Lecture 5

Tube and Early Transistor Electronics

Other Uses

- So last week we saw vacuum tubes amplifying things.
- In Lab 4 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.

Except it isn't truly a dead tech…there is one area of our lives with tubes…

- We've come to rely on it.
- It is in almost all homes
- And in almost all dorms
- It nourishes us

On Last Friday Night...

- Had a power outage...
- Microwave was throwing a **PF** error code when we woke up.
- I thought I needed to change the fuse (this was wrong just needed to hold down cancel for ten seconds, but whatever)
- So had to pull the entire microwave down since I also discovered the fan inside it was mounted the wrong way by previous owners...ugh.

Inside…

Magnetron
A simple sort of vacuum tube

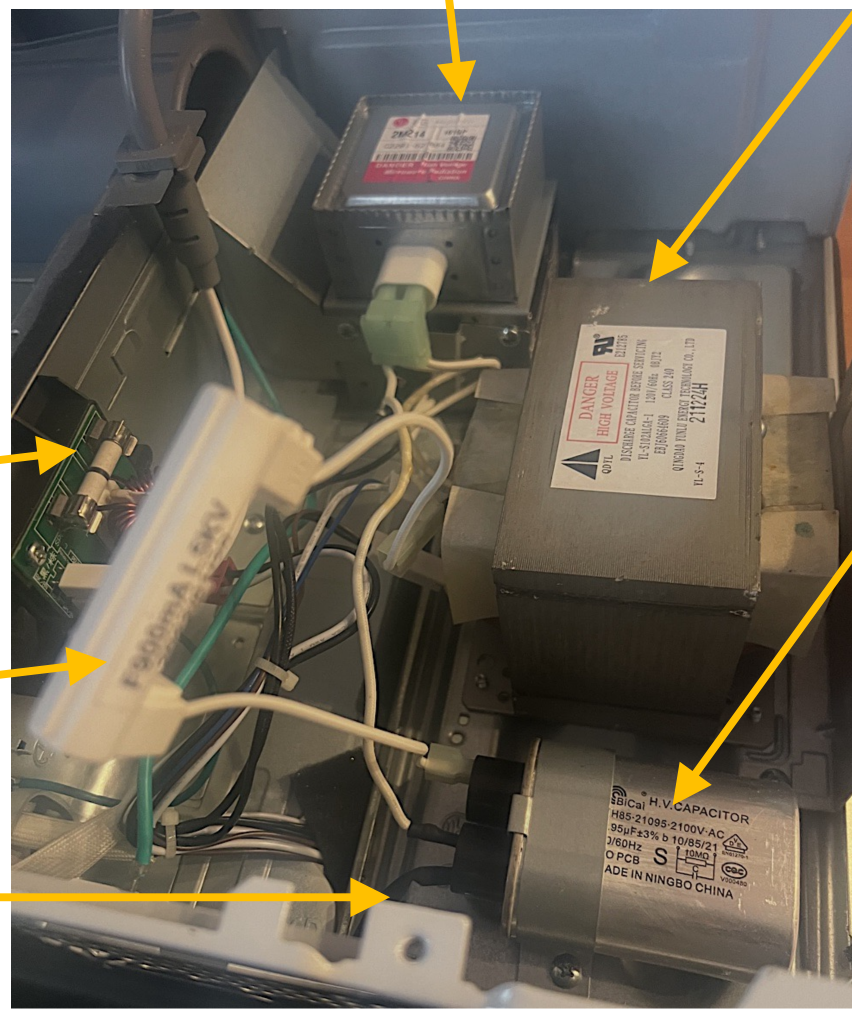
HV step up transformer

HV Capacitor

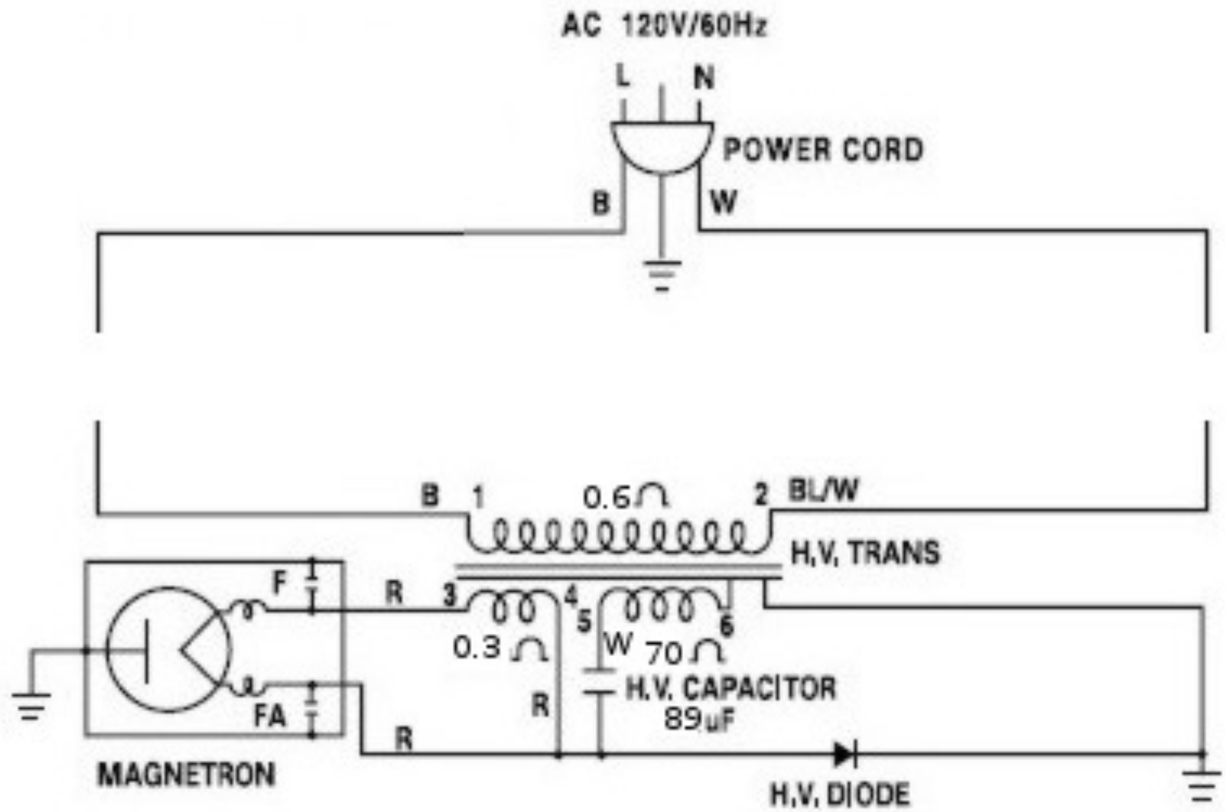
LV Fuse

HV Fuse

Diode (hidden)

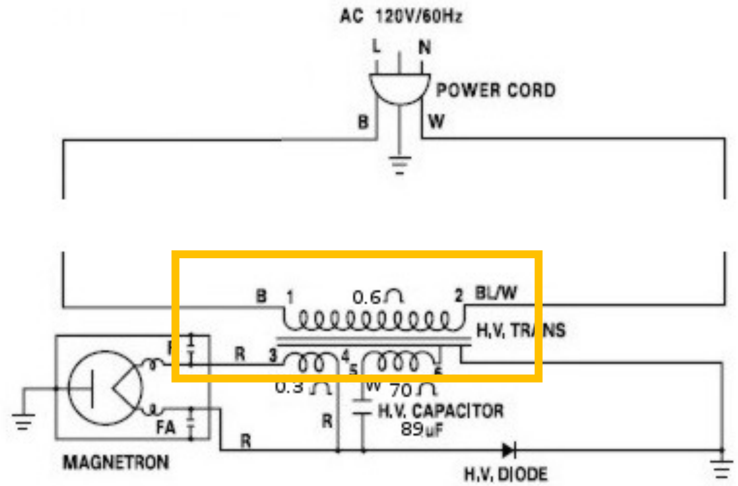


Basic Microwave Schematic

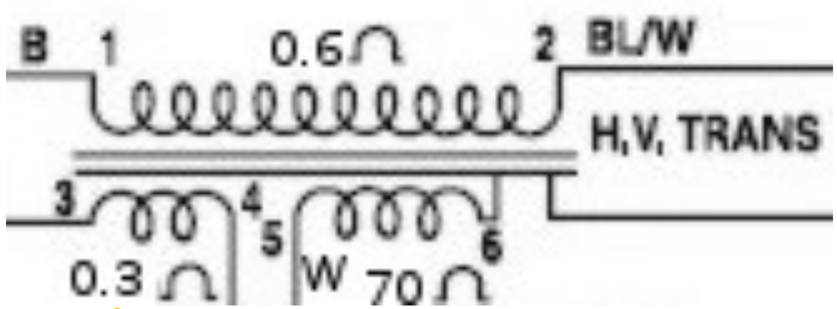


https://somanyhobbies.wordpress.com/2013/03/09/microwave-repair/

Transformer



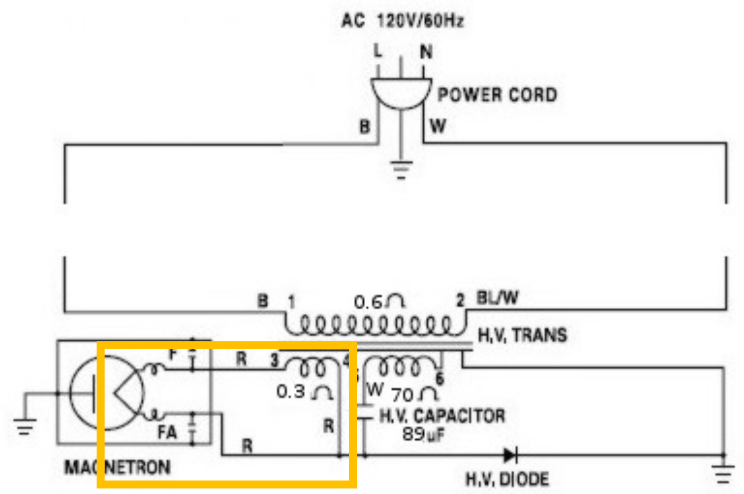
120V$_{rms}$ Input



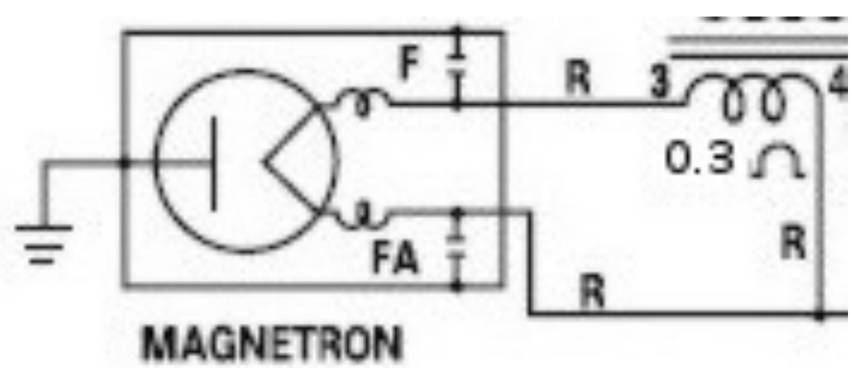
3.2V$_{rms}$ for filament

~1kV$_{rms}$ for Plate-to-Cathode voltage

Filament Heating

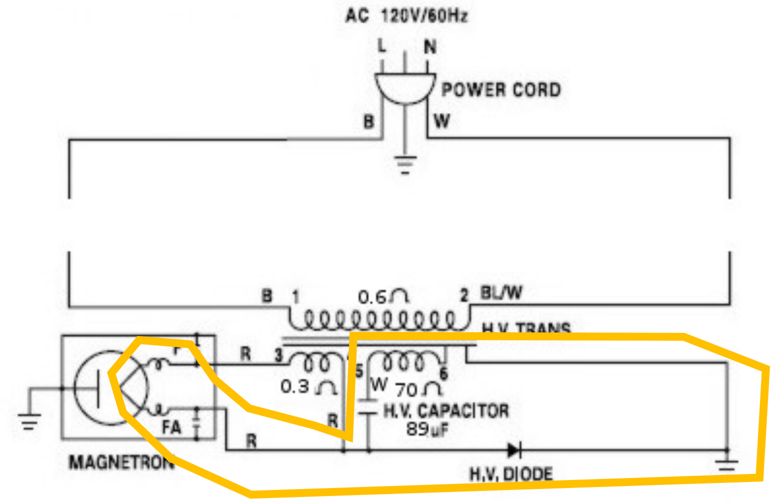


- Directly Heated Cathode
- No separate cathode...electrons are emitted directly off the heater



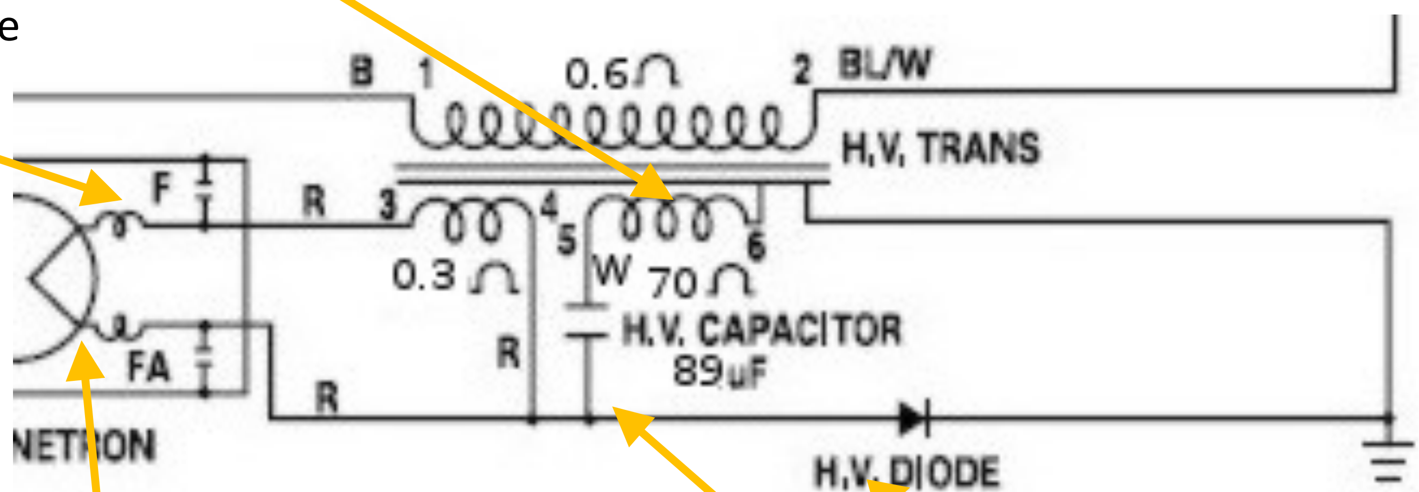
https://somanyhobbies.wordpress.com/2013/03/09/microwave-repair/

Massive Voltage



Transformer steps up to high voltage

Very Large Negative Voltage +3.2V builds up here



Very Large Negative Voltage builds up here

Capacitor/Diode form a simple voltage doubler

Magnetron

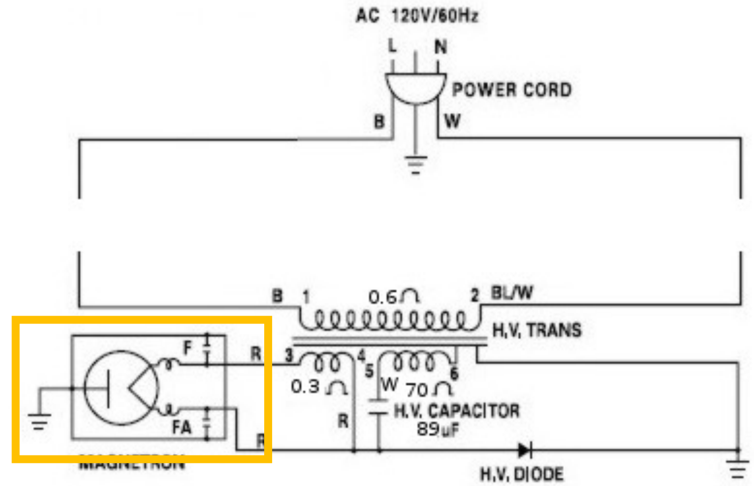
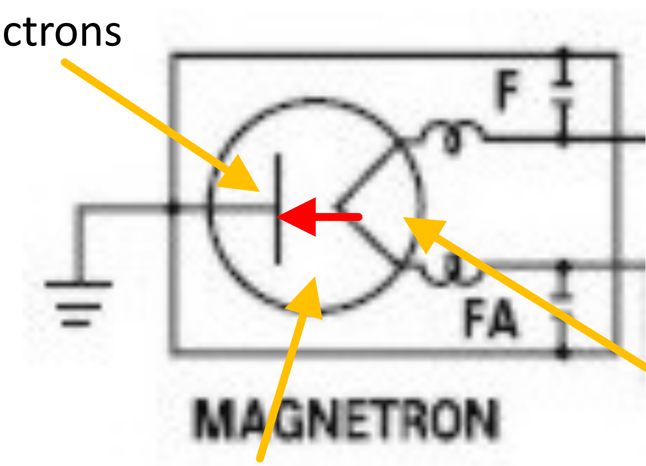


Plate is very "positive" relative to origin of electrons

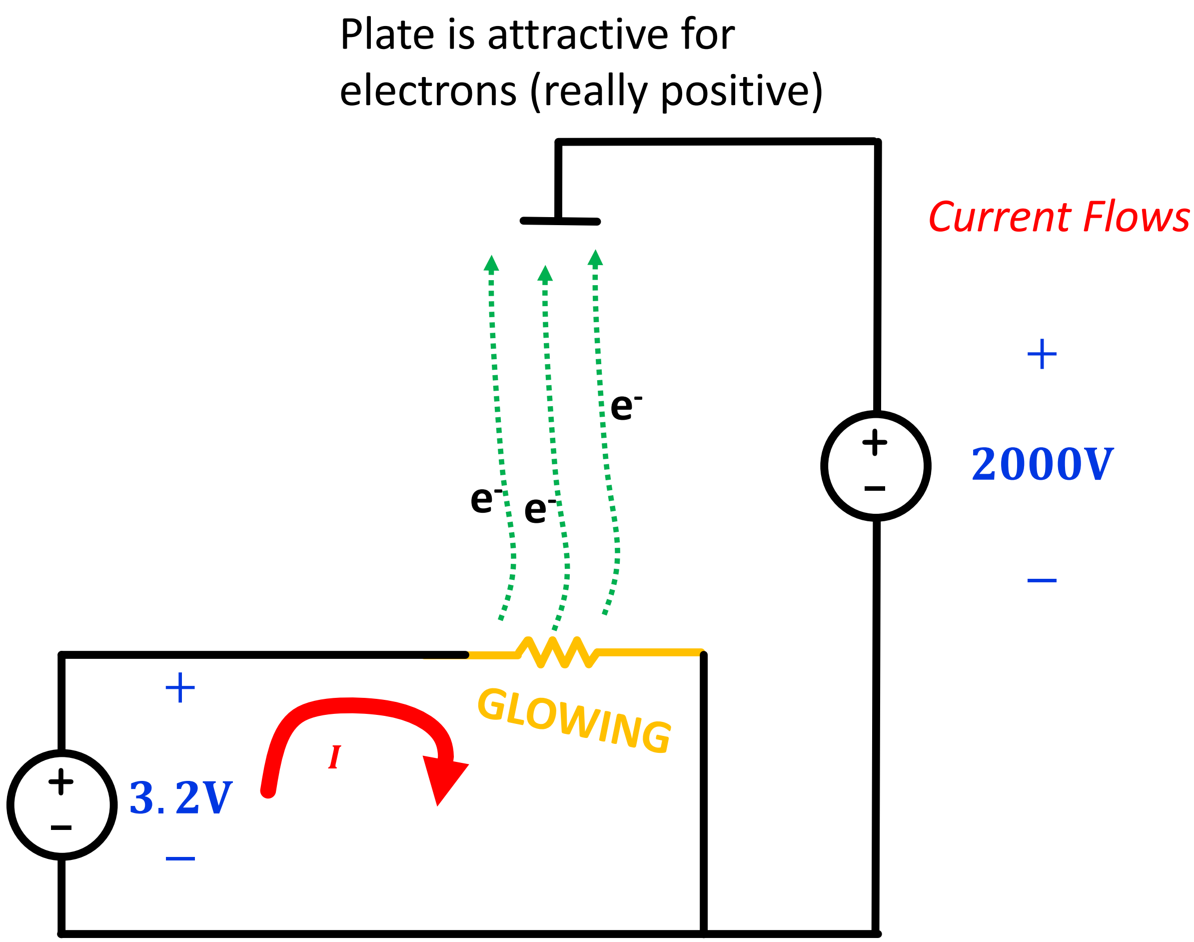


Cathode is extremely negative relative to cathode...electrons flee it

Flow of electrons

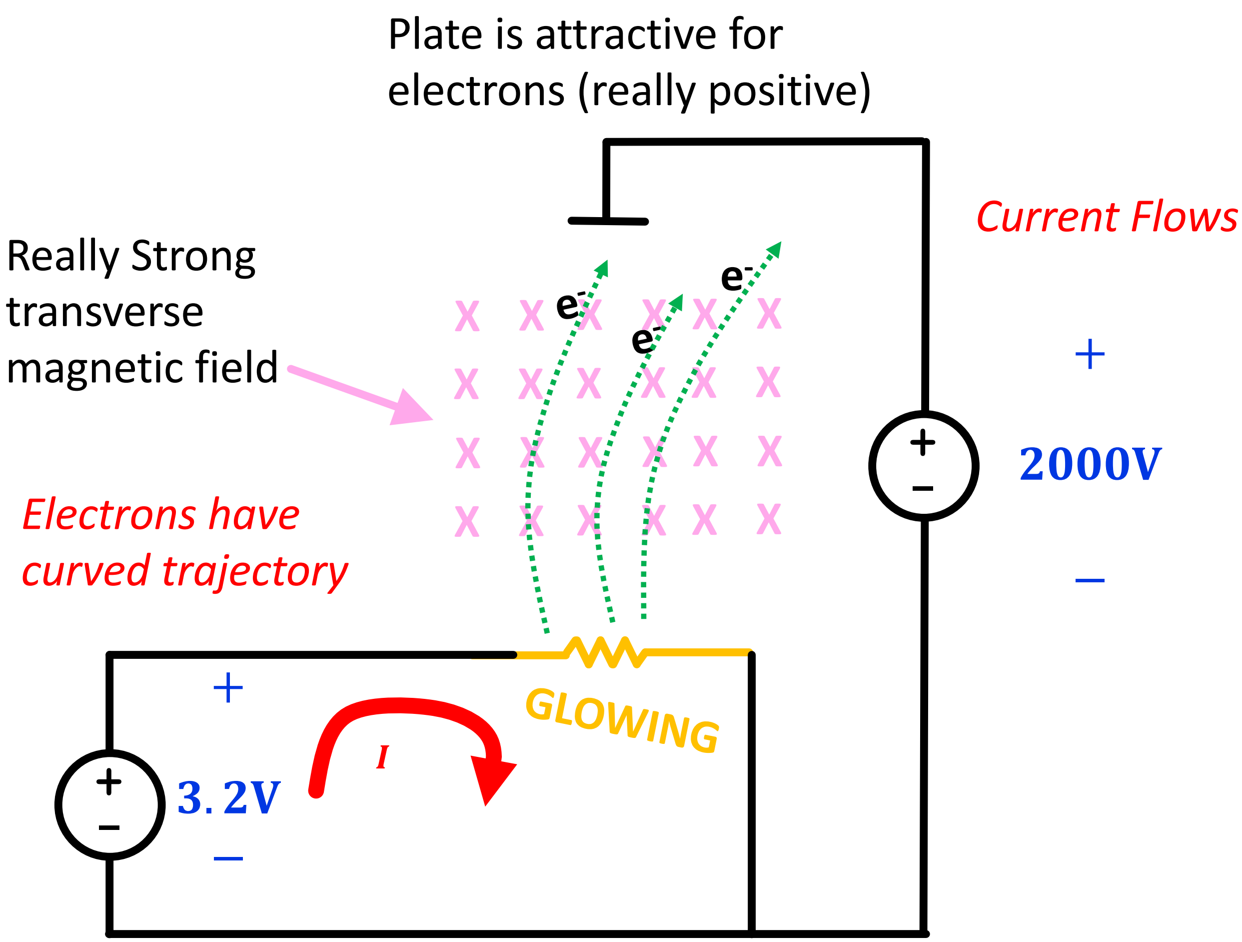
The Vacuum Tube Diode

- This is our regular tube diode...
- Same thing as a microwave magnetron
- But there's more...



