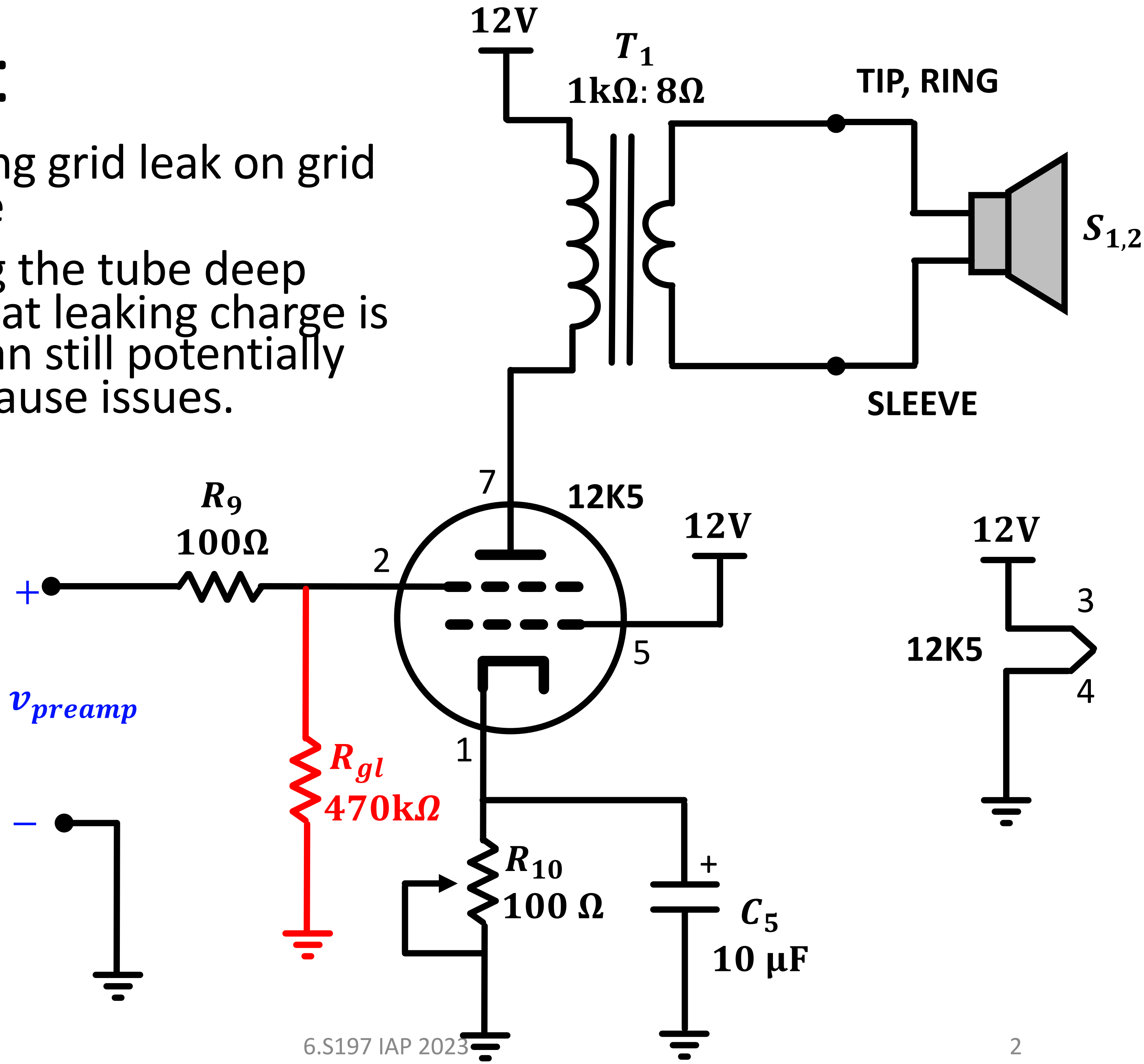
Lecture 5

Tube Electronics

For Lab 2:

- Consider adding grid leak on grid of output tube
- We are biasing the tube deep enough in – that leaking charge is nA, but that can still potentially build up and cause issues.



Other Uses

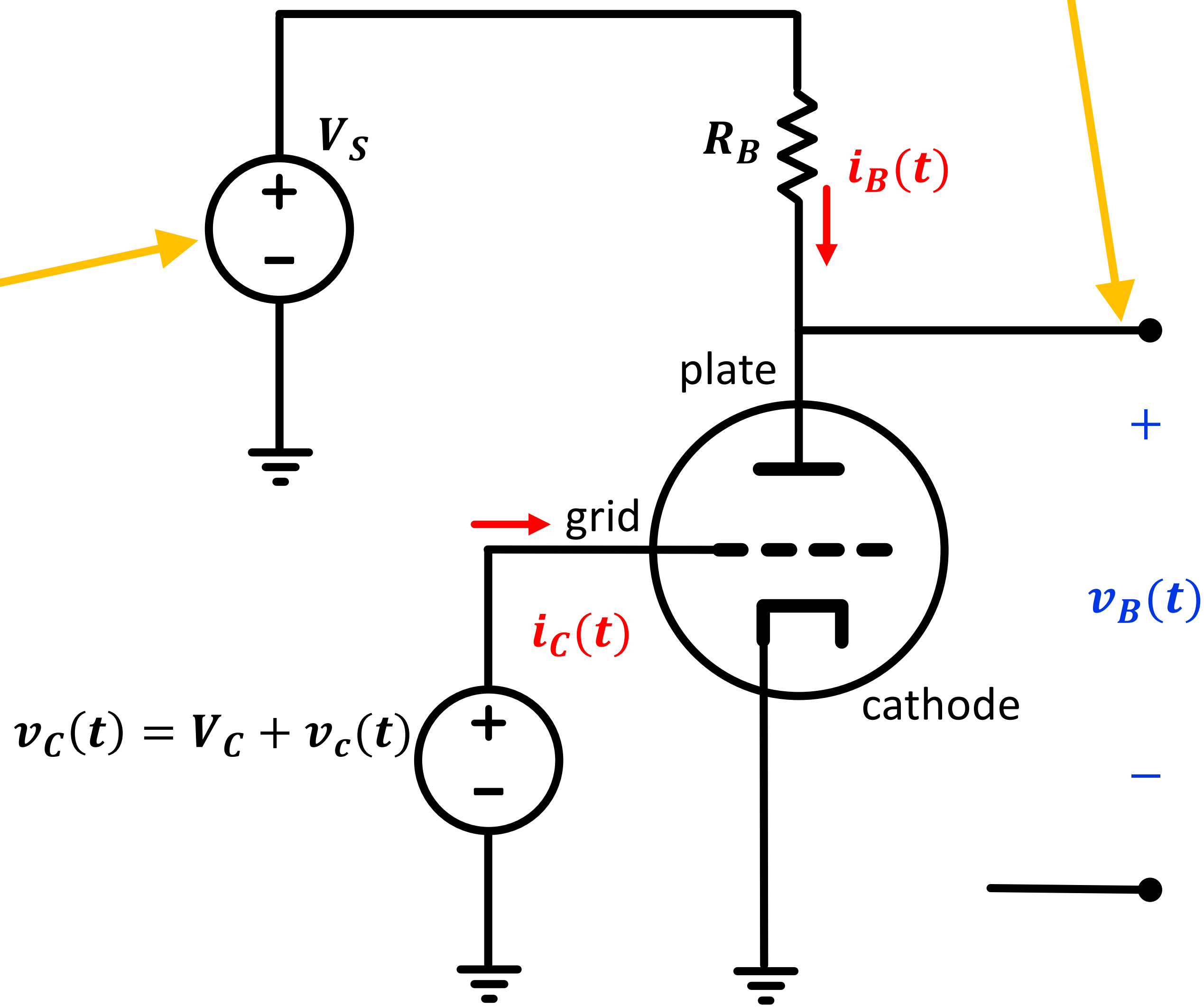
- So last week we saw vacuum tubes amplifying things.
- In Lab 2 you built/are building an amplifier
- The tube was the first purely electronic amplifying and non-linear device that was reasonably robust. The floodgates opened in terms of developments as a result:
  - Detectors
  - Oscillators
  - Feedback Theory
  - Mixers
  - Memory/Digital Logic
  - Etc..
- While tubes are largely a dead tech now they were the clay upon which all modern EECS was prototyped.

Basic Triode Setup

Output voltage:
- Fixed bias: V_B
- Signal: $v_b(t)$

- Our Basic Triode setup:

Supply voltage (fixed)



Cathode voltage:
- Fixed bias: V_C
- Signal: $v_c(t)$

All together

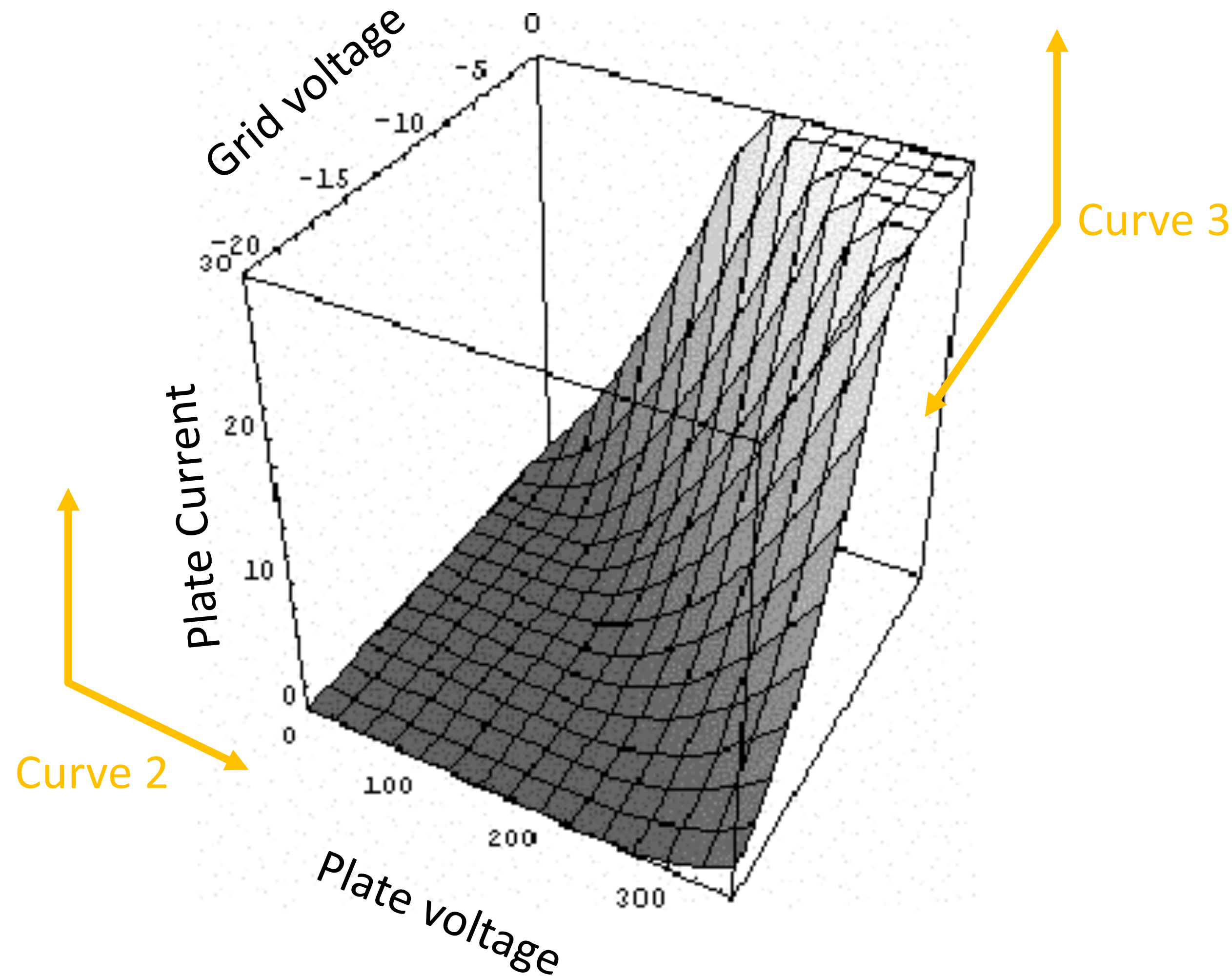
- The two plots are slices across two of the three axes
- The general rough pattern is

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

Whole mess of physical constants

Grid voltage

Plate voltage



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

This equation isn't really the whole truth

- If it were just $I_B = P\left(V_C + \frac{V_B}{\mu}\right)^{3/2}$ then one could claim that both the grid V_C and the plate V_B voltages manifest in the same shape at I_B (to the 3/2 power)
- In reality μ is far from a constant and is more like $\mu(V_B, I_B, \mathrm{x}, \mathrm{y}, \mathrm{z})^*$ so there's some difference

*function of spatial location in the tube

Plate Current as f of Plate Voltage

- This is the one we usually use for amplifier design.
- Pick some curves, slap some load lines on it, boom

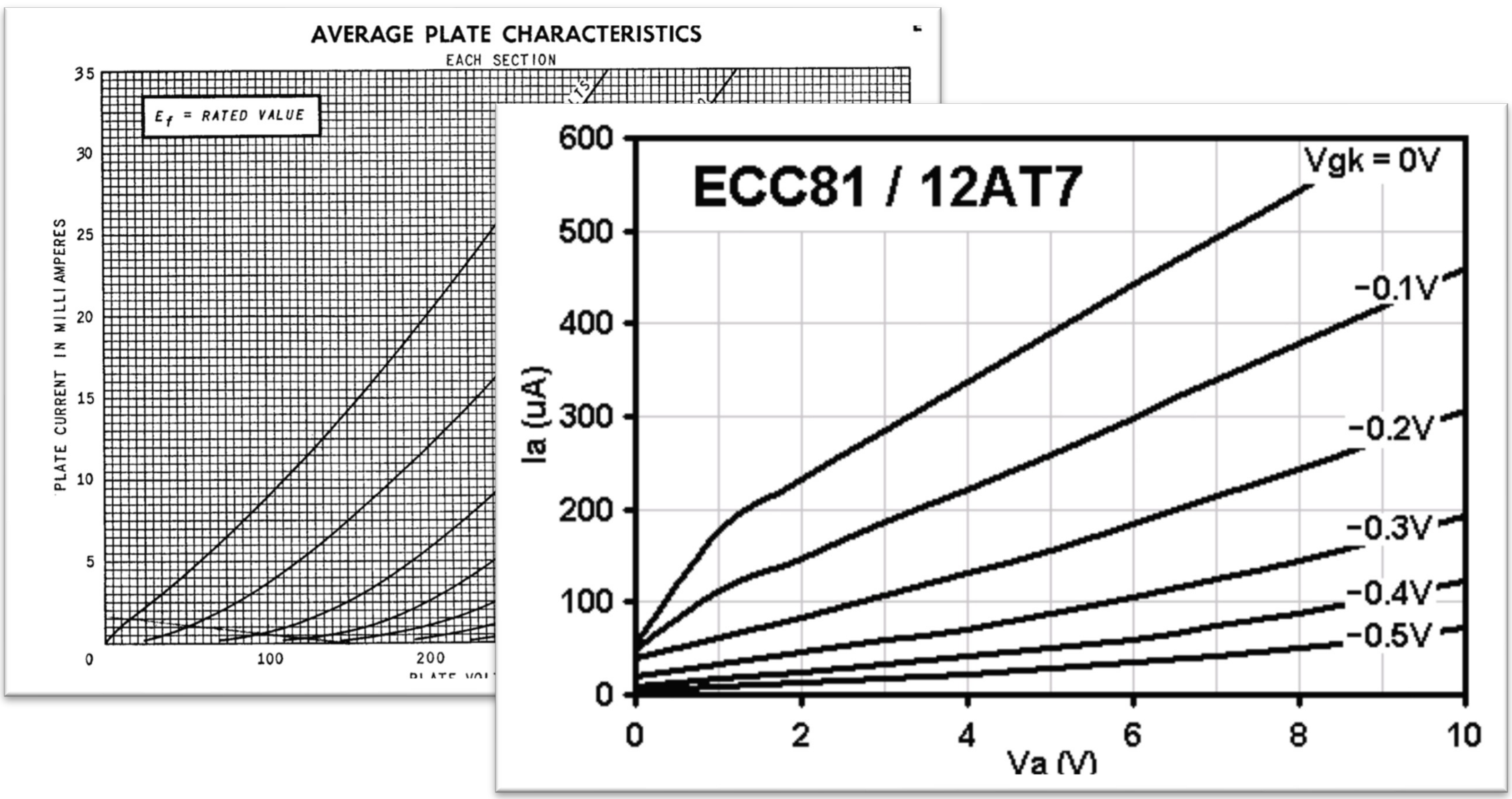
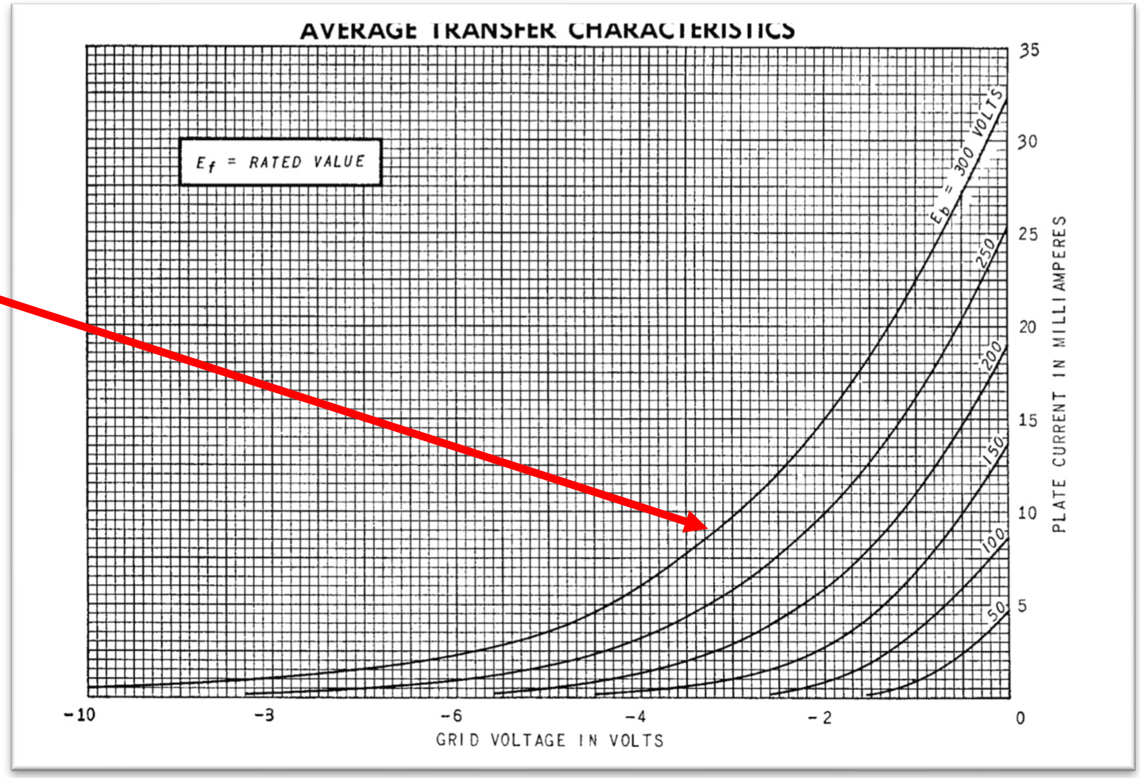


Plate Current as f of Grid Voltage

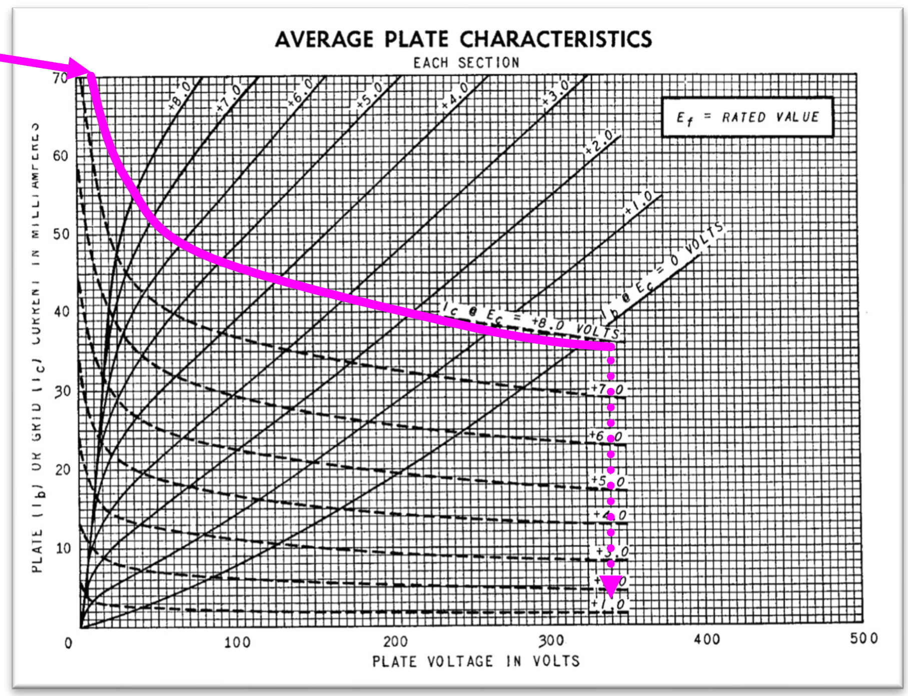
- Plate current as a function of grid voltage for specific plate voltages is also interesting:

As mentioned, grid voltage isn't modulated by that μ value so it follows the 3/2 power a bit more cleanly



Grid Current as f of Grid Voltage?

- Assumed that was mostly 0 so far and/or assumed very tiny for the purposes of grid leak, but what exactly is its i-v relationship?
- They do include it on one of the 12AT7 data sheet plots:
- weird way to look at it…



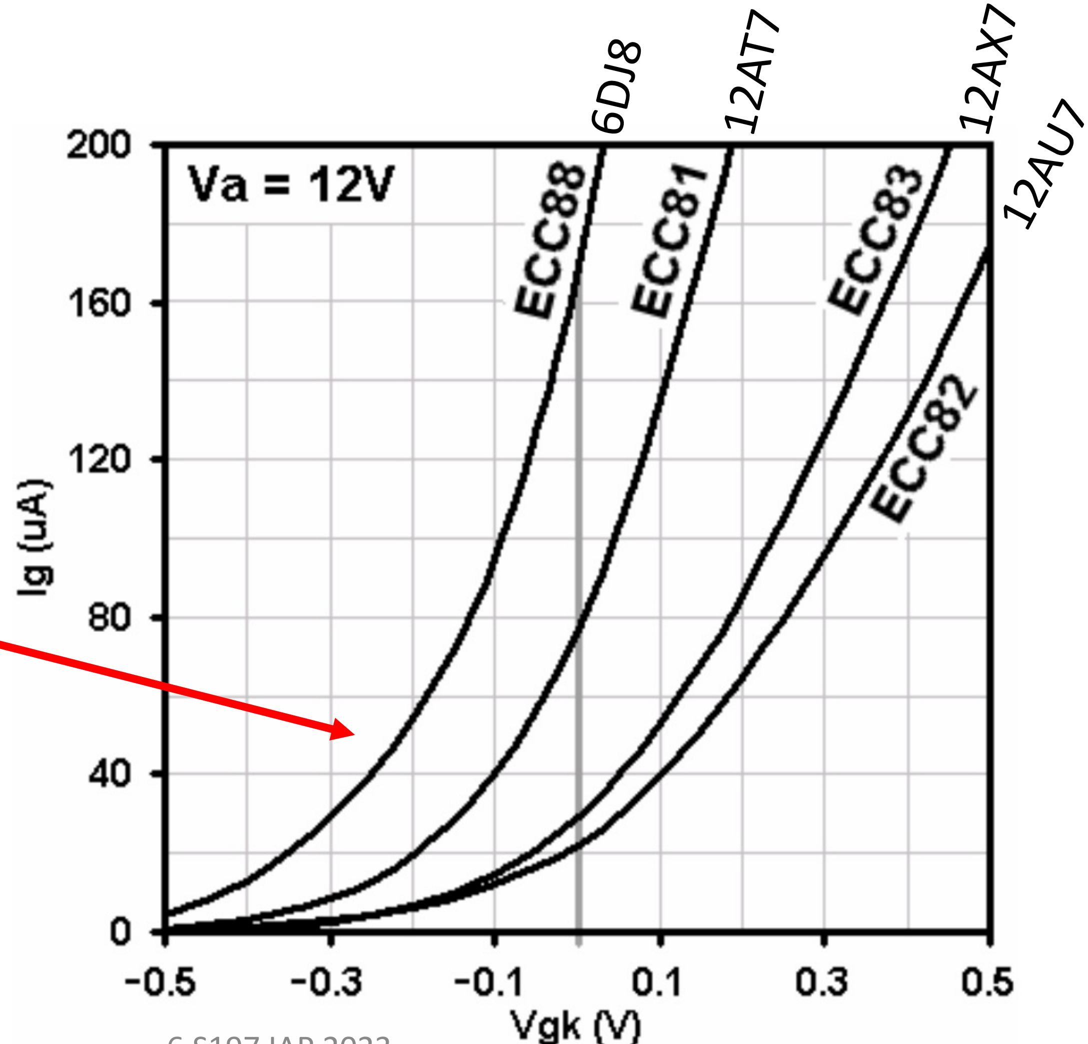
Grid Current as f of Grid Voltage?

