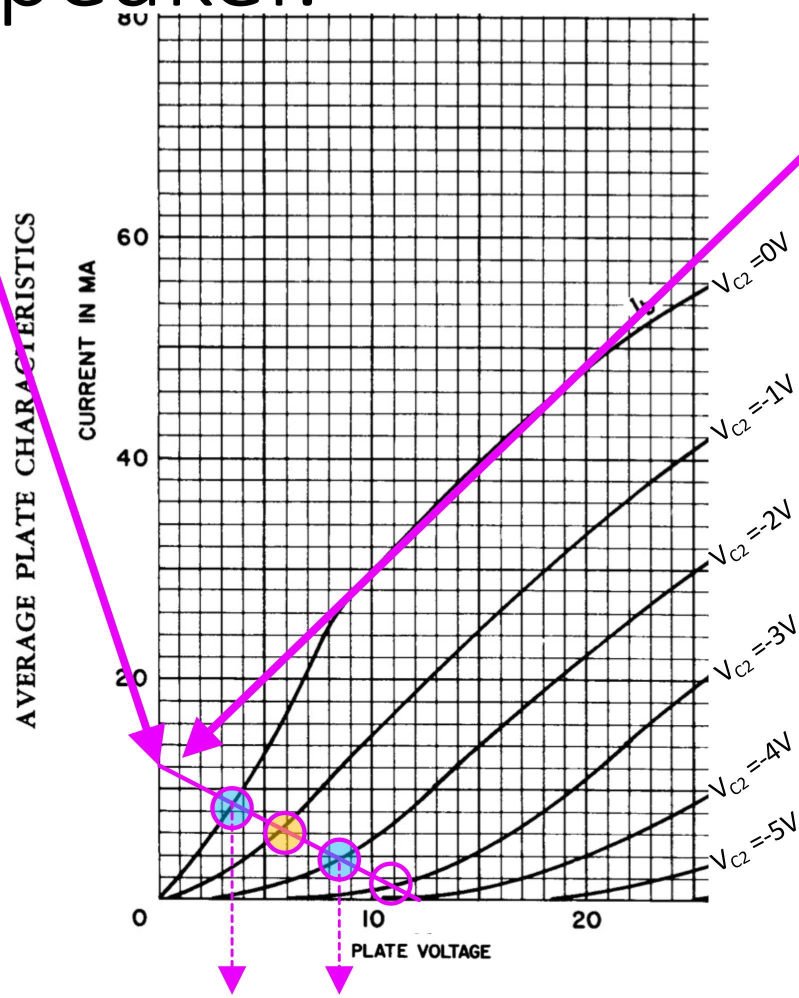


We are Driving an impedance-matched speaker.

- Load Line:

y (i_B)-intercept will be:

$$12\text{ mA} = \frac{12\text{V}}{1000\Omega}$$



$$\Delta V_b \approx 8.5\text{V} - 3.5\text{V}$$

Slope is $-\frac{1}{1000}$
This thing is essentially vertical

At the bias point of -1V for the grid,

$$A_v = \frac{\Delta V_b}{\Delta V_{C2}} \frac{8.5\text{V} - 3.5\text{V}}{-3\text{V} - -1\text{V}} = -2.5$$

IS THIS OK?

lunno this is just a number

How much power is delivered to load?

- For a $2V_{pp}$ input sine wave, we get out a $5V_{pp}$ sine wave into an 10000 Ohm Load
- A 5 V_{pp} sine wave has an amplitude of 2.5 V
- A sine wave with amplitude 2.5 V has an V_{RMS} of 1.76V
- Power delivered to 1000 Ohm load from this signal is $P_L = \frac{V_{RMS}^2}{R_L} = \frac{1.76^2}{1000\Omega} \approx 3\text{mW}$
- Assuming all the power delivered to the transformer goes into the speaker (reasonable assumption) , that means we're delivering way more power!

IS THIS OK?