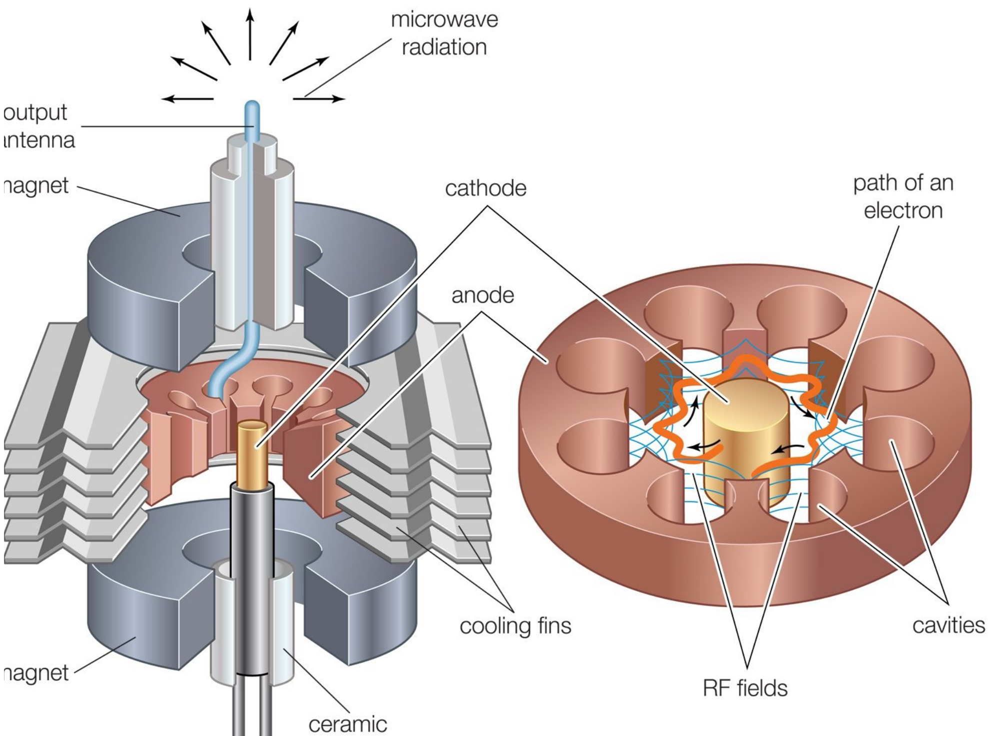
Now Add a magnetic Field

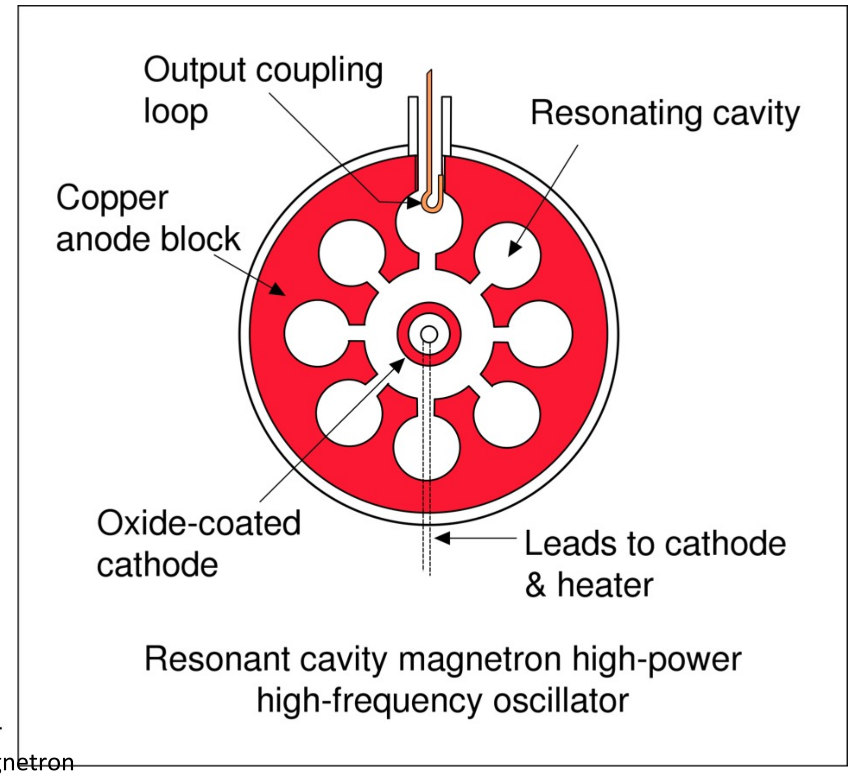
- Expose the electrodes to a strong magnetic field during their travel.
- What happens?



https://phys.libretexts.org/Bookshelves/University_Physics/Physics_(Boundless)/21%3A_Magnetism/21.4%3A_Motion_of_a_Charged_Particle_in_a_Magnetic_Field

Cylindrical Symmetry in Diode design



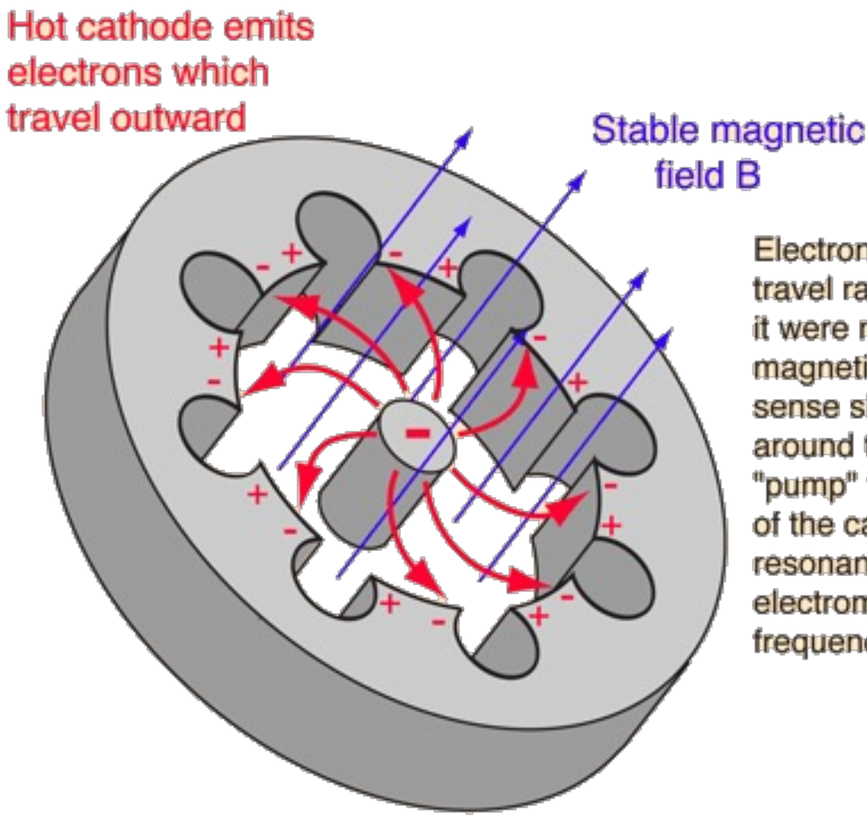


Resonant cavity magnetron high-power high-frequency oscillator

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

https://www.britannica.com/technology/magnetron

Electrons give radial

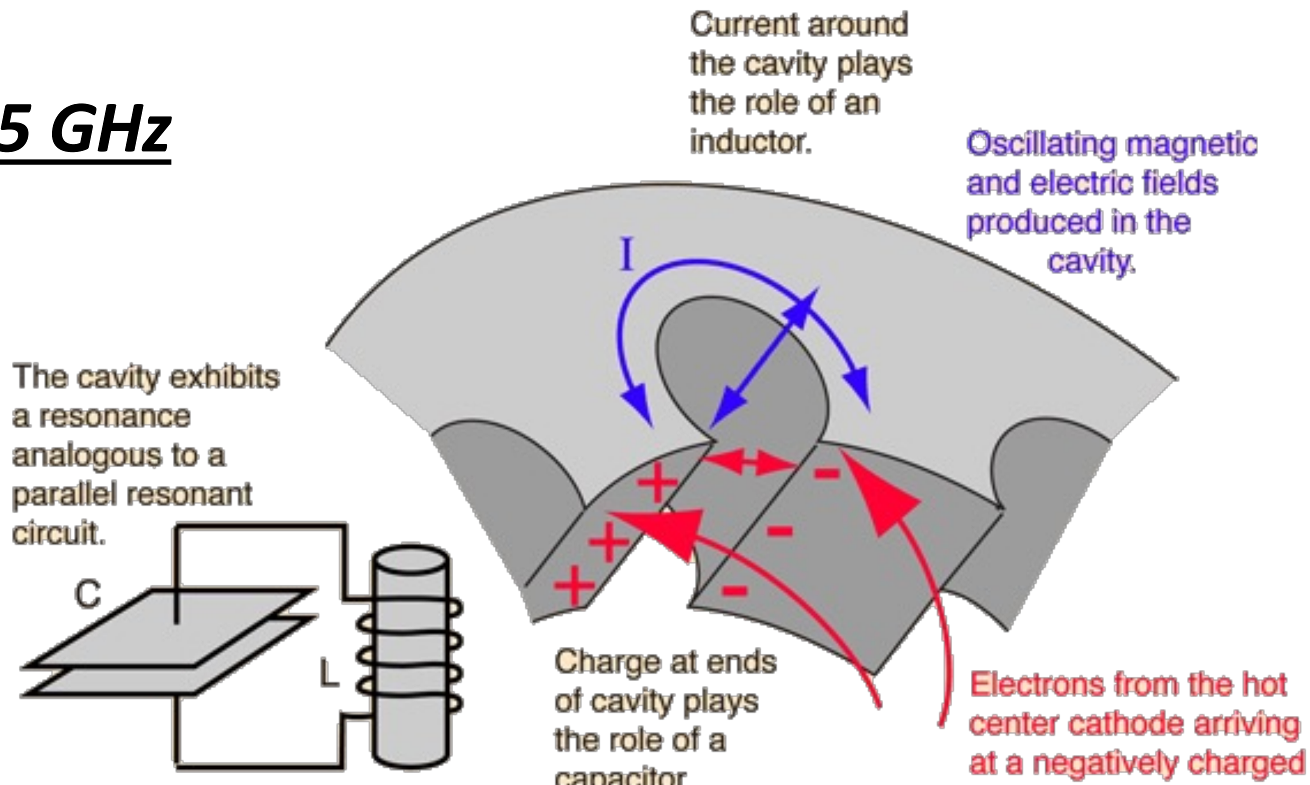


Electrons from a hot filament would travel radially to the outside ring if it were not for the magnetic field. The magnetic force deflects them in the sense shown and they tend to sweep around the circle. In so doing, they "pump" the natural resonant frequency of the cavities. The currents around the resonant cavities cause them to radiate electromagnetic energy at that resonant frequency.

http://hyperphysics.phy-astr.gsu.edu/hbase/Waves/magnetron.html

The weird shape forms resonant cavities

- ***Around 2.45 GHz***

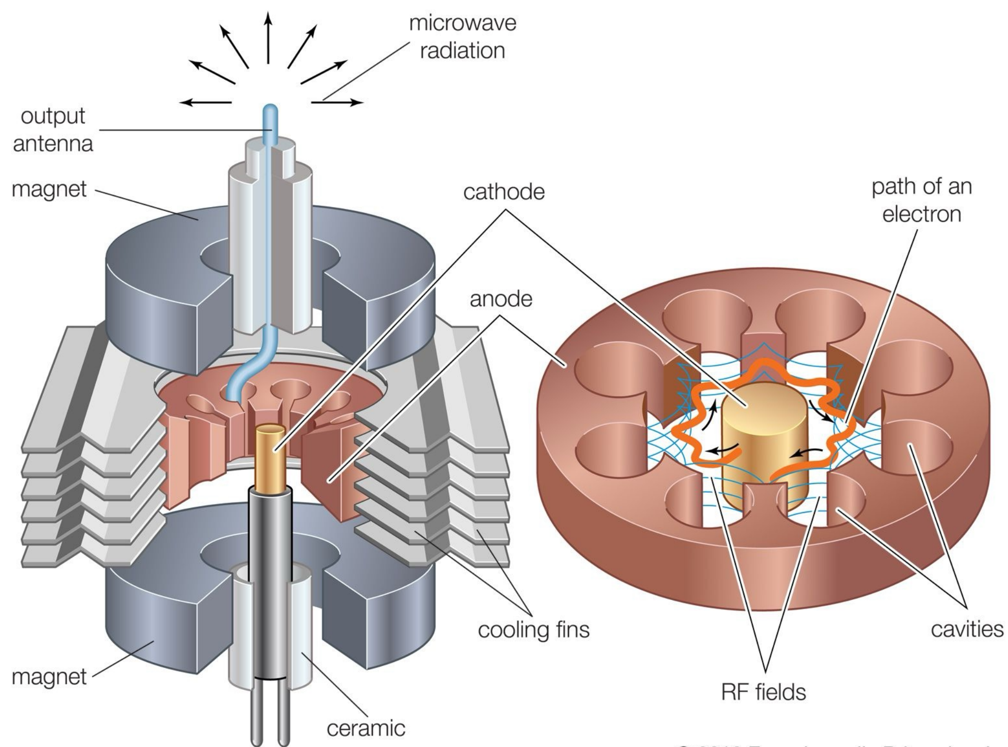


$$f_{resonance} \approx \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

http://hyperphysics.phy-astr.gsu.edu/hbase/Waves/magnetron.html

Attach antenna to one spot on the anode/plate

- Channel the oscillation and you can get very high power emission of about 2.45 GHz!!!
-



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

So what?

- Cavity Magnetrons were originally designed for Radar usage during WW2...emit microwaves at high power
- It also happens that many molecules that are polarized (fats, proteins, water, etc...) respond to electromagnetic fields by rotating
- In the process of spinning, the molecules will generate heat (called dielectric heating)
- This is great for heating up food!
- So Microwave Ovens were born!
- Even in 2025 we still use vacuum tubes for this purpose?

Why Still Vacuum Tubes?

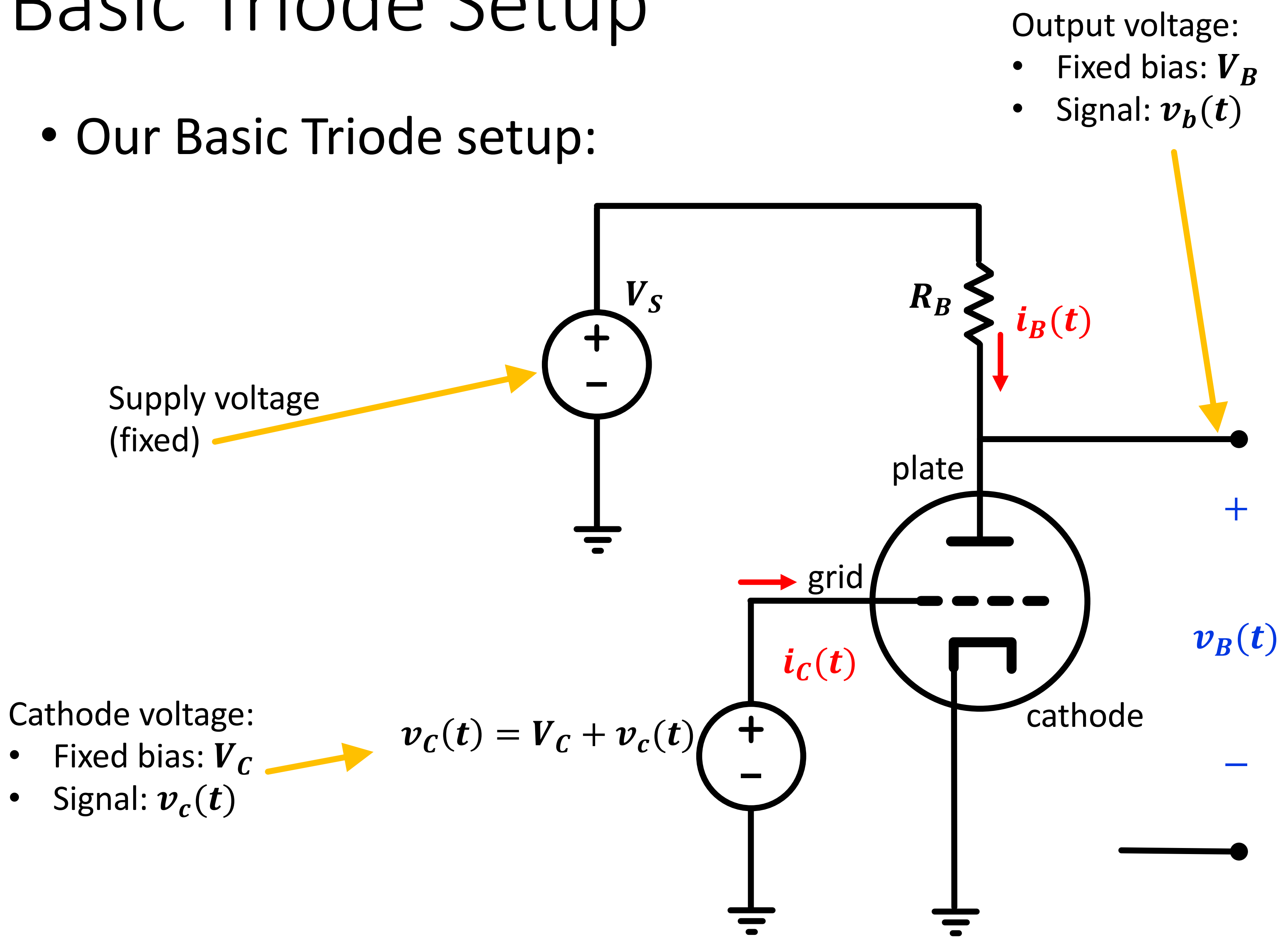
- You can build a pure solid-state transistor-only microwave oven...but there's no point though from a cost-perspective.
- We don't need:
  - Pure RF signal
  - High frequency stability
- A Cavity magnetron is good at just making kinda poor quality microwave radiation into a variety of different load impedances...
- One of the few spots where tube tech is better and it simply from a cost-performance perspective.

So kinda cool...

- Now let’s continue on with our tube journey through history...

Basic Triode Setup

- Our Basic Triode setup:



All together

- The two plots are slices across two of the three axes

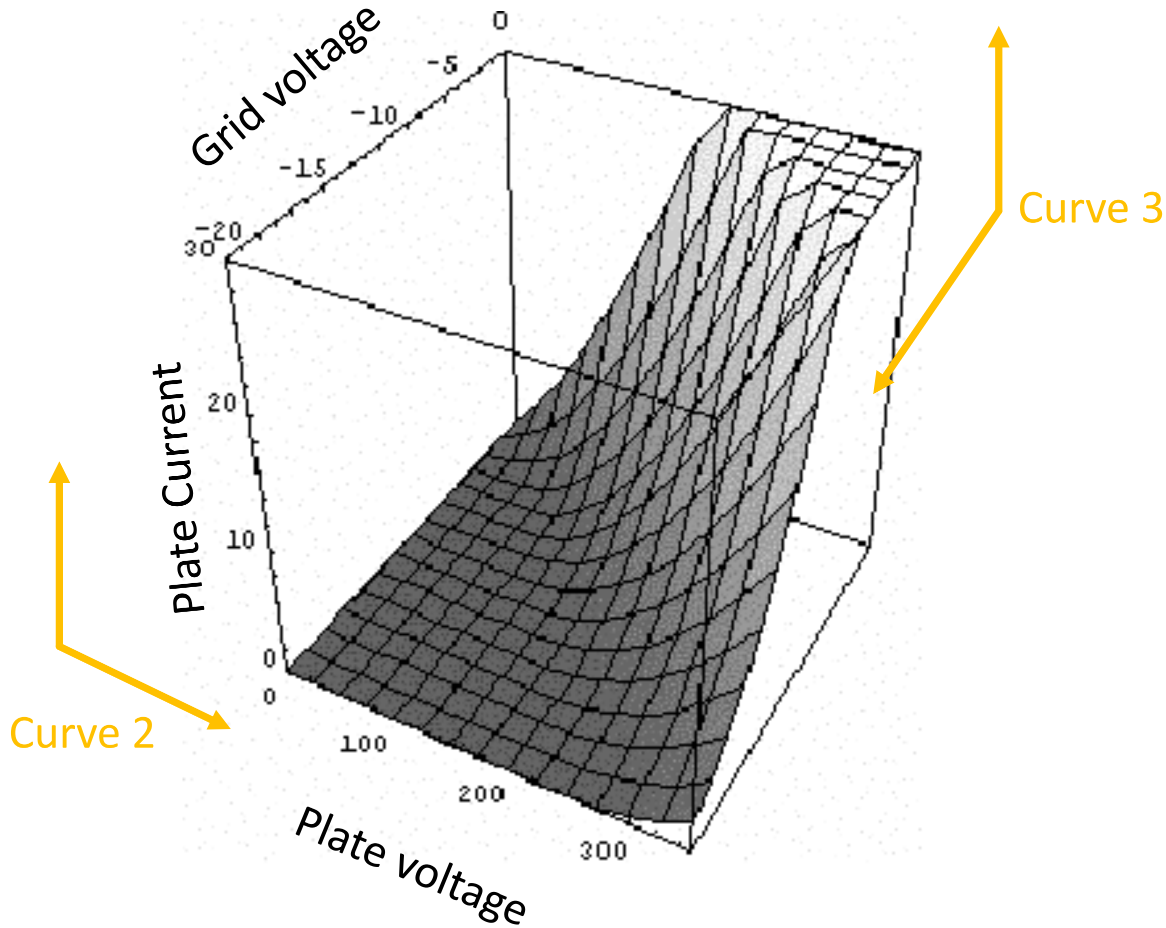
- The general rough pattern is

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

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 $I_B = P\left(V_G + \frac{V_B}{\mu}\right)^{3/2}$ then one could claim that both the grid V_G 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

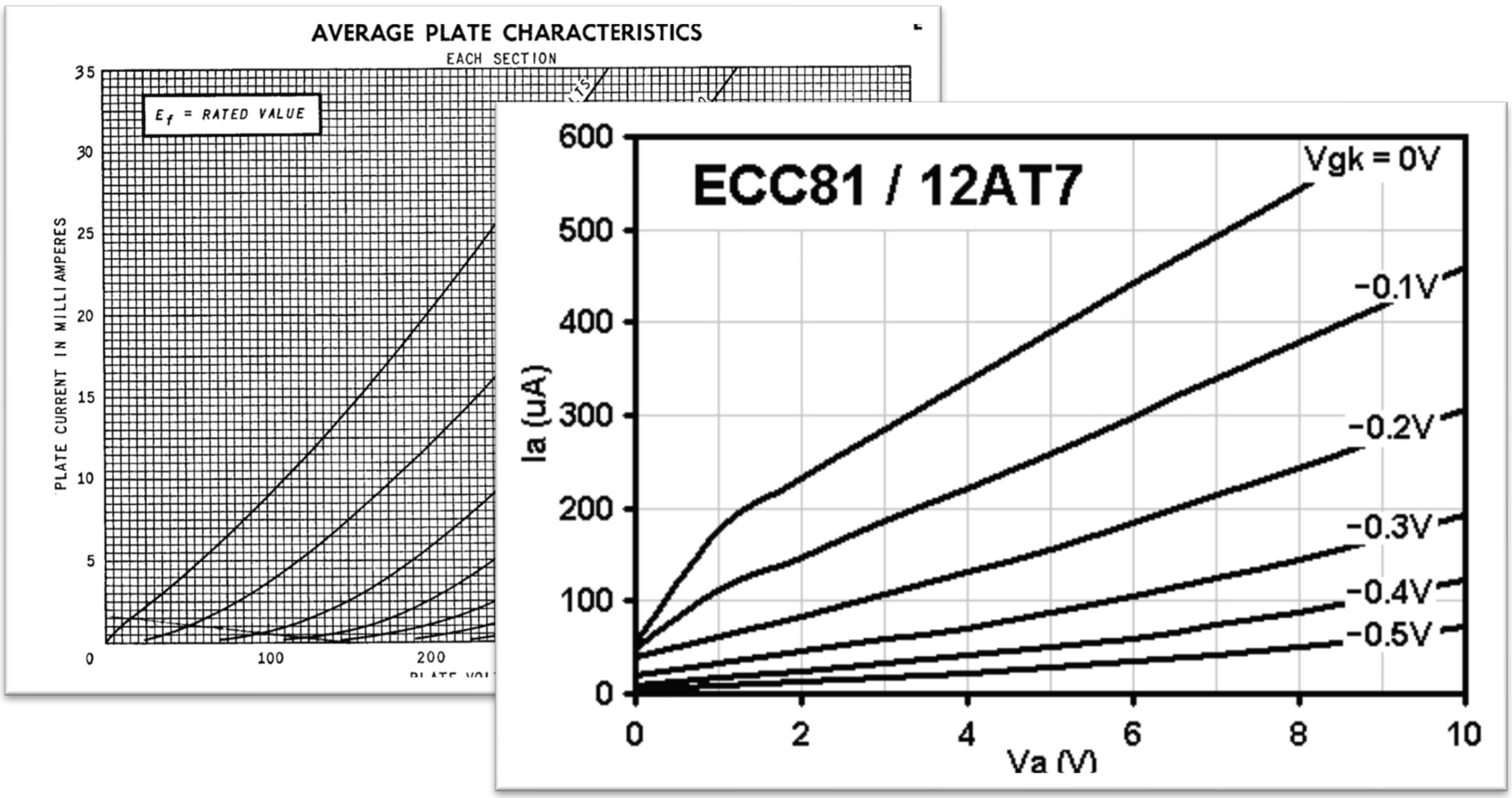
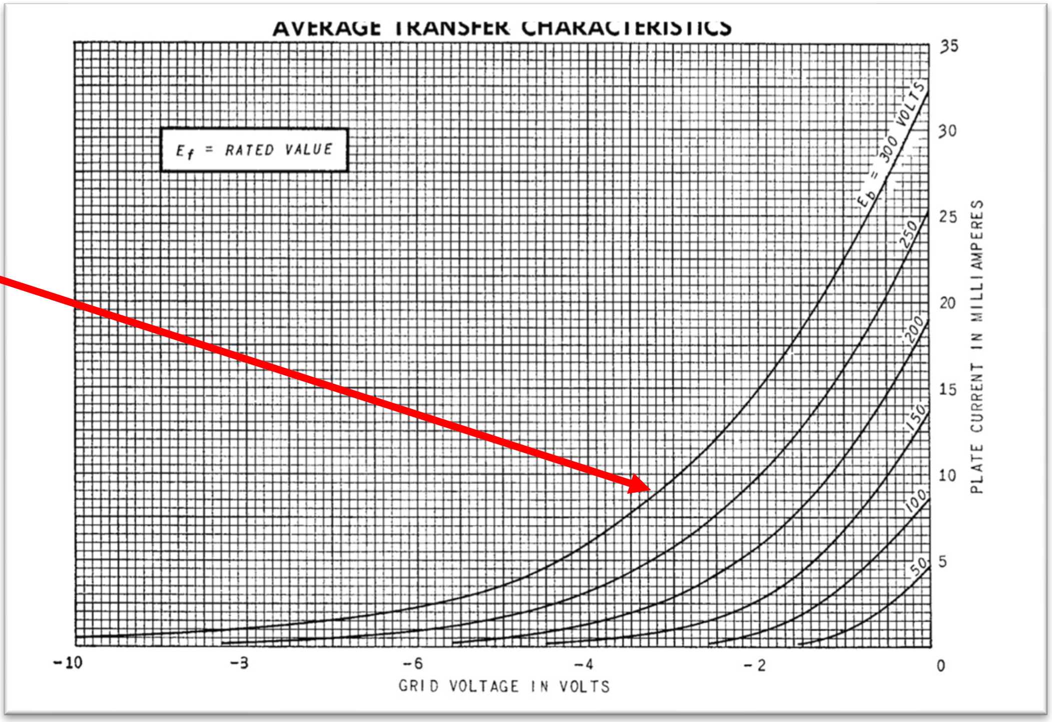