- Plate current as a function of grid voltage for specific plate voltages is also interesting:

As we vary grid voltage we get variations in plate current like this

What do these curves look like?

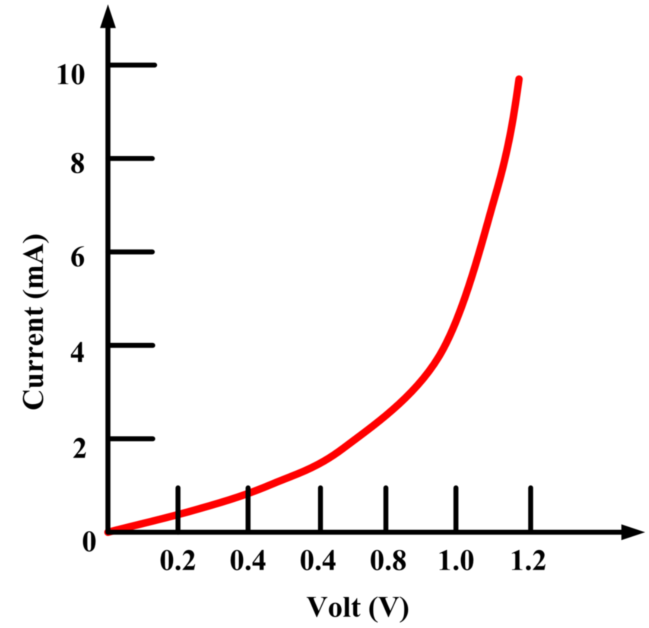
Anything we've seen before?

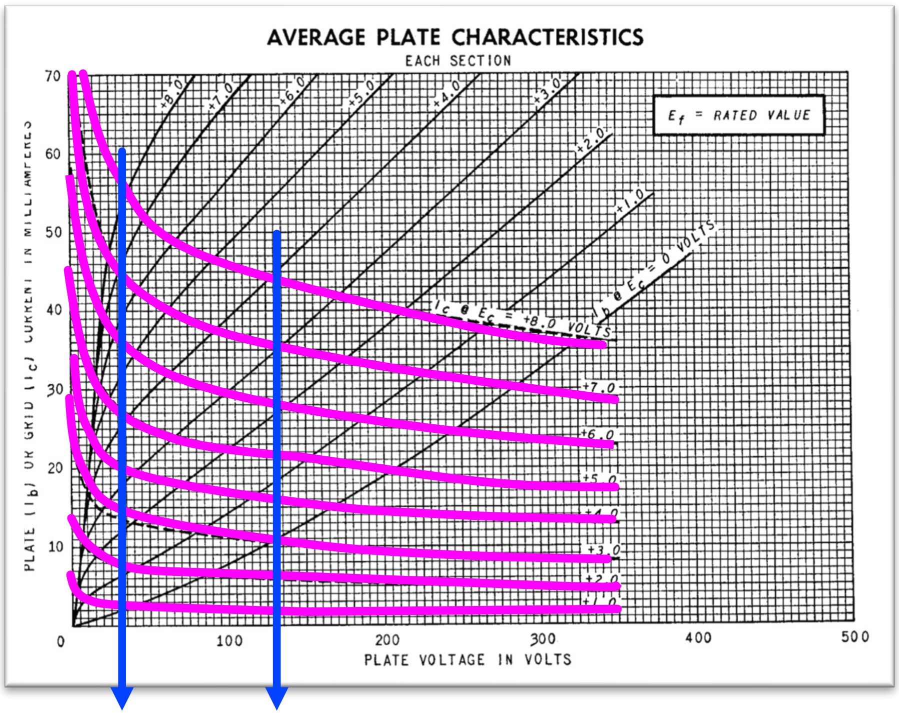


http://www.valvewizard.co.uk/Triodes_at_low_voltages_Blencowe.pdf

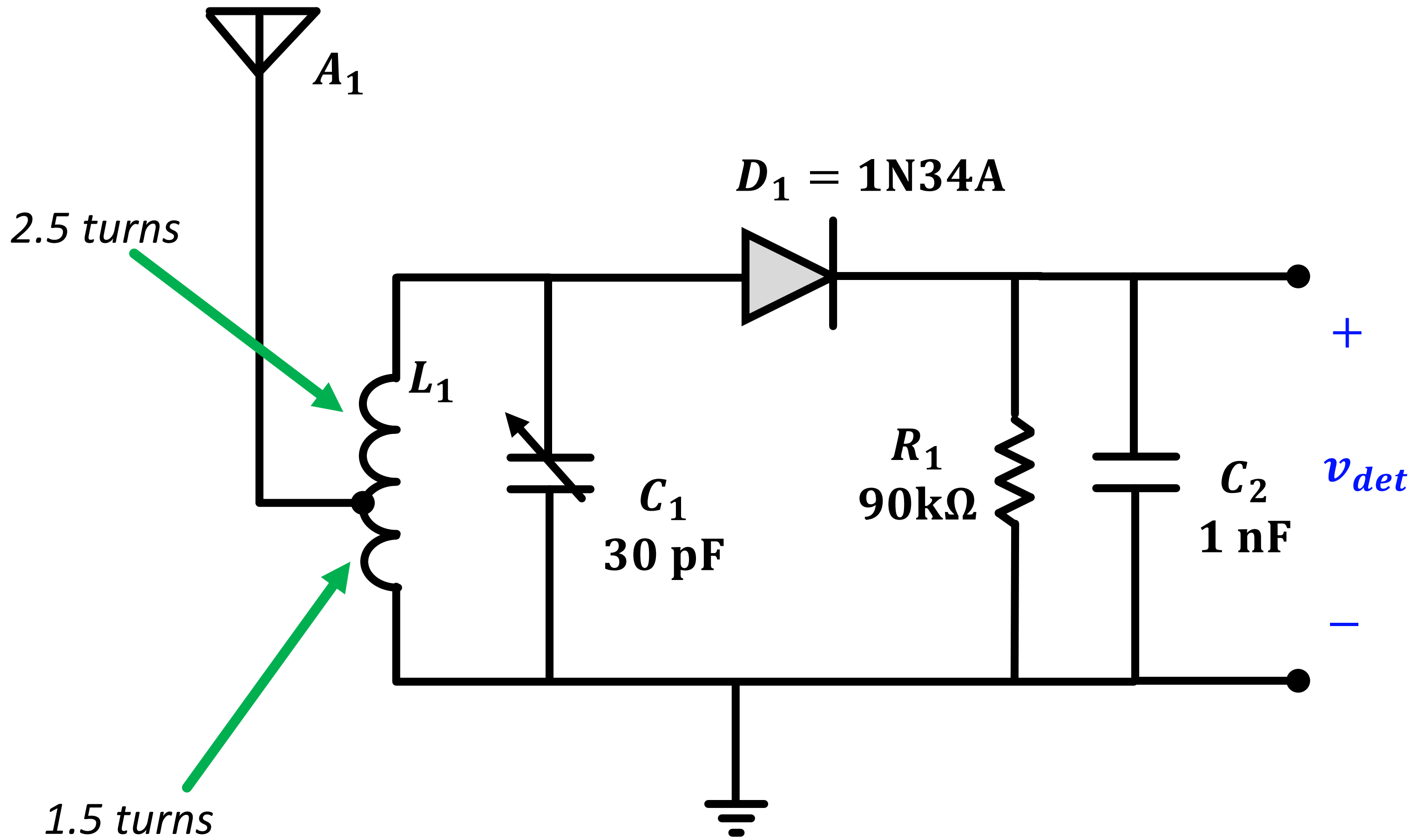
Looks like a Diode!

- Furthermore!...
- Whereas a diode is a diode with one single $i - v$ relationship:
- A tube's cathode voltage also comes in and can provide a means for selecting the type of diode that is seen…interesting

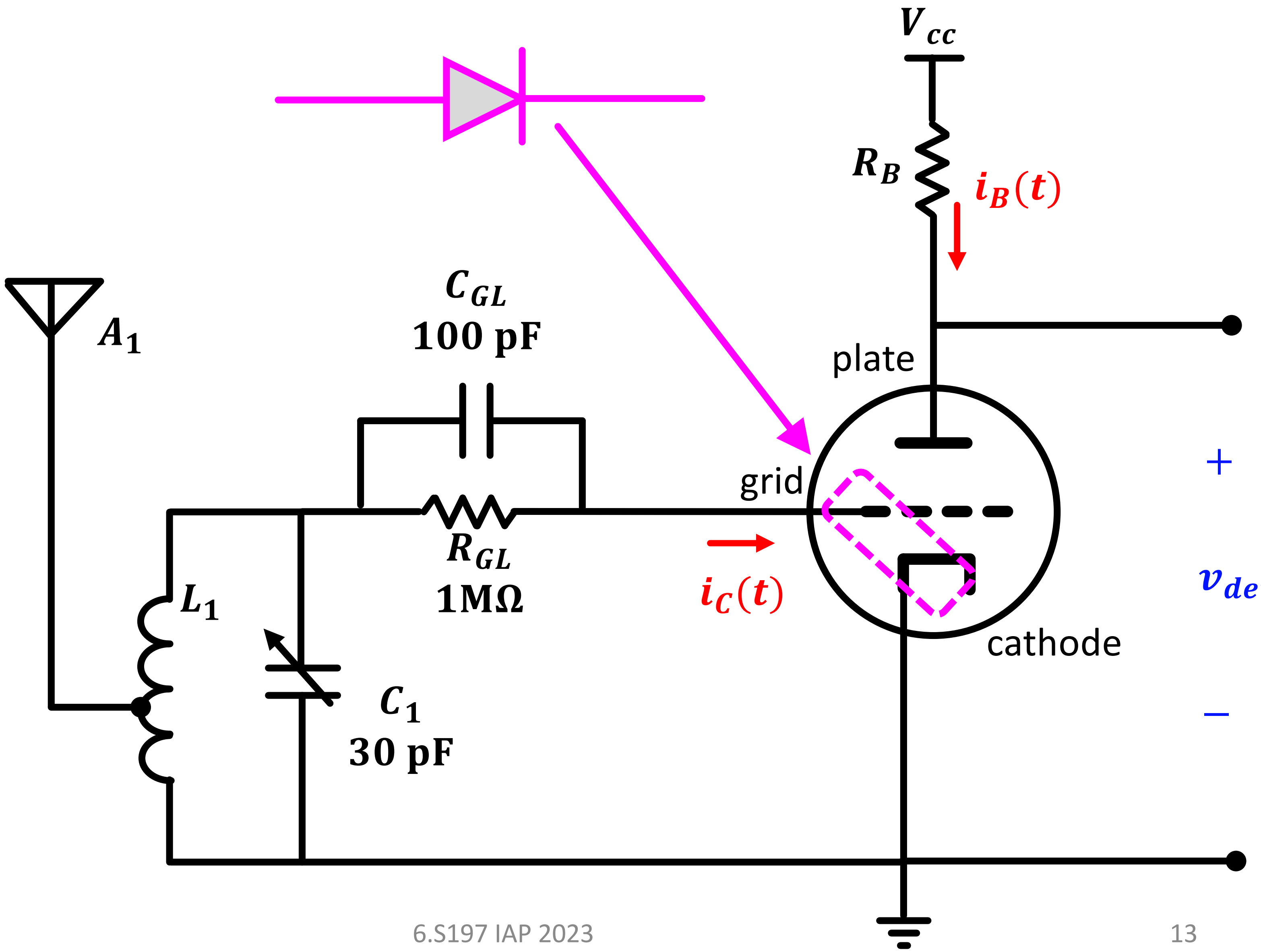




Remember our Crystal Diode Detector



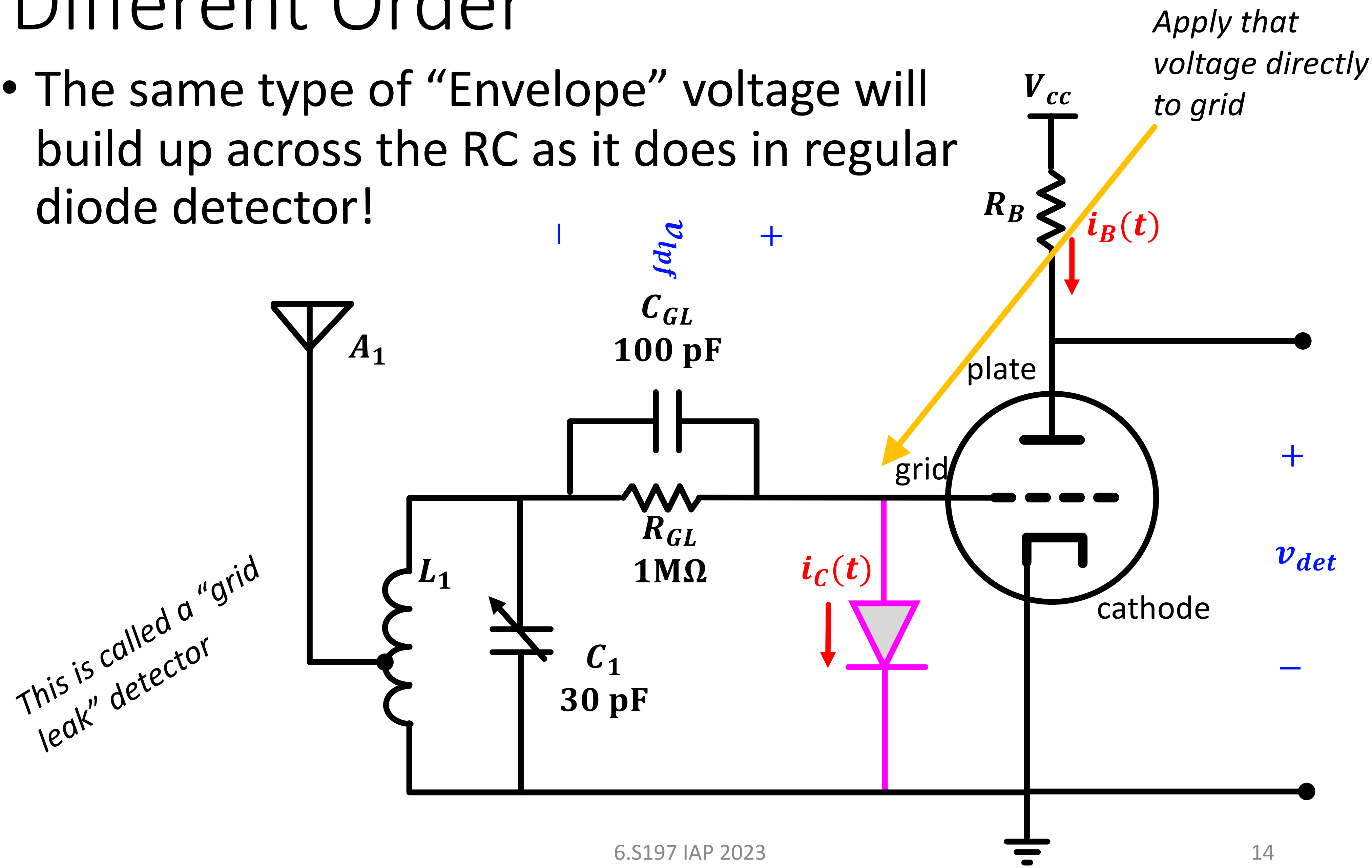
Use the “free” diode that comes with a triode



This is called a “grid leak” detector

Same Diode in Series with RC, Just Different Order

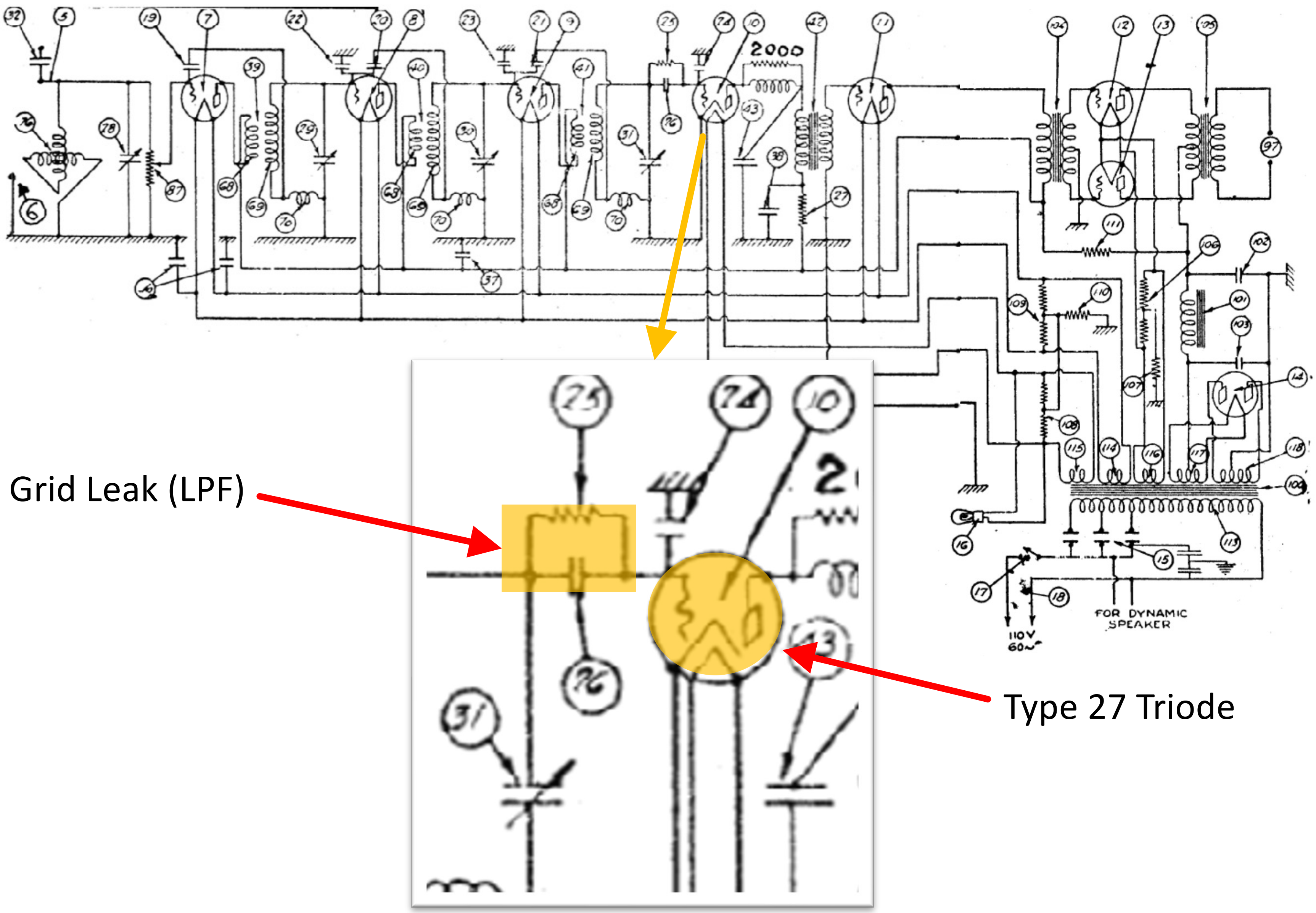
- The same type of "Envelope" voltage will build up across the RC as it does in regular diode detector!



Very Cool…the Grid Leak Detector!

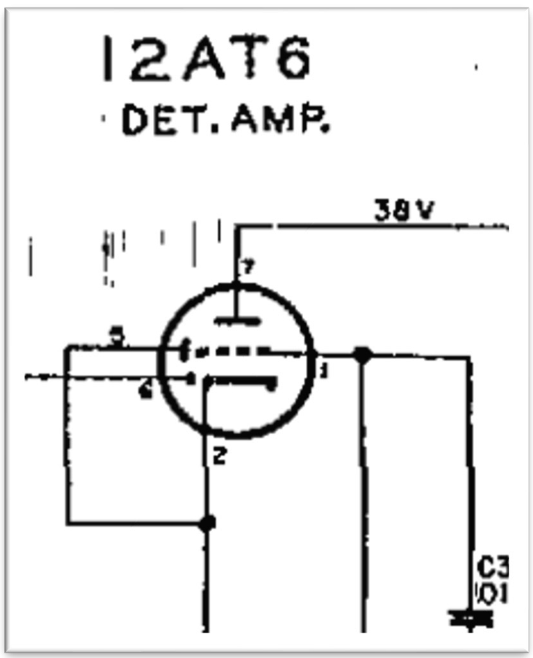
- That same Rectified LPF signal gets built up on the grid directly.
- And that means it can modulate the plate current like it would in a normal amplifier
- So with this circuit topology, you can now simultaneously demodulate and amplify all within one vacuum tube (Saves on parts and minimizes noise!)

1928 Bosch Radio Receiver Schematic

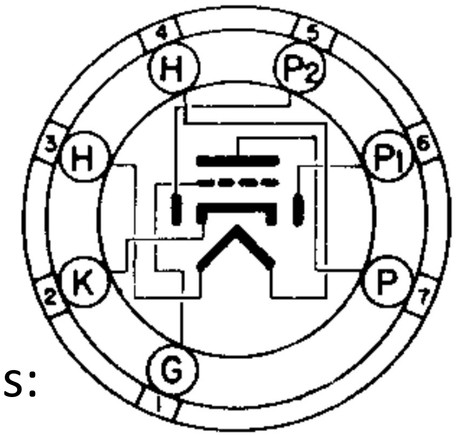


Using same electrode for Grid and Diode Could get Complicated

- Eventually (1930s/40s) developed the double-diode-triode tube:
  - Regular triode, but with:
    - One regular grid for biasing
    - Two small electrodes that could act like diodes:
      - One diode is detector diode
      - One diode is for Automatic Gain Control Feedback (increasing/decreasing gain using a low-pass-filtered variant of our audio signal to increase/decrease earlier gain stages to keep volume relatively the same)…beyond scope of class.