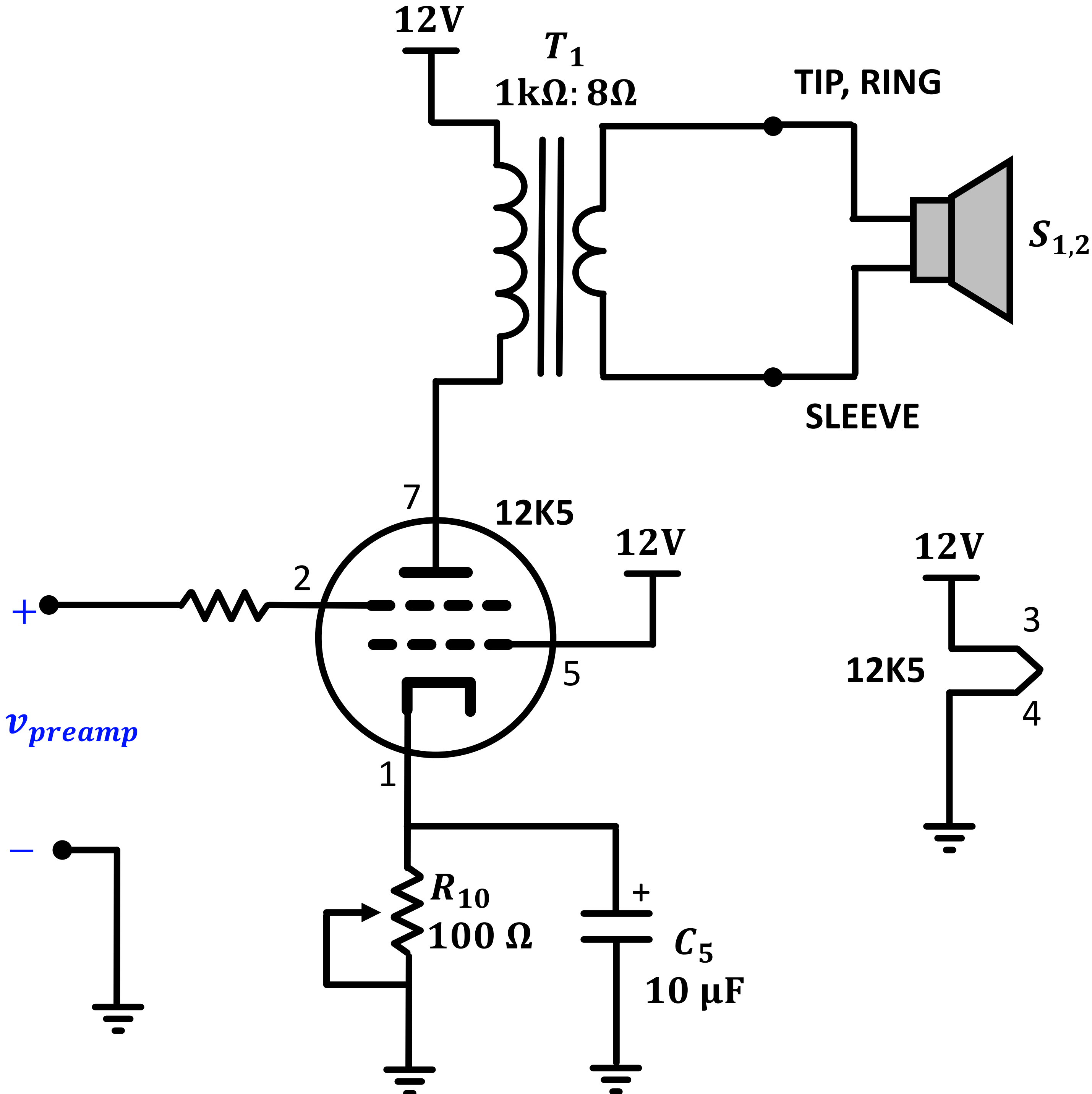
5 TIMES THE POWER! OH YEAH*

*and we're not even that well matched…if we really cared we'd make our own transformer