Plate Current as f of Grid Voltage

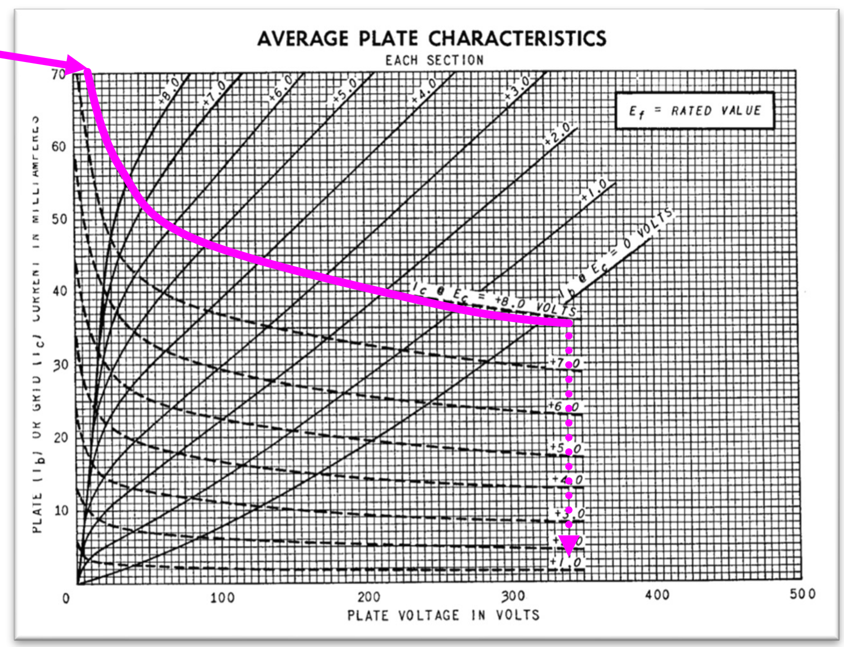
- Plate current as a function of grid voltage for specific plate voltages is also interesting:

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…



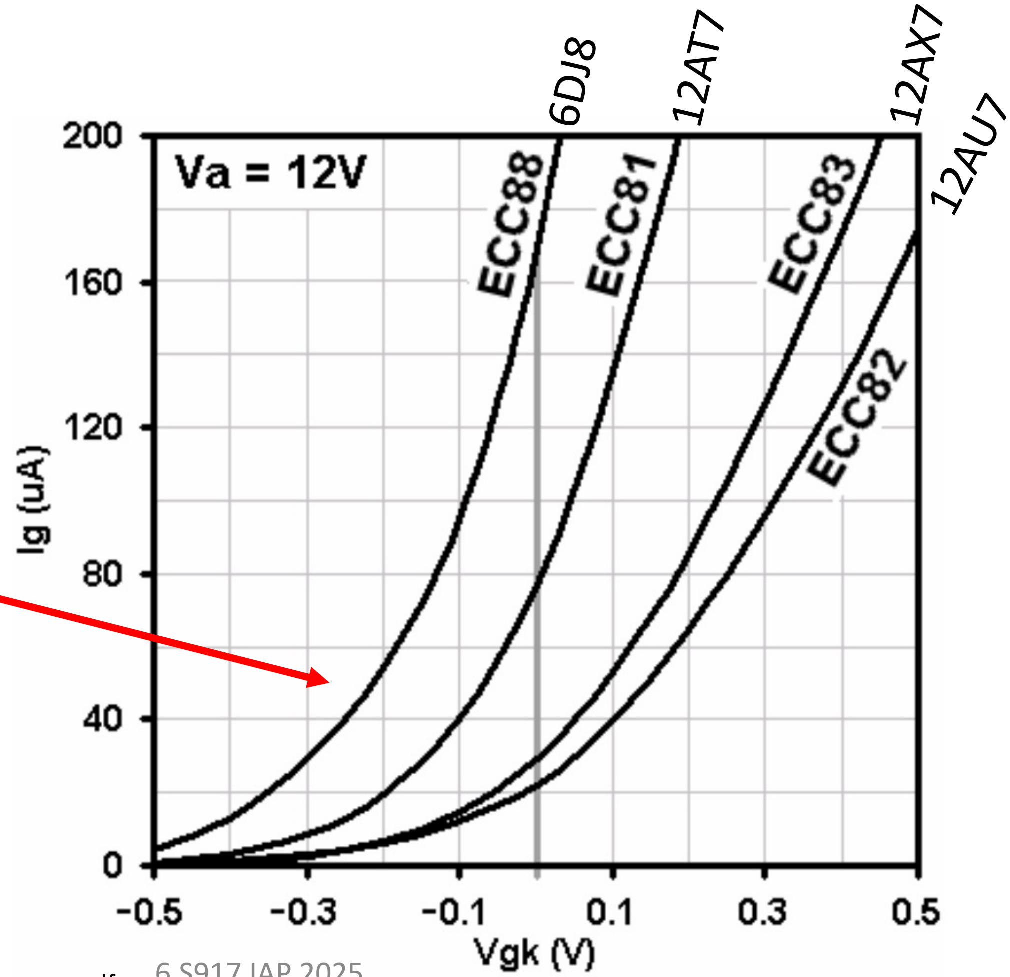
Grid Current as f of Grid Voltage?

- 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?

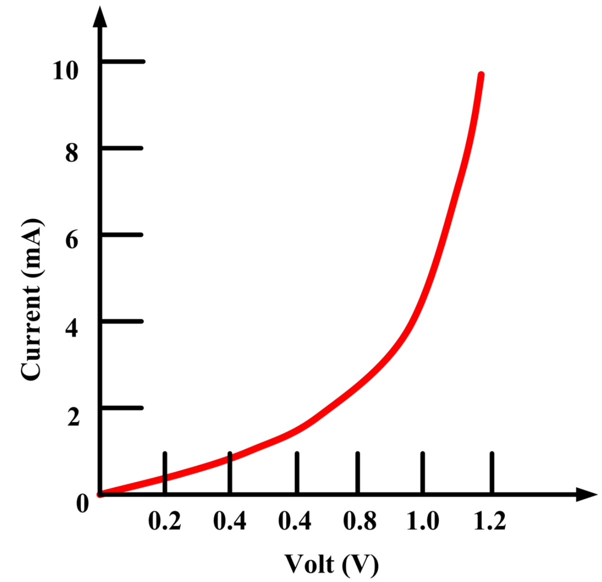
Anything we've seen before?

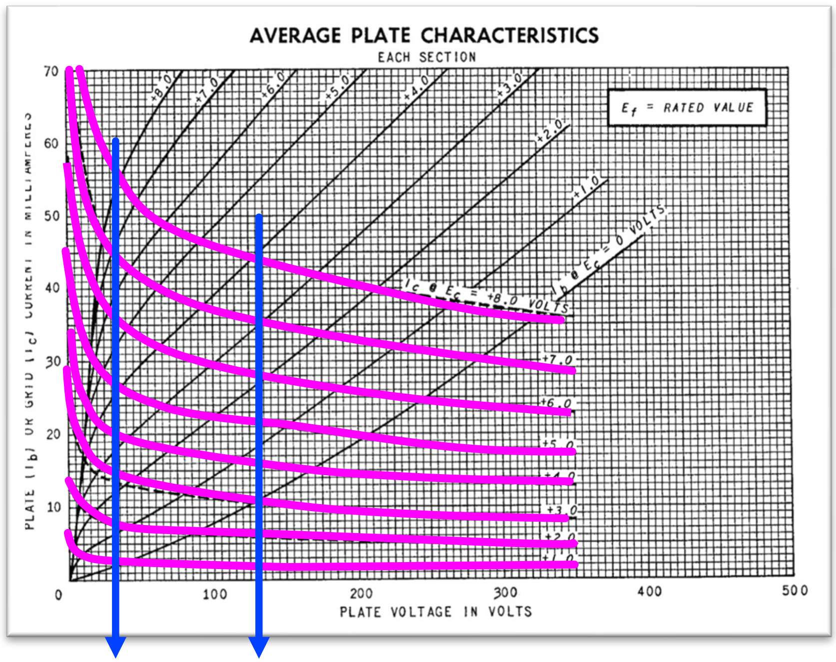


http://www.valvewizard.co.uk/Triodes_at_low_voltages_Blencowe.pdf

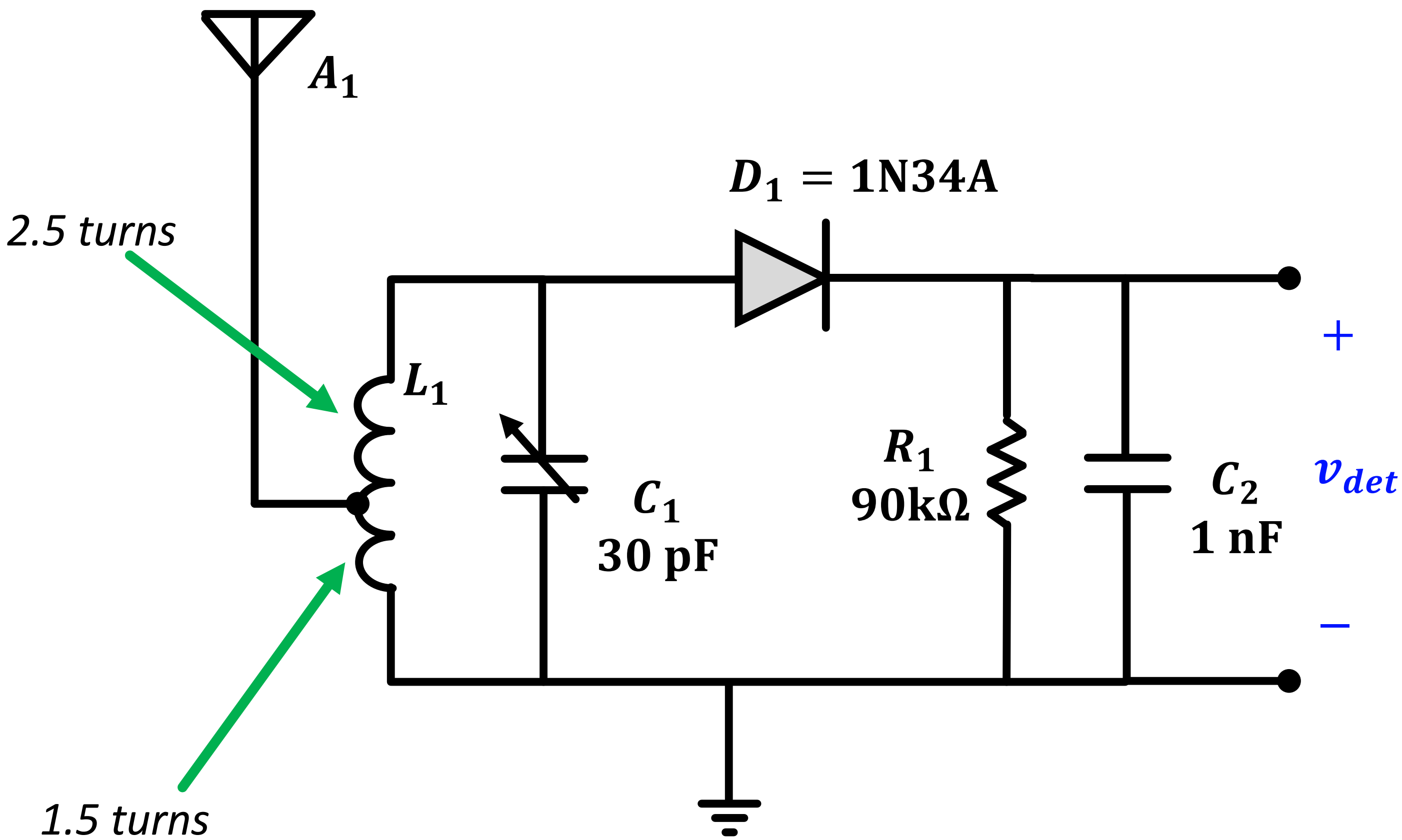
Looks like a Diode!

- 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

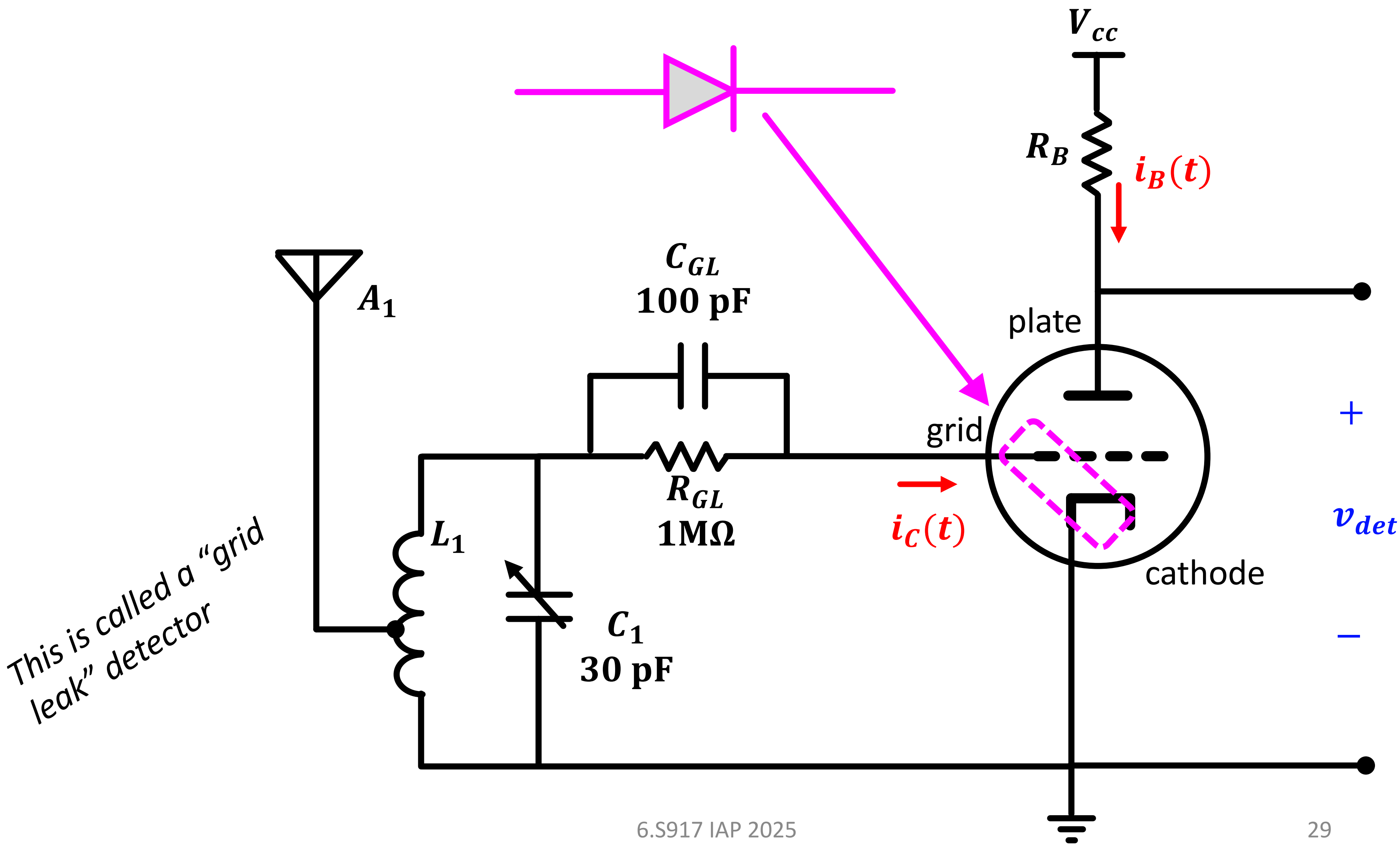




Remember our Crystal Diode Detector

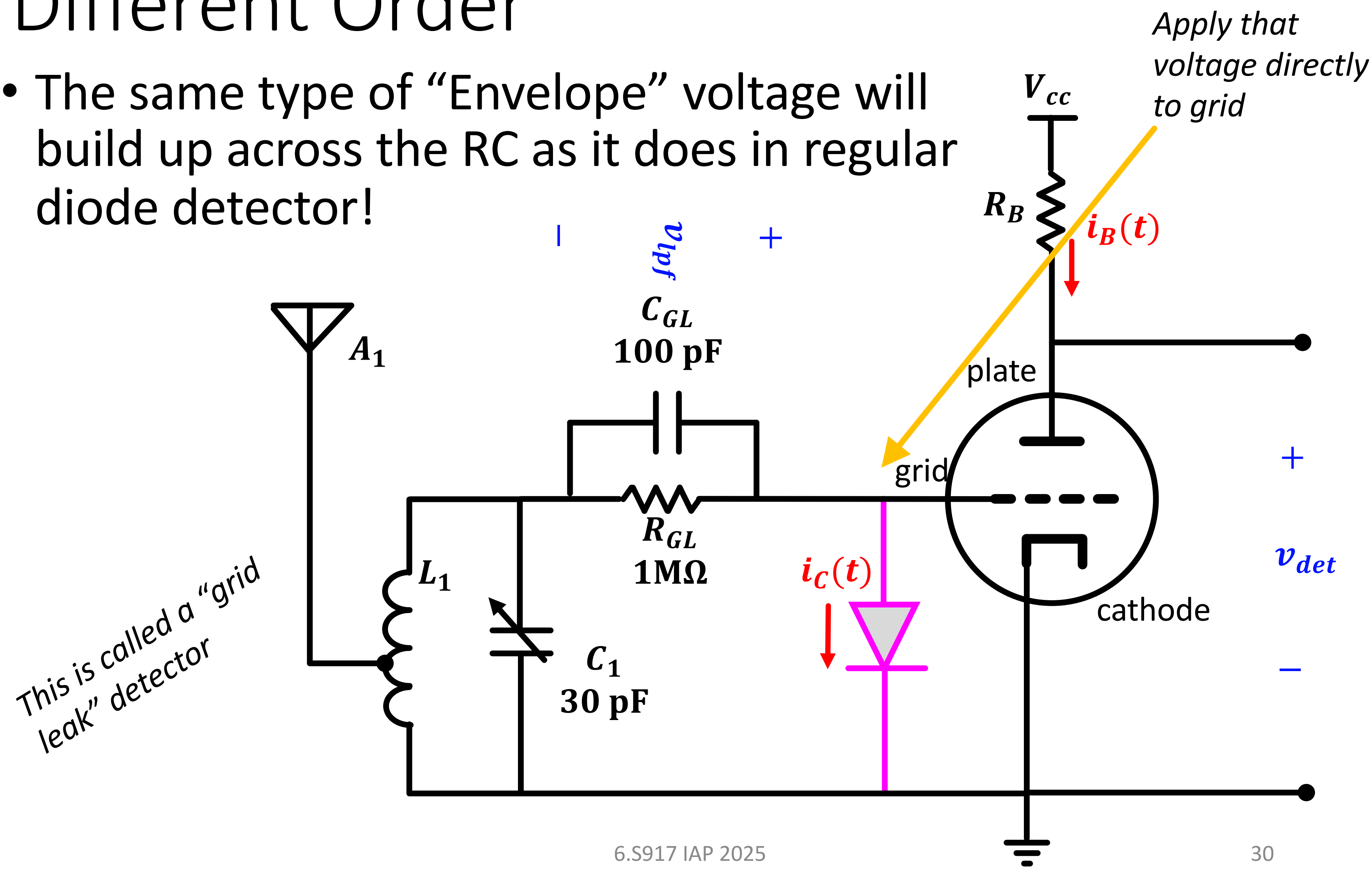


Use the “free” diode that comes with a triode



Same Diode in Series with RC, Just Different Order

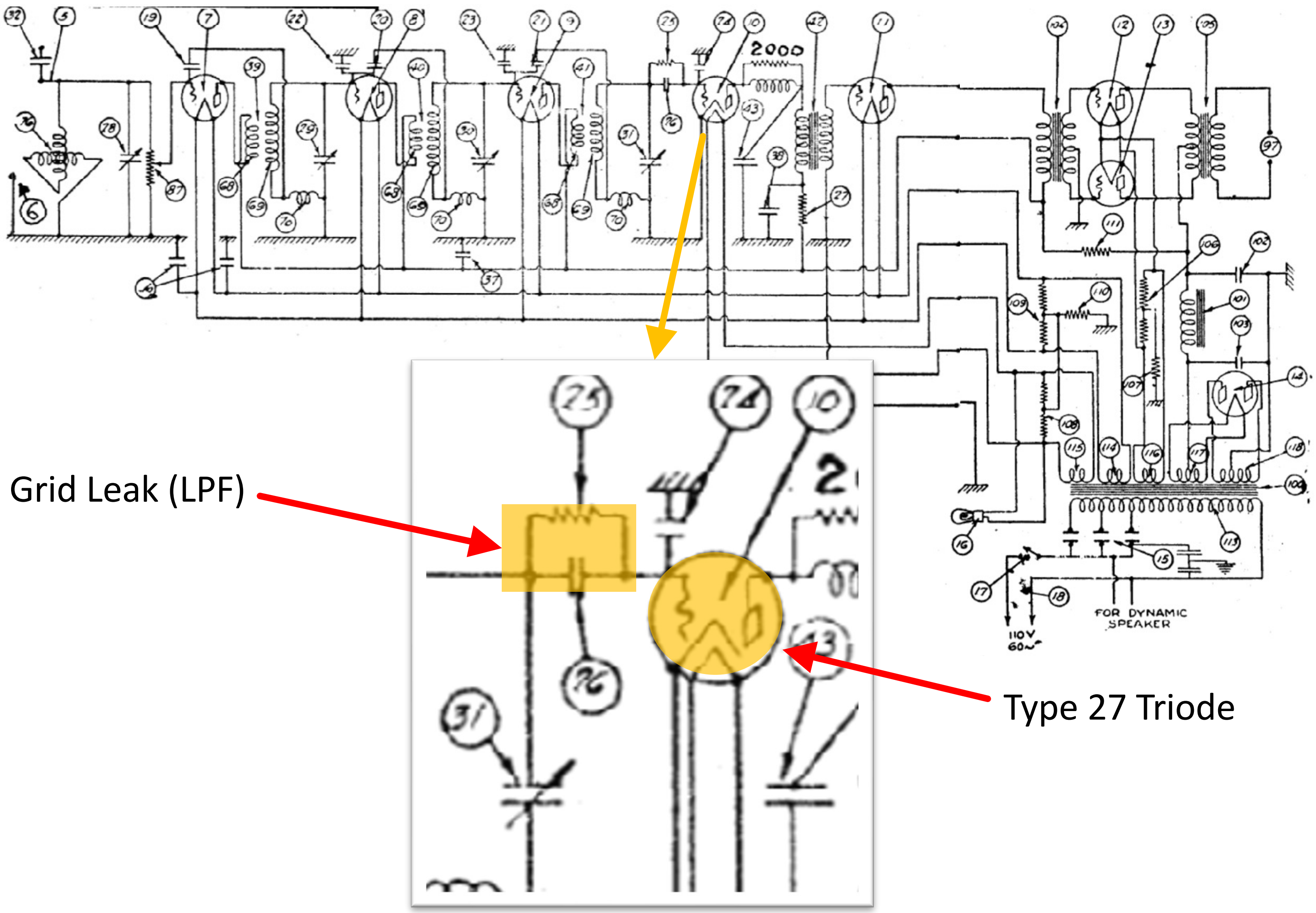
- The same type of "Envelope" voltage will build up across the RC as it does in regular diode detector!



Very Cool…the Grid Leak Detector!

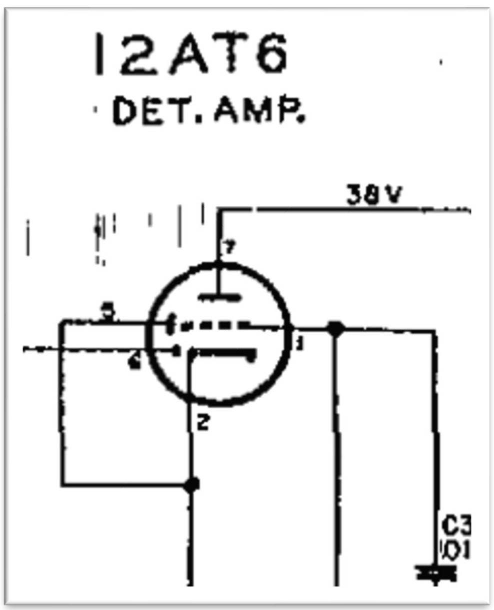
- That same Rectified LPF signal gets built up on the grid directly.
- And that means it can modulate the plate current like it would in a normal amplifier
- So with this circuit topology, you can now simultaneously demodulate and amplify all within one vacuum tube (Saves on parts and minimizes noise!)

1928 Bosch Radio Receiver Schematic

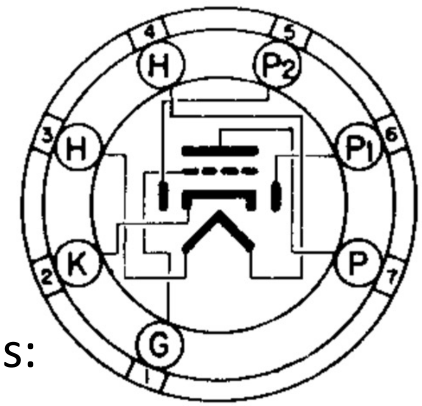


Using same electrode for Grid and Diode Could get Complicated

- 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



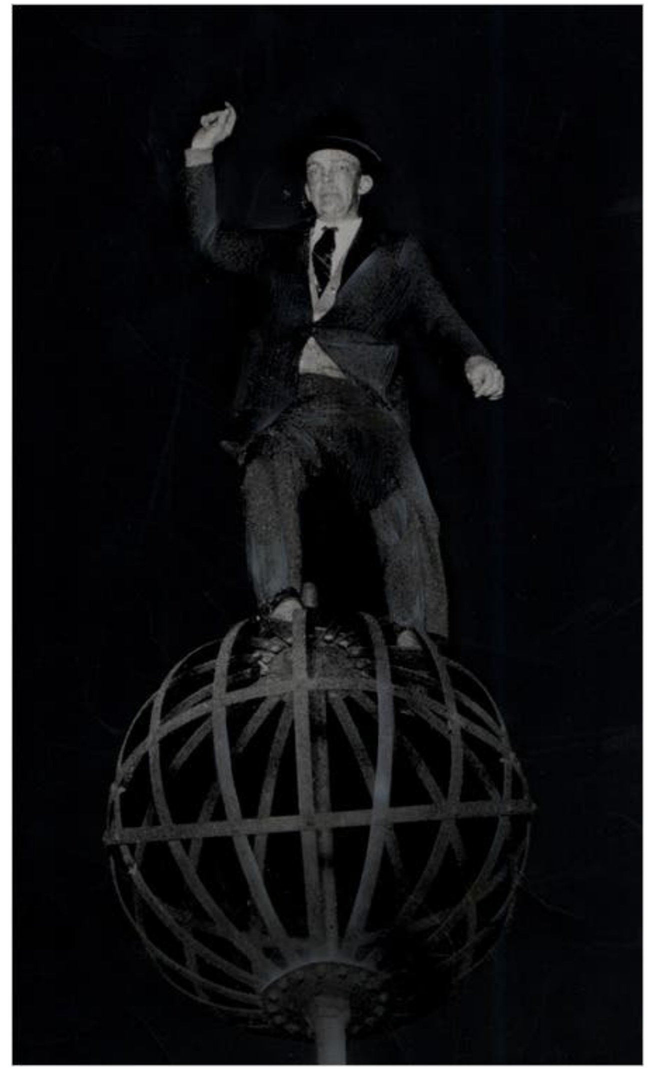
12AT6 pinout

An Interesting Early Circuit Using Grid Leak Detector as Starting Point

- In the 1910’s triodes were *just* getting figured out.
- Triodes also didn’t have very high gain (that wouldn’t come for almost 15 more years).
- Triodes were also very expensive
- Early wireless receivers couldn’t amplify the received signal much
- They also weren’t very selective (stations would bleed into one another…as you saw in lab01)
- ...In comes...