12AT6 in deployment in radio



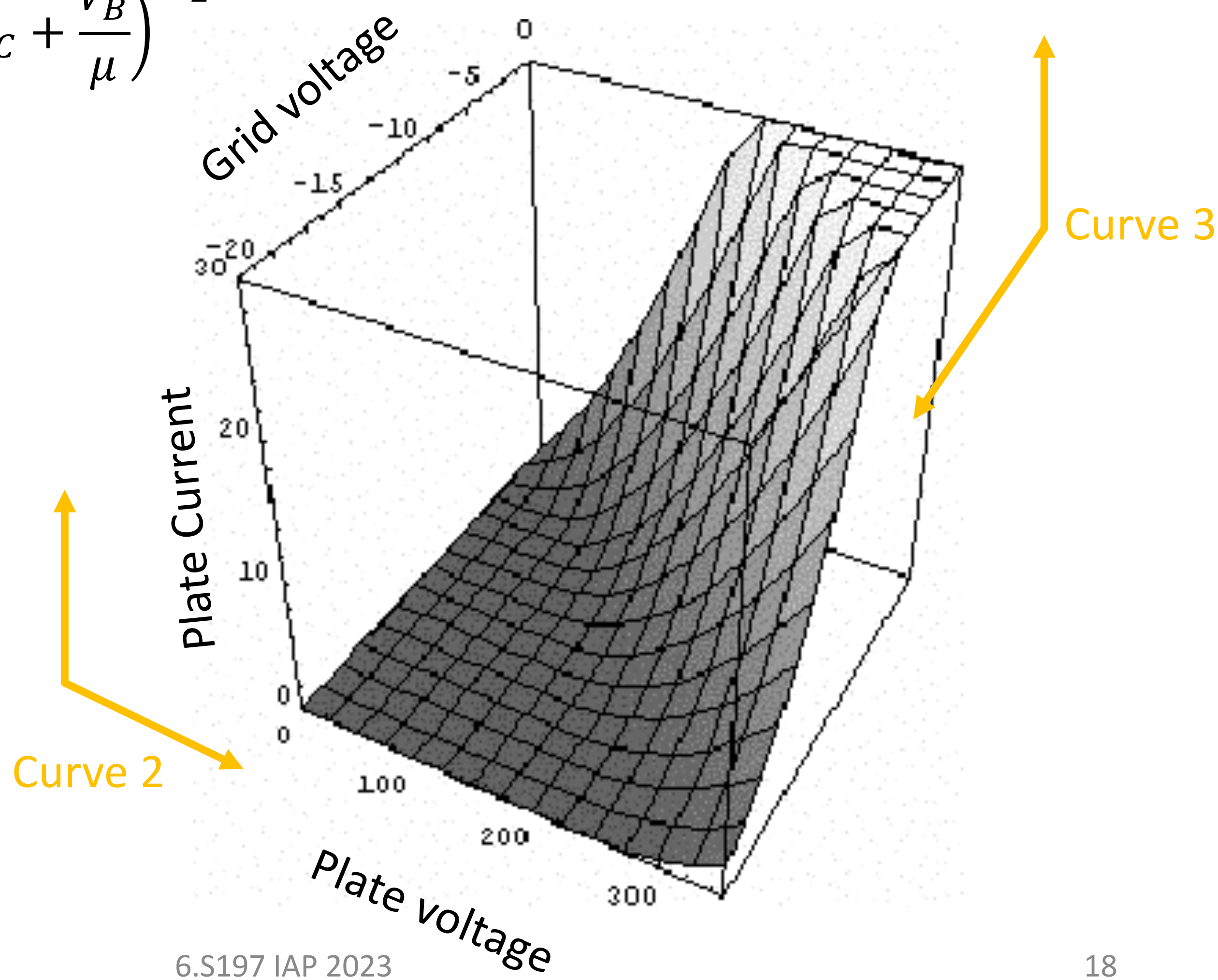
12AT6 pinout

Not Exactly Linear

- You may have noticed, that our triode is not exactly a linear amplifier

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

- Being linear is desired for amplification
- How did they make good amplifiers?



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

Not Exactly Linear But Pretty Close

- As non-linear as a thing to the 3/2 power is, it is actually much closer to linear by “raw” device standards (especially when compared with what was to come historically (pentodes and transistors)
- This is ability to be more linear-ish while in a simple vanilla circuit is one reason why modern “Hi-Fidelity” audio amplifiers still use tubes (though the cool aspect of it is probably really the reason since excellent linear-behavior can be achieved with more modern devices/circuit topologies.

Still…

- Even early in the triode's life in the 1910's people wanted a more linear amplifier capability since *any* non-linearity was always going to be causing all those weird extra frequency components that could get annoying/impossible to filter
- So people set out searching how to linearize an amplifier!
- There were lots of problems…in particular as you made triodes with larger gains, they seemed to become less and less linear*
- So the field kinda got jammed between the more-gain and more linearity directions with no way to go.

*lots of non-idealities started to come into play

The Solution

- Harold Black approached the problem
- During a ferry ride into work in 1927 he came up with the idea of negative feedback
- It turned out that you could trade gain for linearity and other nice features
- The problem was that at first it was just a few years too early.

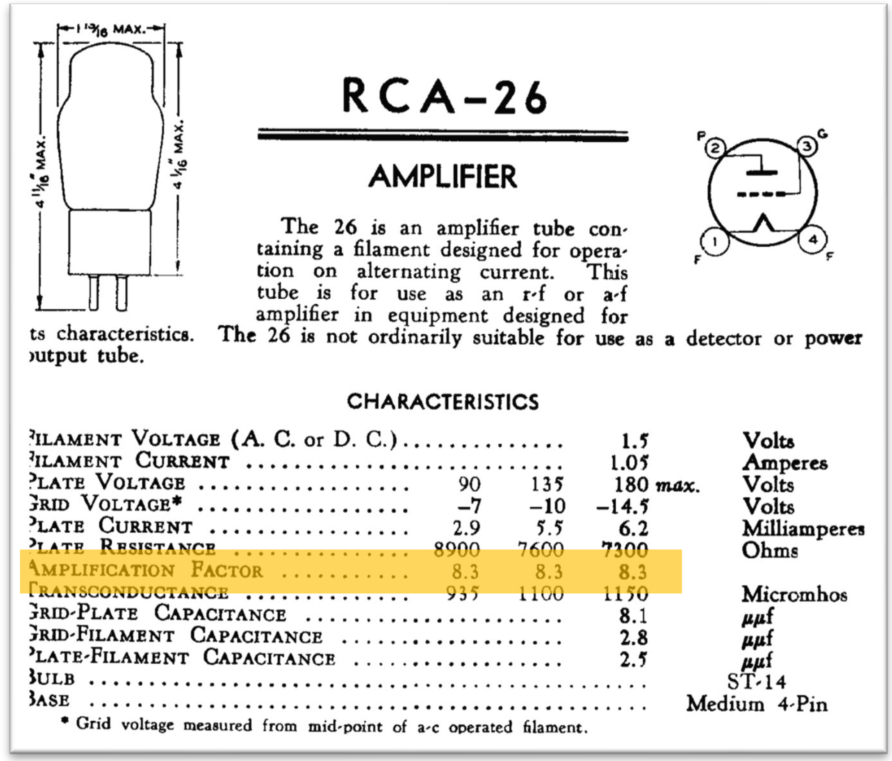
https://en.wikipedia.org/wiki/Harold_Stephen_Black

Feedback

- Early Triodes didn't have much gain so the value proposition of throwing away gain to achieve linearity wasn't exactly a good one…

A few years later…

In 1927:



RCA-26

AMPLIFIER

The 26 is an amplifier tube containing a filament designed for operation on alternating current. This tube is for use as an r-f or a-f amplifier in equipment designed for its characteristics. The 26 is not ordinarily suitable for use as a detector or power output tube.

CHARACTERISTICS

Filament Voltage (A. C. or D. C.)			1.5	Volts
Filament Current			1.05	Amperes
Plate Voltage	90	135	180 *max.*	Volts
Grid Voltage*	−7	−10	−14.5	Volts
Plate Current	2.9	5.5	6.2	Milliamperes
Plate Resistance	8900	7600	7300	Ohms
Amplification Factor	8.3	8.3	8.3	
Transconductance	935	1100	1150	Micromhos
Grid-Plate Capacitance			8.1	μμf
Grid-Filament Capacitance			2.8	μμf
Plate-Filament Capacitance			2.5	μμf
Bulb				ST-14
Base				Medium 4-Pin

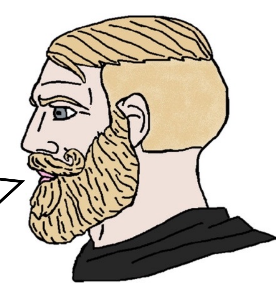
* Grid voltage measured from mid-point of a-c operated filament.

"Currently I have a voltage amplifier with a gain of 2.3 that is slightly non-linear and ass-levels of input and output impedance "

Some loser engineer

"No. Are you crazy? Get away from me with your theories"

"Yes but imagine if you could make a voltage amplifier with a gain of 1.2 and potentially worse in/out impedances that is linear! Doesn't that sound enticing????"



Harold Stephen Black

Feedback

A few years later…


High-Mu Twin Triode
9-PIN MINIATURE TYPE
For High-Fidelity Audio-Amplifier Appli-

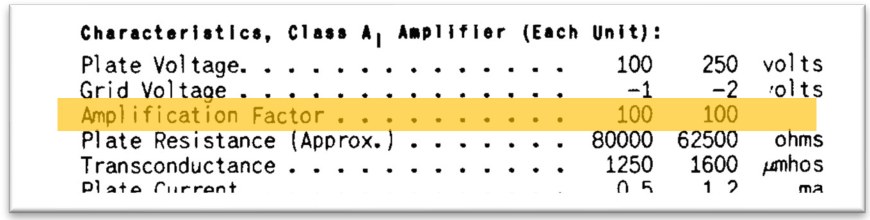

Characteristics, Class A_1 Amplifier (Each Unit):

Plate Voltage	100	250	volts
Grid Voltage	−1	−2	volts
Amplification Factor	100	100	
Plate Resistance (Approx.)	80000	62500	ohms
Transconductance	1250	1600	µmhos
Plate Current	0.5	1.2	ma

- Tubes got better…better gain, cheaper, better I/O char

In 1930s:


Some loser engineer

"Currently have voltage amp with gain of 270 that's non linear ☹"

"Yes but imagine if you could make a voltage amplifier with a gain of 100 with negligibly worse in/out impedance that is linear! Doesn't that sound enticing????"


Harold Stephen Black


Now an enlightened engineer

"Your ideas intrigue me, and I would like to subscribe to your newsletter."


Harold Stephen Black

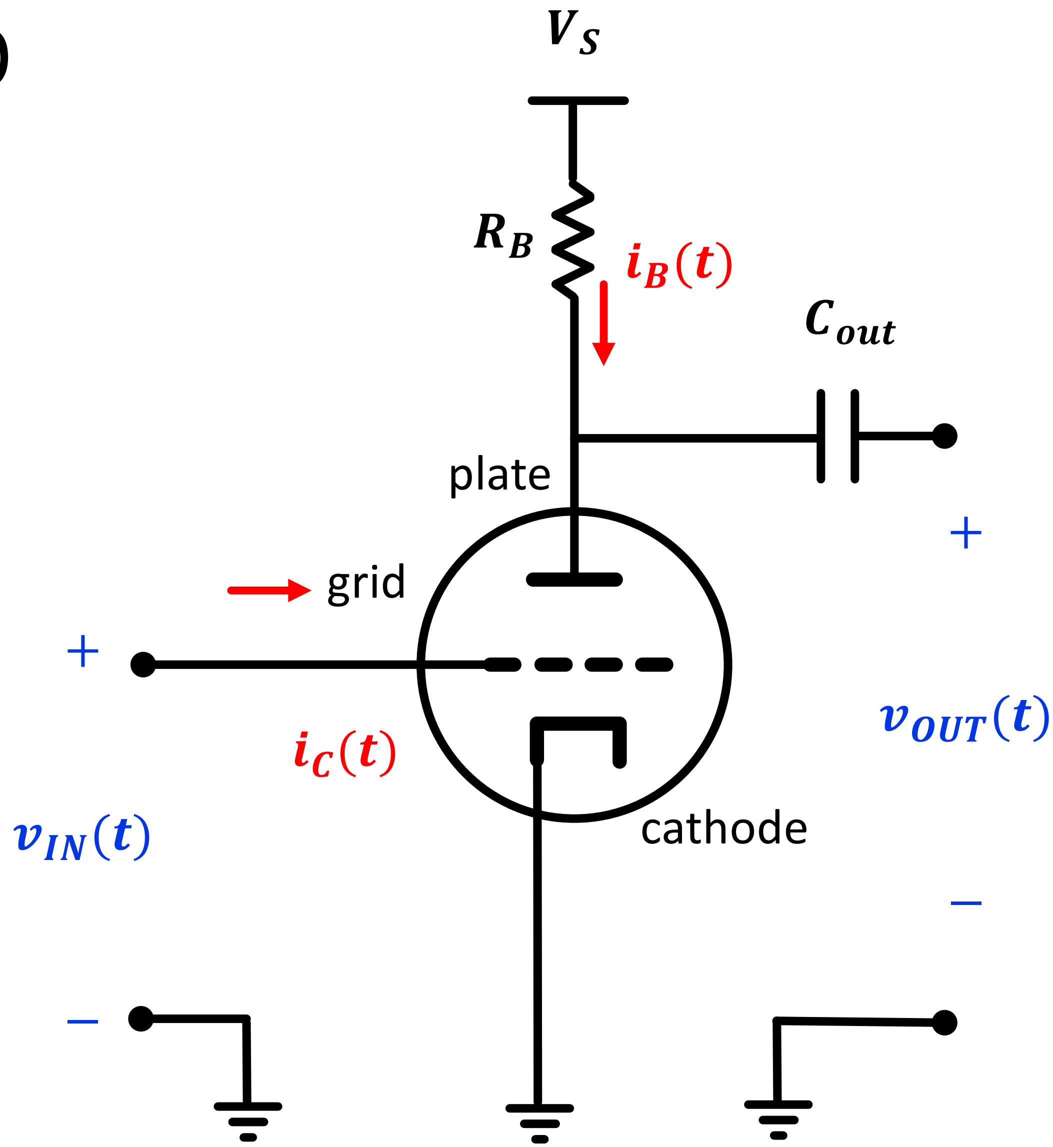
Basic Triode Setup

- Our Basic Triode setup in open loop:

$$v_{OUT} = A_o \cdot v_{IN}$$

What is A_o ? It was the value we eyeballed from looking at our load-line plots last week. It will be non-linear and will also be affected by source and load impedances.

Nominally: $A_o = -\frac{R_B \cdot \mu}{R_B + R_p}$



**ignore grid bias and things for these examples to keep things simple!*

Critical Coefficients

- Three important values characterize a Triode and are related by this equation:

$$R_p = \frac{\mu}{G_m}$$

Voltage amplification factor: The factor by which the grid voltage changes the voltage at the plate. (unitless)

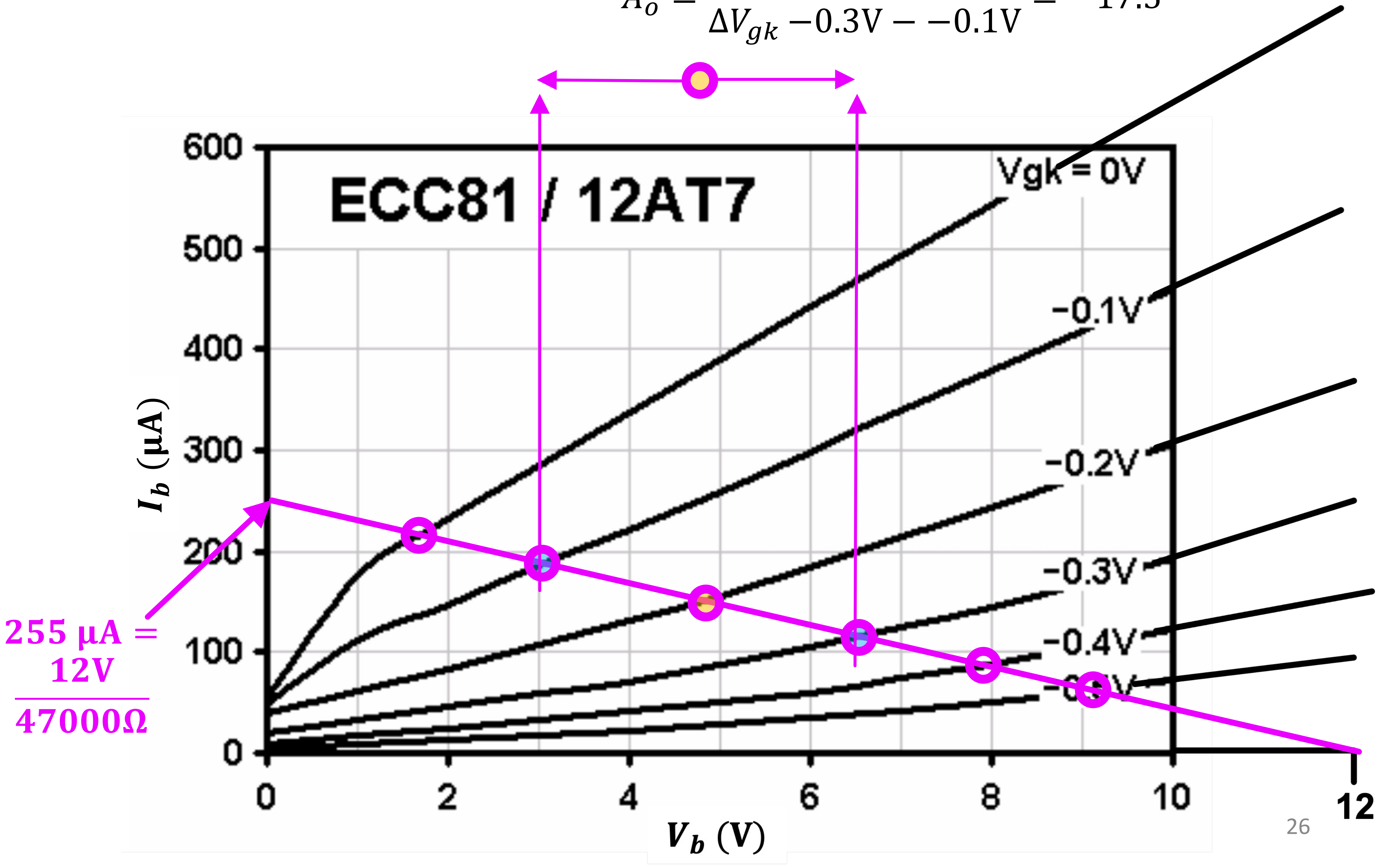
Plate Resistance: The output resistance of the tube at the plate (in Ohms)

Mutual Conductance (Transconductance): The factor by which a change in grid voltage causes a change in plate current (units of conductance…so Mhos or Siemens)

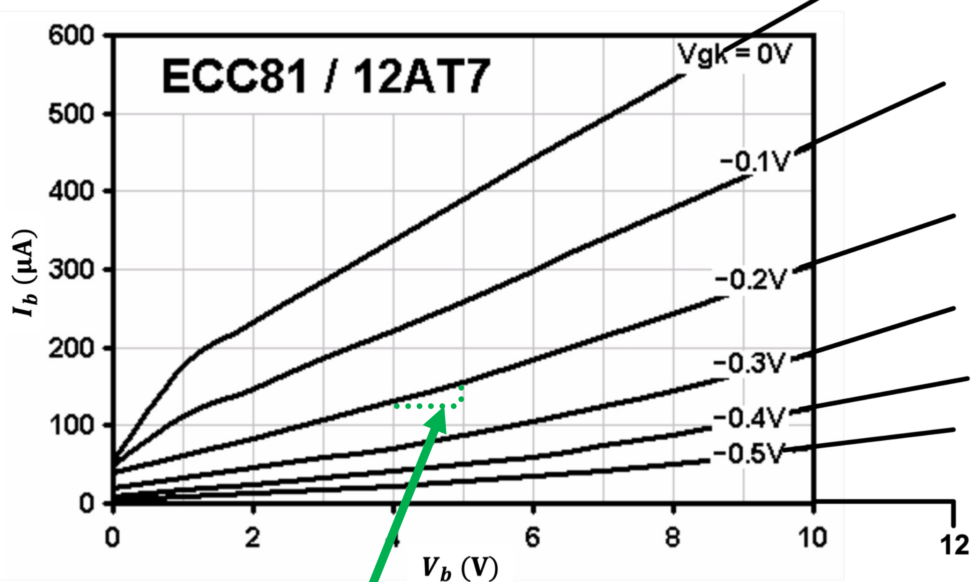
- These numbers are extracted from the values and slopes of the transfer function plots
- They are NOT Constants!

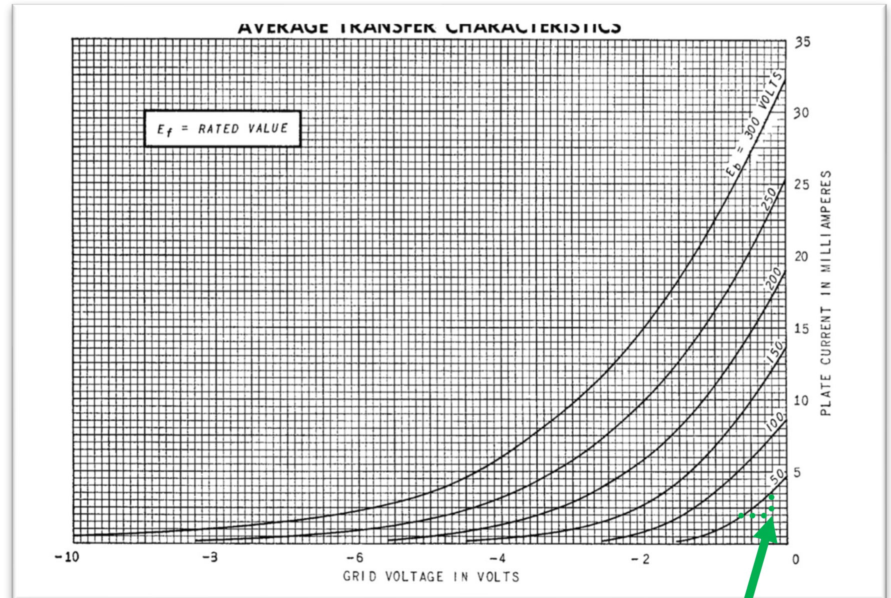
Graphically Extract Estimate/Average from Load Line

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



Extract parameters from Plots and then use actual formula





$$\frac{\Delta I_b}{\Delta V_b} = \frac{1}{R_P}$$

$$\frac{\Delta I_b}{\Delta V_c} = G_m$$

$$\mu = R_p G_m$$

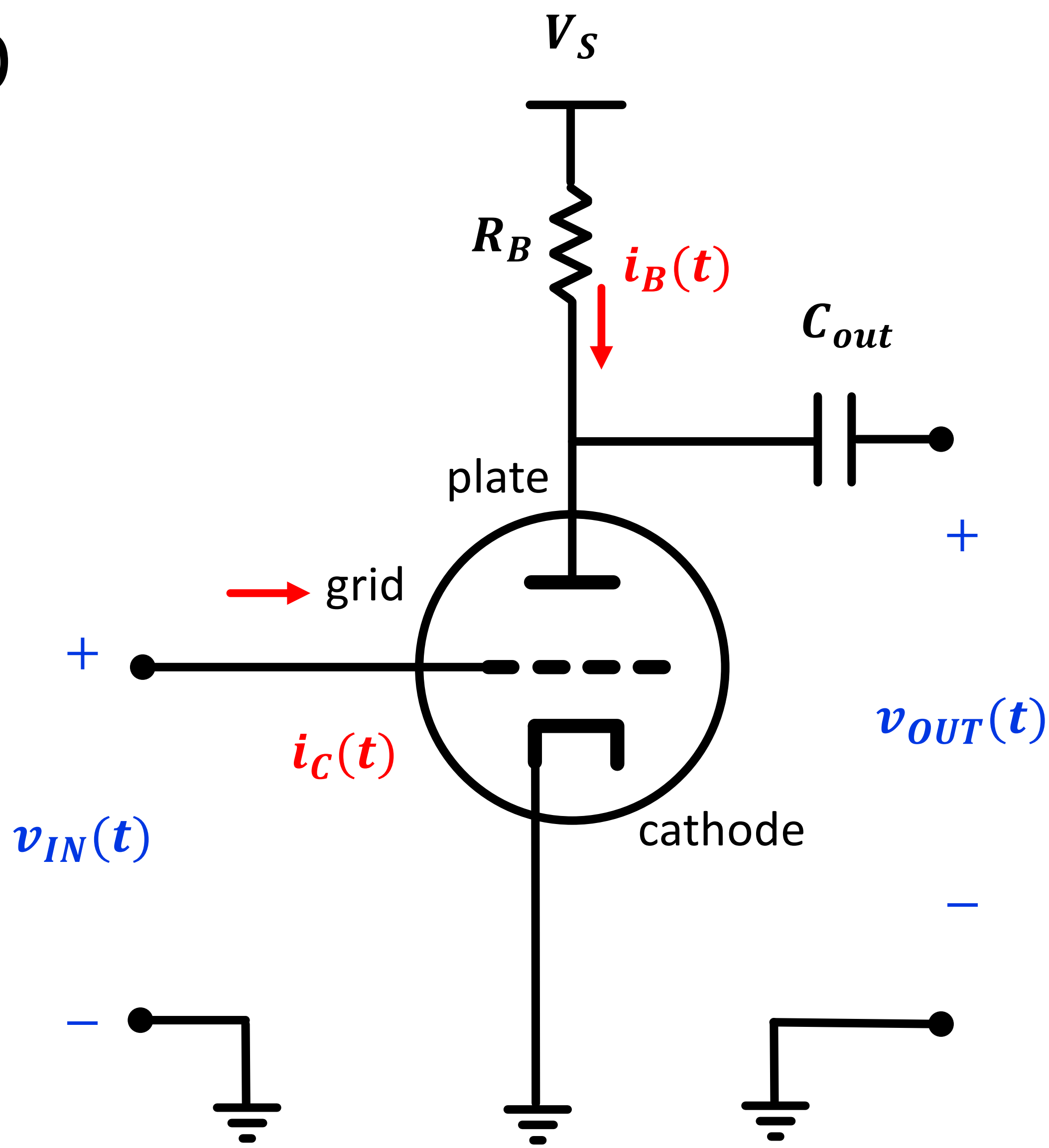
$$\boldsymbol{A_o = -\frac{R_B \cdot \mu}{R_B + R_p}}$$