OK Gotta bias this last stage

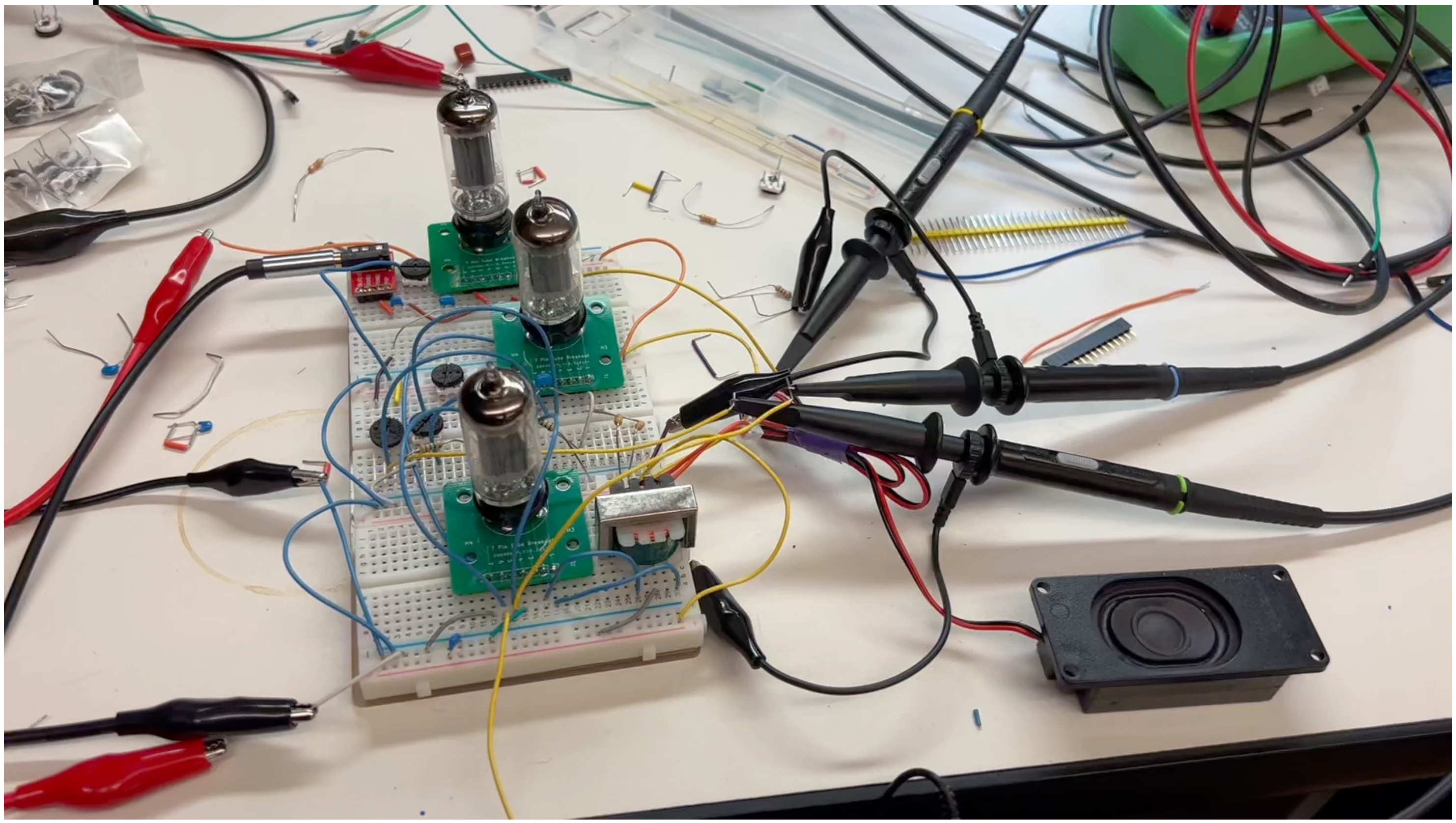
- Let's do cathode biasing.
- Current will be in the 10-ish mA region
- Let's put a trimmer pot of ~100 Ohms on cathode
- This should nudge V_{cathode} to around 1V
- So $V_{\text{grid}} - V_{\text{cathode}}$ will be negative -1V
- Also, like before, put big juicy cap in parallel to short the cathode resistor at audio frequencies so it doesn't eat into our audio swing
- And put a grid stopper resistor for some filtering

Done:


12V
T_1
1kΩ: 8Ω
TIP, RING
$S_{1,2}$
SLEEVE
7
12K5
12V
2
+
5
v_{preamp}
1
−
R_{10}
100 Ω
+
C_5
10 μF
12V
3
12K5
4

2024 Lab 2 is a bit different

- But also many of the same ideas…
- Will have three stages…
  - Preamp
  - Phase Splitter
  - Push-Pull Amplifier