Edwin Howard Armstrong

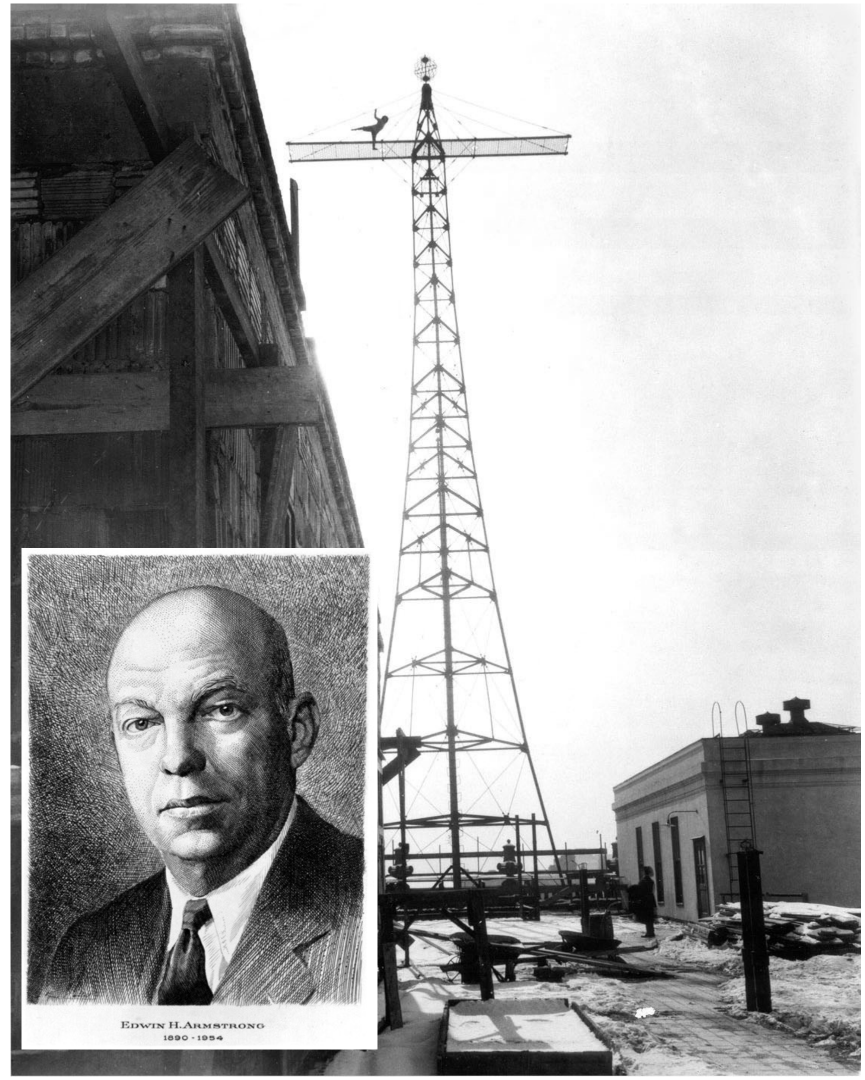
- An early 20^{th} century EE who developed some of the most influential circuits of the last 100 years.
- The man worked in vacuum tube electronics the way other artists might work in oils or clay. It was his true medium, a master.
- His designs still have impact today.



Edwin H. Armstrong, on top of the WJZ station's antenna tower in New York in 1923, several hundred feet in the air.Credit...*Edwin H. Armstrong Papers, Rare Book and Manuscript Library, Columbia University*

Armstrong

- Born in 1890
- In 1913, while a senior at Columbia Engineering in NYC he solved the problem we're talking about (getting more gain out of early tubes)



http://www.theradiohistorian.org/wjzgallery/images/wjz_armstrong.jpg

Here's Edwin again dancing on that antenna on another day.

Aside:

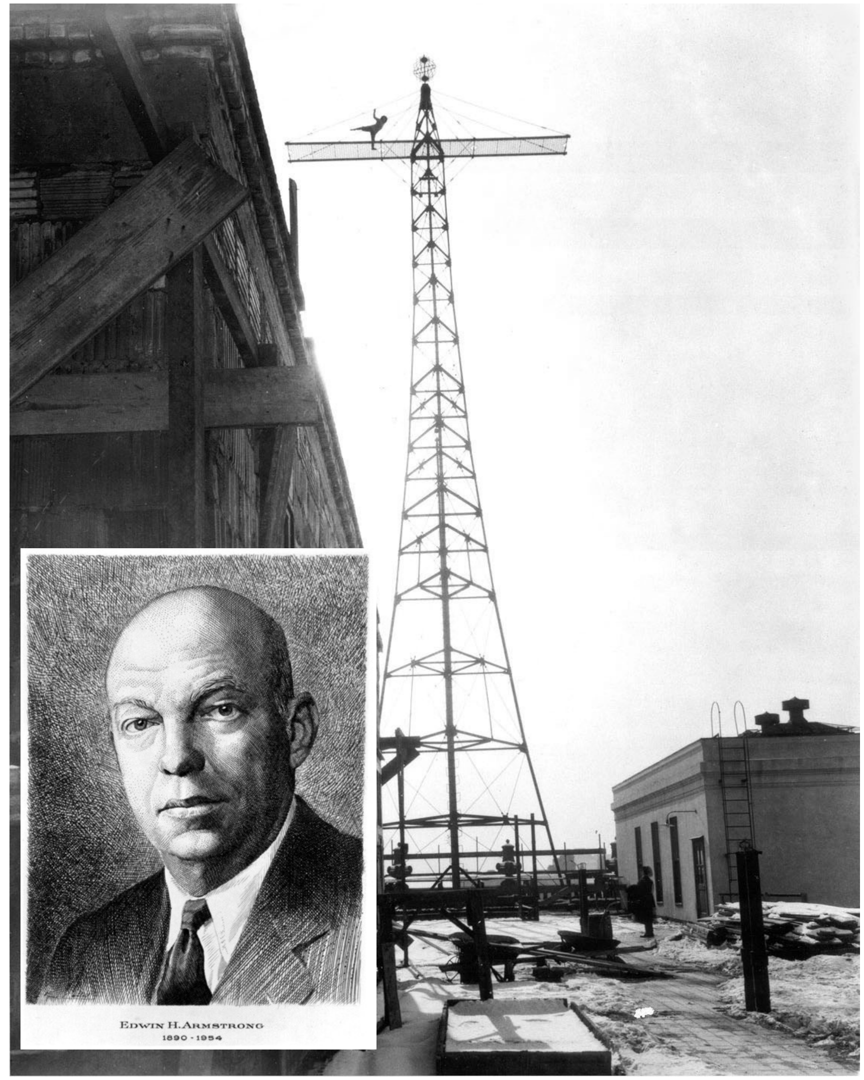
- Humans really got into doing things way up in the sky in the 1920s for some reason likely because skyscrapers and radio towers were shooting up in some cities and were unlike anything ever seen before.
- As a result people were like, :
    - what if I balanced chairs at the top of that building
    - Or sit on a flagpole for 20 hours?
    - These were all the tiktok challenges of the day
- So Edwin was not *that* weird considering the fads of the time

https://viewing.nyc/vintage-photograph-shows-nyc-daredevil-balancing-on-a-stack-of-chairs-20-stories-up-circa-1920/

https://vintagenewsdaily.com/the-flagpole-sitting-trend-of-the-1920s-was-widely-popularized-in-the-u-s-by-alvin-shipwreck-kelly/

Armstrong

- Born in 1890
- In 1913, while a senior at Columbia Engineering in NYC he solved the problem we're talking about (getting more gain out of early tubes)
- …so back to the problem…

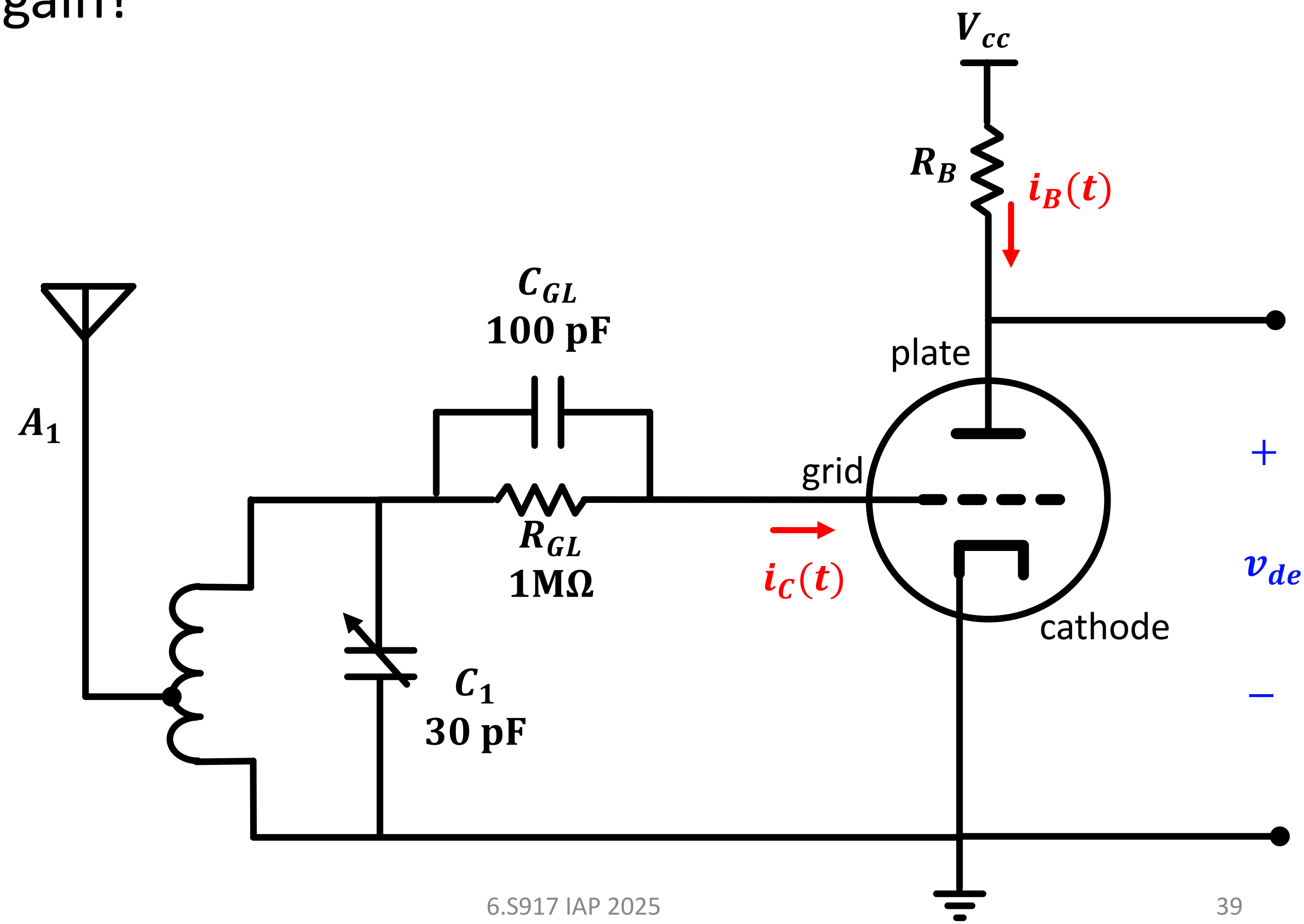


Here's Edwin again dancing on that antenna on another day.

http://www.theradiohistorian.org/wjzgallery/images/wjz_armstrong.jpg

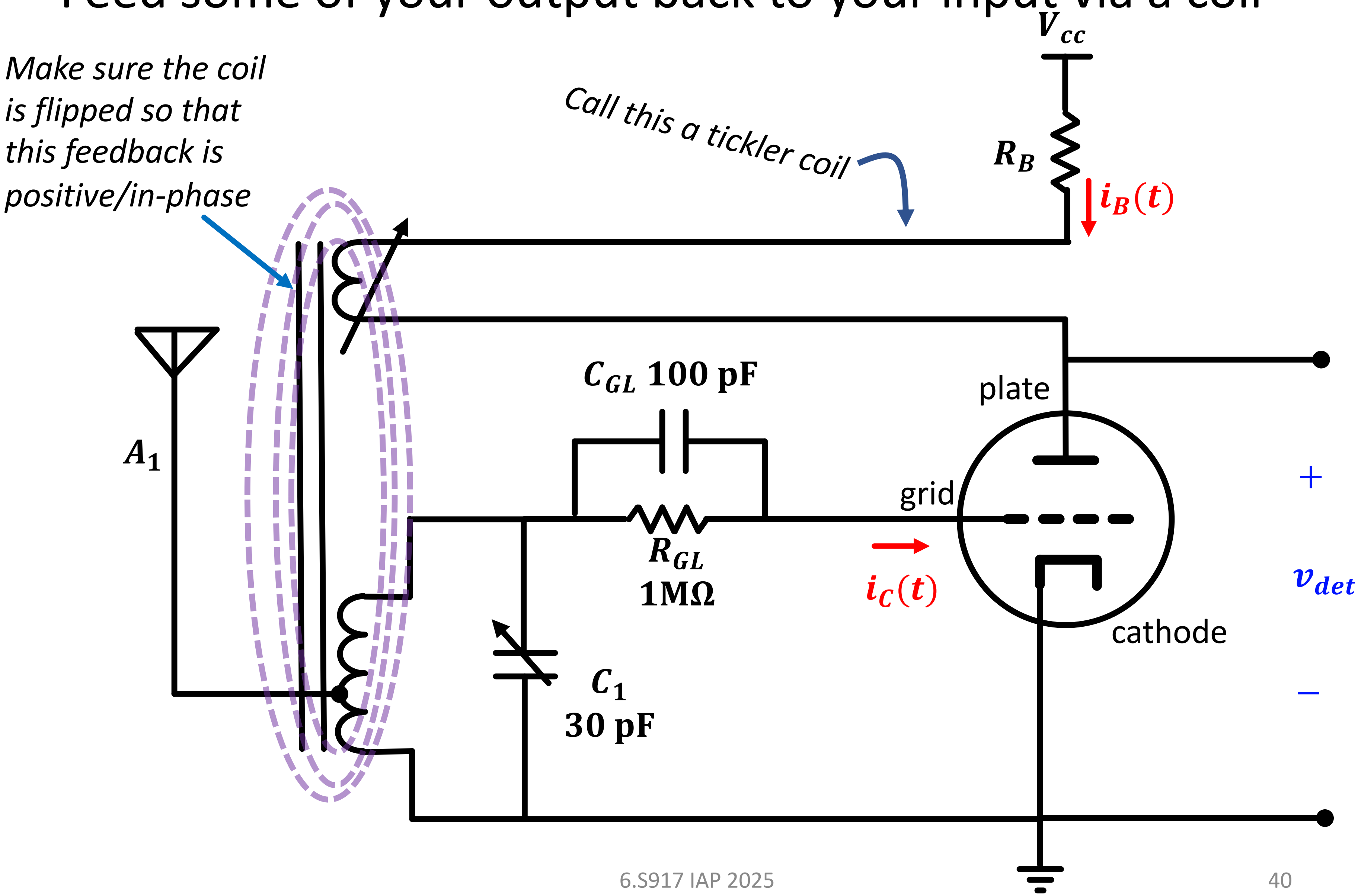
The Grid Leak Detector

- So we got this circuit…How can I get more gain?



The Fix

- Feed some of your output back to your input via a coil

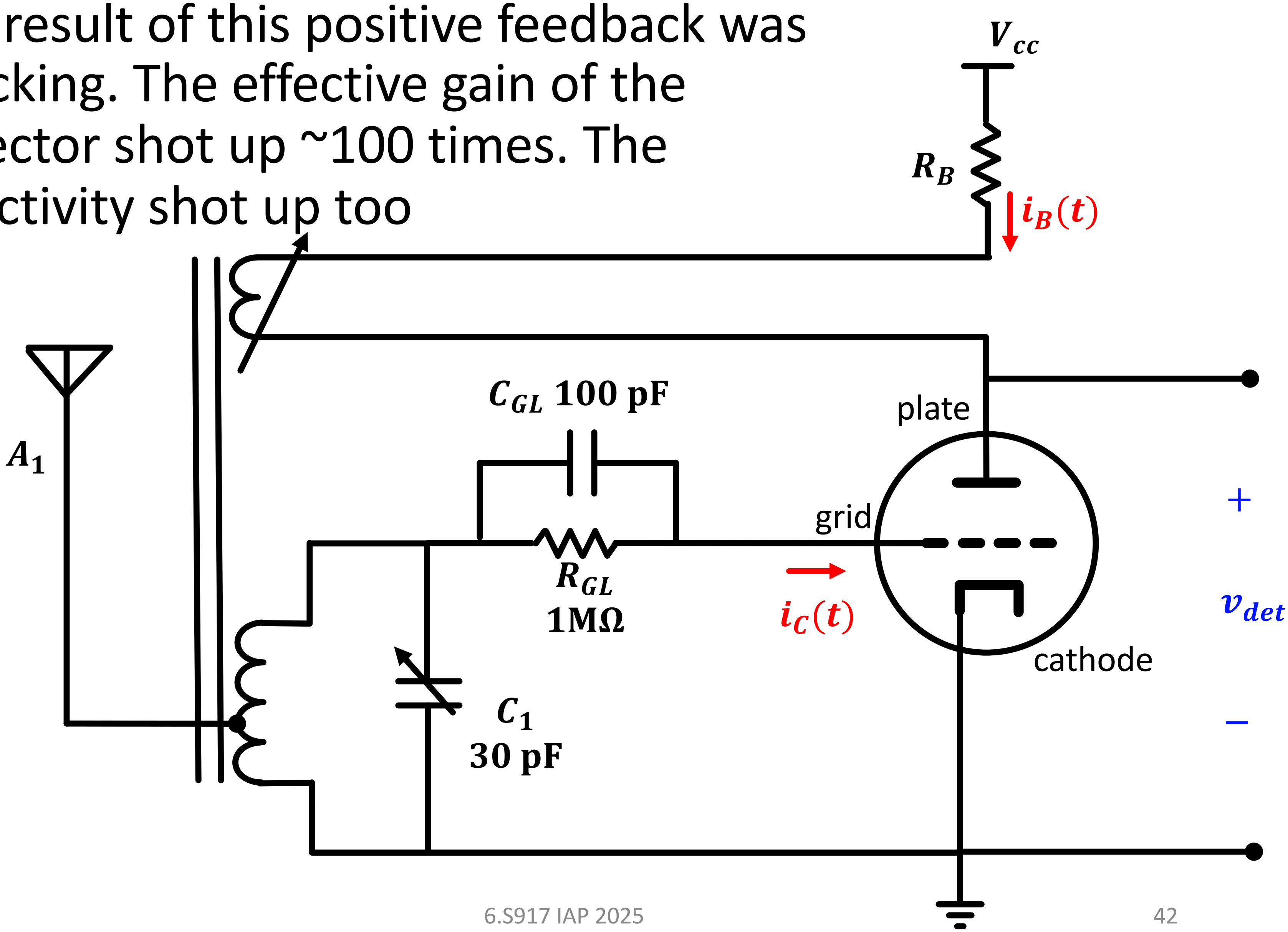


Positive Feedback

- As engineers we often seek out negative feedback in designs. Negative feedback is stabilizing and makes things work reliably (will talk about on Thursday/lec06)
- There are times and places where positive feedback is what we want:
  - Nuclear weapons for example
  - Modern digital electronics use it in certain spots
  - In teaching we often give students “positive feedback” but this is a misnomer…positive feedback in education would help good students do better, but also it would tell students not doing well to suck harder and that’s not good...feedback in education involves asymmetry/nonlinearity
- But positive feedback is finicky and you have to be careful.

Feeding/Refeeding a Signal Repeatedly

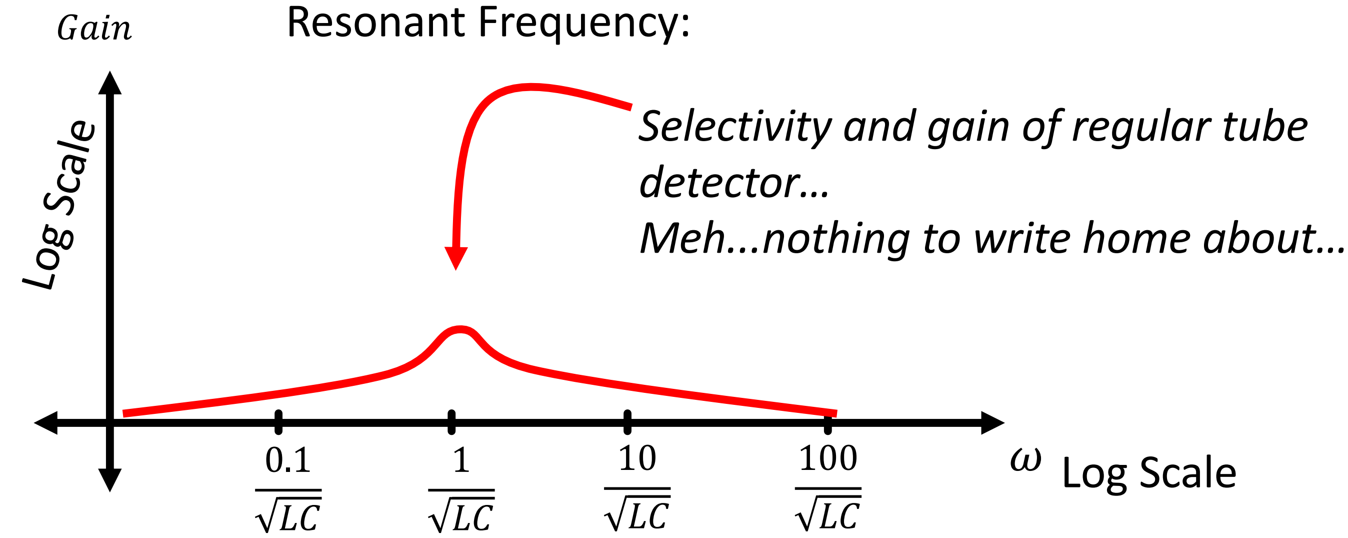
- The result of this positive feedback was shocking. The effective gain of the detector shot up ~100 times. The selectivity shot up too

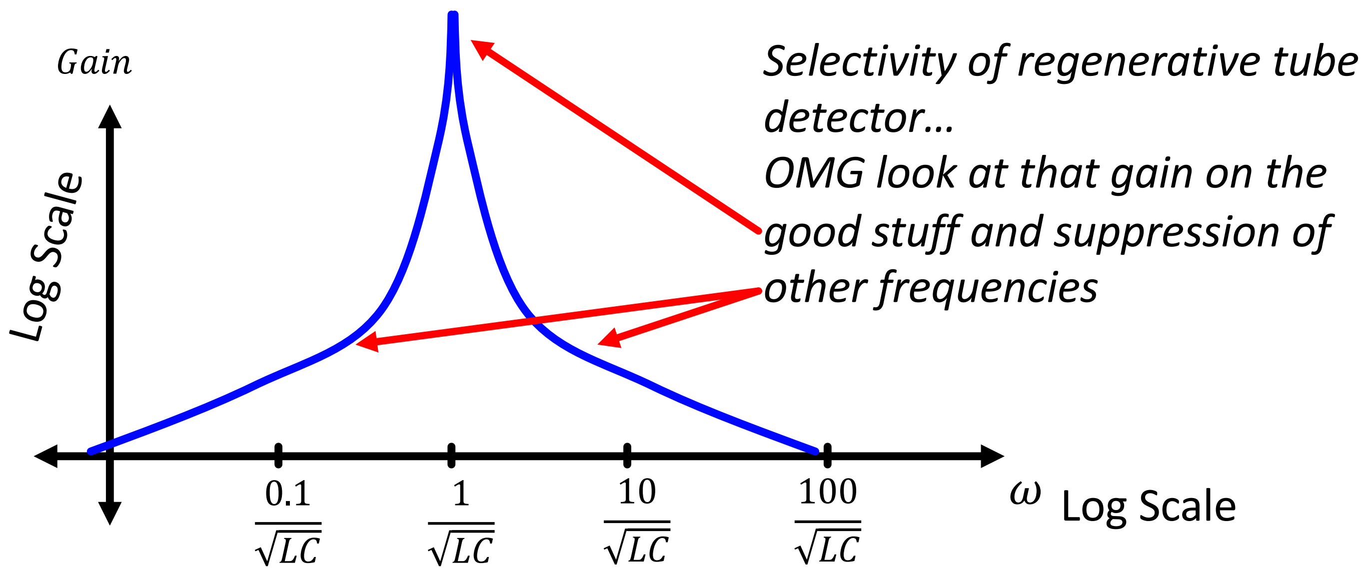


The LC (+parasitic R) tuner

One way to think of the regenerative circuit is that it is reusing the circuit for multiple passes. Run the signal through once to filter/amplify it…then run it through again…and again…and again.