Basic Triode Setup

- Regardless of How we get the open loop gain, the important thing is that it is a varying, non-linear quantity!

$$v_{OUT} = A_o(*) \cdot v_{IN}$$

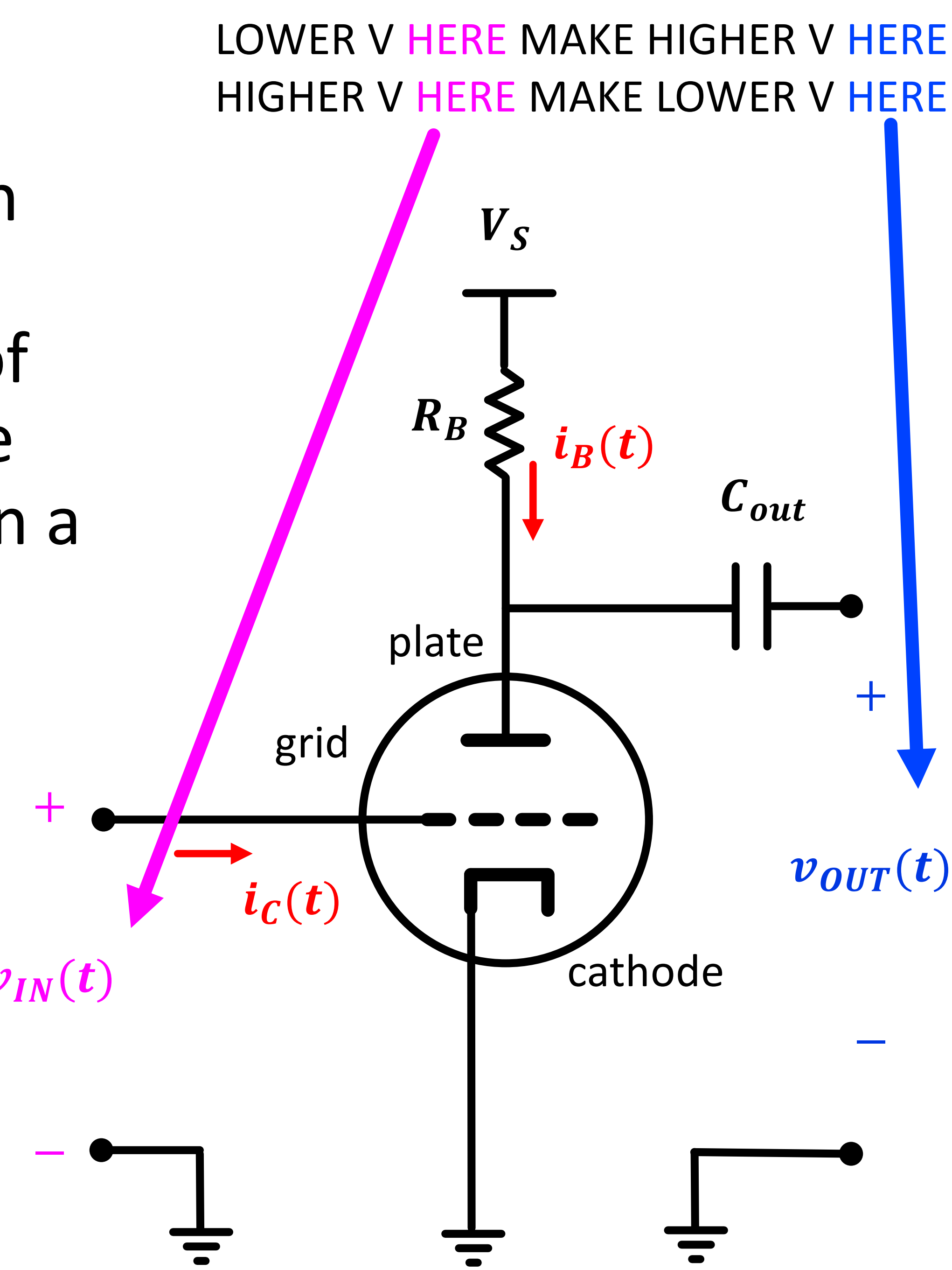
So let's just say that A_o is a function of everything (is wildcard) to indicate it is a nonlinear thing…and as a result, the entire equation is going to be nonlinear! Our job isn't to know exactly the nonlinearity, just recognize the shape*



**ignore grid bias and things for these examples to keep things simple!*

Sign of Gain

- Regardless of how non linear or not our open loop gain is, the sign of our gain will always be **negative** since we're in a inverting amplifier topology!



Add a Feedback Path

- Take some of our output…and using a voltage divider, feed it back to the input…
- Assuming $\boldsymbol{i_c}$ is ~0:

The voltage at the grid is:

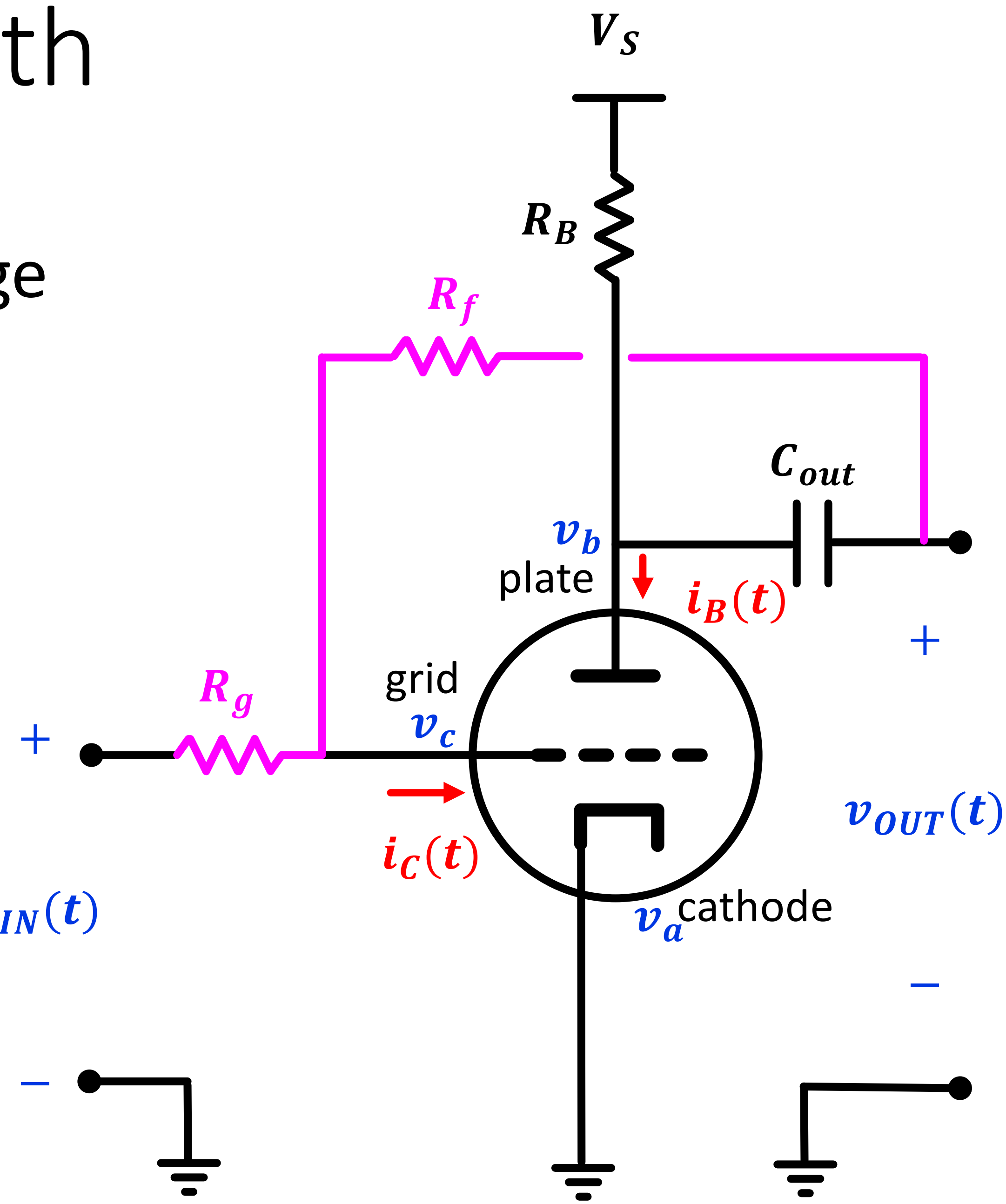
$$v_c = v_{in} + (v_{out} - v_{in})\frac{R_g}{R_g + R_f}$$

Like before the output is a function of voltage at input (grid):

$$v_{out} = A_o(*) \cdot v_c$$

Or put another way:

$$v_c = \frac{v_{out}}{A_o(*)}$$



So Putting This Together:

$$v_c = v_{in} + (v_{out} - v_{in})\frac{R_g}{R_g + R_f}$$

$$v_c = \frac{v_{out}}{A_o(*)}$$

Therefore:

$$\frac{v_{out}}{A_o(*)} = v_{in} + (v_{out} - v_{in})\frac{R_g}{R_g + R_f}$$

Therefore:

$$v_{out}\left(\frac{1}{A_o(*)} - \frac{R_g}{R_g + R_f}\right) = v_{in}\left(1 - \frac{R_g}{R_g + R_f}\right)$$

Therefore:

$$\frac{v_{out}}{v_{in}} = \frac{\left(1 - \frac{R_g}{R_g + R_f}\right)}{\left(\frac{1}{A_o(*)} - \frac{R_g}{R_g + R_f}\right)}$$

Therefore:

$$\frac{v_{out}}{v_{in}} = \frac{A_o(*)R_f}{\left(R_g + R_f - A_o(*)R_g\right)}$$

Therefore:

$$v_{out} = \frac{A_o(*)R_f}{\left(R_g + R_f - A_o(*)R_g\right)}v_{in}$$

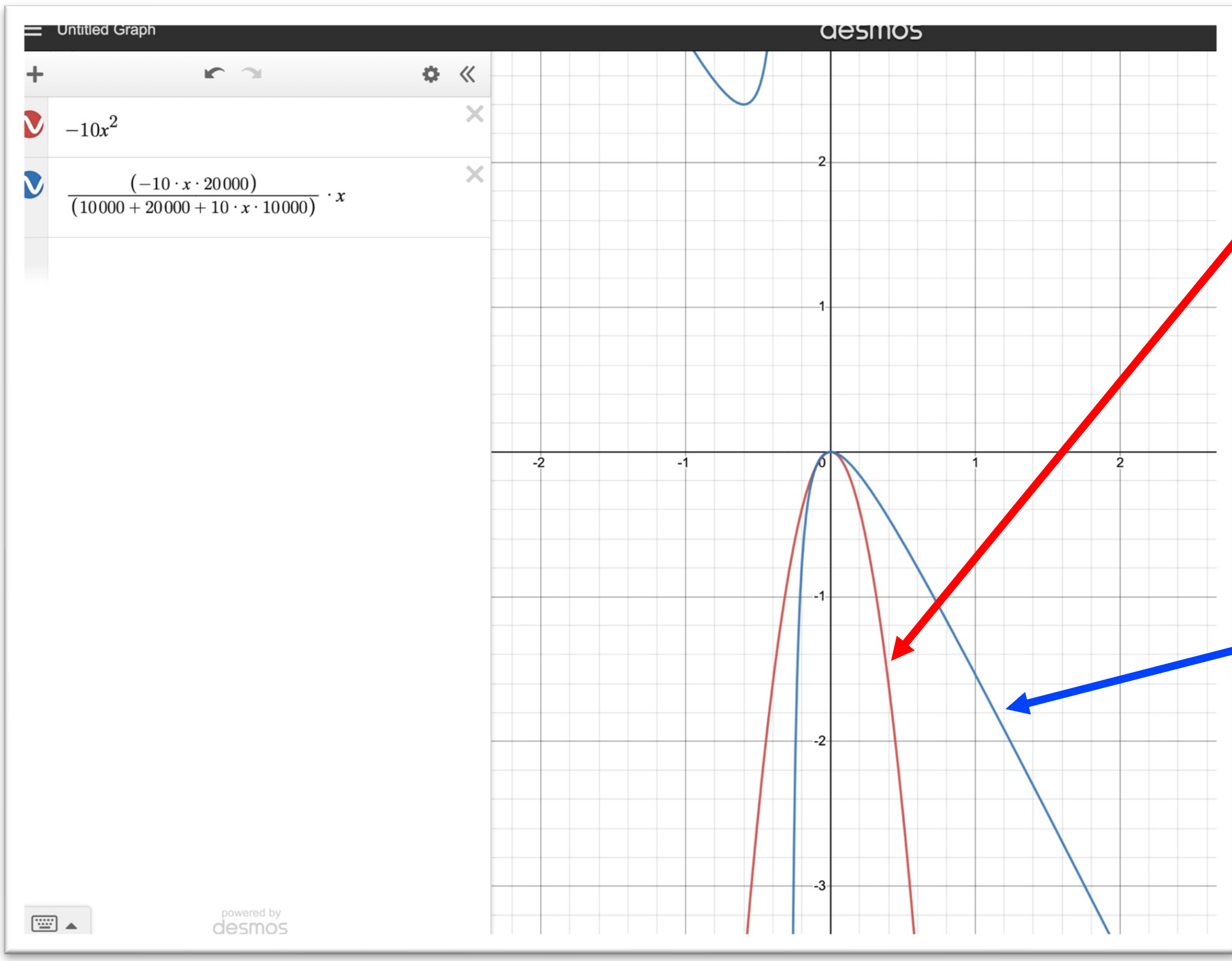
Conclusions I

- The result of this feedback had some interesting properties…
- Let's say we had a non-linear amp system where the gain was a simple function of $\boldsymbol{v_{in}}$ such that: $\boldsymbol{A_o(*) = -10v_{in}}$
- If we just applied this to our known I/O equation:
  - $\boldsymbol{v_{out} = -10 \cdot v_{in} \cdot v_{in} = -10 \cdot v_{in}^2}$…in other words, $\boldsymbol{v_{out}}$ is highly non-linear with $\boldsymbol{v_{in}}$
- In the context of feedback therefore:
  - $\boldsymbol{v_{out} = \frac{-10v_{in}R_f}{(R_g+R_f--10v_{in}R_g)}v_{in}}$
- For reasonable values for those resistors, this equation is actually more "linear" than the original

Conclusions I

$$v_{out} = -10 \cdot v_{in}^2 \quad \text{vs.} \quad v_{out} = \frac{-10 v_{in} R_f}{(R_g + R_f - -10 v_{in} R_g)} v_{in}$$

$$R_f = 20\text{k}\Omega \; R_g = 10\text{k}\Omega$$



The original open loop exhibits highly non-linear relation of input to output

The system with closed loop negative feedback exhibits a shape that looks more linear-ish, albeit at a lower gain!

Conclusions II

- Further investigation reveals another interesting pattern. And this one is **critical:**
- For the equation $\boldsymbol{v_{out}} = \frac{\boldsymbol{A_o}(*)\boldsymbol{R_f}}{(\boldsymbol{R_g}+\boldsymbol{R_f}-\boldsymbol{A_o}(*)\boldsymbol{R_g})}\boldsymbol{v_{in}}$ as the overall magnitude of $\boldsymbol{A_o}(*)$ gets larger and larger, ($\boldsymbol{A_o}(*) \to \infty$) both top and bottom of the fraction become dominated by it and the overall equation will simplify to the following:
- $\boldsymbol{v_{out}} \approx -\frac{\boldsymbol{R_f}}{\boldsymbol{R_g}}\boldsymbol{v_{in}}$

Conclusions I

- The result of this feedback had some interesting properties…
- Let's say we had a non-linear amp system where the gain was a simple function of $\boldsymbol{v_{in}}$ such that: $\boldsymbol{A_o(*) = -1000 v_{in}}$
- If we just applied this to our known I/O equation:
  - $\boldsymbol{v_{out} = -1000 \cdot v_{in} \cdot v_{in} = -1000 \cdot v_{in}^2}$…in other words, $\boldsymbol{v_{out}}$ is highly non-linear with $\boldsymbol{v_{in}}$
- In the context of feedback therefore:
  - $\boldsymbol{v_{out} = \frac{-1000 v_{in} R_f}{(R_g + R_f - -1000 v_{in} R_g)} v_{in}}$
- For reasonable values for those resistors, this equation is <u>far, far more "linear" than the original</u>

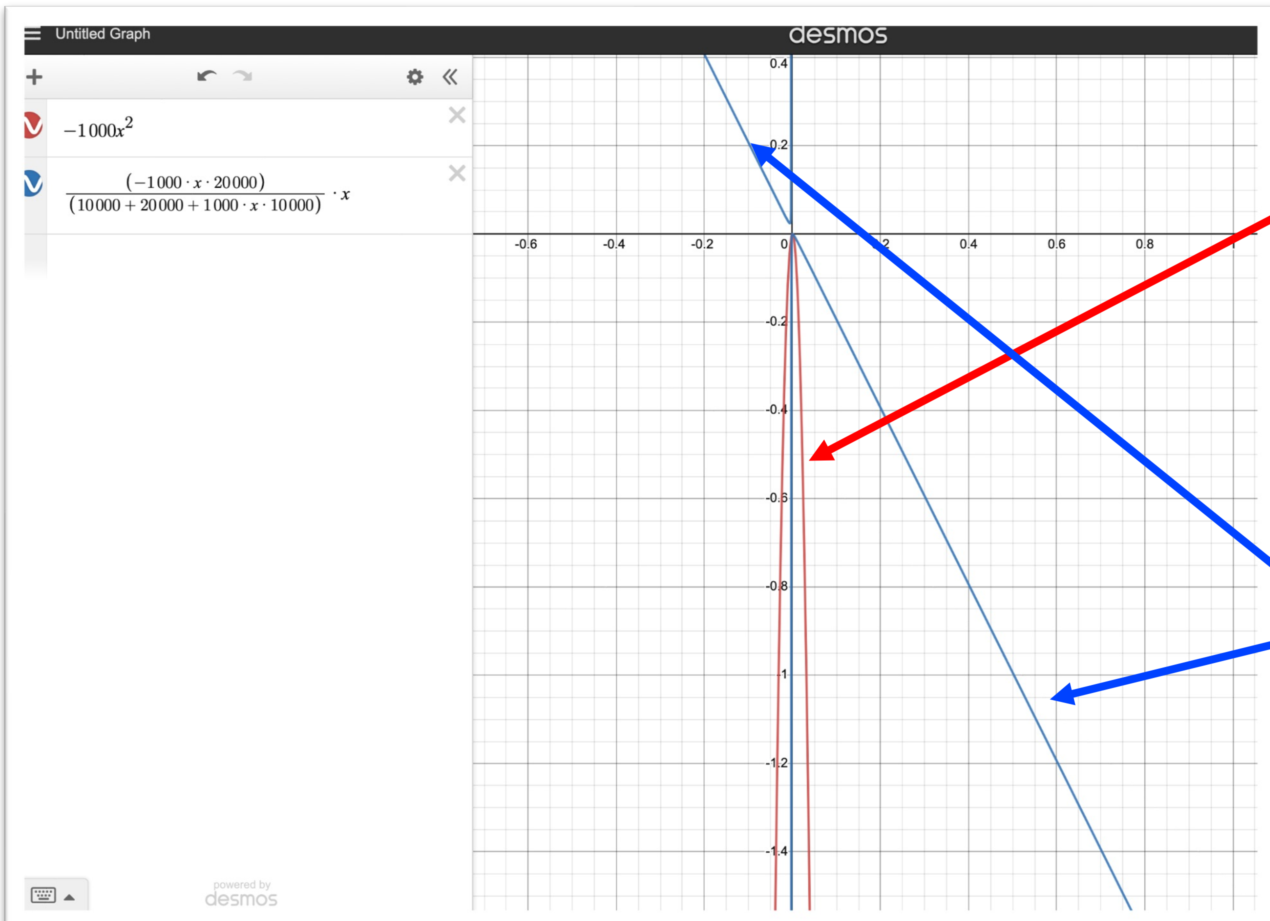
Conclusions II

$$v_{out} = -1000 \cdot v_{in}^2$$

vs.

$$v_{out} = \frac{-1000 v_{in} R_f}{(R_g + R_f - -1000 v_{in} R_g)} v_{in}$$

$$R_f = 20\text{k}\Omega \; R_g = 10\text{k}\Omega$$



The original open loop exhibits highly non-linear relation of input to output

The system with closed loop negative feedback exhibits a shape that is essentially linear!

Conclusions IIb

- Because of the invention and perfection of negative feedback the exact "shape" of a tube's gain became less important
- What became important was that you have a lot of gain to start with. If you can have a lot of gain, even if non-linear, you can trade it off for a more linear behavior of gain at a more moderate overall magnitude of gain
- This freed up engineers to push forward with making higher gain tubes and not obsess so much with the linearity of the tube itself! The circuit it lives in can fix that problem.