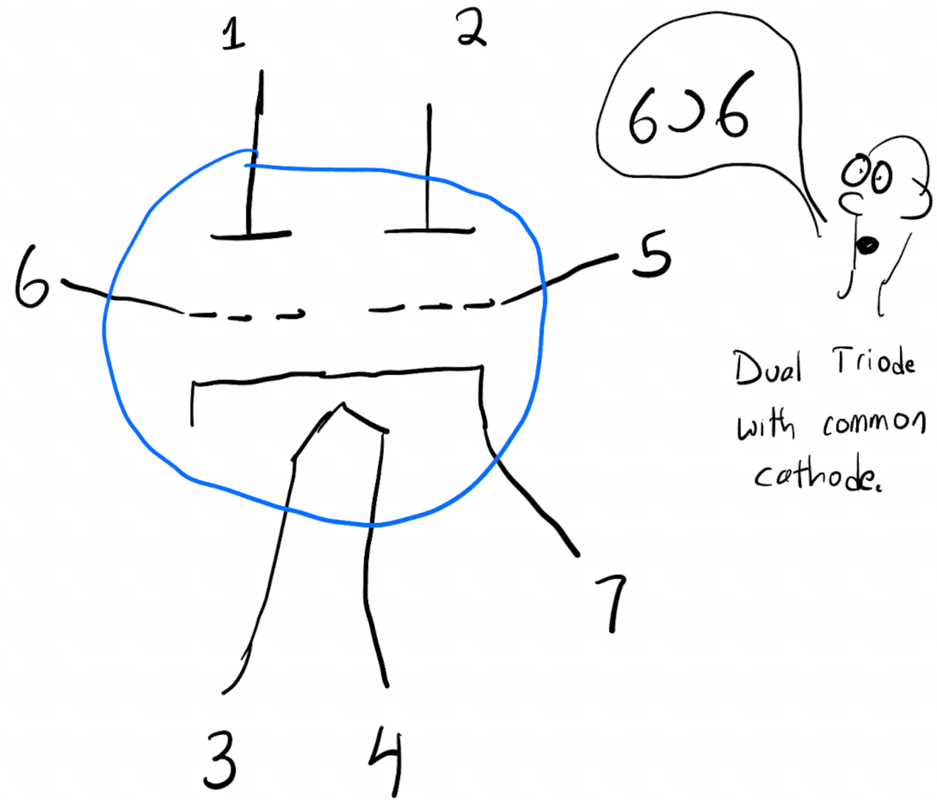
2024 Tube

- 12AT/X/U7's got expensive because audiophiles like them.
- Looked for "forgotten tube"
- 6J6. Got a couple unopened trays of a hundred for chump change

6J6

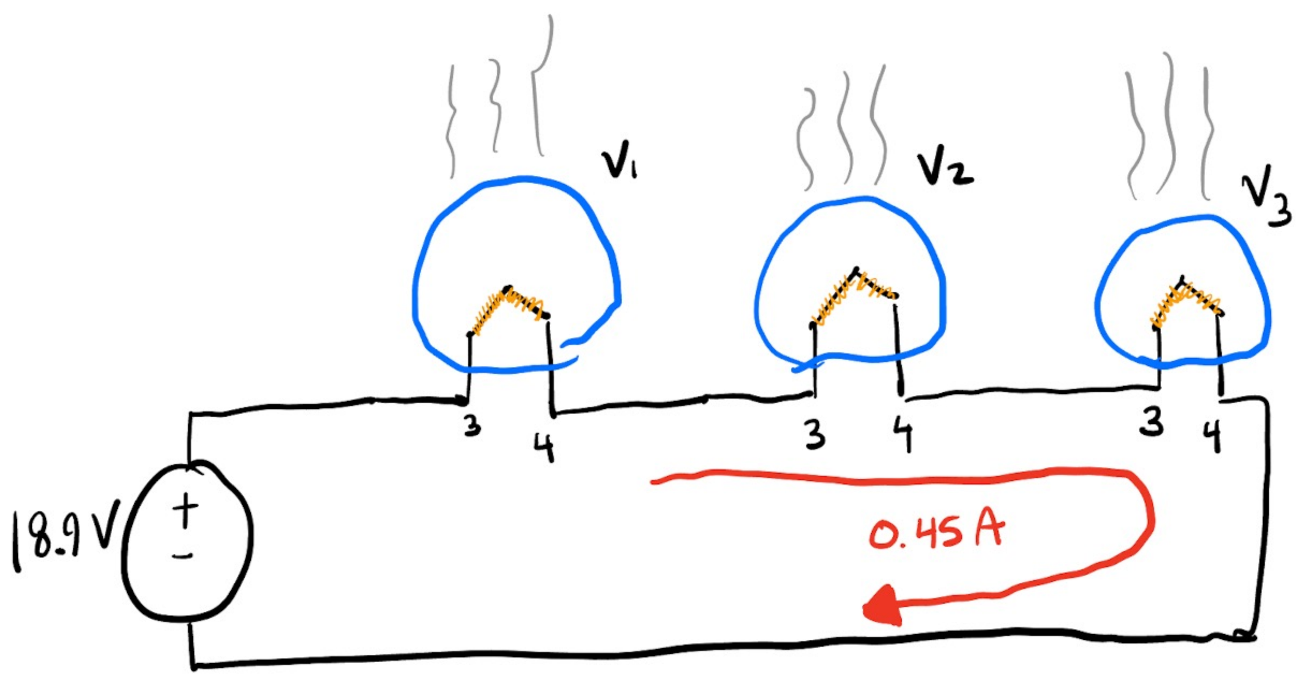
- (see datasheet)