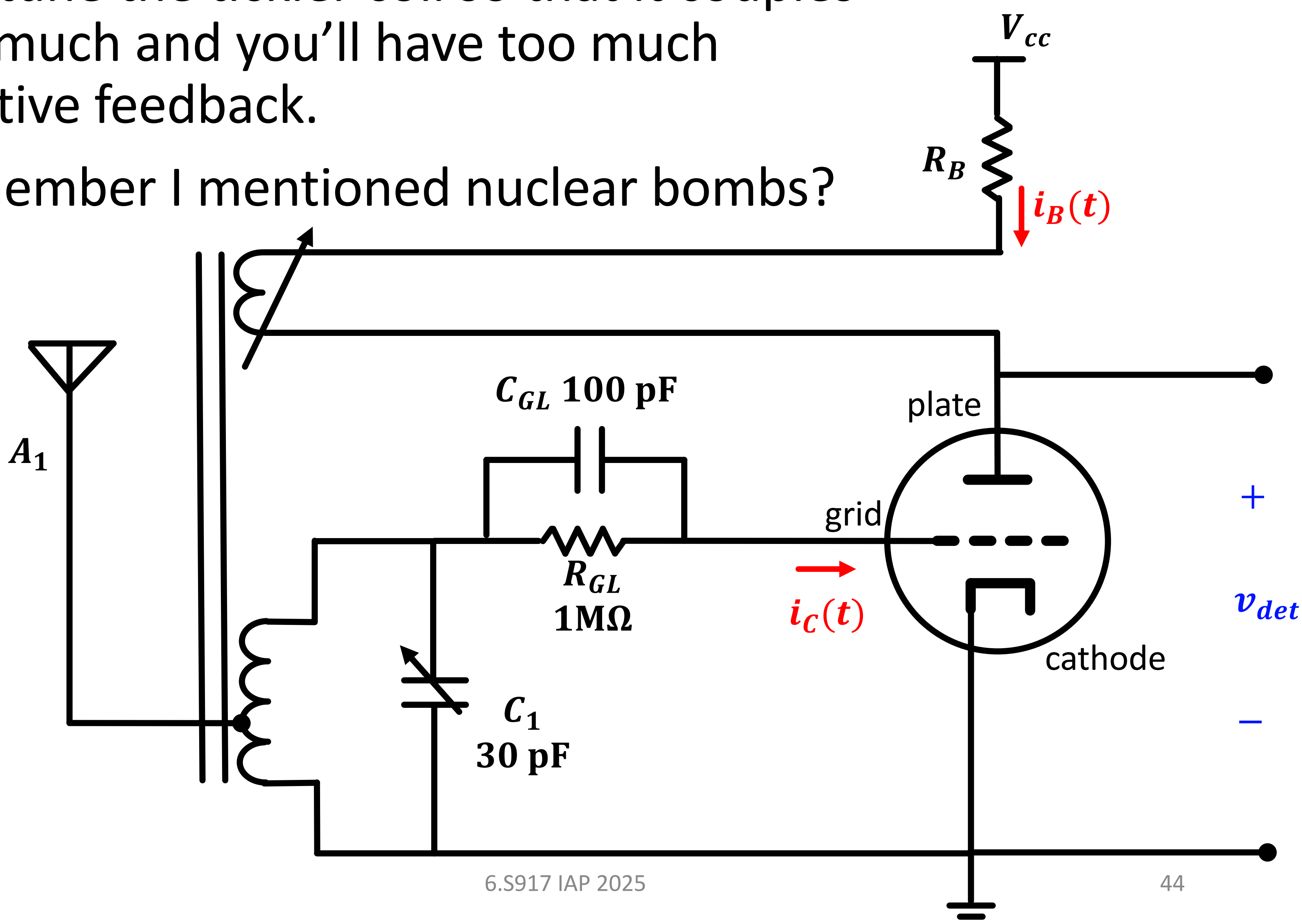
Resonant Frequency:





Of Course…this is Positive Feedback

- You tune the tickler coil so that it couples too much and you'll have too much positive feedback.
- Remember I mentioned nuclear bombs?



Regenerative Receivers

- When tuned well were amazing! Great selectivity and gain (for the time)
- Became dominant receiver design up through early 1920s…
- BUT…
- If too much positive feedback showed up though, the circuit would turn into an oscillator, and at the very frequency you were trying to listen at….and the thing was connected to an antenna…
- As a result a receiver could very quickly switch from receiving into transmitting and jam everyone nearby

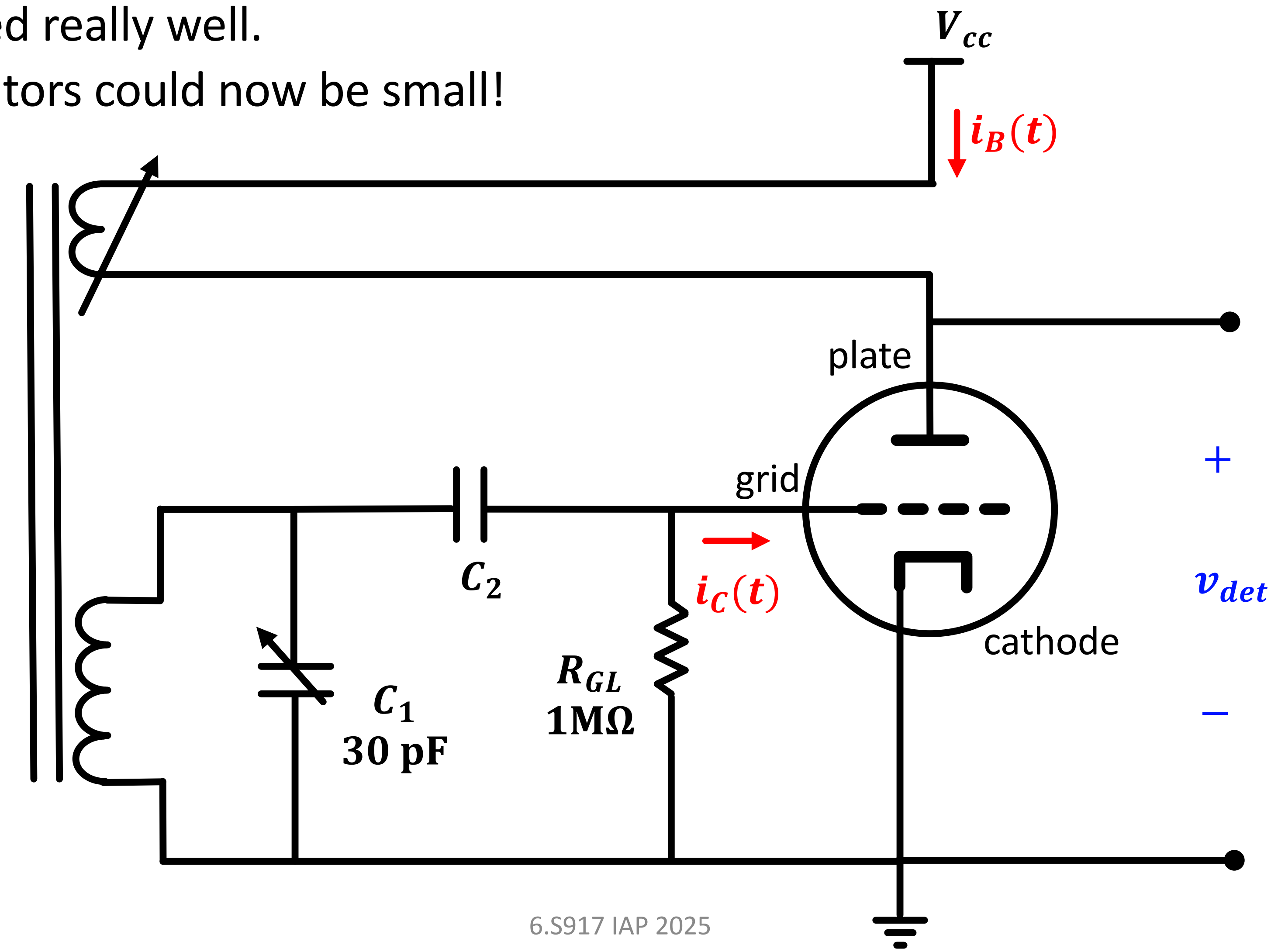
When Life Gives you Oscillators, Make Oscillade

- The regenerative receiver was step in the right direction. So Armstrong patented it. Made 500K USD off it (1920 money)…
- The fact that it could turn into a transmitter wasn't awful either. In fact it was a useful discovery in its own right…Armstrong had developed the first tube-based electrical oscillator.*
  - Before that, they'd been electromechanical/spark-wheel based/gas-discharge-based

**In fact Armstrong had the oscillator part figured out first, documenting it in 1912, months before regeneration.*

The Armstrong Oscillator

- Basically the same circuit. Still had the tickler coil for positive feedback!
- First fully-described electronic oscillator
- Worked really well.
- Oscillators could now be small!

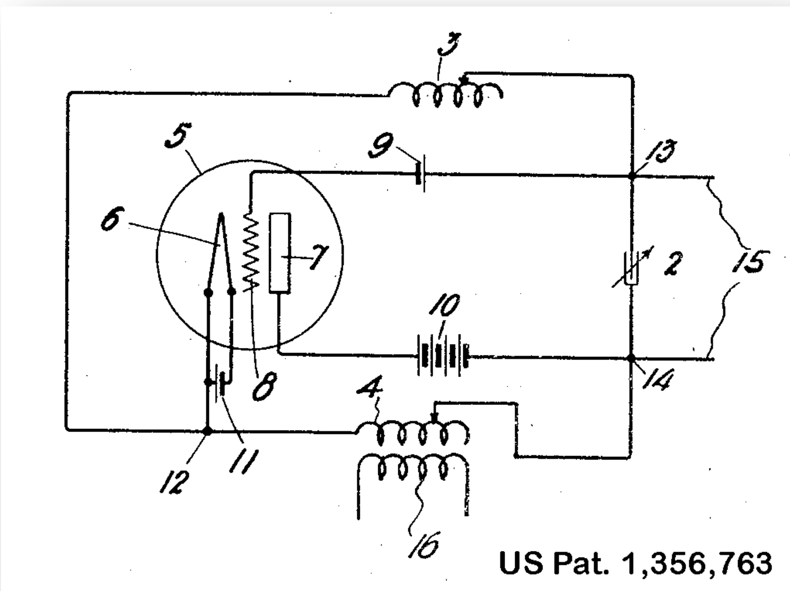


Start of Aside: Oscillations and Feedback

- …We will return to Armstrong in future classes.
- But the chase for oscillations was very important and lots of experimenting was going on....
- The Armstrong oscillator was soon outclassed by other variants.

Other Oscillators soon followed

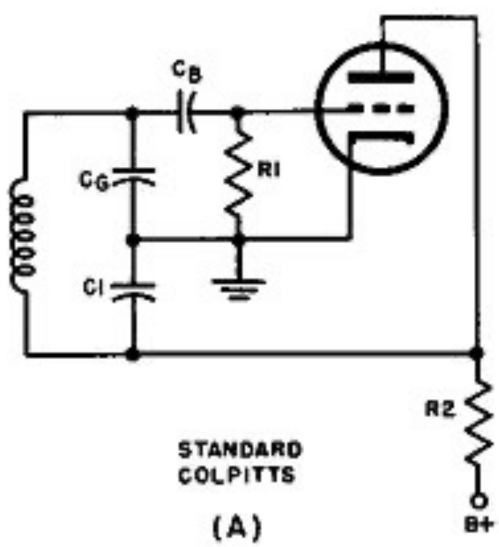
- Ralph Hartley developed one in 1915:
- Using a LC tank with a tapped L (and positive feedback ofc)

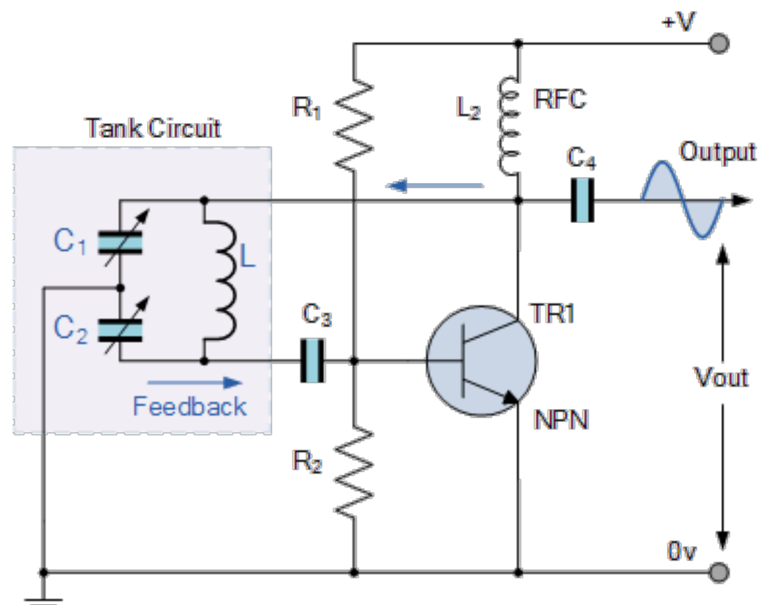


https://circuitdigest.com/tutorial/hartley-oscillator

Others soon followed

- Colpitts developed one in 1919:
- Using a LC tank with a “tapped” C (and positive feedback ofc)





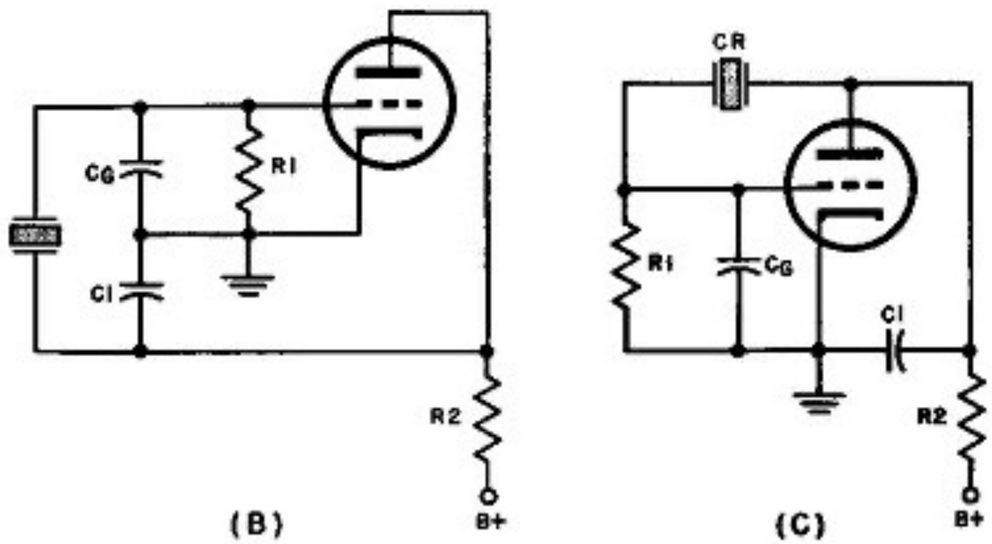
“modern” transistorized Colpitts Oscillator

https://www.industrial-electronics.com/crystal_osc_4.html

https://www.electronics-tutorials.ws/oscillator/colpitts.html

Others soon followed

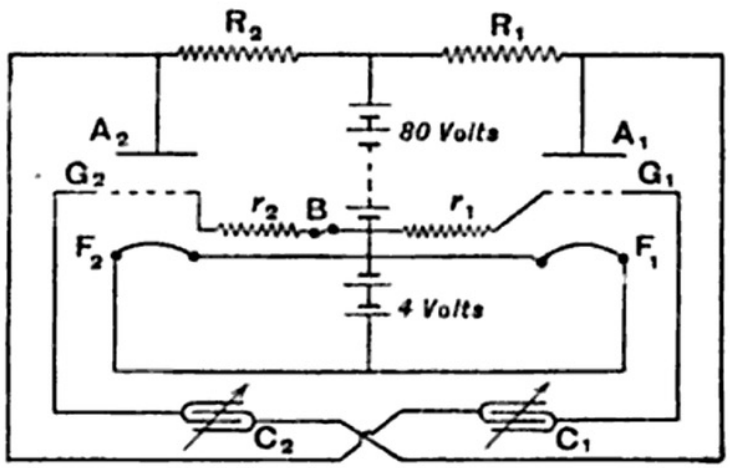
- Miller (of Miller capacitance fame who we'll encounter in a little bit) developed one in 1919:
- Early experimentation with quartz crystals (which act like LC tanks) and positive feedback



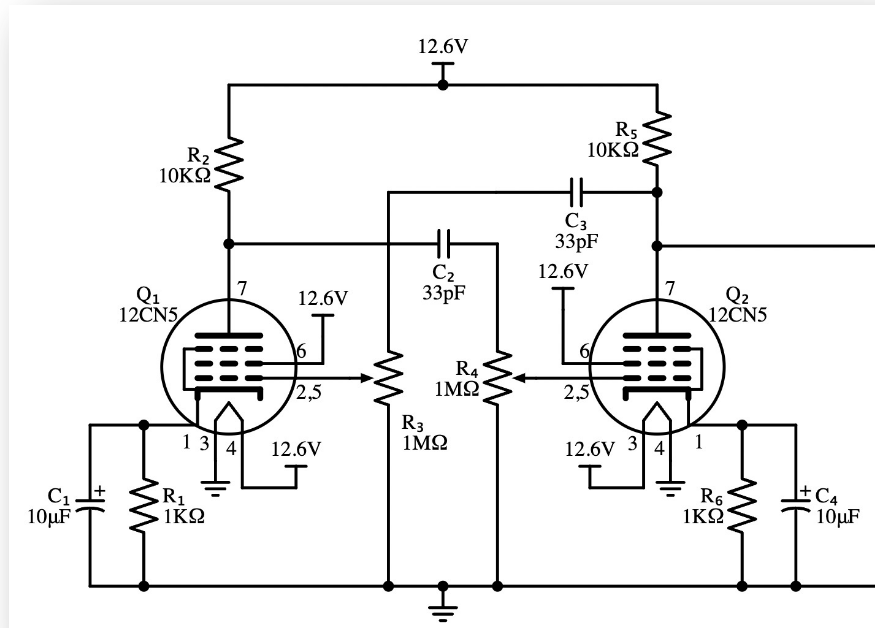
https://www.industrial-electronics.com/crystal_osc_4.html

Others soon followed

- Abraham and Bloch found out that with two tubes, they could get oscillations



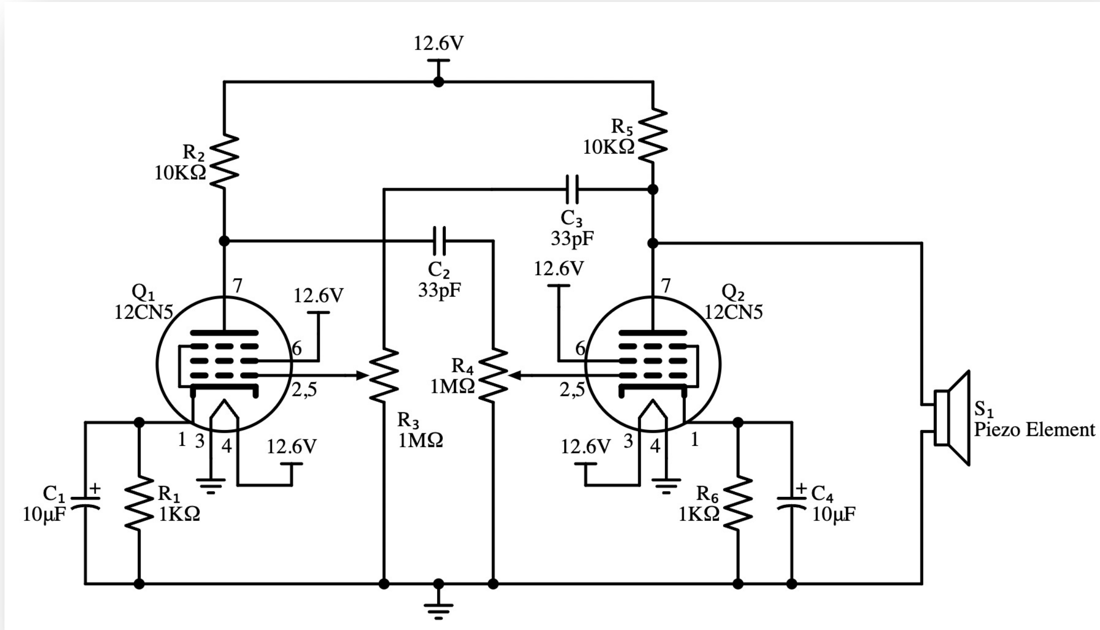
Original 1919 Circuit



Circuit to build in Lab 05

Two Active Devices in a Feedback Chain

- This circuit formed what is now known as a **multivibrator**
  - With Caps for feedback paths it is **astable**….meaning it will oscillate
  - Having predominantly resistive feedback paths, the circuit can become **bistable**



Circuit to build in Lab 05

Think about this more on Thursday too...

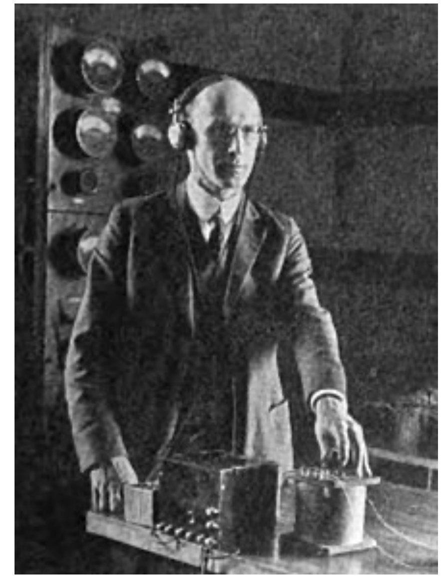
Meanwhile in tube development land....

- Other things were happening and they were concerning.

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

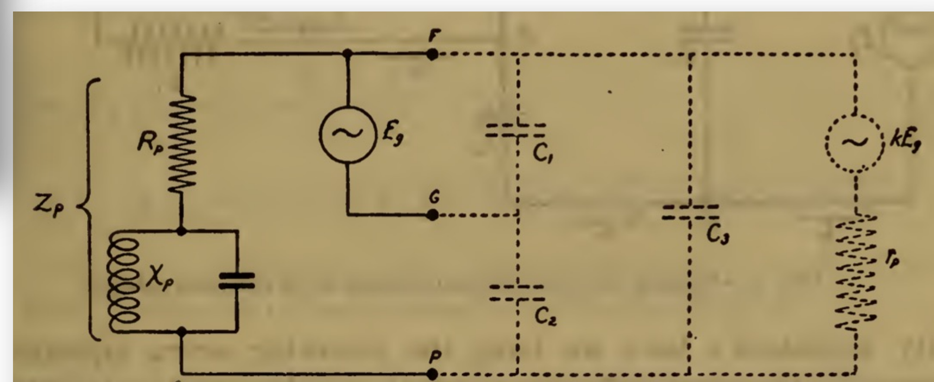


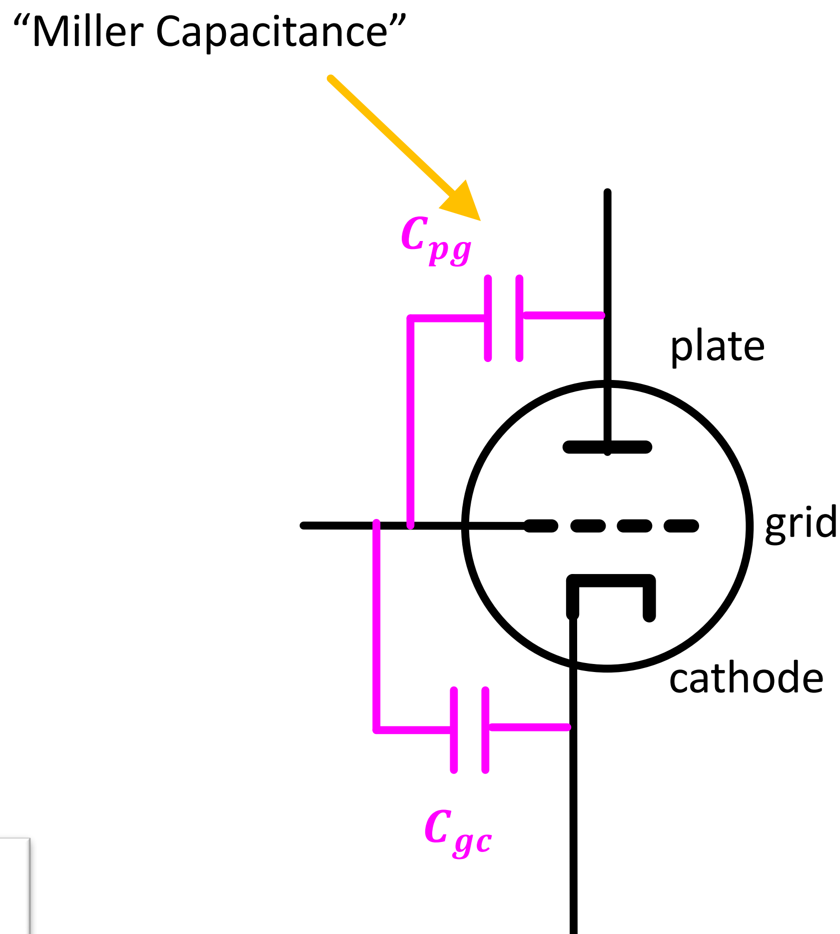
FIG. 1.—*Diagramatic representation of a vacuum tube and external circuits*

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



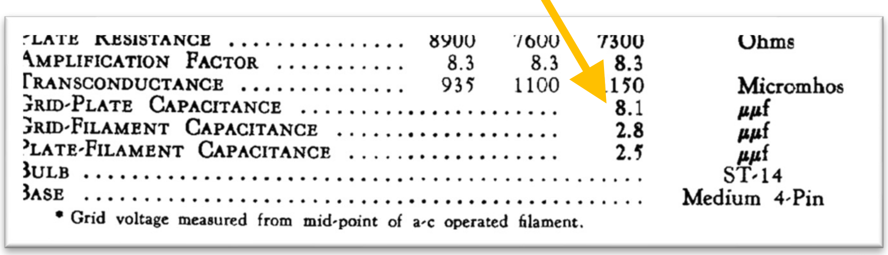


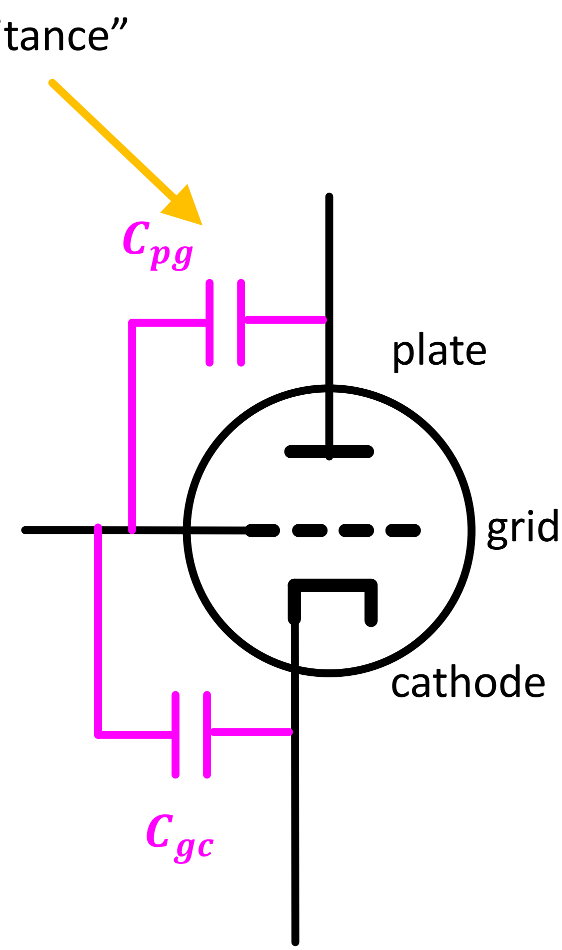
PLATE RESISTANCE	8900	7600	7300	Ohms
AMPLIFICATION FACTOR	8.3	8.3	8.3	
TRANSCONDUCTANCE	935	1100	1150	Micromhos
GRID-PLATE CAPACITANCE			8.1	μμf
GRID-FILAMENT CAPACITANCE			2.8	μμf
PLATE-FILAMENT CAPACITANCE			2.5	μμf
BULB				ST-14
BASE				Medium 4-Pin