Results are Shockingly Good

- The original Harold Black paper from 1934, arguably one of the greatest EECS papers of all time, is built around the study of this circuit:
- A multi-stage tube amplifier with the output negatively fed back to the input:

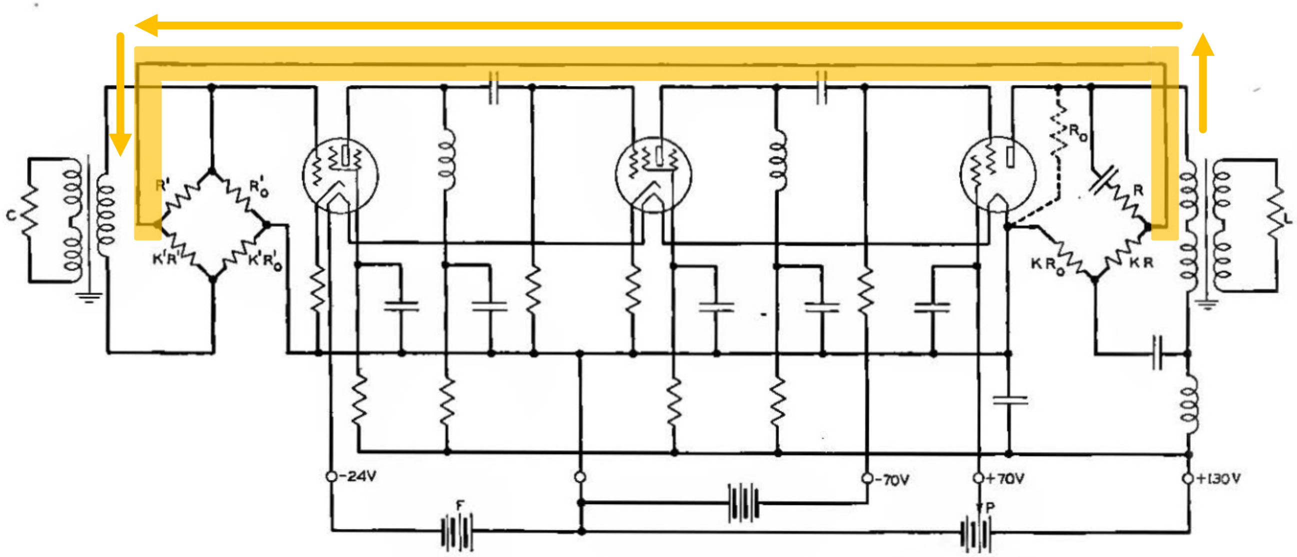
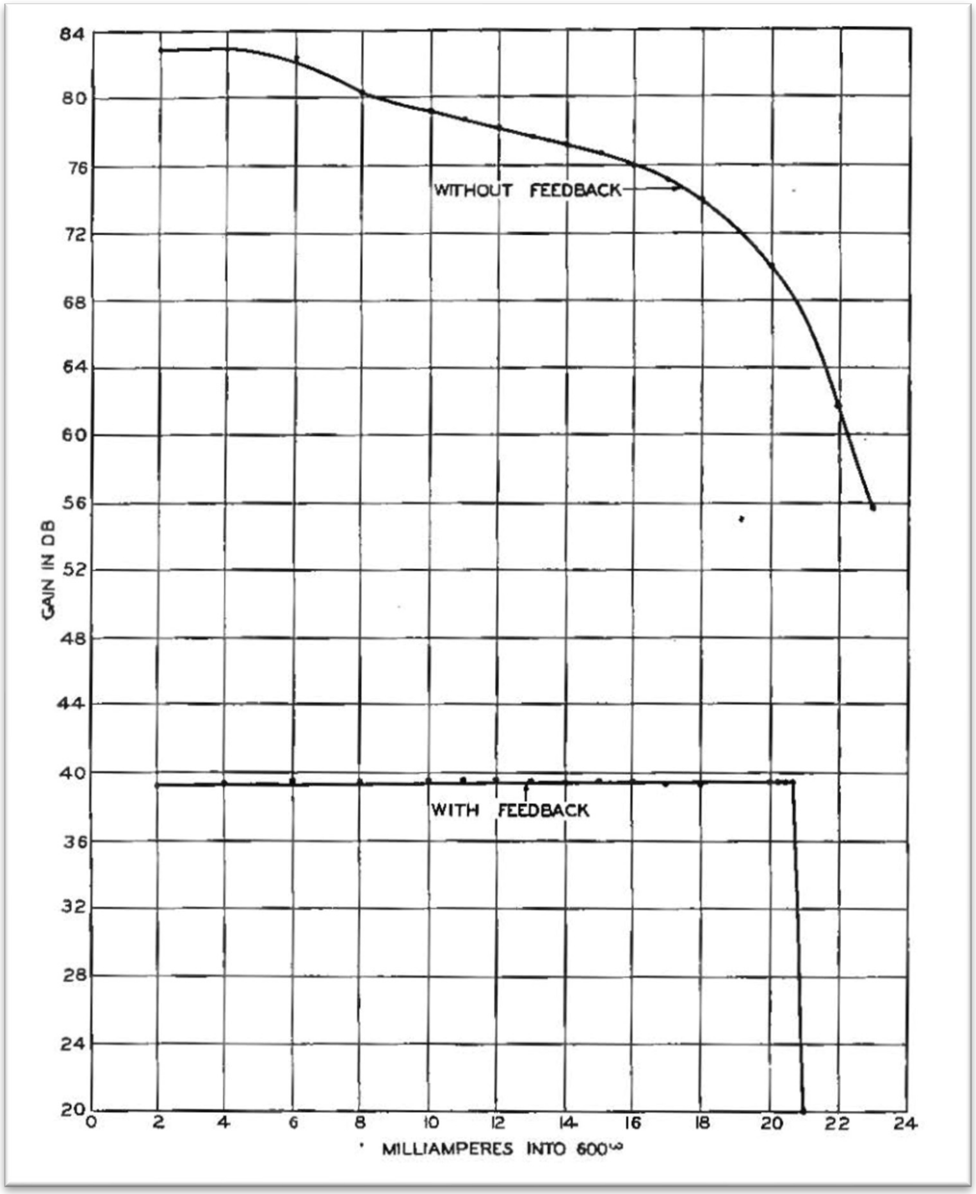


Fig. 2—Circuit of a negative feedback amplifier.

H.S. Black, "Stabilized feed-back amplifiers", *Electrical Engineering*, vol. 53, pp. 114-120, Jan. 1934.

Compare that circuit with/without feedback

- Gain now stays flat for a variety of output loads! (showing how as value of resulting output signal goes up/down, it stays proportional with input signal)
- Non-linearity suppressed at the expense of lower overall gain



H.S. Black, "Stabilized feed-back amplifiers", *Electrical Engineering*, vol. 53, pp. 114-120, Jan. 1934.

Works in Frequency Space Too!

- Gain stays constant for a variety of frequencies!
- Yes it is lower overall in magnitude but it is consistent!

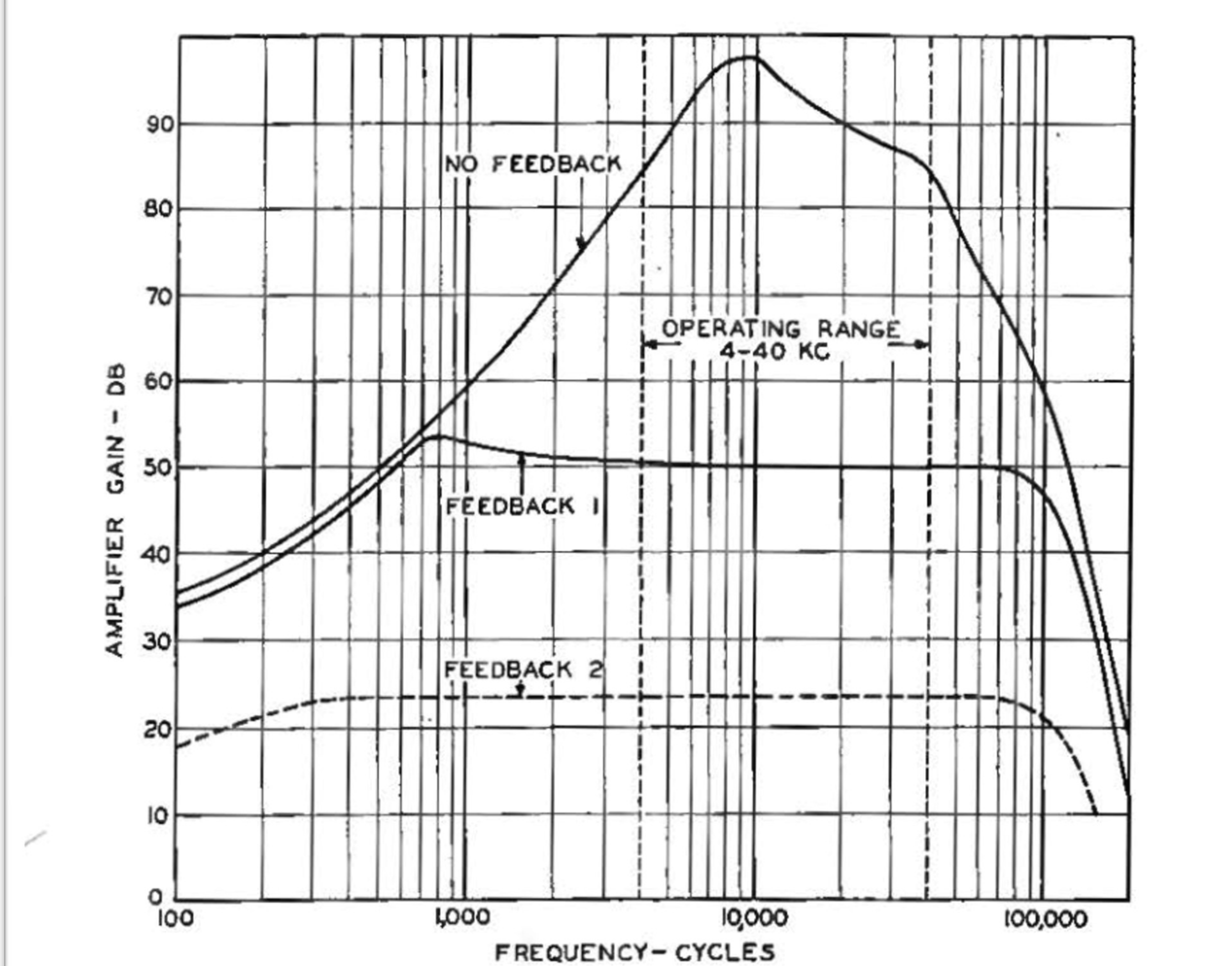
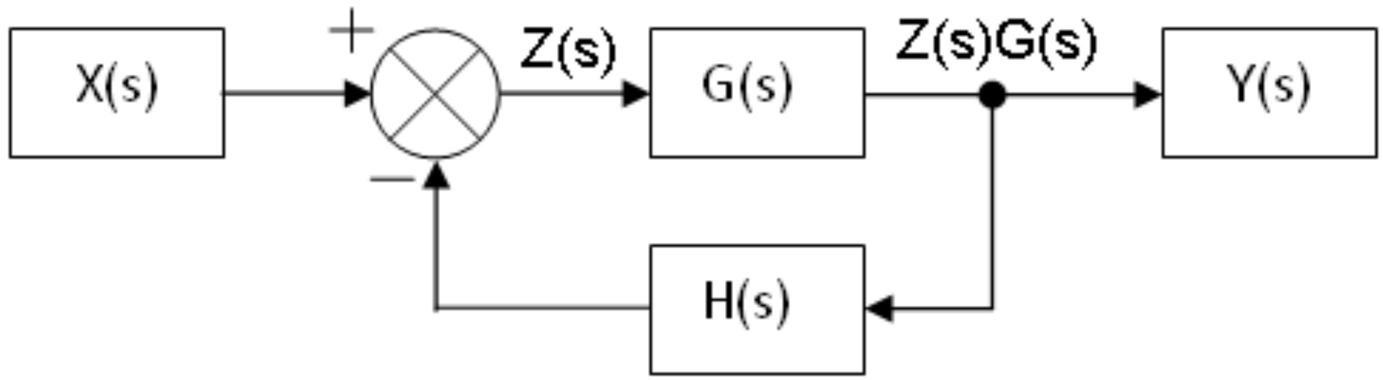


Fig. 6—Gain frequency characteristics with and without feedback of amplifier of Fig. 2.

H.S. Black, "Stabilized feed-back amplifiers", *Electrical Engineering*, vol. 53, pp. 114-120, Jan. 1934.

This result

- All modern control theory is built around the work of Black:



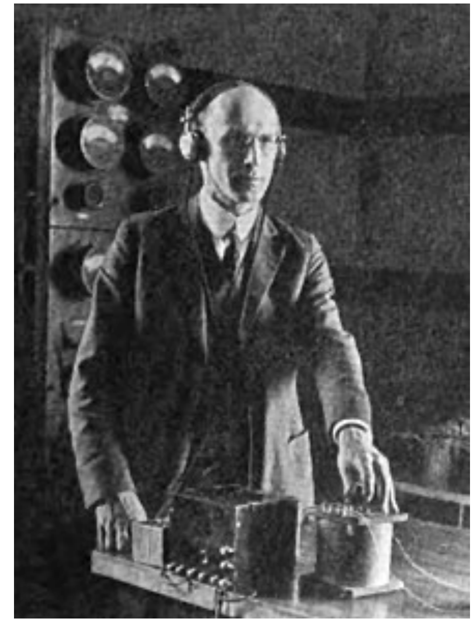
https://en.wikipedia.org/wiki/Closed-loop_transfer_function

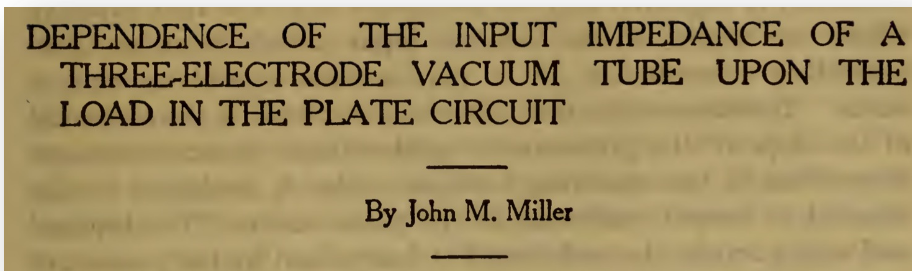
So we're making tubes with more gain

- But there's other problems showing up right at the same time…ugh
- Triodes were roughly good at low frequencies. However as you increased the frequency they started to lose gain (non-linear or otherwise).
- Problem was even worse in higher mu tubes
- What was going on?
- Different problem from non-linearity but also greatly limited tubes applications to higher speed circuits! :/

The Miller Effect

- John Miller studied this phenomenon in late 1910's and published a famous paper describing the whole phenomenon in 1920





DEPENDENCE OF THE INPUT IMPEDANCE OF A THREE-ELECTRODE VACUUM TUBE UPON THE LOAD IN THE PLATE CIRCUIT

By John M. Miller

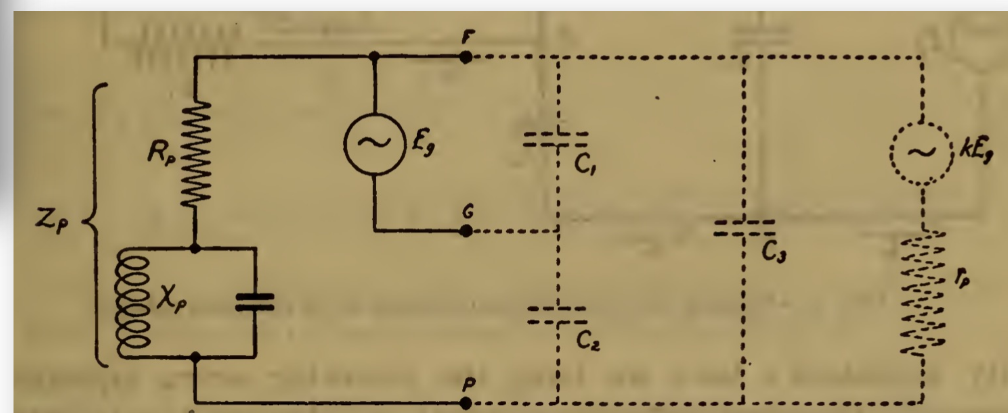


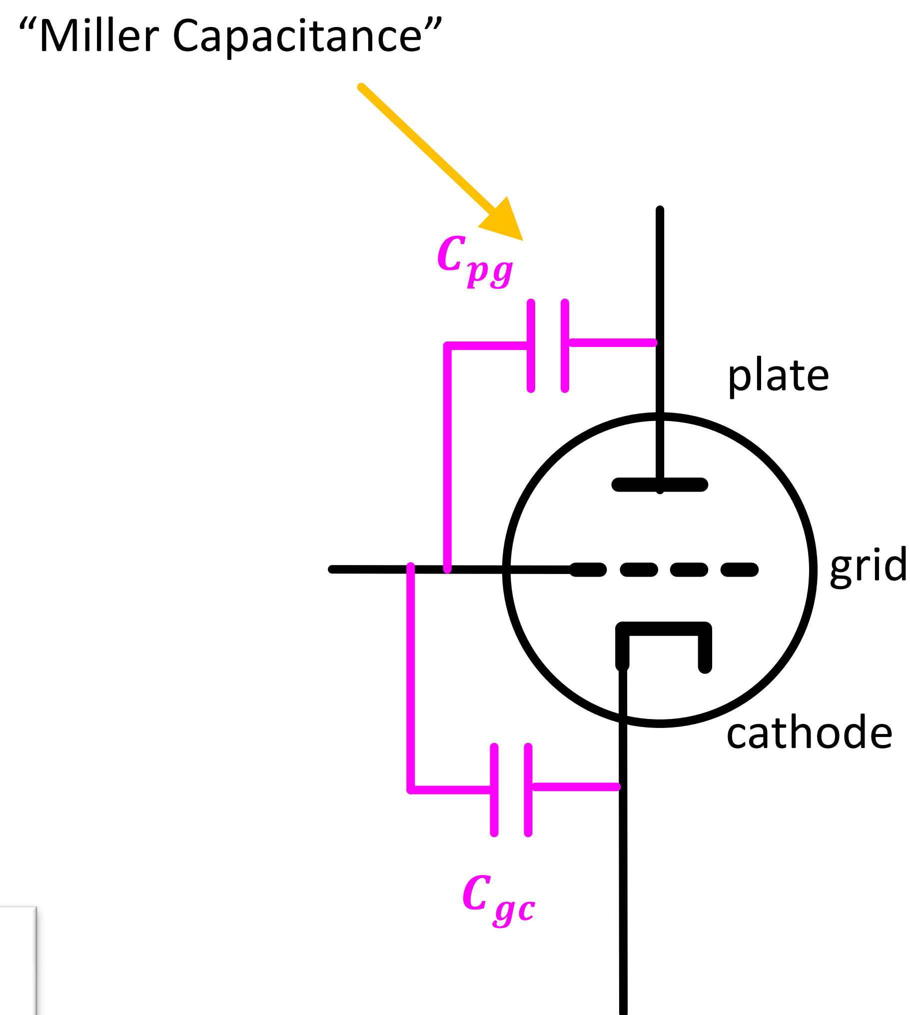
FIG. 1.—*Diagramatic representation of a vacuum tube and external circuits*

https://en.wikipedia.org/wiki/John_Milton_Miller

John M. Miller, "Dependence of the input impedance of a three-electrode vacuum tube upon the load in the plate circuit", *Scientific Papers of the Bureau of Standards*, 15(351):367-385, 1920.

Parasitic Capacitance

- Miller identified and described the presence of parasitic capacitances in a triode as well as their effect
- At first glance the parasitic values seemed minimal…on the order of picoFarads



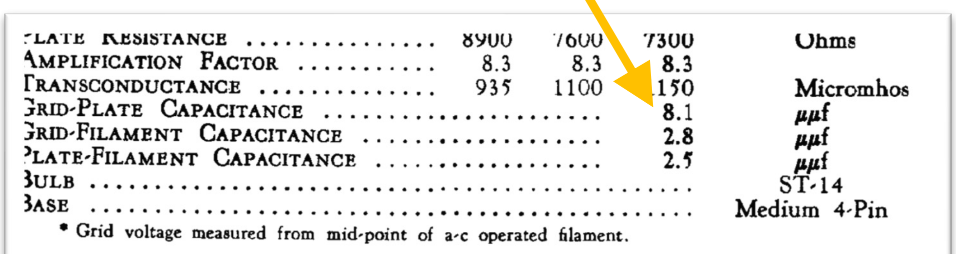


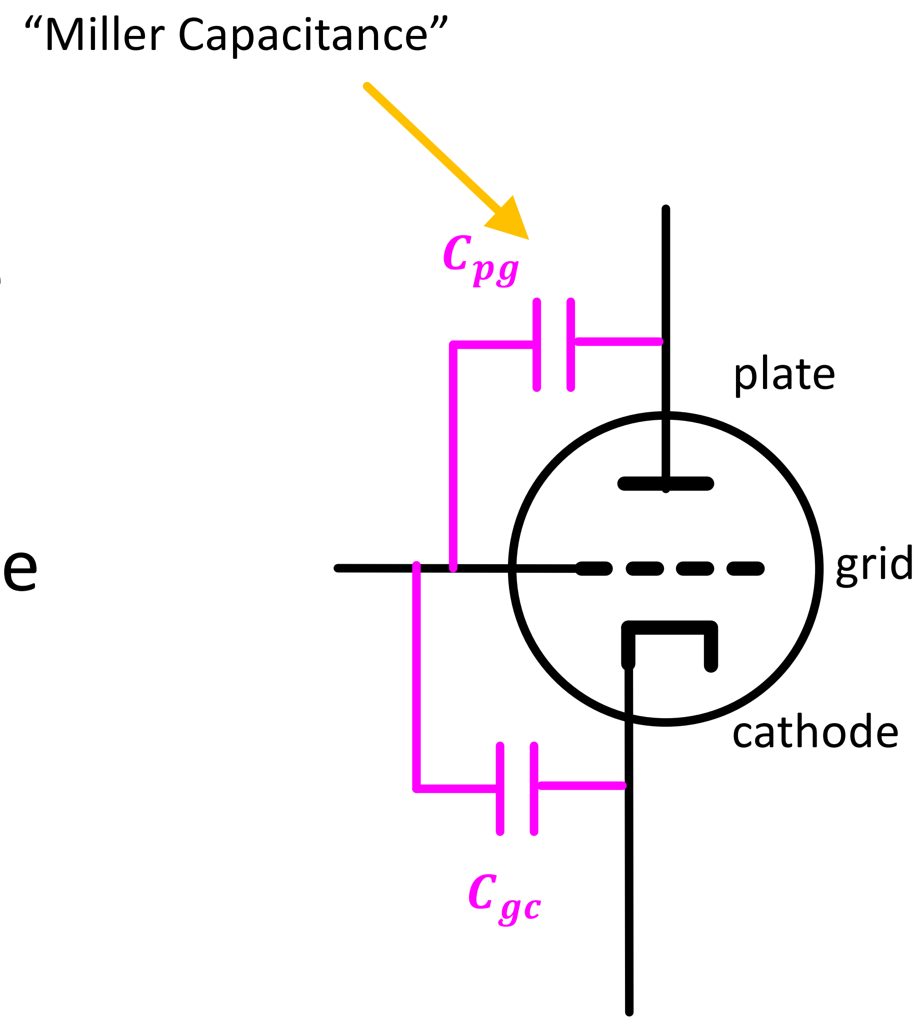
Plate Resistance	8900	7600	7300	Ohms
Amplification Factor	8.3	8.3	8.3	
Transconductance	935	1100	1150	Micromhos
Grid-Plate Capacitance			8.1	μμf
Grid-Filament Capacitance			2.8	μμf
Plate-Filament Capacitance			2.5	μμf
Bulb				ST-14
Base				Medium 4-Pin

* Grid voltage measured from mid-point of a-c operated filament.