- Dual Triode
- 7 pin tube
- Common Cathode
- 6.3V filament
  - 0.45A
  - 0.30A “high” efficiency model (lol)



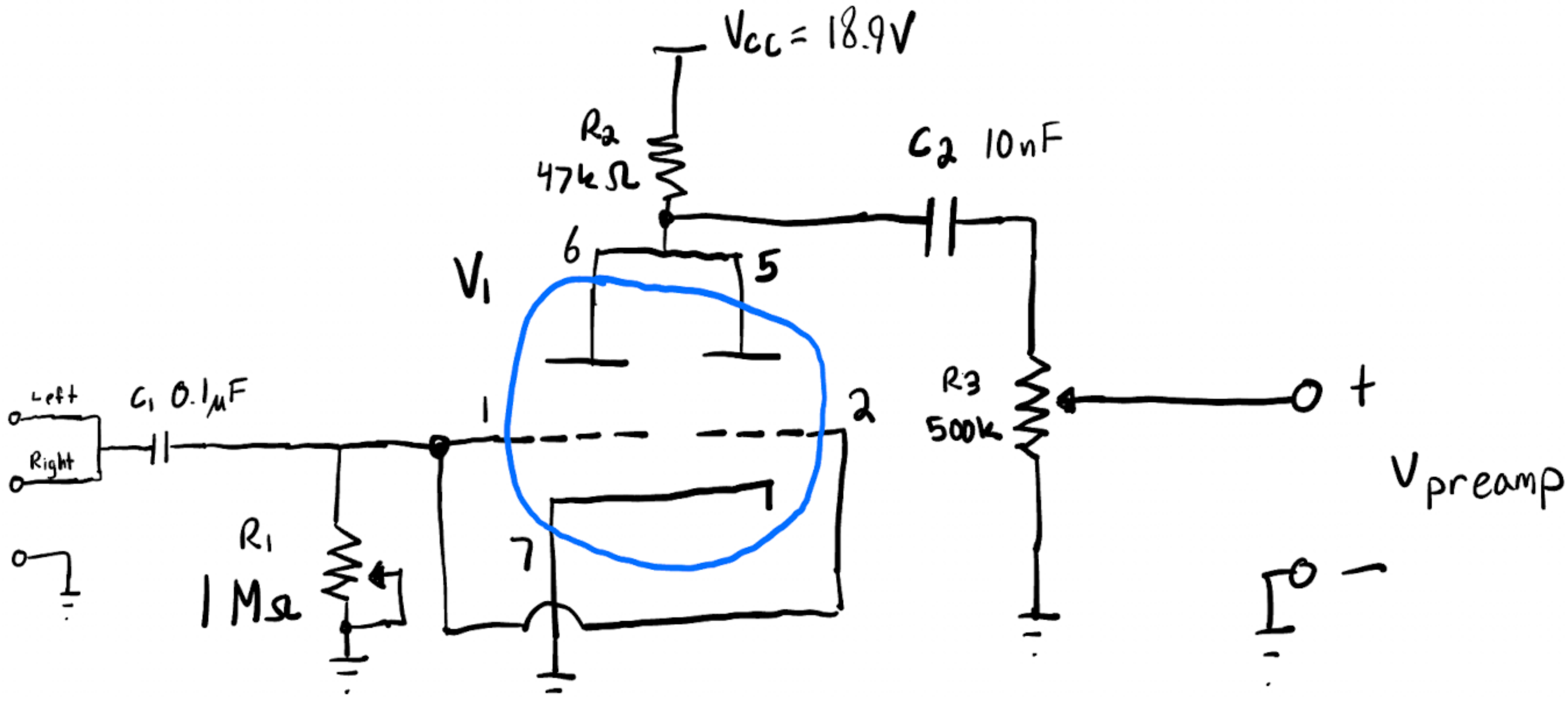
2024: Power

- Three tubes. All 6.3 V filaments at 0.45 A…run them *in series!!!*
- Make our system power supply 18.9V then.