* 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

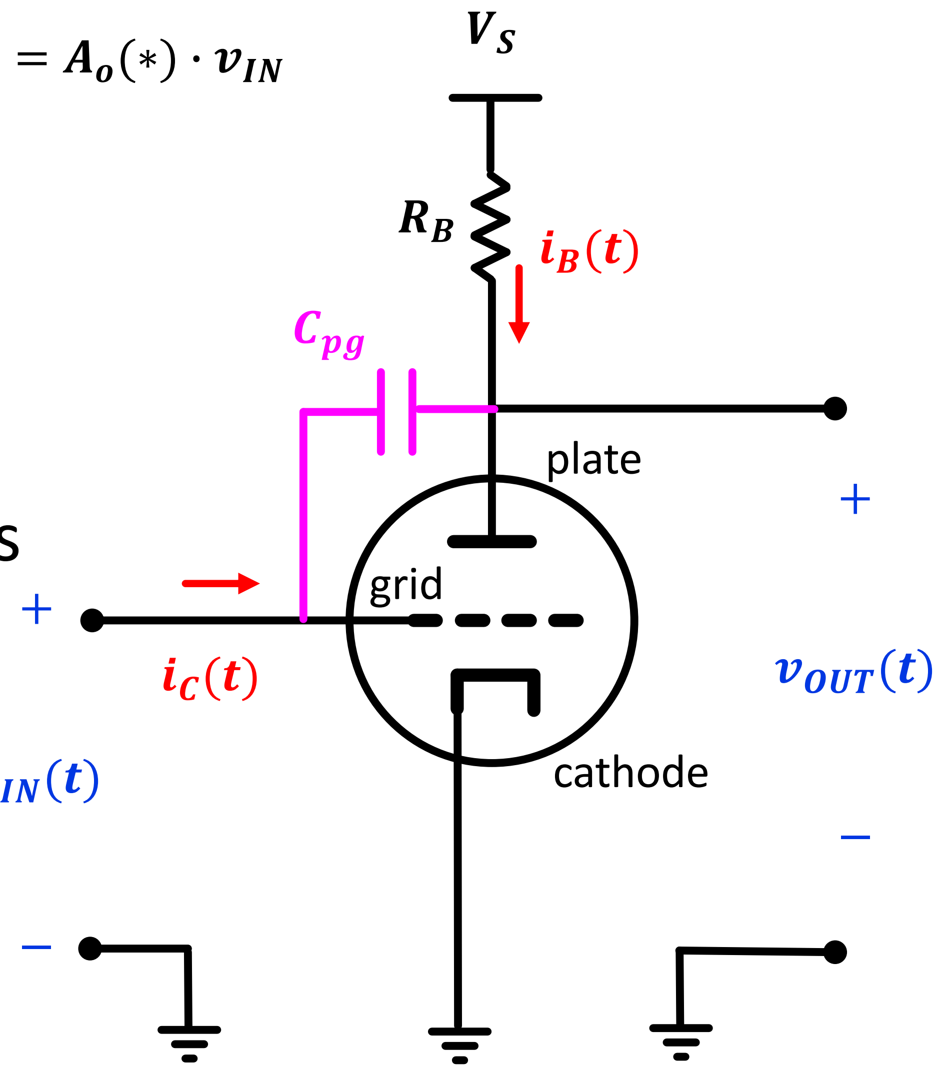


Characteristics for early triode (Type 26)

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

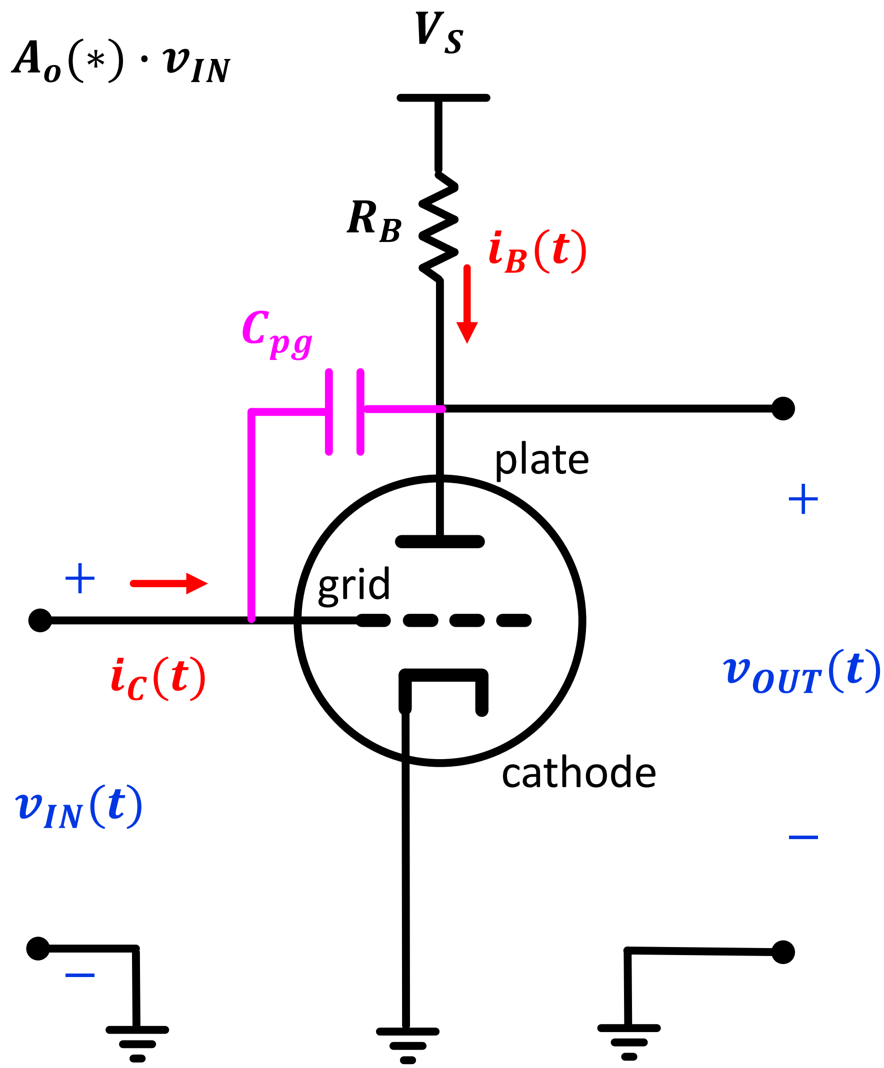


**ignore grid bias and things for these examples to keep things simple!*

Derivation

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

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



**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:

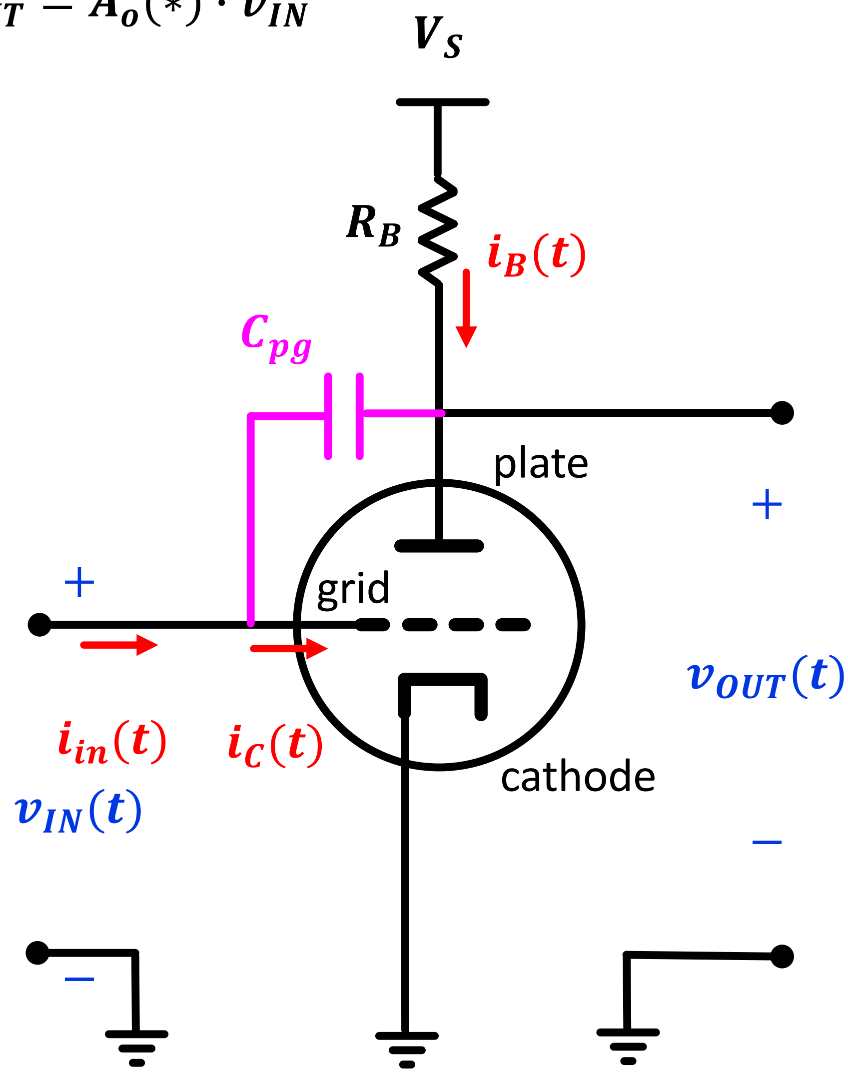
$$\tilde{I}_{in} = \frac{\tilde{V}_{pg}}{Z_{pg}} =$$

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:

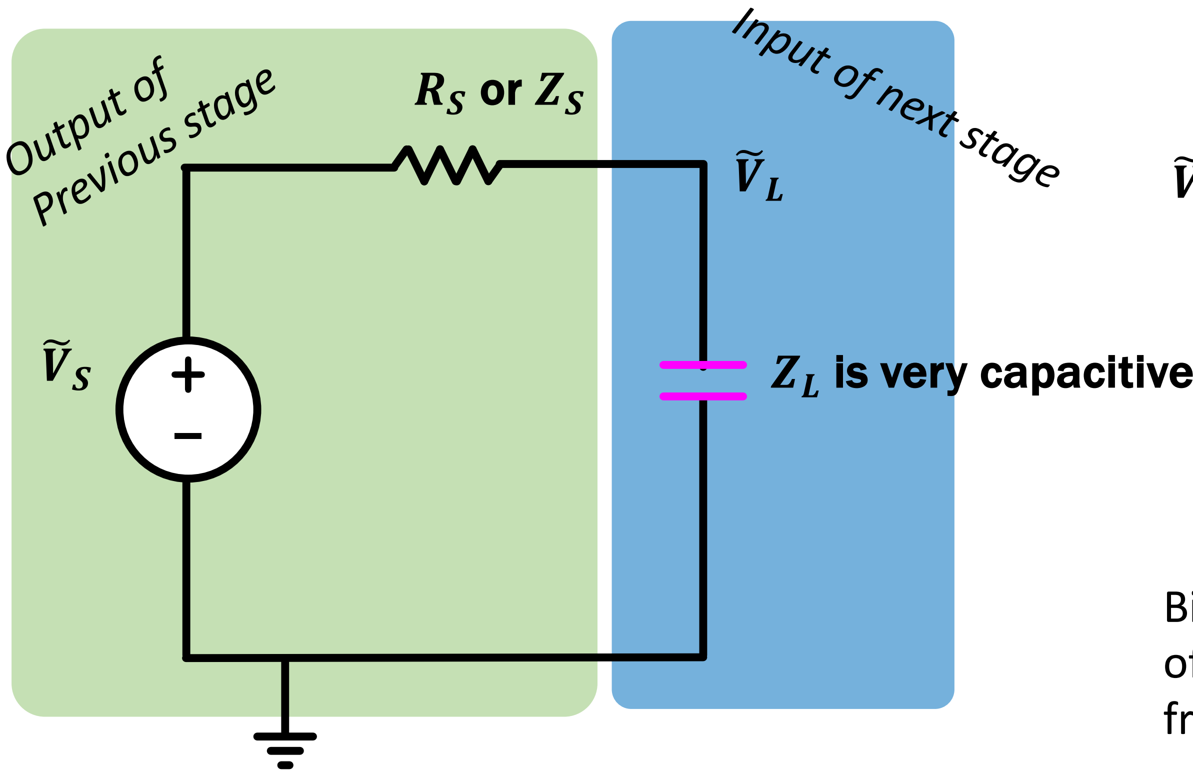
As a result:

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

- 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:



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

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

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

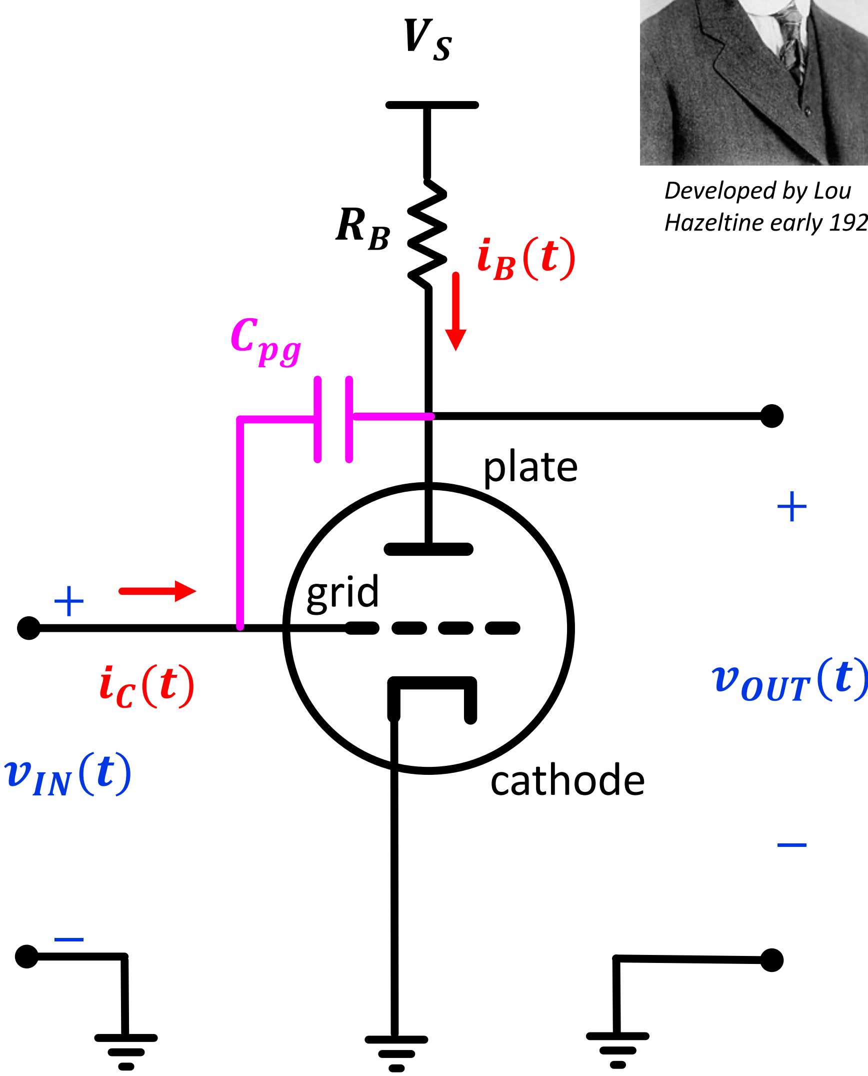
Bigger C_L means turns off at lower and lower frequencies!☹

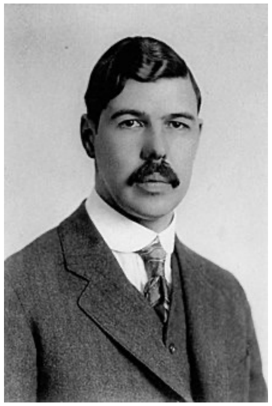
Miller Effect was Real Problem

- 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?



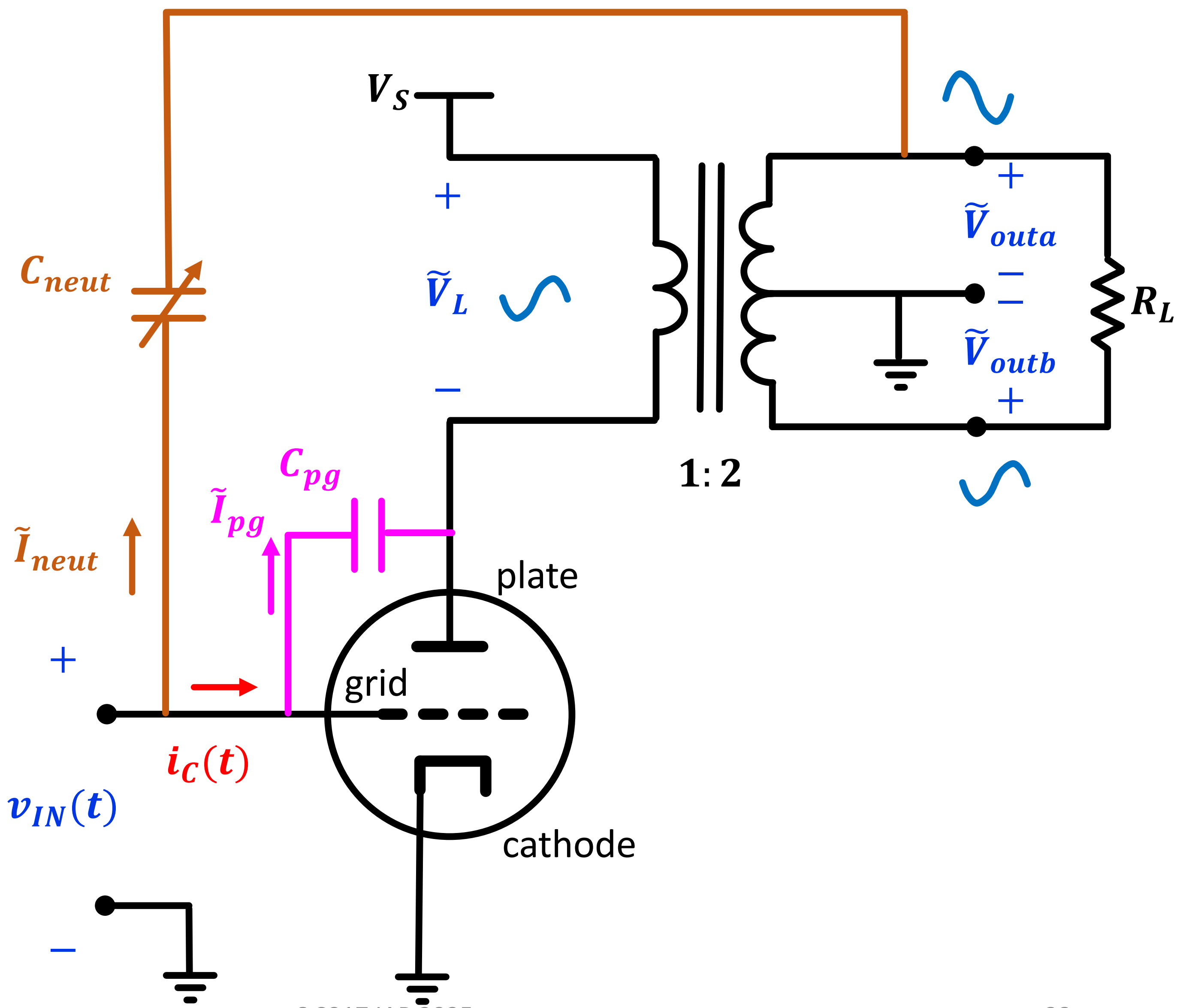


Developed by Lou Hazeltine early 1920s

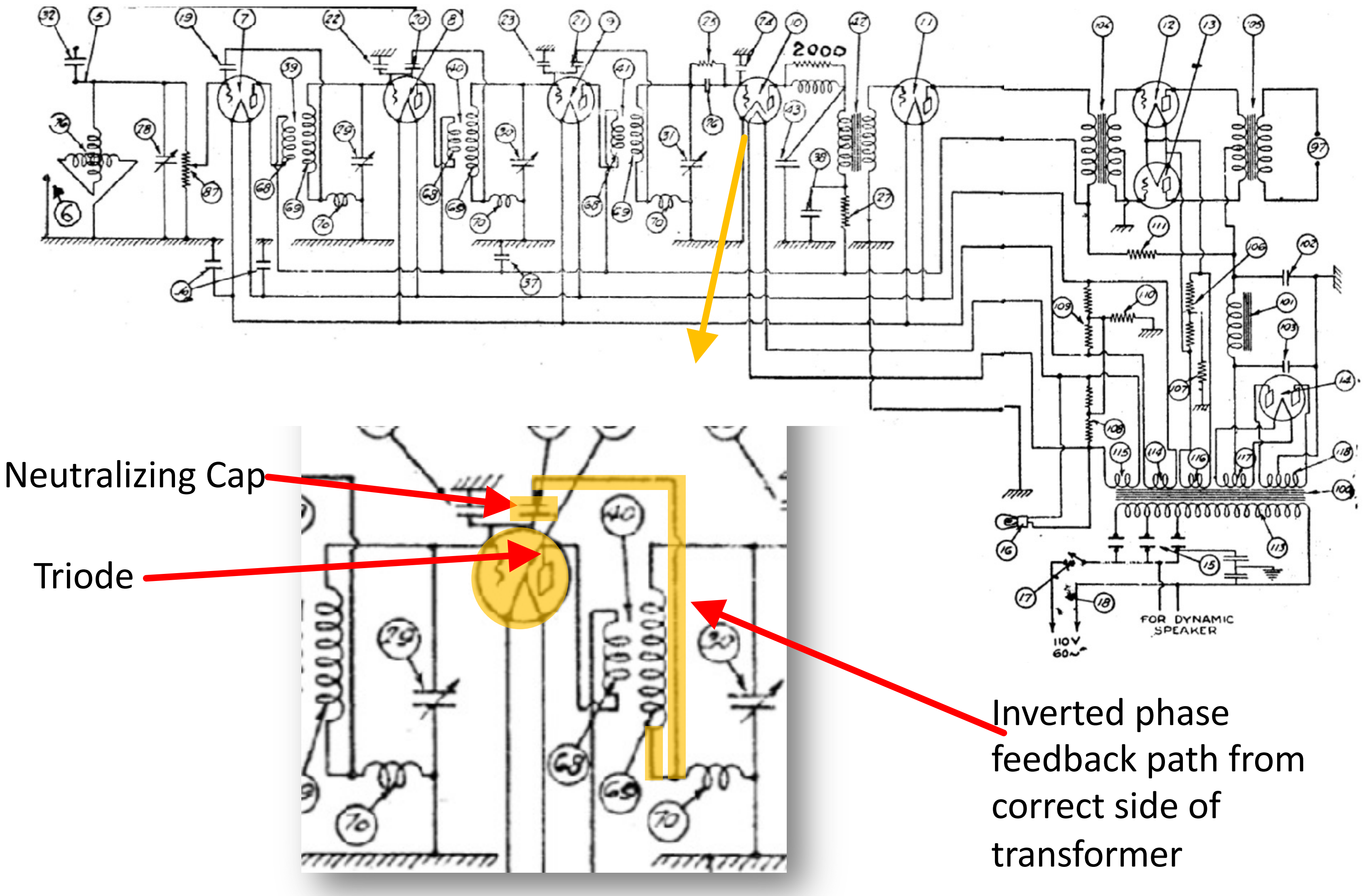
https://en.wikipedia.org/wiki/Louis_Alan_Hazeltine