Characteristics for early triode (Type 26)

The Miller Capacitance was a Problem

- The other capacitances were annoying but not debilitating
- The capacitance between plate and grid proved deadly and needed to be dealt with.
- Why? Because it scaled with the gain of the tube/circuit
- If you made a higher gain tube, you ended up with a larger Miller Capacitance, which meant you'd have even worse high-frequency performance

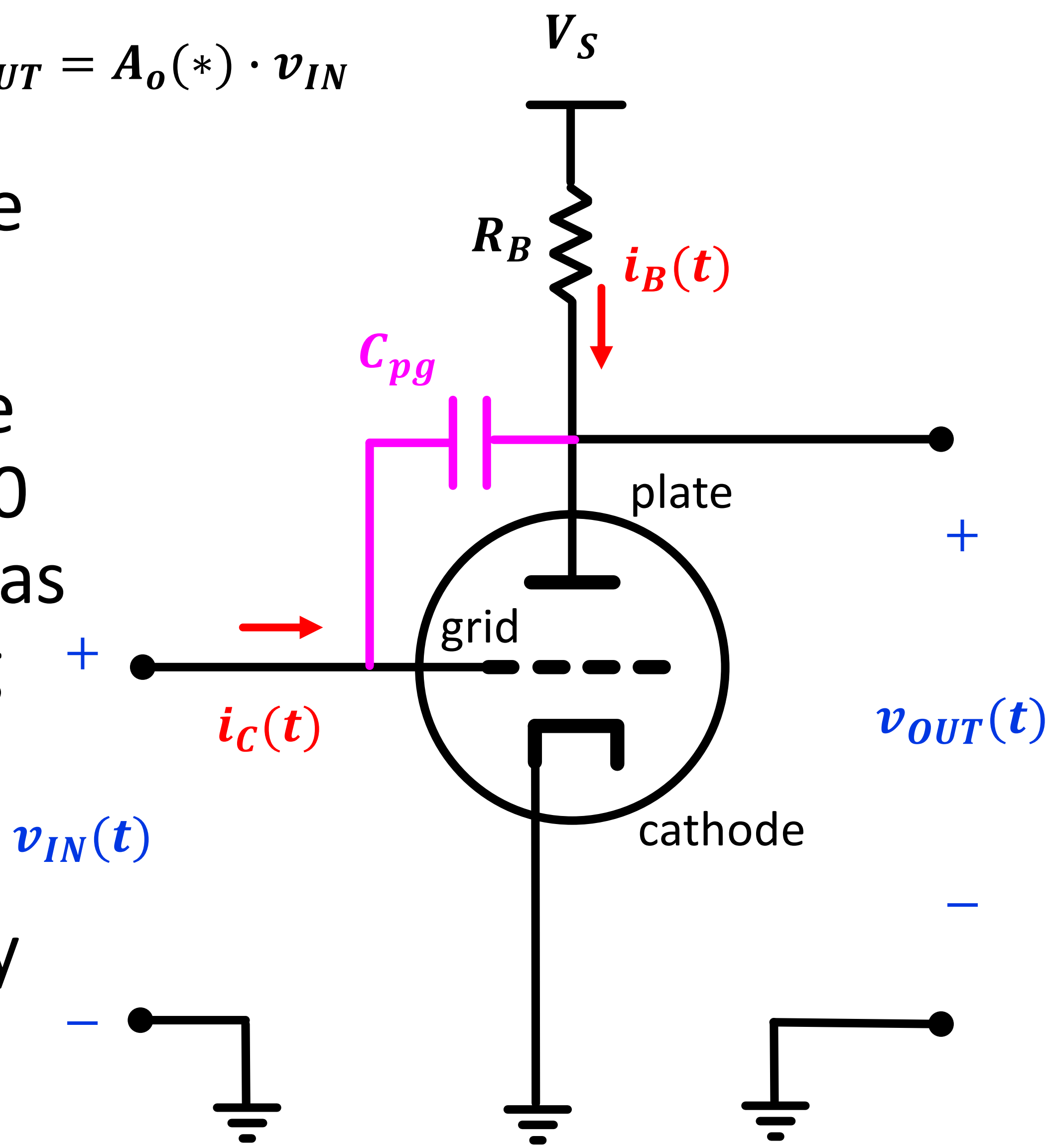


Characteristics for early triode (Type 26)

Derivation

$v_{OUT} = A_o(*) \cdot v_{IN}$

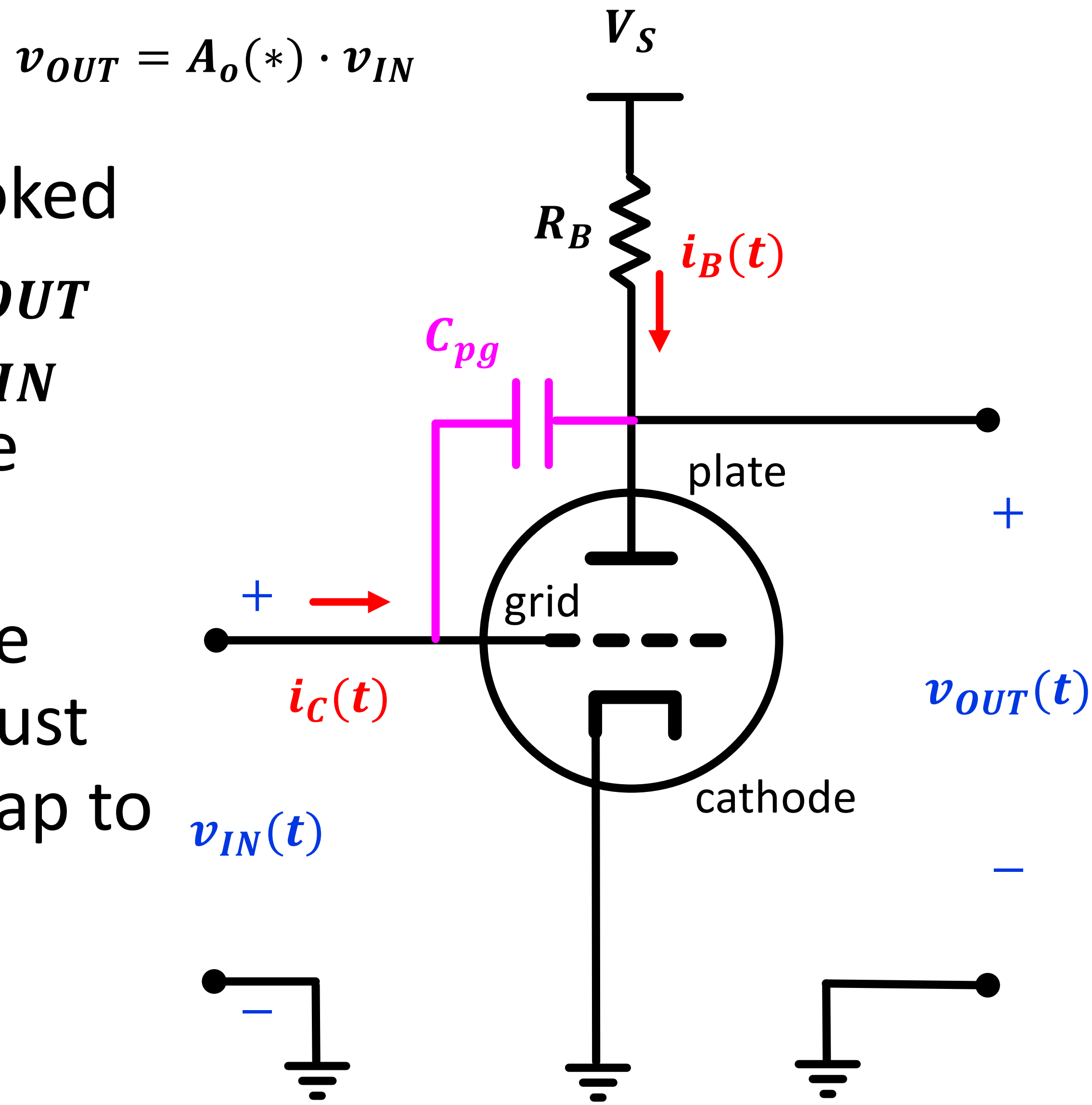
- Return to our basic triode stage again:
- Normally current into the tube (grid) was basically 0 since input impedance was very high. Even assuming that C_{pg} exists, its value was a few pF, so that's a $Z = \frac{1}{j\omega 10^{-12}}$ which is very large at first glance
- HOWEVER



*ignore grid bias and things for these examples to keep things simple!

Derivation

- That capacitor not hooked up to GROUND, but $\boldsymbol{v_{OUT}}$ and $\boldsymbol{v_{OUT} = A_o(*) \cdot v_{IN}}$ AND $\boldsymbol{A_o(*)}$ is gonna be negative!
- That means the voltage across that cap is not just $\boldsymbol{v_{IN}}$ as it would be in cap to ground but:
- $\boldsymbol{v_{IN} - v_{OUT}}$ or…
- $\boldsymbol{v_{IN} - A_o(*) \cdot v_{IN}}$ or …
- $\boldsymbol{v_{IN}(1 + |A_o(*)|)}$



ignore grid bias and things for these examples to keep things simple!

Derivation

$$v_{OUT} = A_o(*) \cdot v_{IN}$$

Remembering that with impedances Ohm's Law is still just:

$$\tilde{V} = \tilde{I}Z$$

For a given v_{IN} :

$$\tilde{V}_{in} = \tilde{I}_{in}Z_{in}$$

All the current into the circuit will flow through the Miller Capacitor:

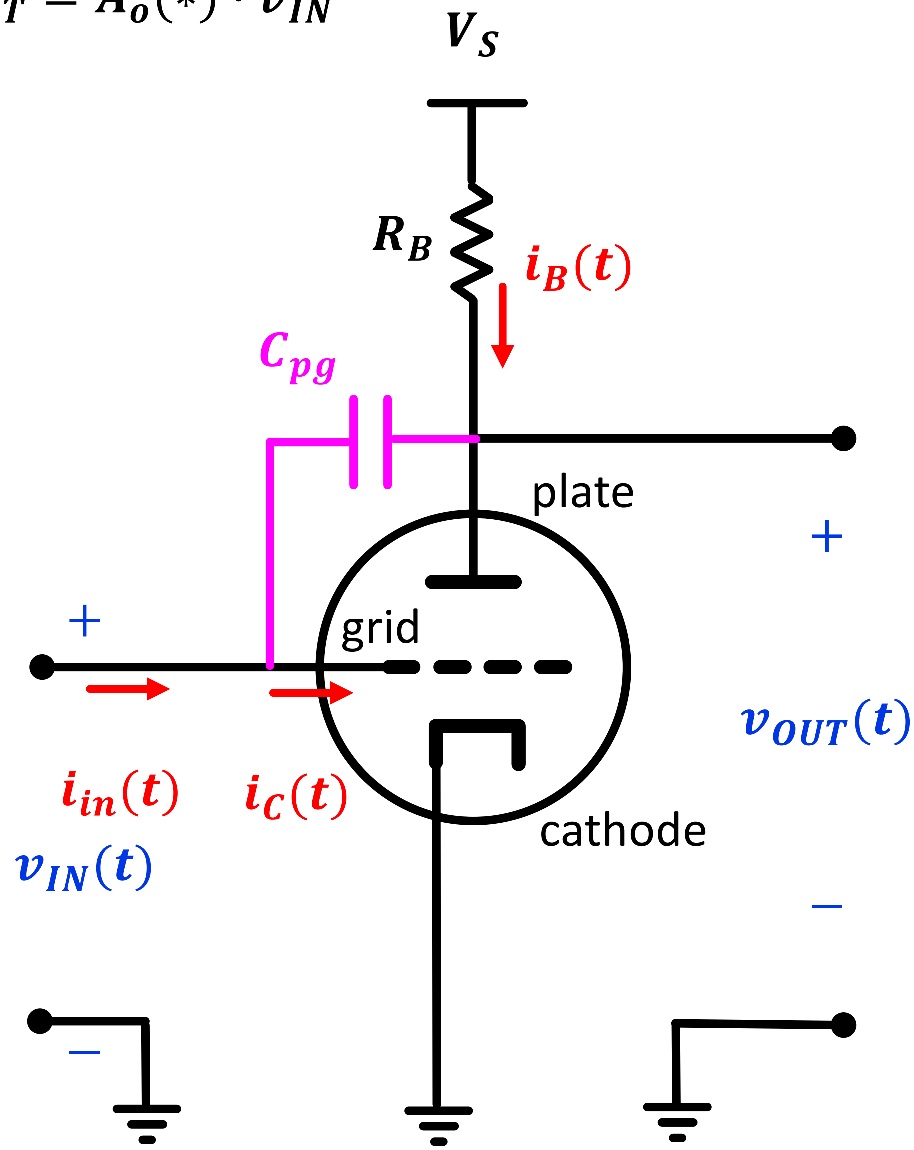
$$\tilde{I}_{in} = \frac{\tilde{V}_{pg}}{Z_{pg}} =$$

The cap is still whatever it is, but the voltage across the cap is scaled!:

$$\tilde{I}_{in} = \frac{\tilde{V}_{in}(1 + |A_o(*)|)}{1/j\omega C_{pg}} = \frac{\tilde{V}_{in}}{\frac{1}{j\omega C_{pg}(1 + |A_o(*)|)}}$$

Substitute back in:

$$\tilde{V}_{in} = \frac{\tilde{V}_{in}}{\frac{1}{j\omega C_{pg}(1 + |A_o(*)|)}} Z_{in}$$



As a result:

$$Z_{in} = \frac{1}{j\omega C_{pg}(1 + |A_o(*)|)}$$

Conclusion

- The input impedance of any triode stage will now be dominated by this expression:

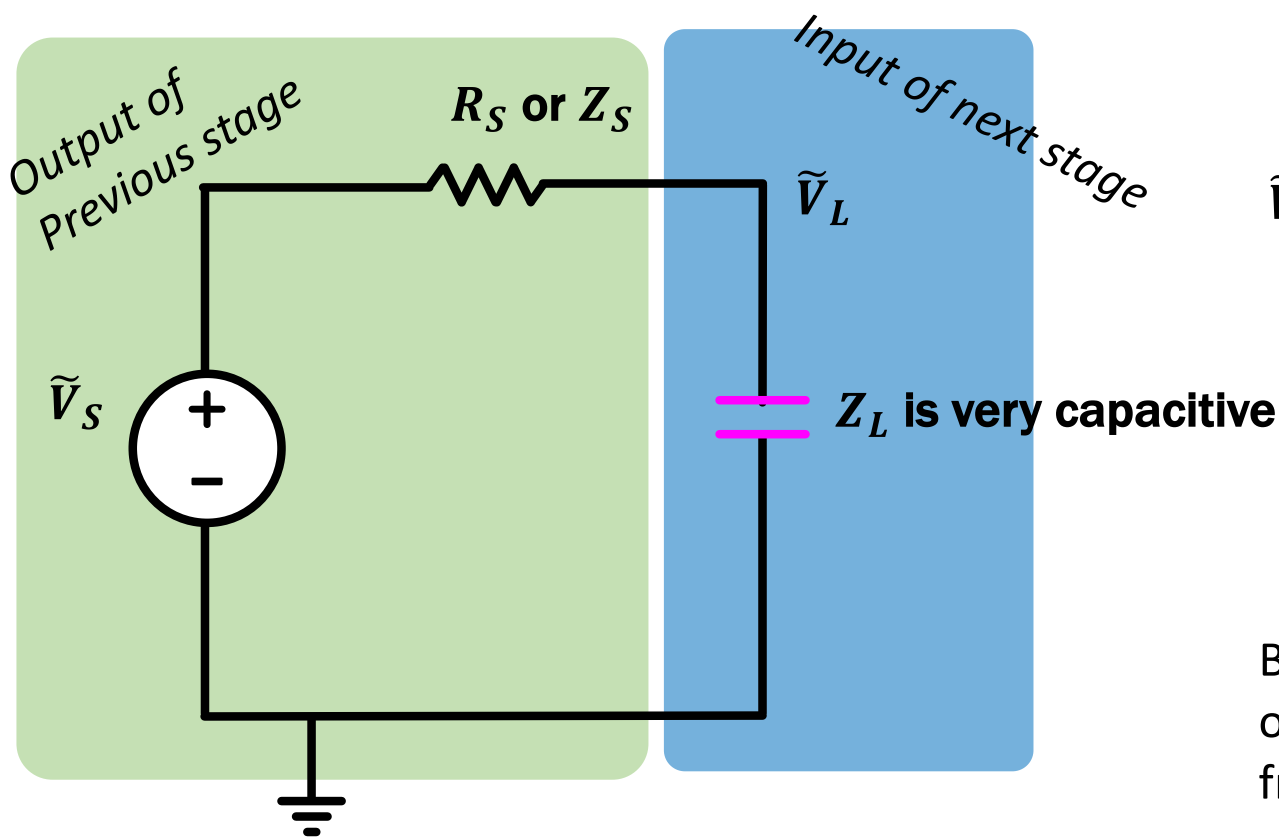
As a result:

$$Z_{in} = \frac{1}{j\omega C_{pg}(1 + |A_o(*)|)}$$

- Which is essentially equivalent to a capacitor 1+gain times larger than it actually is.

Capacitive Input 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:



$$\widetilde{V}_L(j\omega) = \frac{Z_L}{Z_L + R_S}\widetilde{V}_S(j\omega)$$

$$\widetilde{V}_L(j\omega) = \frac{1}{1 + j\omega R_S C_L}\widetilde{V}_S(j\omega)$$

Low pass filter with "knee" at $^{1}/_{2\pi R_S C_L}$

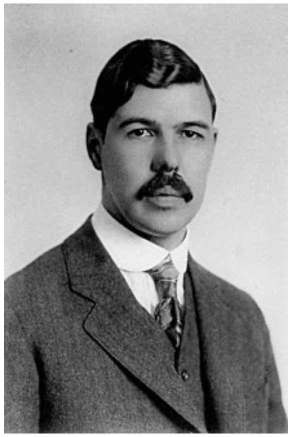
Bigger C_L means turns off at lower and lower frequencies!☹

Miller Effect was Real Problem

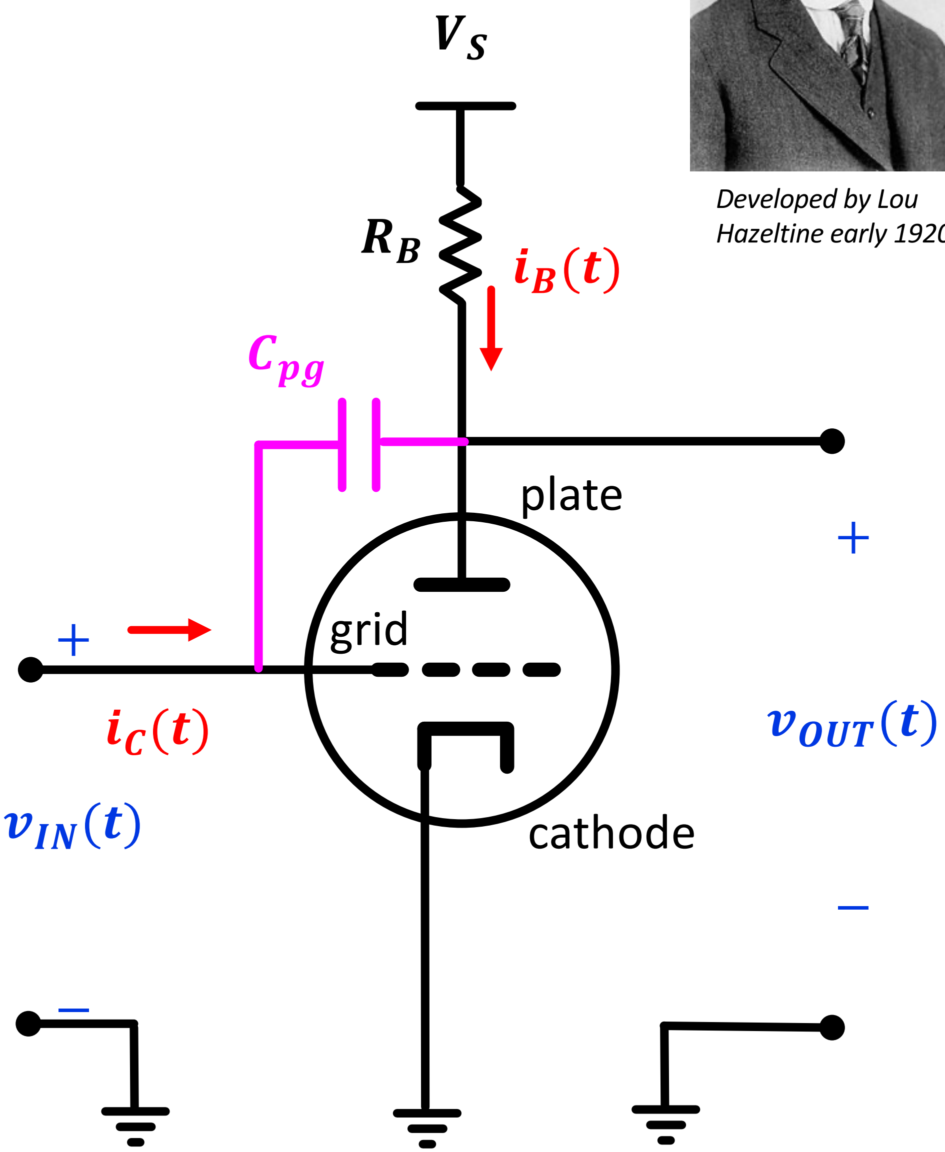
- Kept systems from having much gain at higher frequencies, greatly limiting the ability to process faster data work at higher radio frequencies, etc…
- Also it got worse with more gain on tubes…so it isn't like you could just brute force your way through it to overcome loss…
  - Increase gain → increased capacitance→ any benefit is basically munched up by the circuit goblins
- What to do?

Solution 1: Circuit Approach (Neutrodyning)

- Can't get rid of the capacitance.
- Can you add anything to cancel it out?
- Add another capacitor in feedback of equal value but have the voltage it sees be the exact opposite (out of phase)
- How the F do you do that?



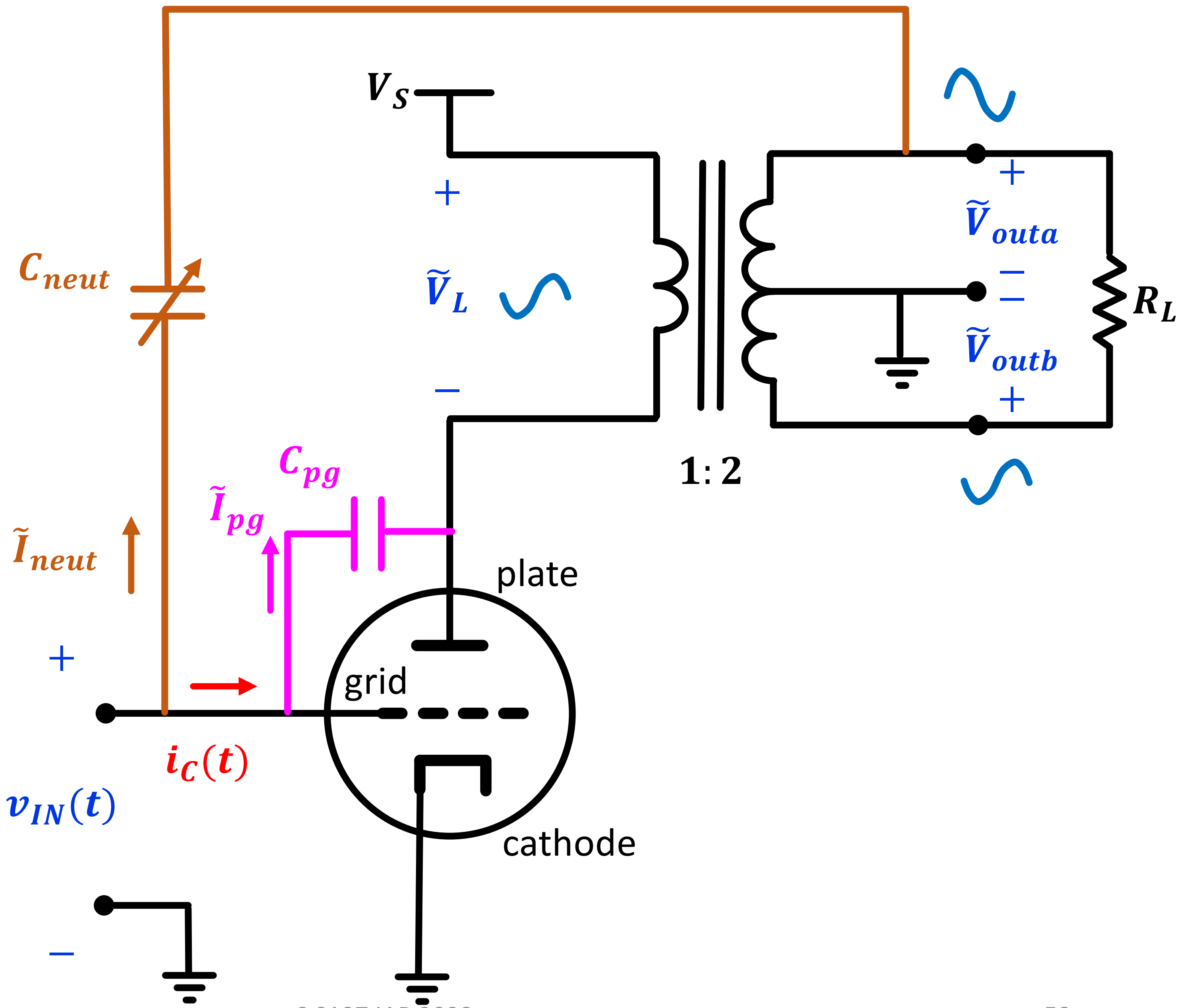
Developed by Lou Hazeltine early 1920s



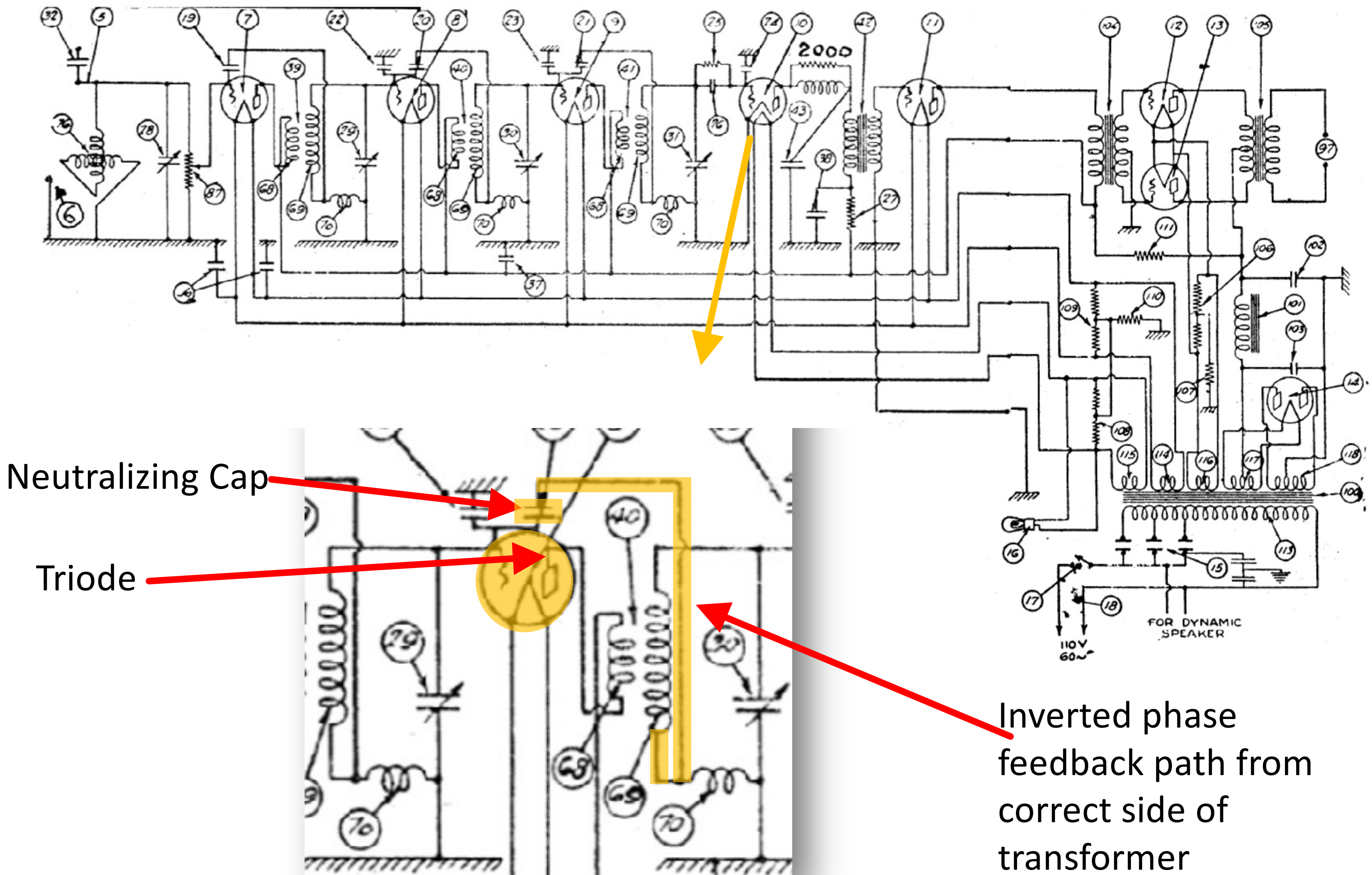
https://en.wikipedia.org/wiki/Louis_Alan_Hazeltine