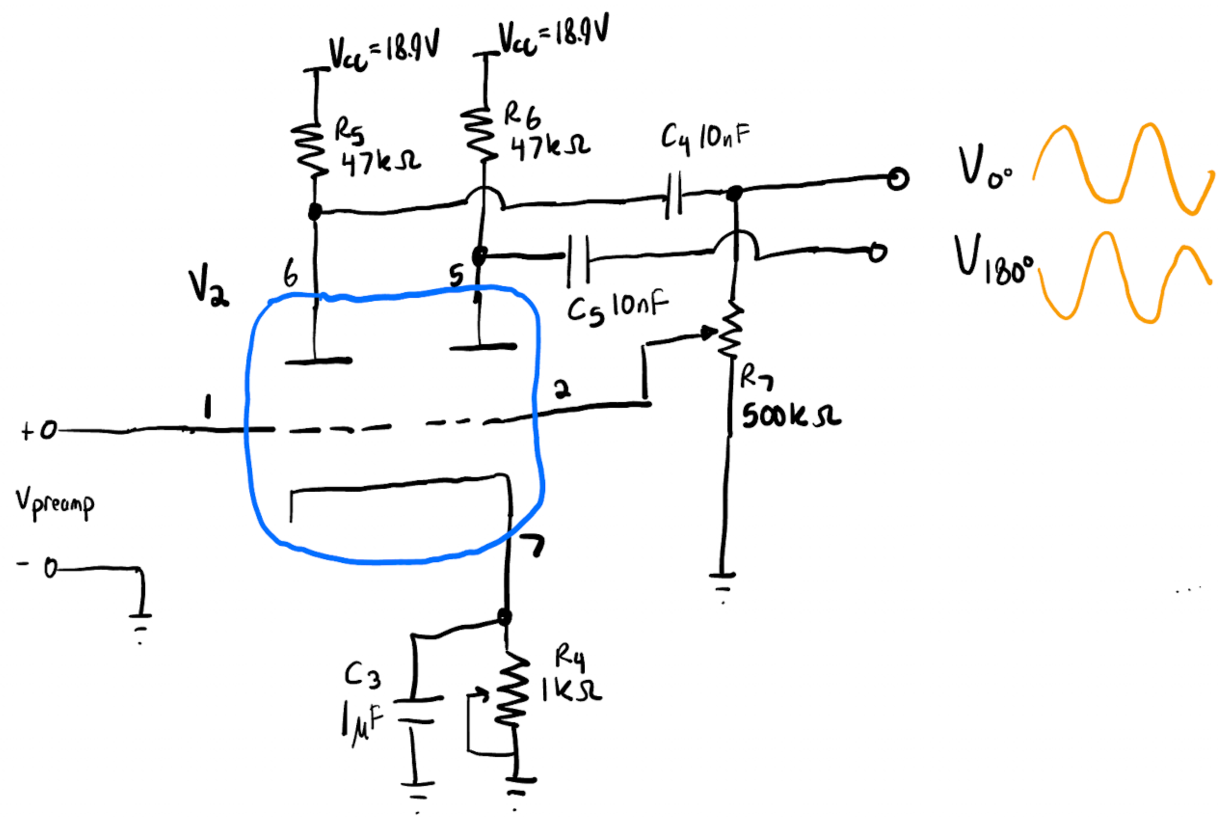
PreAmplifier

- Run two triodes in parallel
- Bias with grid-leak
- Cap couple output



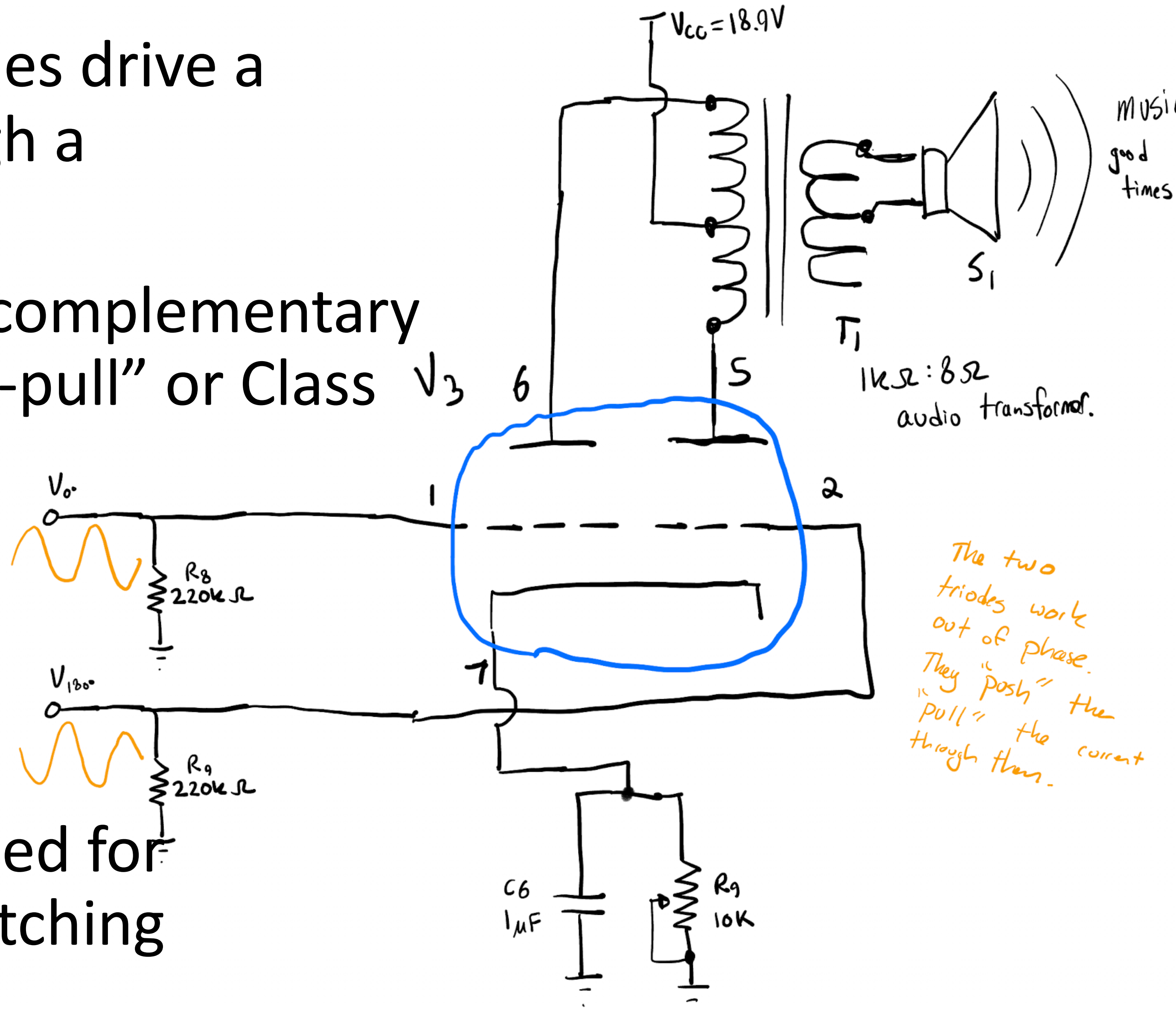
Phase Splitter

- One triode does a little more gain (not much)
- Feed its output into a second one… with adjustment it will have gain of unity but phase delay of pi radians



"Power Amplifier"

- Have Two triodes drive a speaker through a transformer.
- Tubes work in complementary fashion…"push-pull" or Class B/AB



- Transformer used for impedance matching

So lab.

- I’ll finish writeup after class and have out tonight. Forgive me.

Coming Up #2

- In next lecture:
  - Look at triode failings
  - Look at new tube types and what they brought to table
  - Continue to move through history