Why use a transformer, of course

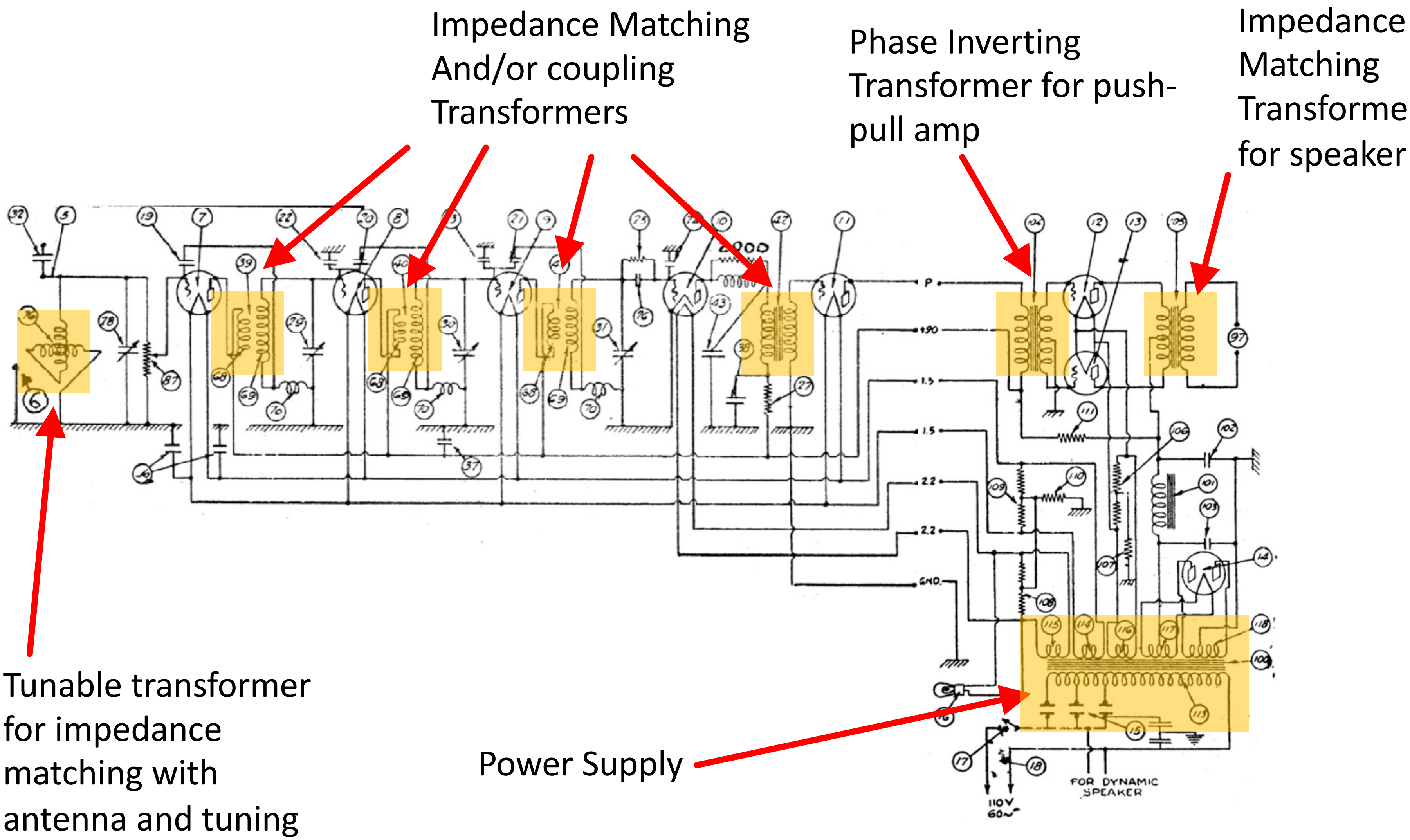
- Tune that neutralizing cap until the current into it just cancels out the current into the Miller cap.
- Boom no more cap



1928 Bosch Radio Receiver Schematic



1928 Bosch Radio Receiver Schematic



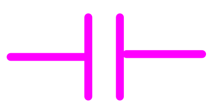
Neutrodyning

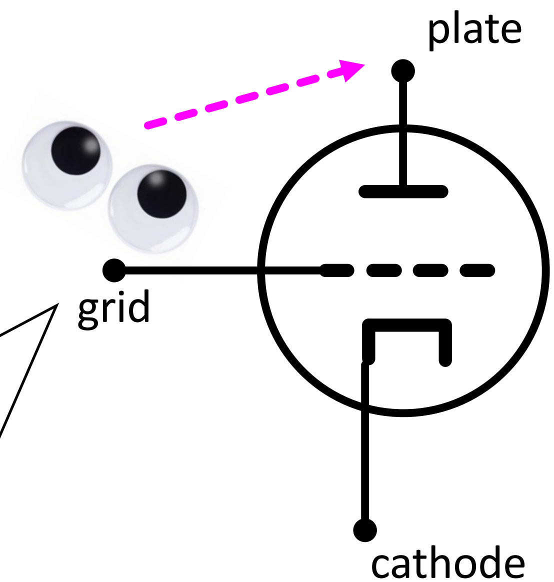
- Used in tons of circuits throughout 1920s. Allowed early forays into higher frequencies
- Still…kinda annoying. Need all extra circuit crap. Also could drift as gain of tube changed over time…needed retuning to account
- If cap drifted (not rare in early caps) you could get too much positive feedback 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

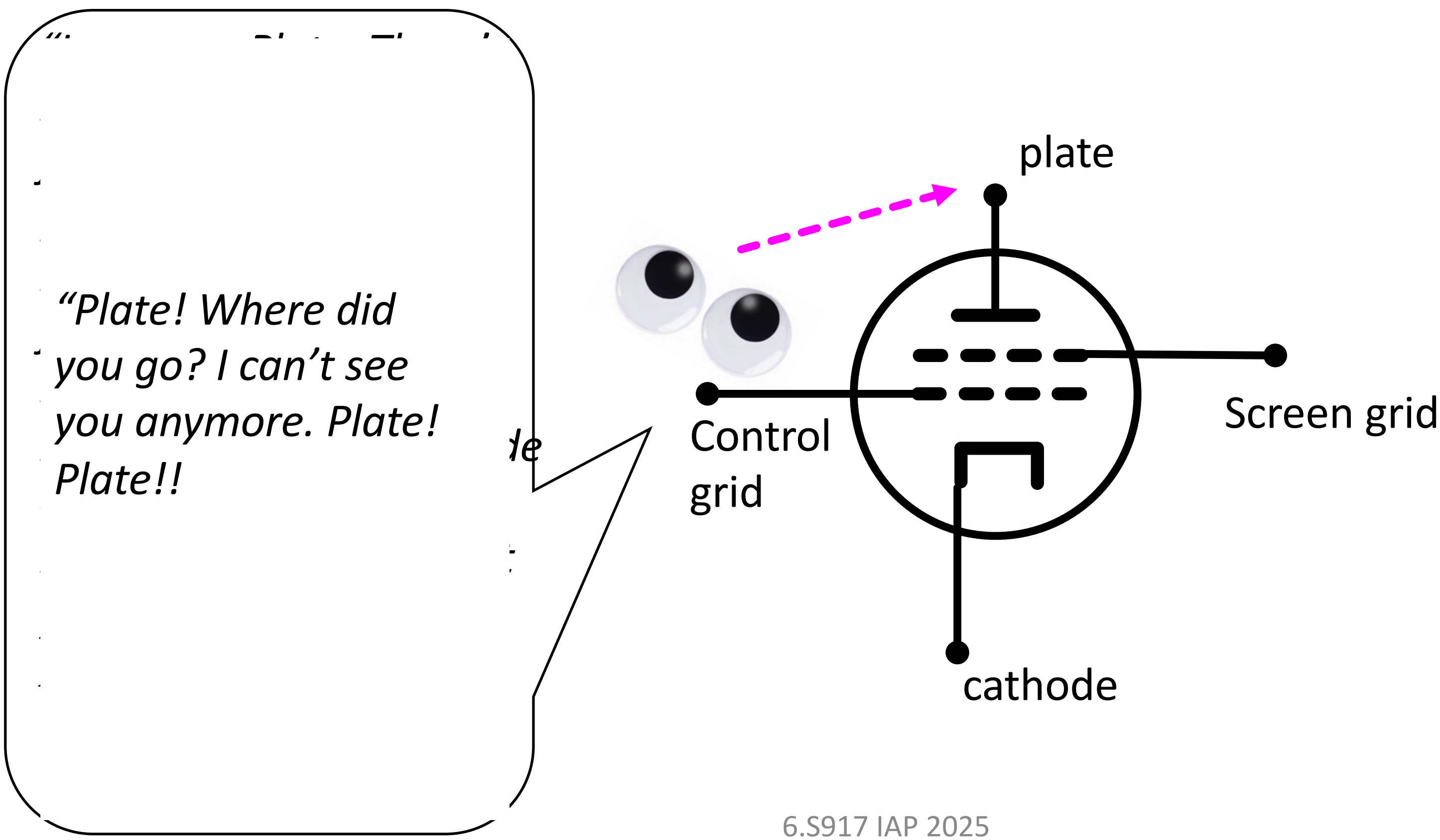
“I see you, Plate. There’s no denying our feelings for one another…We’re going to develop a non-negligible electric field…just you and me…Yes I’m still going to have a thing with Cathode on the side, but that’s minor compared to what you and I have because A_o *is large.”*





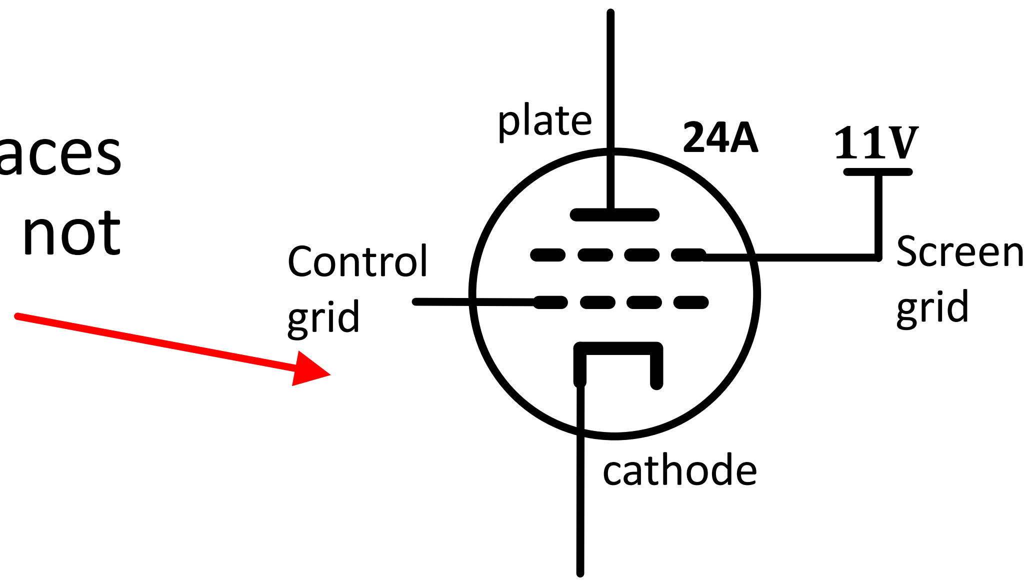
Solution 2: Device Level. Make a New Tube

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



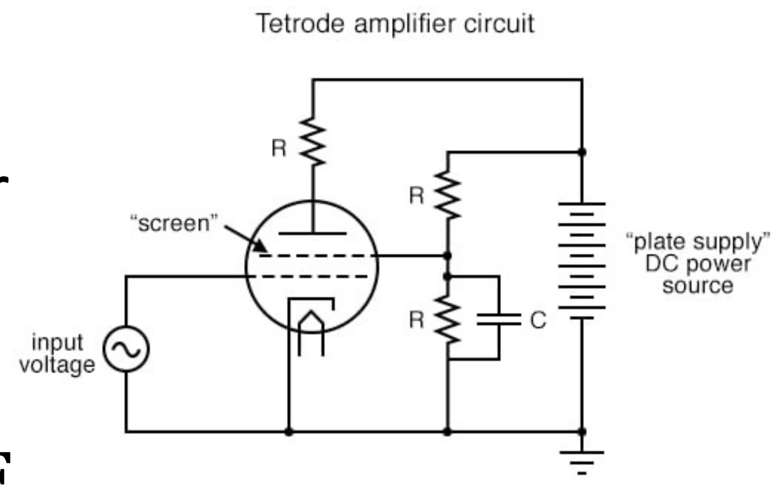
This new tube had four electrodes

- Call it the screen-grid tetrode.
- **Screen-grid tetrode** places new grid close to plate not tetrode to shield plate



The Tetrode Was Ok

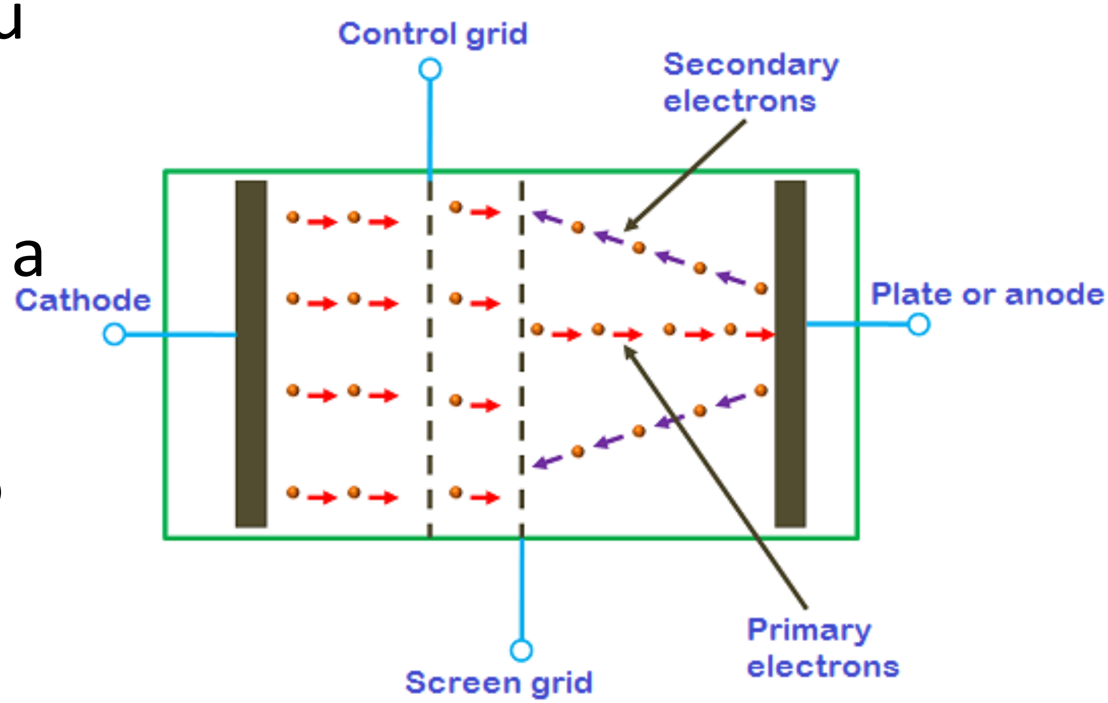
- Tetrode definitely cut down Miller Effect.
- Early triodes had a $C_{Miller} = 8\text{pF}$
- Tetrodes had a $C_{Miller} = 0.015\text{pF}$
- Still there, but orders of mag less
- Usually hold screen grid at a positive voltage close to supply.
- Majority of field lines from grid to cathode therefore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



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

Big Issue!

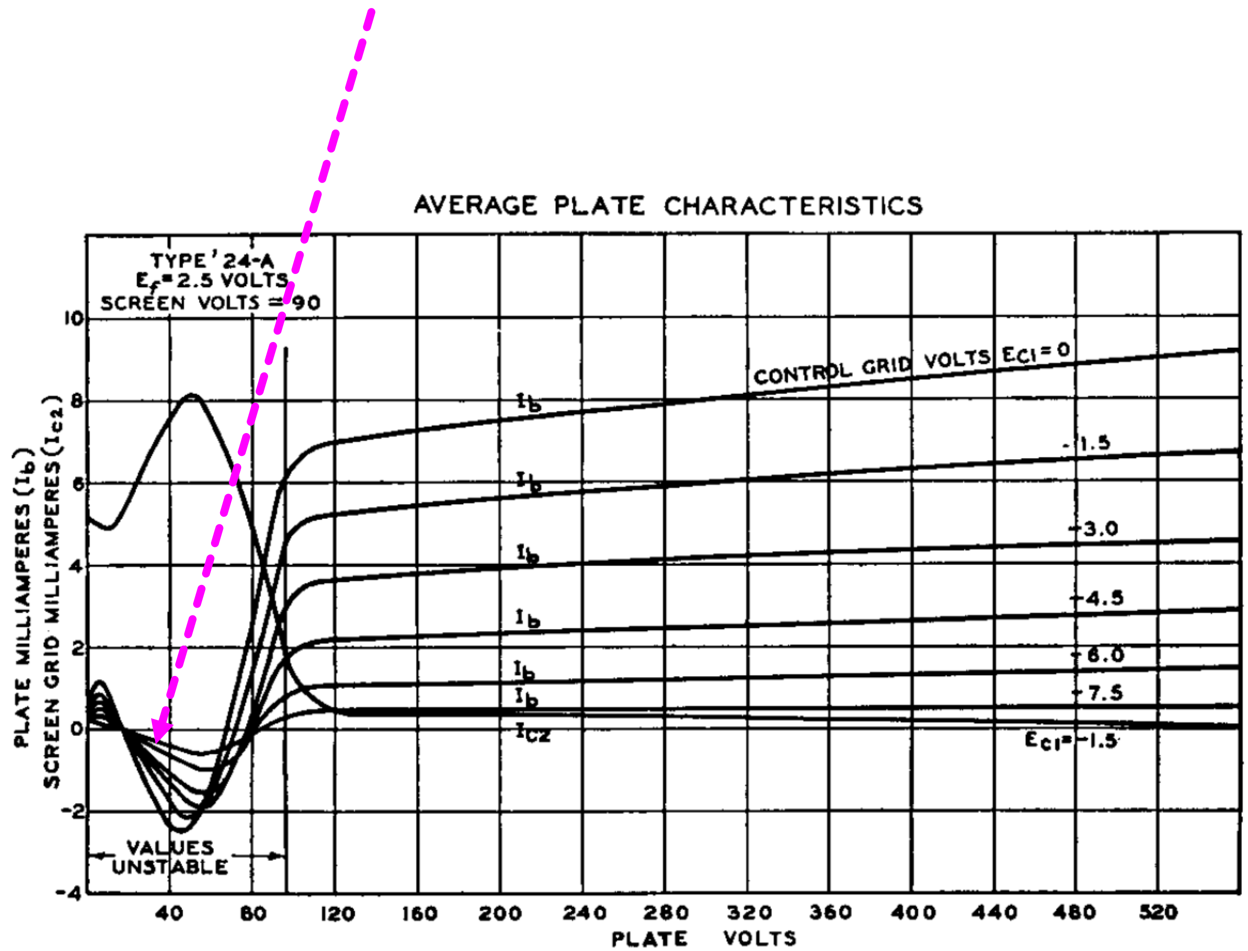
- The presence of the screen grid had some issues… if screen grid potential was higher than that on the plate (which would happen during down swings), secondary emission of bouncing electrons on plate would happen:
  - In this situation you could have regions where the plate characteristics had a trend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



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

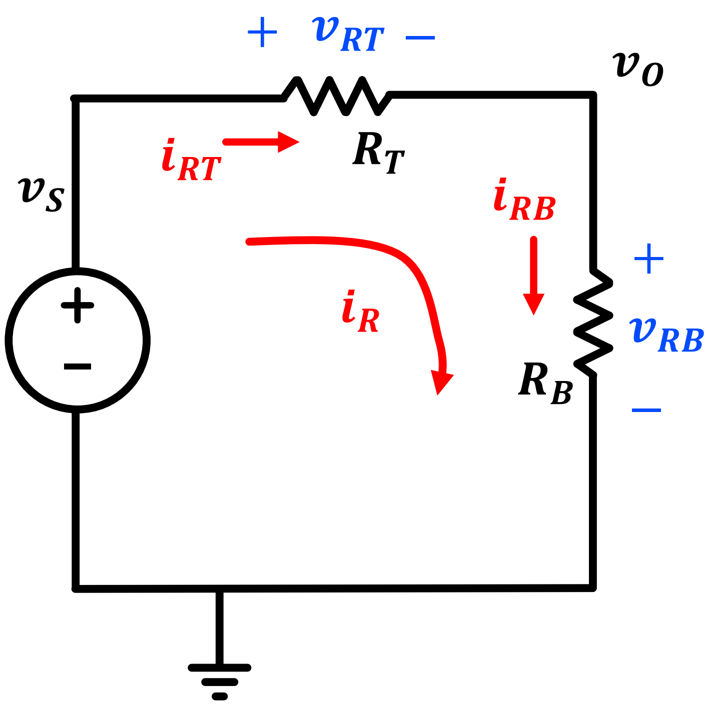
Big Issue!

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

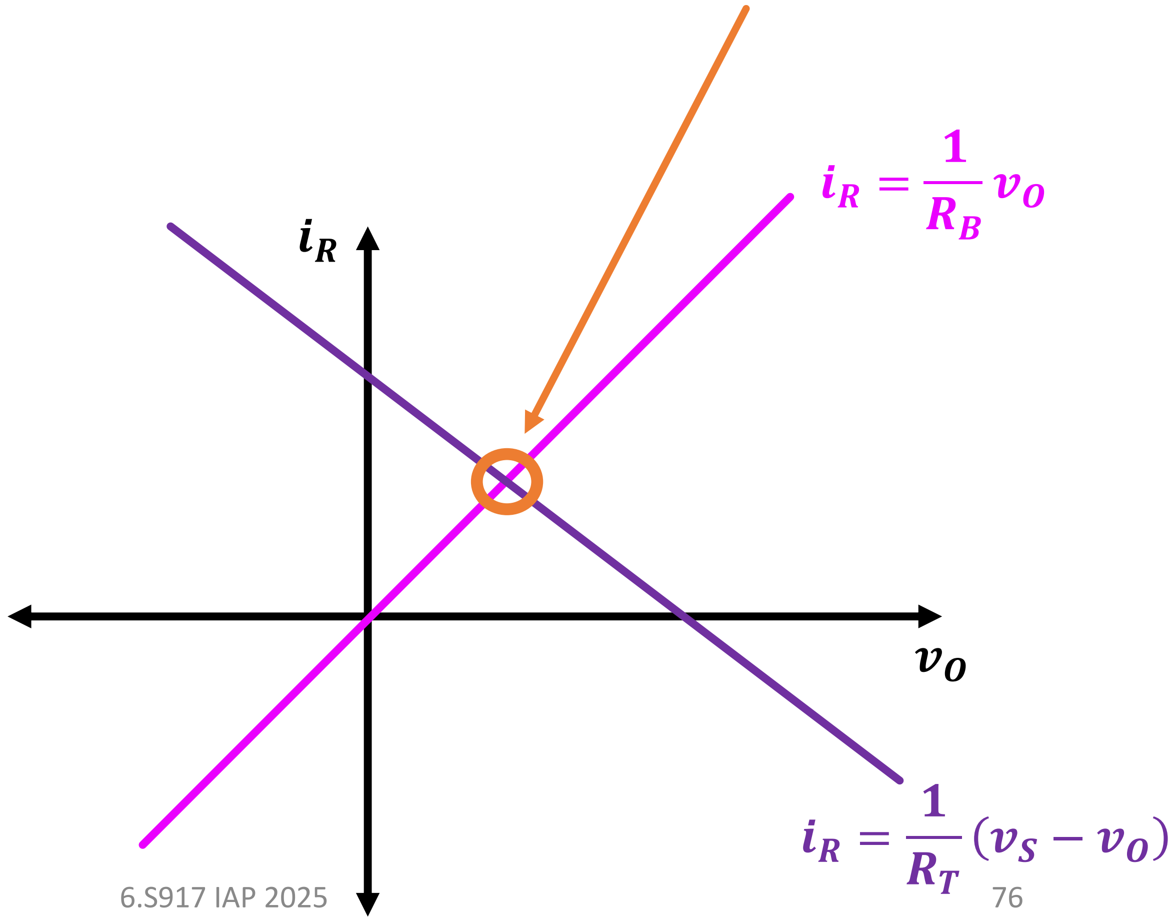


https://www.physics-and-radio-electronics.com/electronic-devices-and-circuits/vacuum-tubes/vacuumtetrode.html

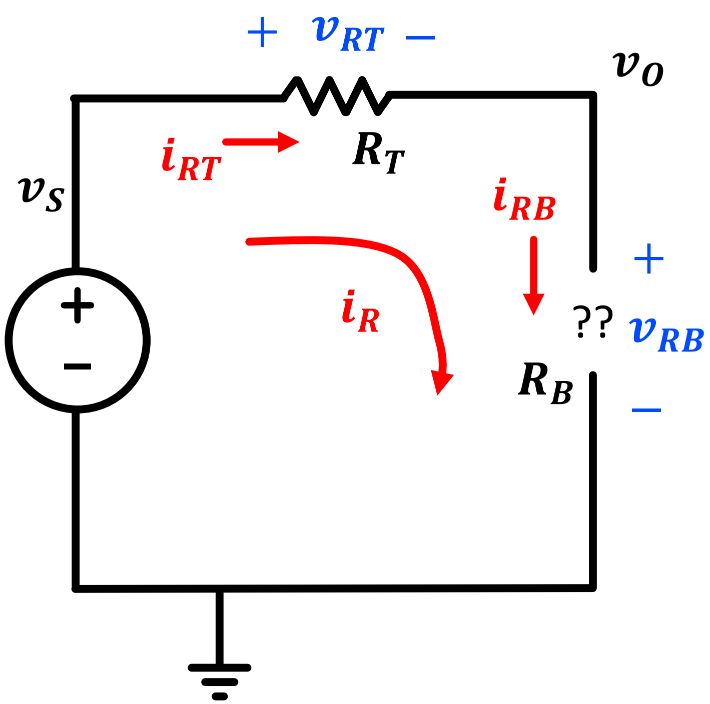
Remember the Load Line!



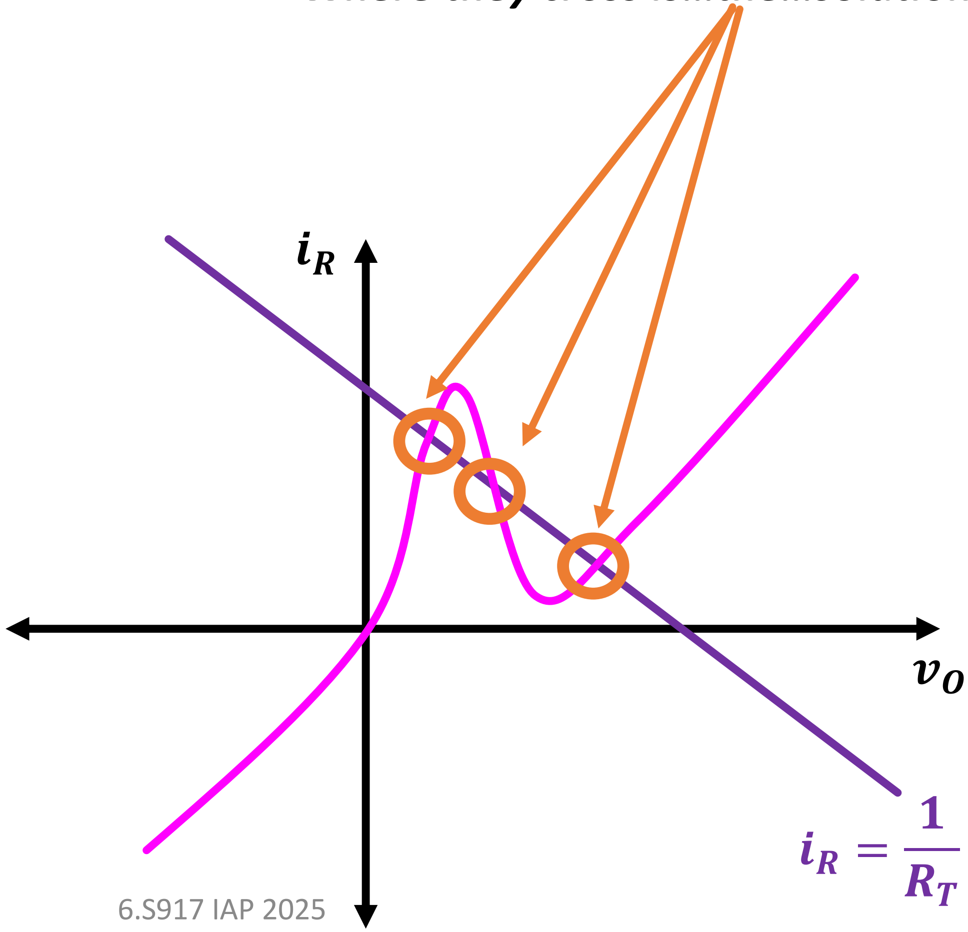
Where they cross is the solution!