Why use a transformer, of course

- Tune that neutralizing cap until the current into it just cancels out the current into the Miller cap.
- Boom no more cap



1928 Bosch Radio Receiver Schematic

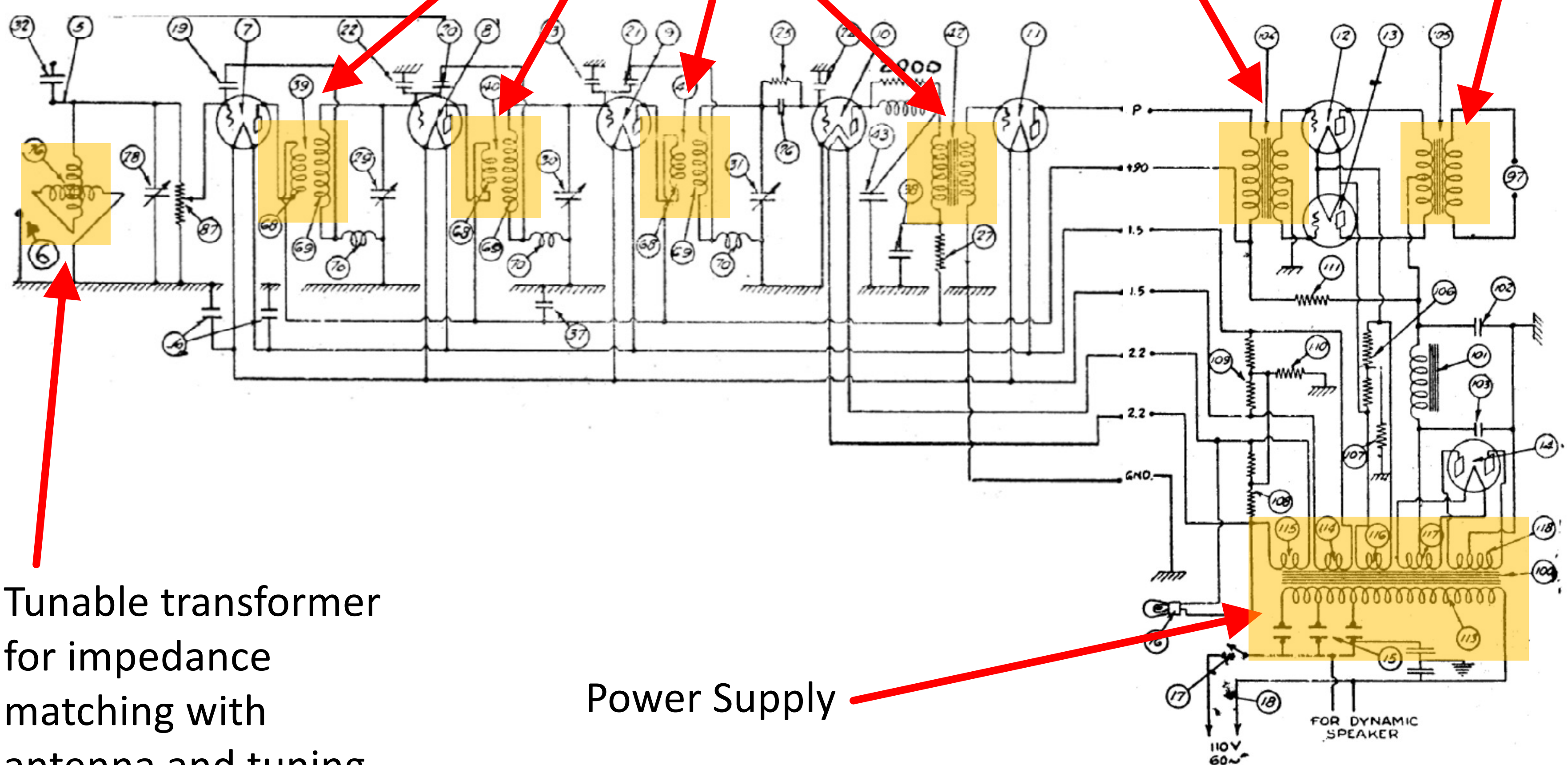


1928 Bosch Radio Receiver Schematic

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

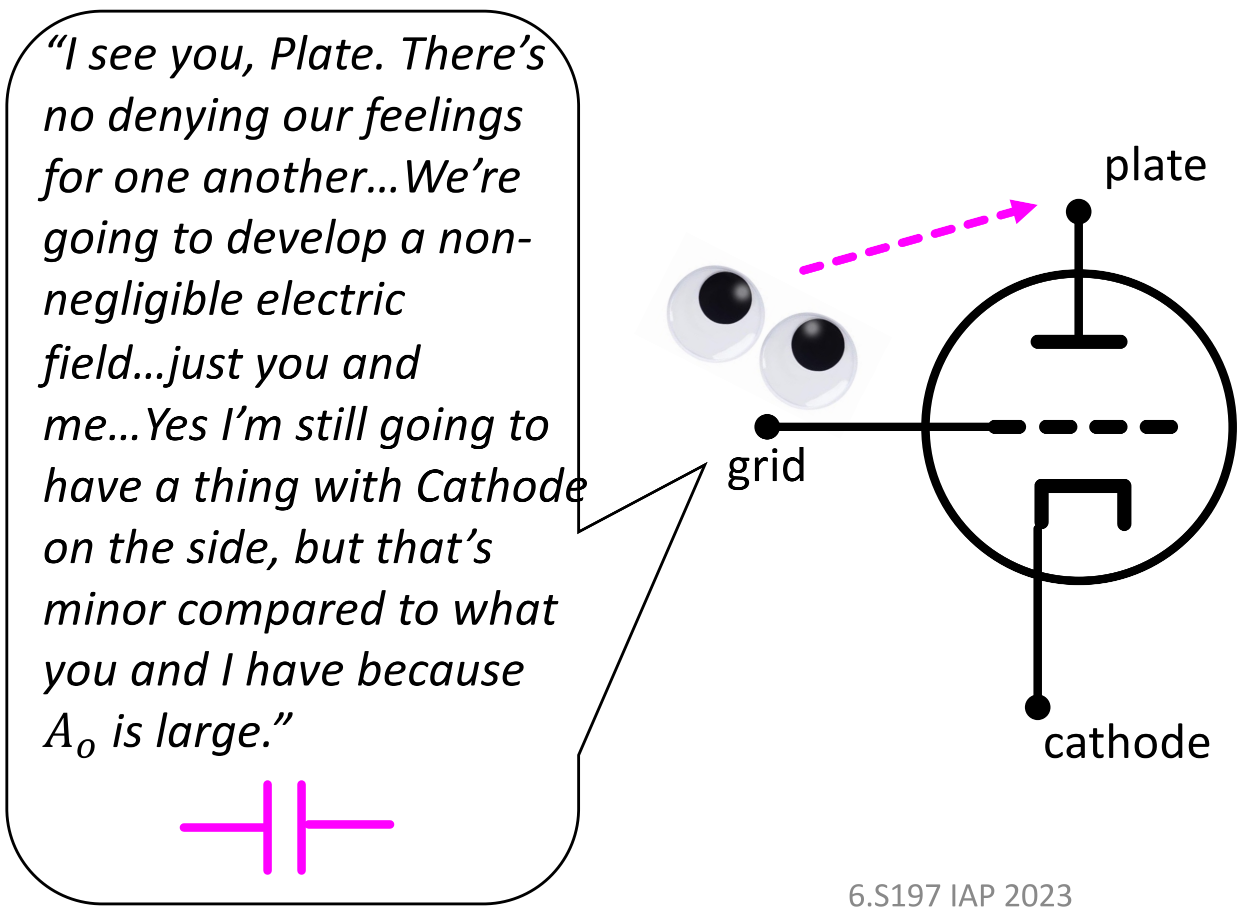
Power Supply

Neutrodyning

- Used in tons of circuits throughout 1920s. Allowed early forays into higher frequencies
- Still…kinda annoying. Need all extra circuit crap. Also could drift as gain of tube changed over time…needed retuning to account
- If cap drifted (not rare in early caps) you could get too much positive feedback and then the circuit would turn into an oscillator…just not good
- So other solutions to the Miller Effect were sought…

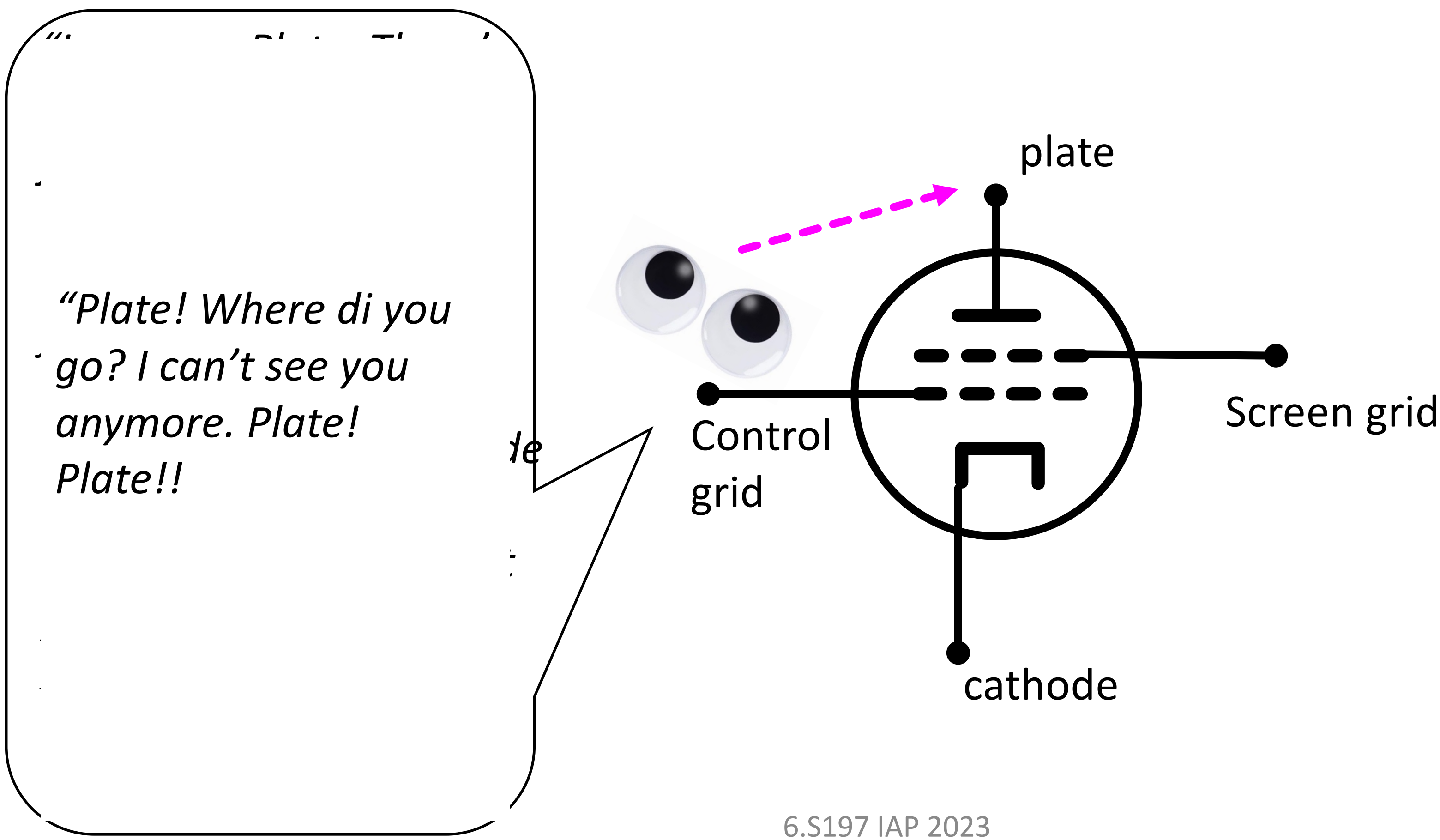
Solution 2: Device Level. Make a New Tube

- The Miller Effect was present because the grid could very easily see the plate, electrically speaking



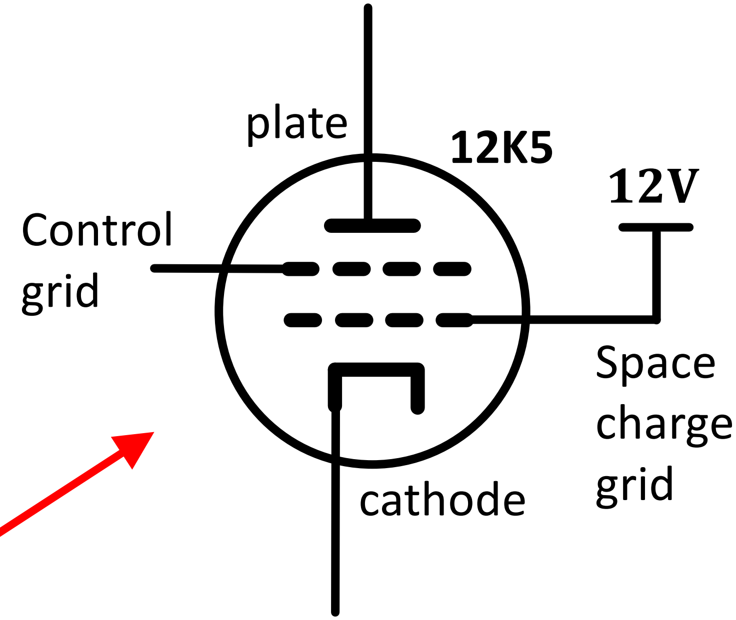
Solution 2: Device Level. Make a New Tube

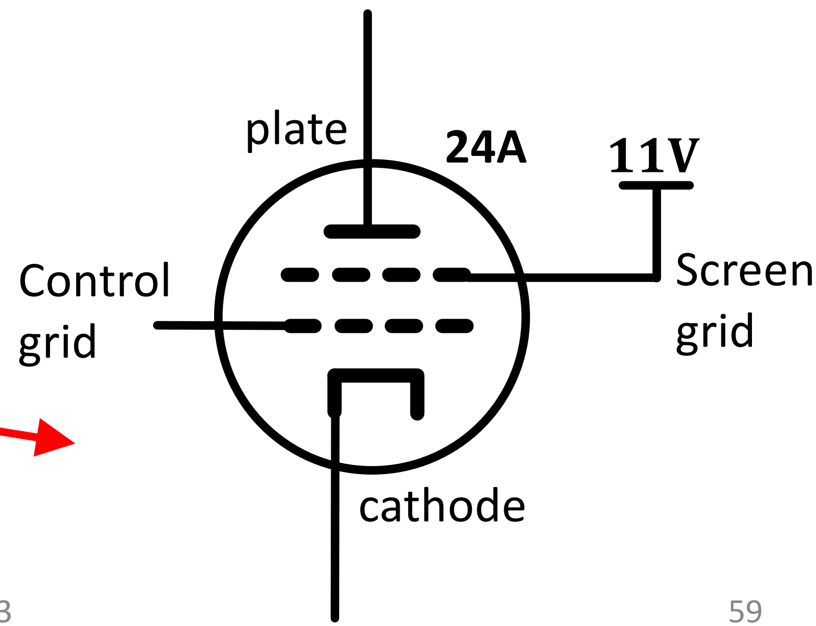
- Add another Grid in near the plate to screen it from the grid



This new tube had four electrodes

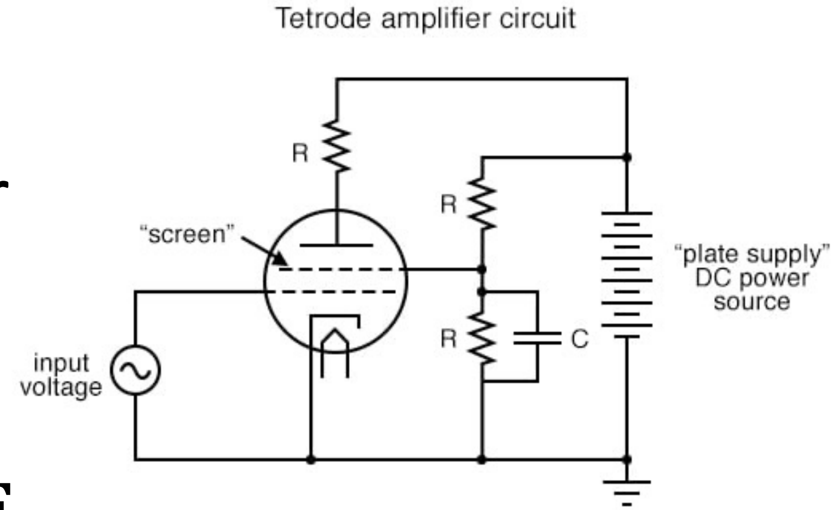
- Call it the screen-grid tetrode.
- Note this is different from the tetrode used in lab 2. That's a space-charge tetrode. Its new grid is used for accelerating electrons away from cathode.
- Screen-grid tetrode places new grid close to plate not tetrode to shield plate





The Tetrode Was Ok

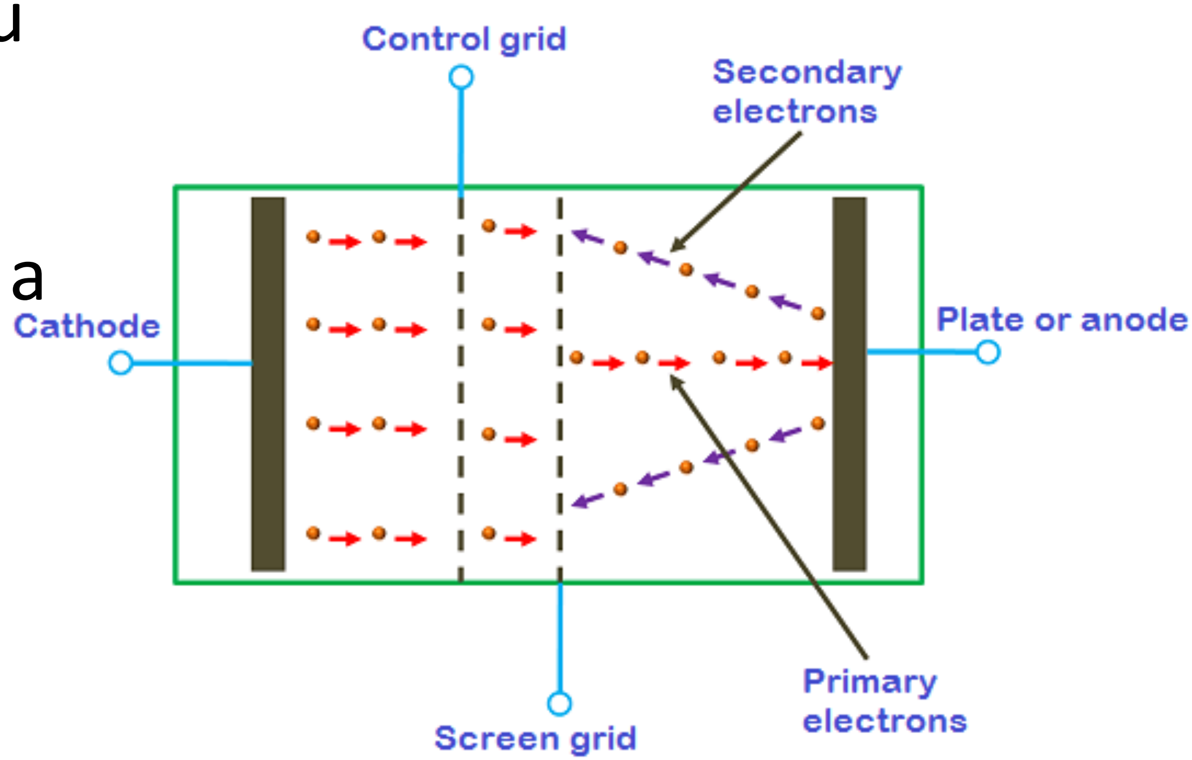
- Tetrode definitely cut down Miller Effect.
- Early triodes had a $C_{Miller} = 8\text{pF}$
- Tetrodes had a $C_{Miller} = 0.015\text{pF}$
- Still there, but orders of mag less
- Usually hold screen grid at a positive voltage close to supply.
- Majority of field lines from grid to cathode therefore got diverted
- Screen grid did pull some current though!



https://www.allaboutcircuits.com/textbook/semiconductors/chpt-13/the-tetrode/

Big Issue!

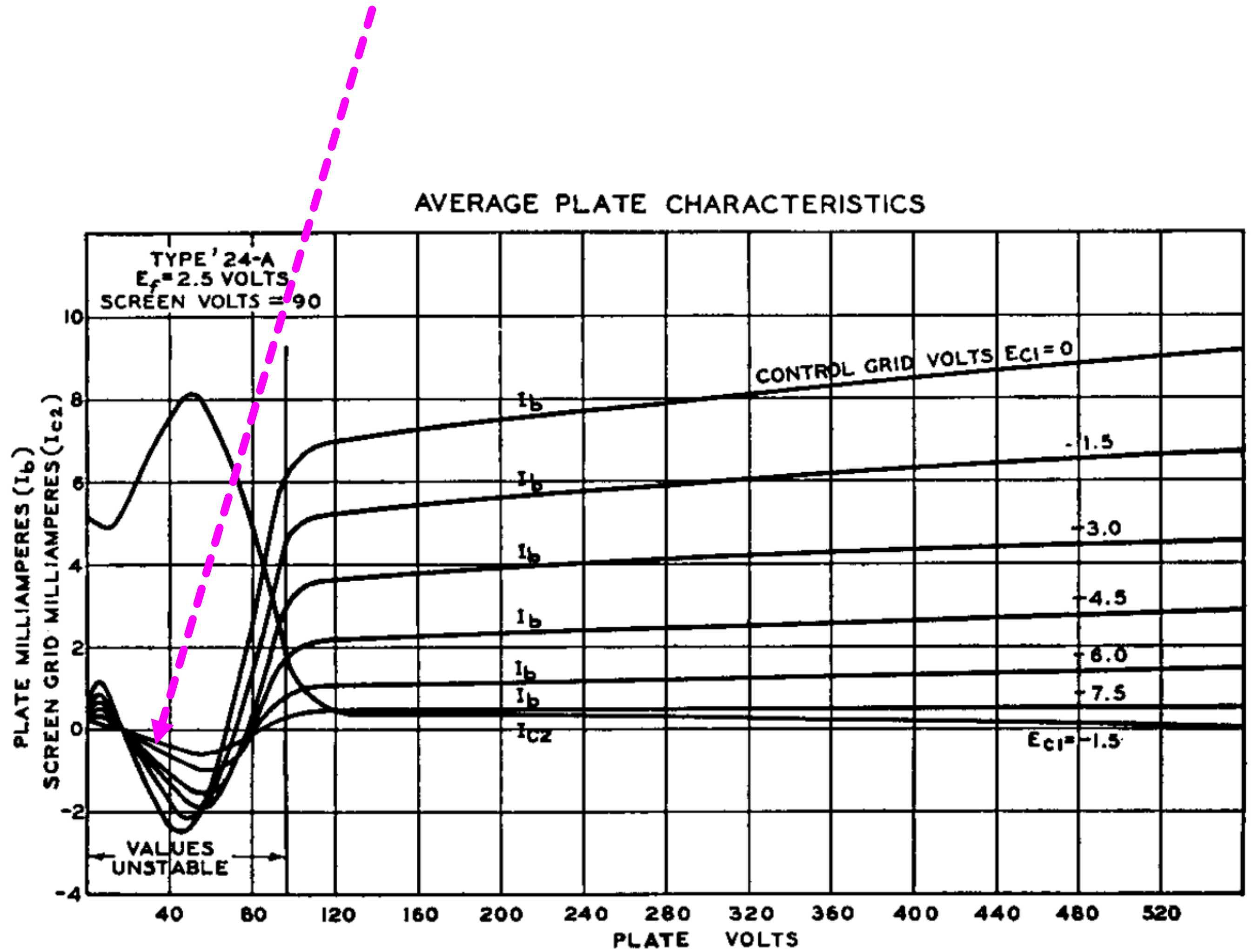
- The presence of the screen grid had some issues… if screen grid potential was higher than that on the plate (which would happen during down swings, secondary emission of bouncing electrons on plate would happen:
  - In this situation you could have regions where the plate characteristics had a trend like:
    - Voltage go higher…current go lower… uh oh…



https://www.physics-and-radio-electronics.com/electronic-devices-and-circuits/vacuum-tubes/vacuumtetrode.html

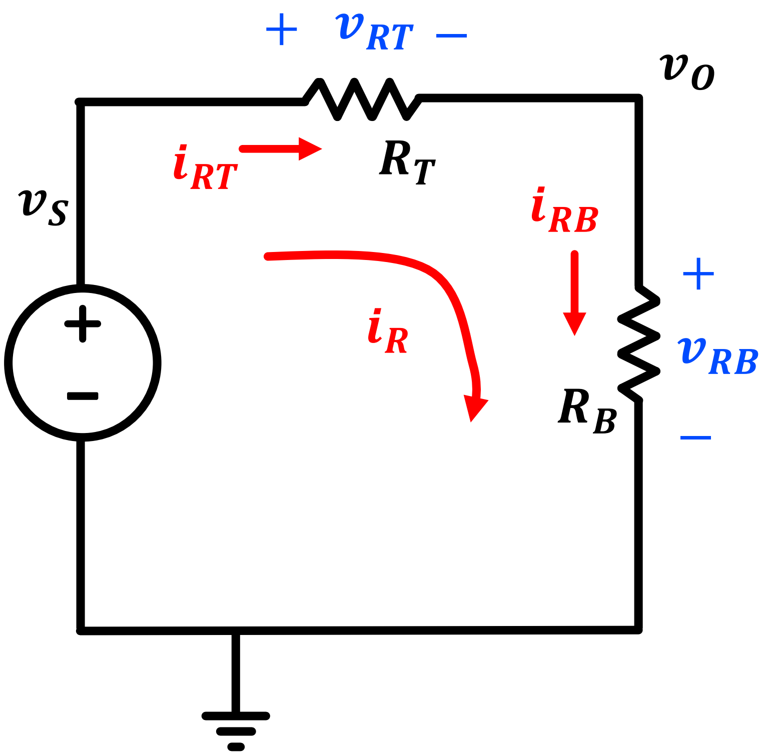
Big Issue!

- Oh god…is that…is that *negative* resistance?
- It is.
- Not good.

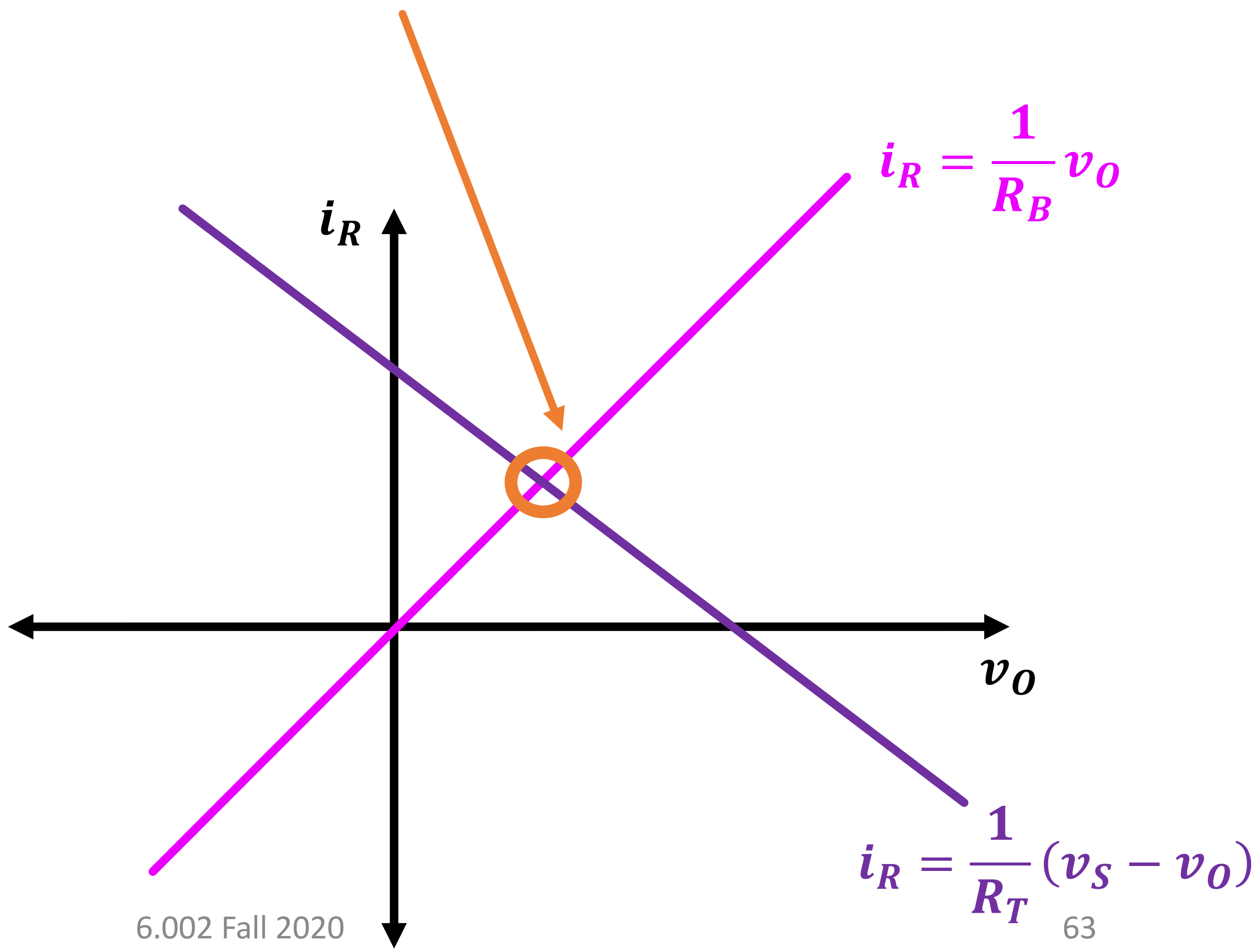


https://www.physics-and-radio-electronics.com/electronic-devices-and-circuits/vacuum-tubes/vacuumtetrode.html

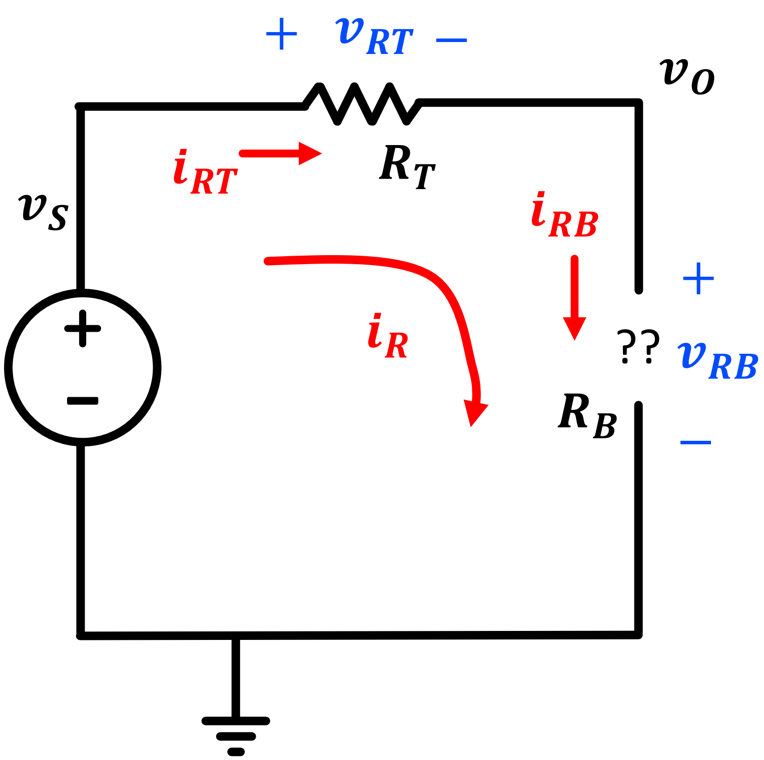
Remember the Load Line!



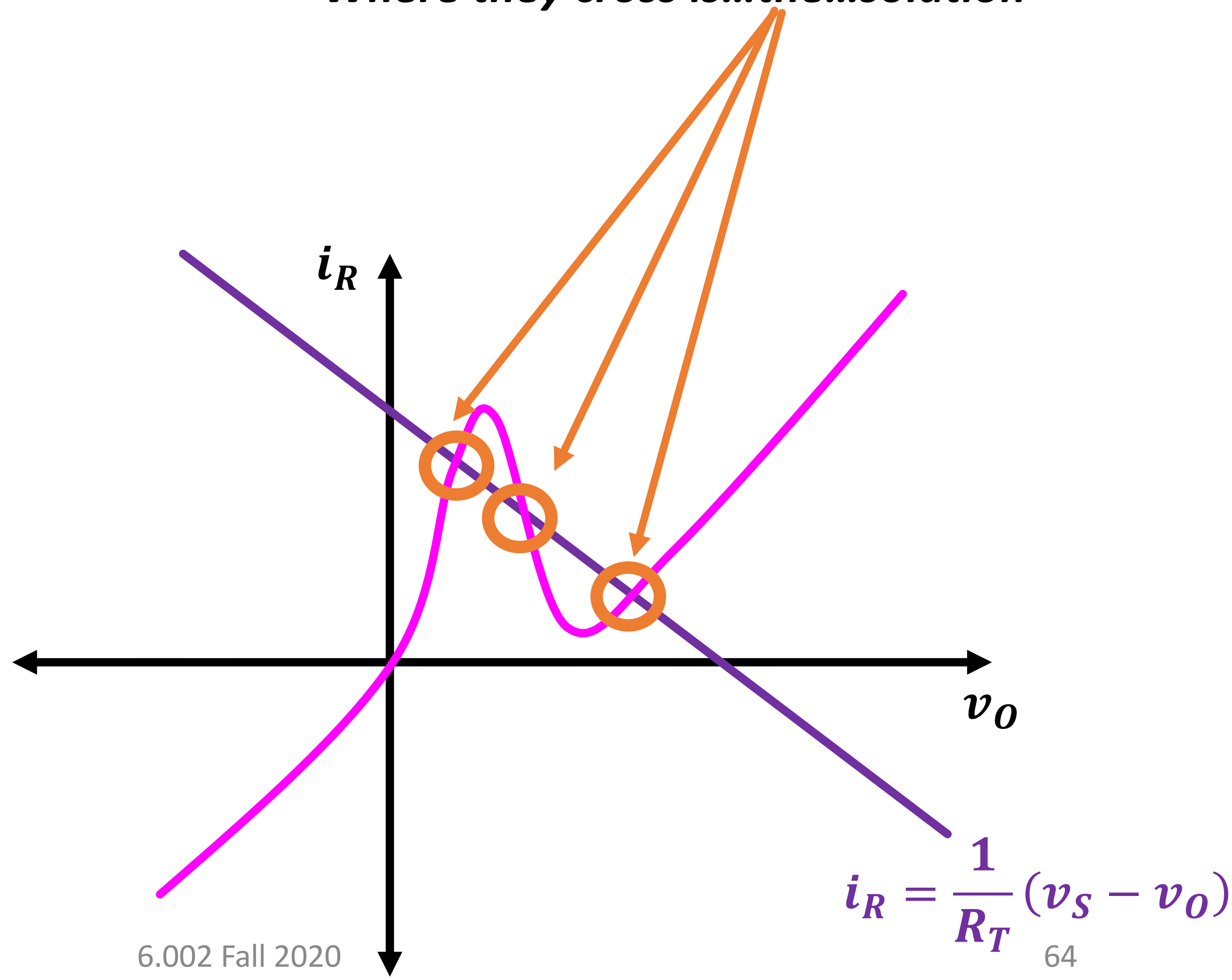
Where they cross is the solution!



What if….

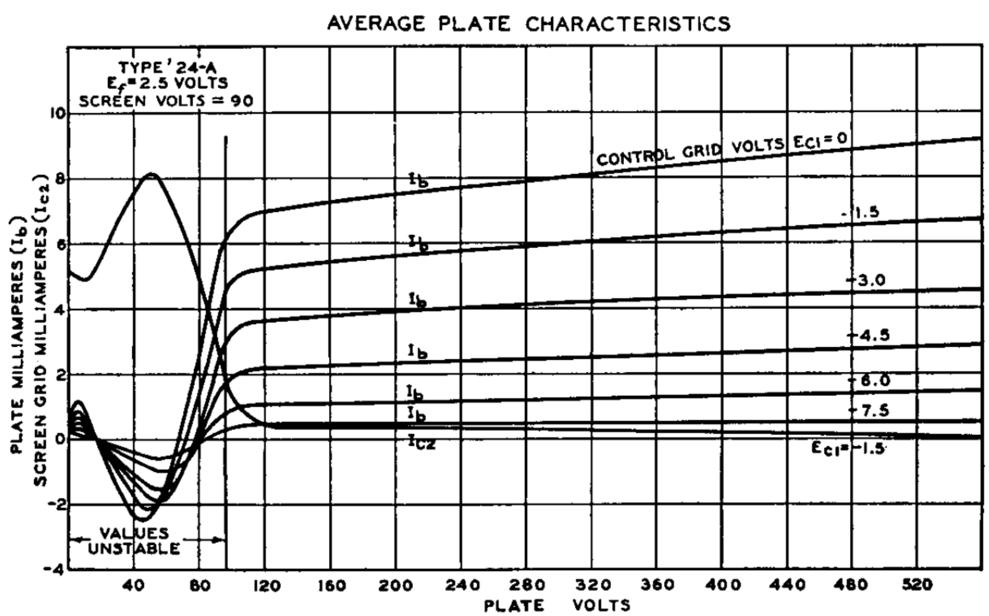


Where they cross is…the…solution



Tetrodes

- Screen Grid Tetrodes were very prone to generating unstable circuit situations…lead to lots of oscillations
- Required very careful design…and the whole point of this was to avoid having to design carefully
- Screen Grid Tetrodes weren't long for this world.



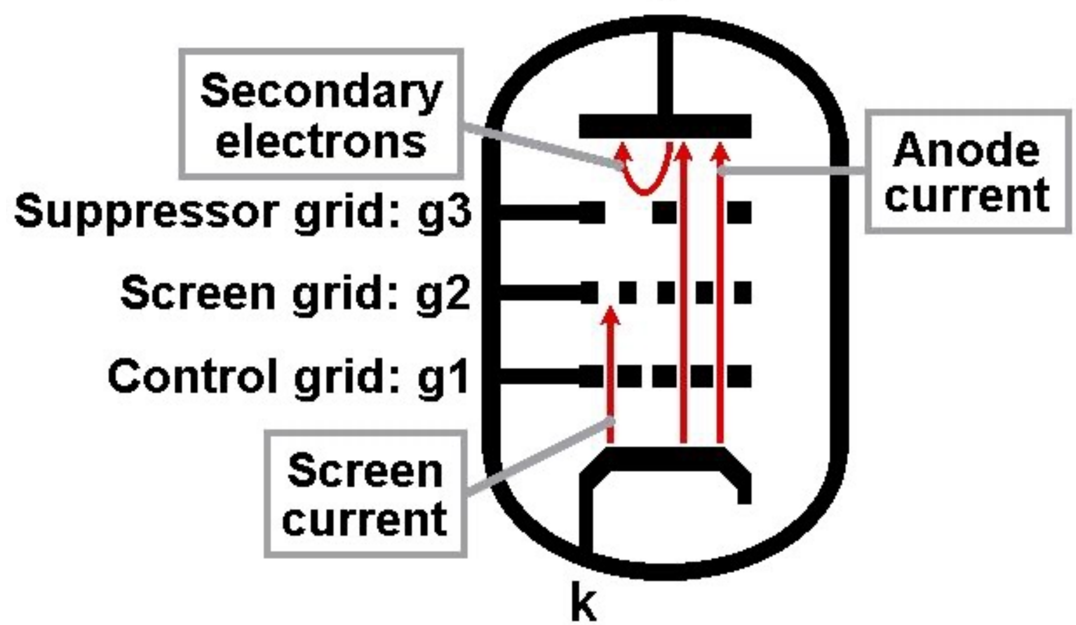
Solution…Add *Another* Grid

- Adding yet another thing turned out to make the tetrode eventually work

https://www.youtube.com/watch?v=P9yruQM1ggc

The Suppressor Grid

- Screen will still have some current, but putting a grid at low voltage between it and the plate will make any electrons think twice before bouncing off plate and going back to the screen.
- Invented by:
  - Holst and Tellegen
  - Late 1920s

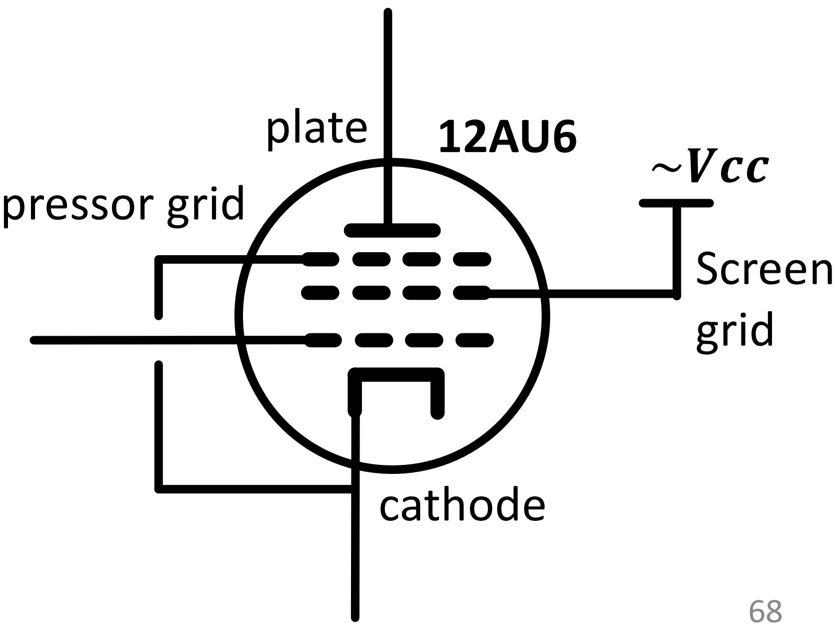


https://www.valvewizard.co.uk/pentode.html

The Pentode Was Born

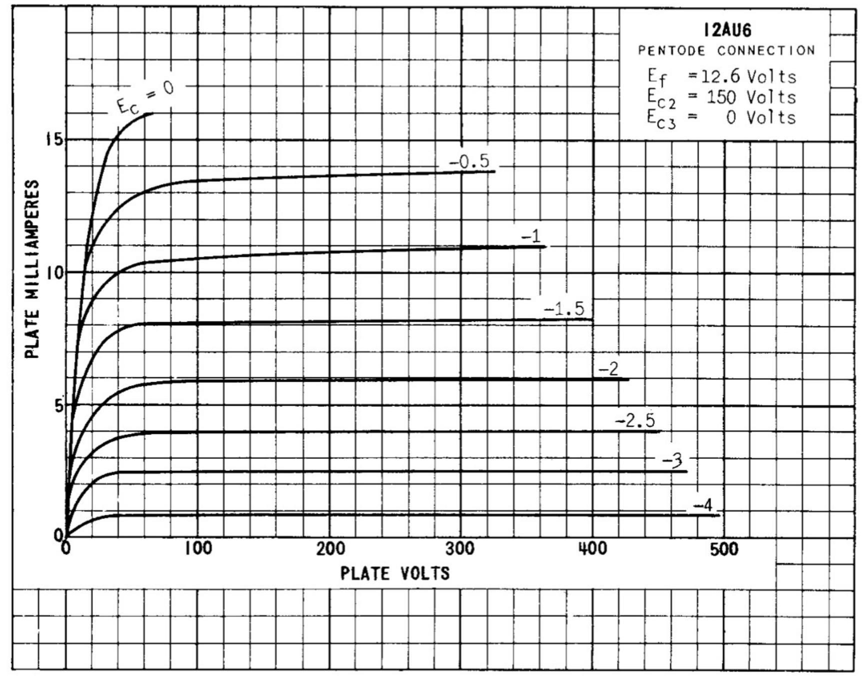
- Five electrodes
- Pent-ode
- Almost always tied suppressor to cathode

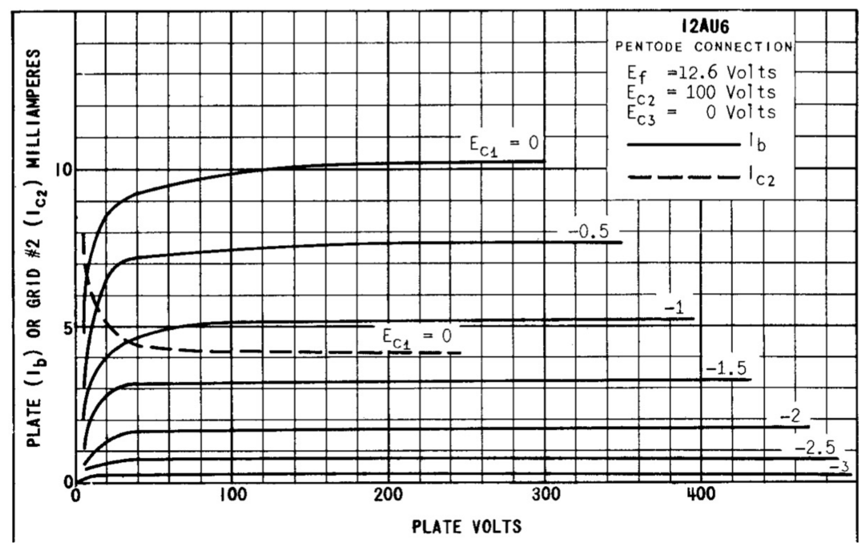
- Net result was…



Pentode Curves

- Resulting curves were very different than triodes, but were much more stable out to high frequencies.
- These curves essentially look like what we know and love about modern-day transistors.
- In some sense, pentodes were the first modern amplifier





Downsides of Pentodes

- More Noise (so not necessarily good for things like detection/demodulation)
- Higher Output impedance (very flat in plate current for varying plate voltage)…though this is also a benefit in some situations

Next Time

- Look a bit at Pentodes and other flavors
- Look at Oscillators
- Look at Mixers
- Look at Early Digital Logic