What if….

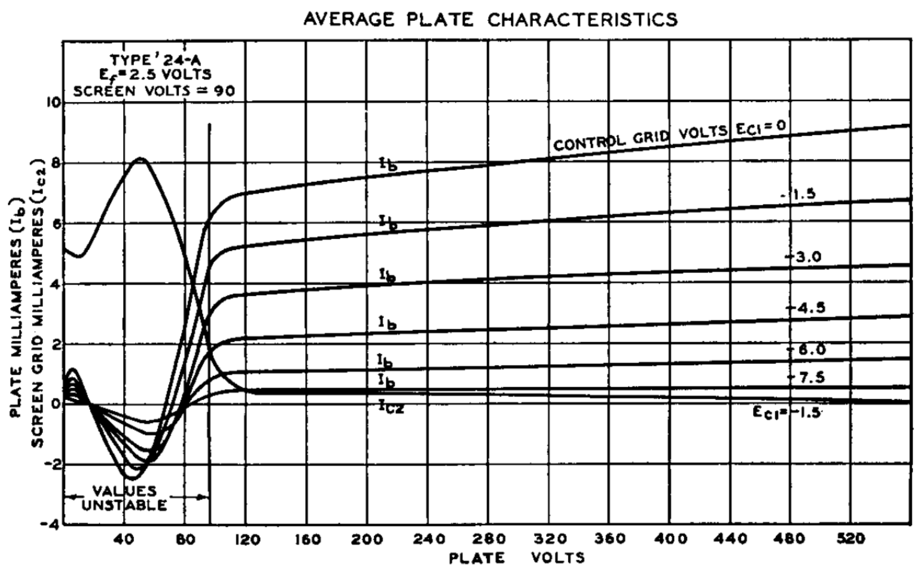


Where they cross is…the…solution



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.



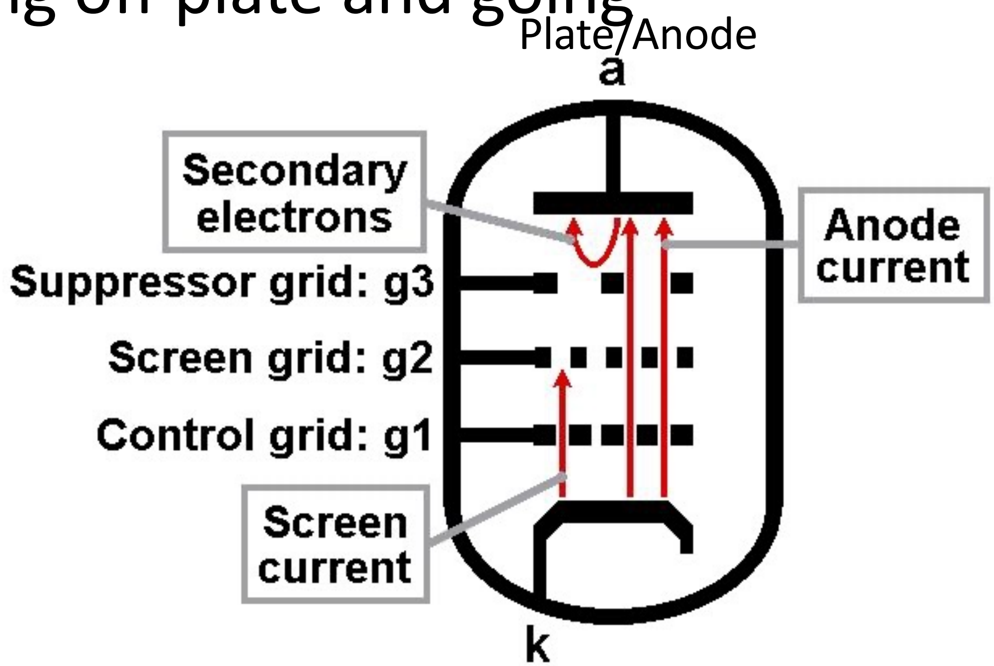
Solution…Add *Another* Grid

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

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

The Suppressor Grid

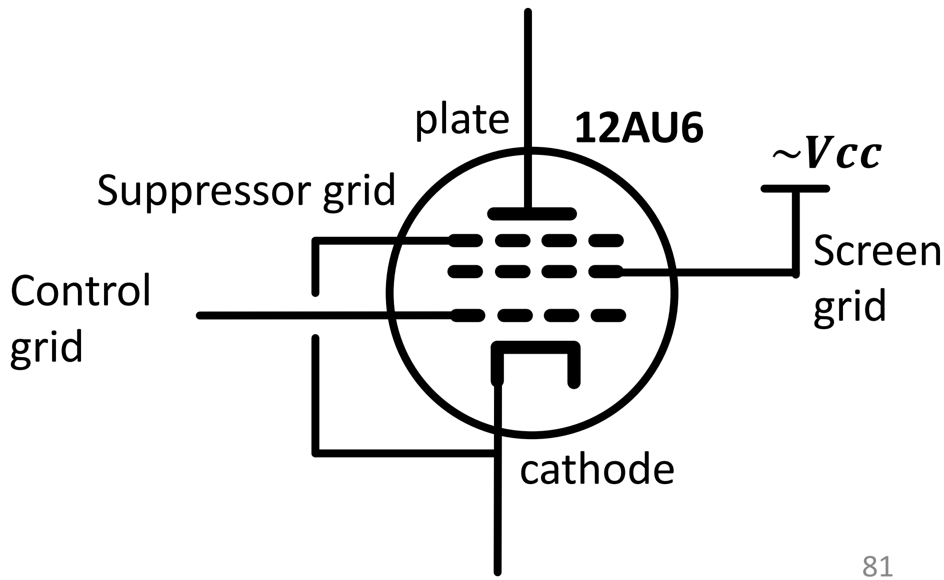
- Screen will still have some current, but putting a grid at low voltage between it and the plate will make any electrons think twice before bouncing off plate and going back to the screen.
- Invented by:
  - Holst and Tellegen
  - Late 1920s



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

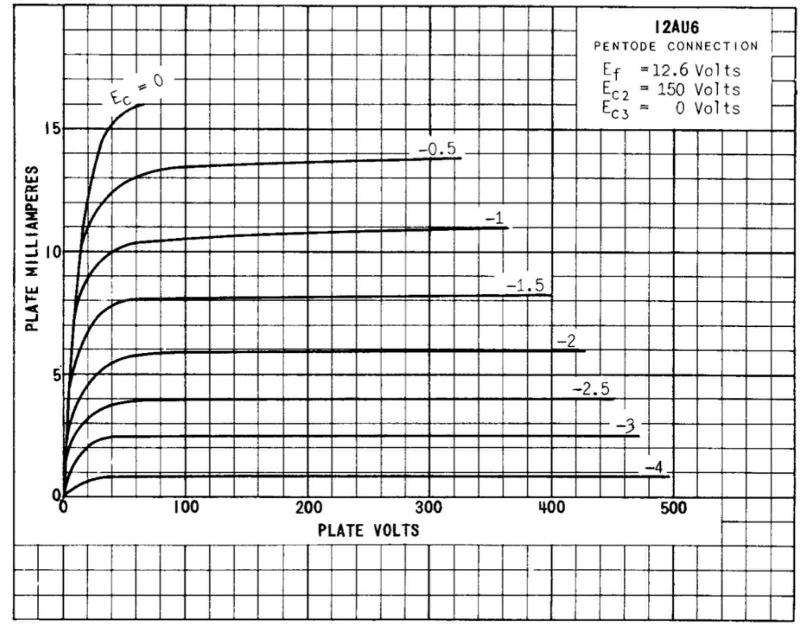
The Pentode Was Born

- 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



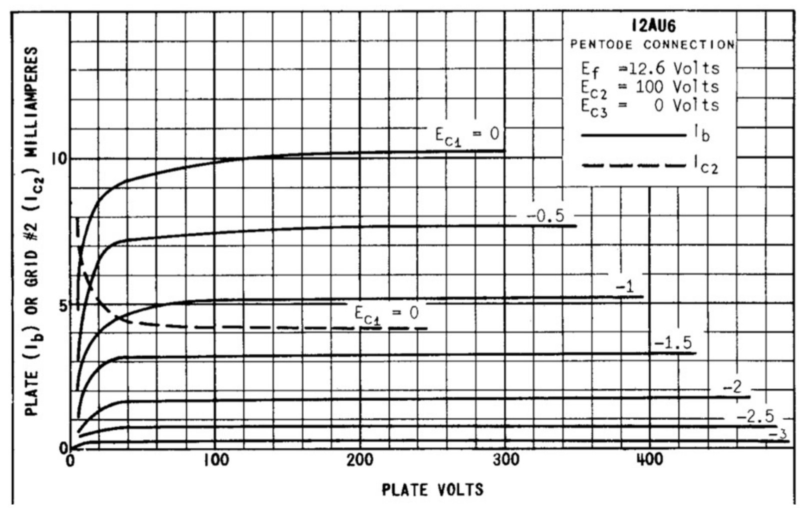


Plate-to-Grid Capacitance

- 12AT7 Triode Capacitance (grid to plate):

Direct Interelectrode Capacitances	With Shield*	Without Shield	
Grid to Plate, Each Section	1.5	1.5	$\mu\mu f$
Input, Each Section	2.2	2.2	$\mu\mu f$

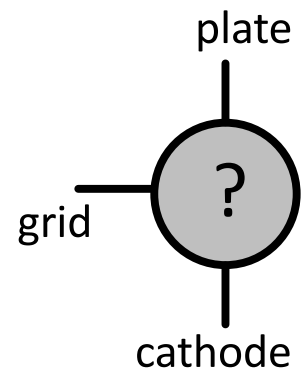
- 12AU6 Pentode Capacitance (grid to plate):

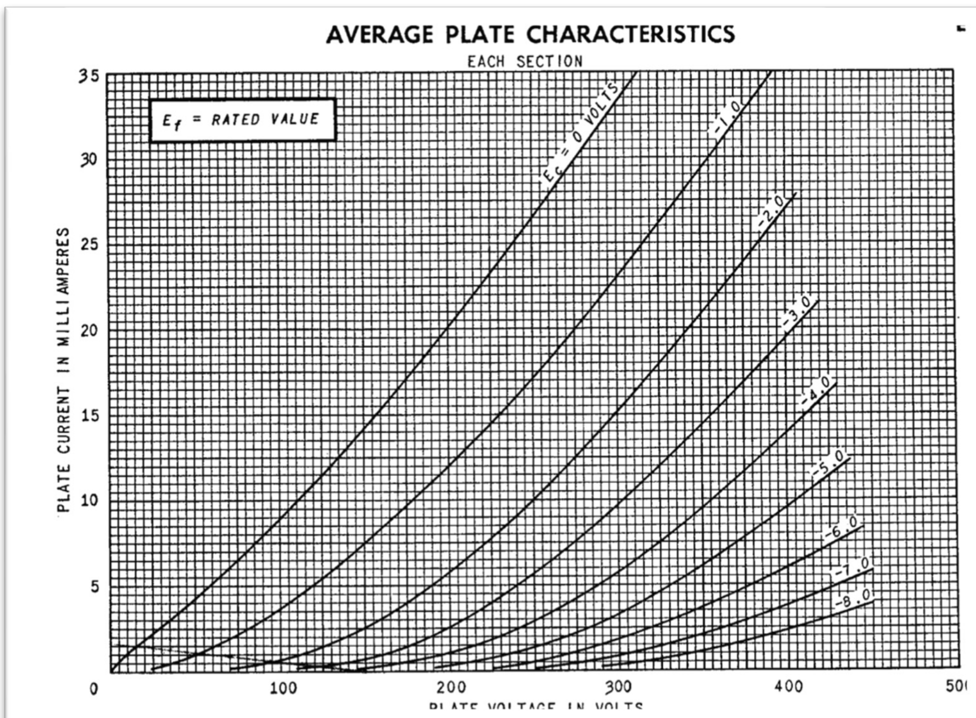
DIRECT INTERELECTRODE CAPACITANCES

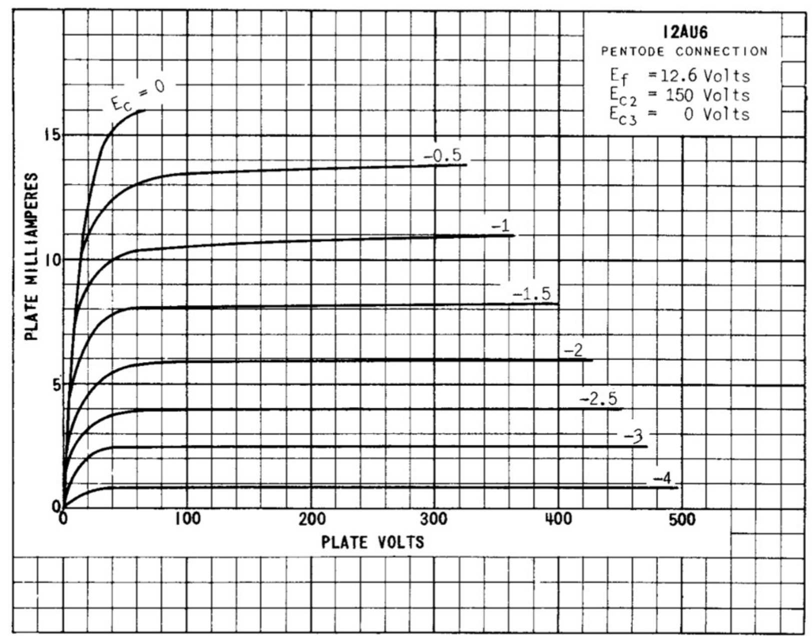
PENTODE CONNECTION:	WITH SHIELD[A]	WITHOUT SHIELD	
GRID TO PLATE: (G_1 TO P) MAX.	.0035	.0035	pf
INPUT: G_1 TO ($H+K+G_2+G_3$&IS)	5.5	5.5	pf

Change in what was a Gain Element

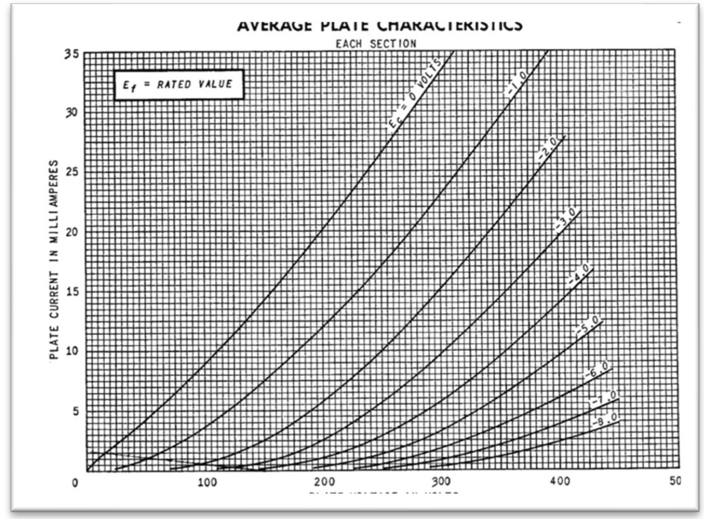
- Still had three terminal devices
- I-V relationships now very different



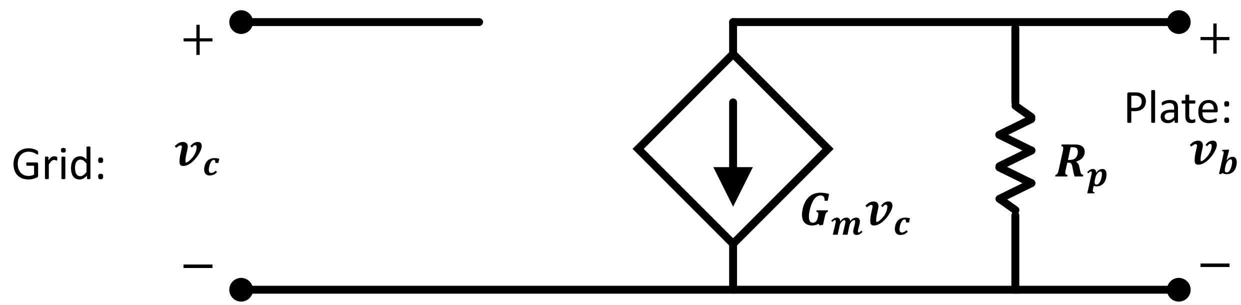


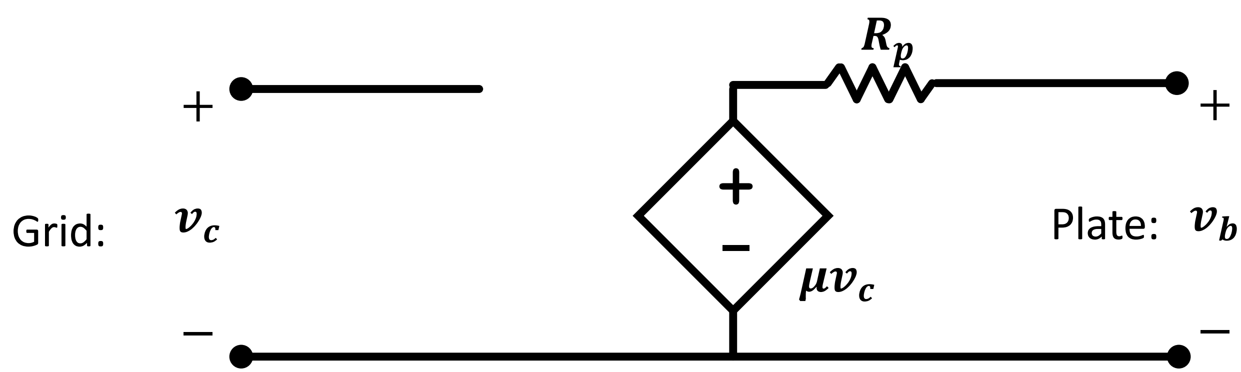


Triodes Kinda Acted Like



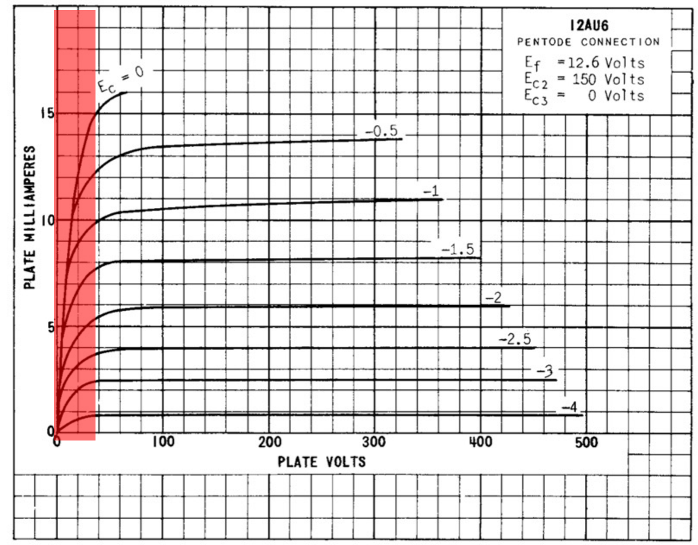
- Either of the following:

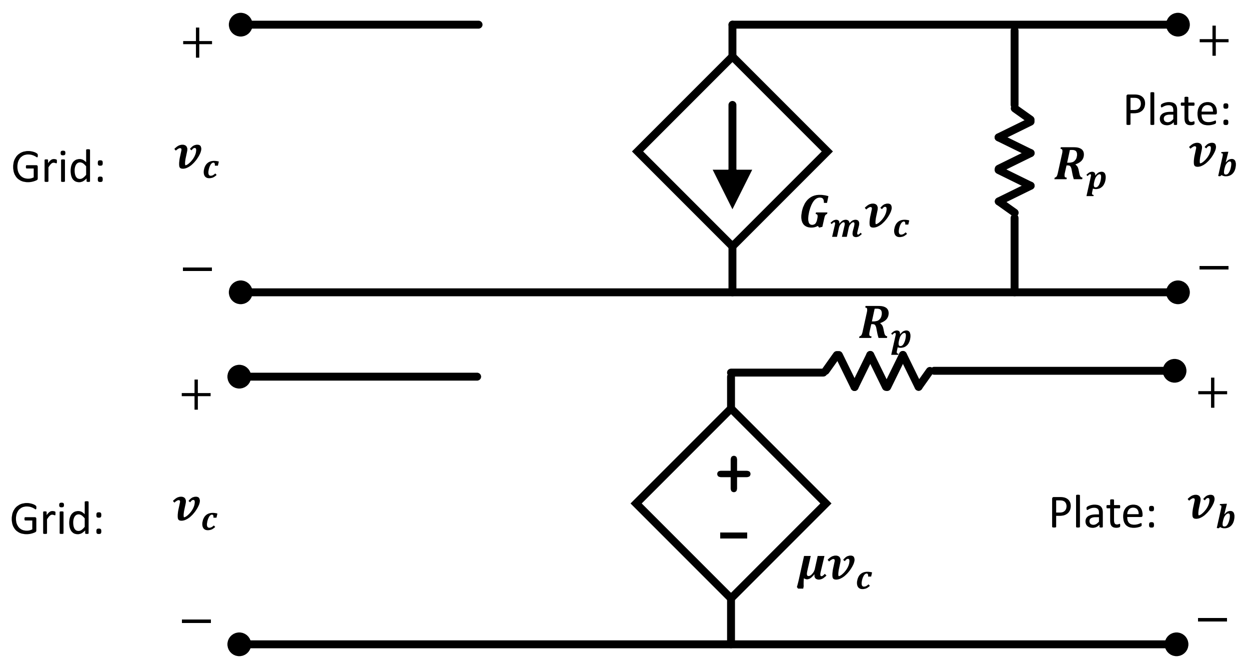




Pentodes…different

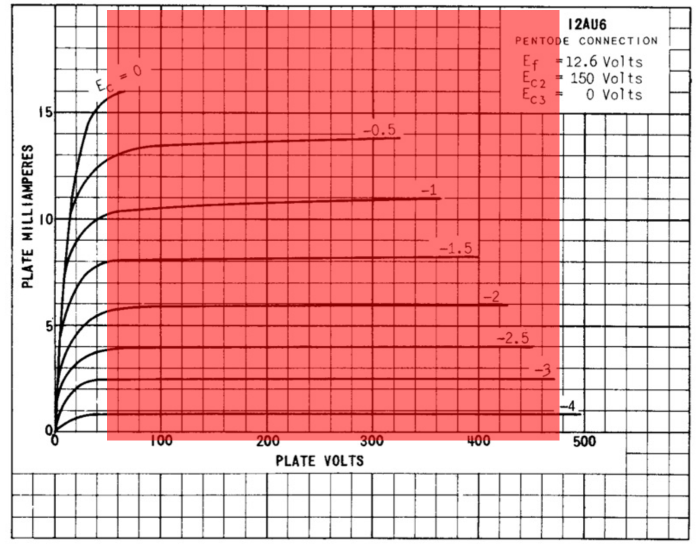
- At low plate voltages acted like very low resistance triodes ($\boldsymbol{R_p}$ small)

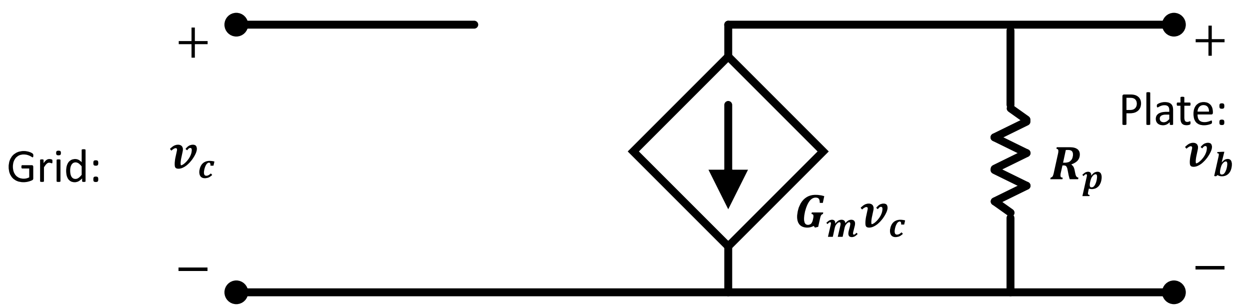




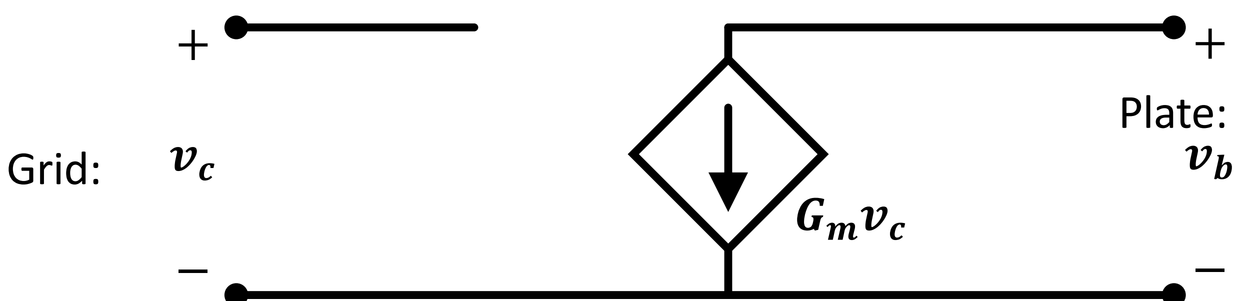
Pentodes…different

- At higher plate voltages acted like very high resistance current source (R_p almost infinite)





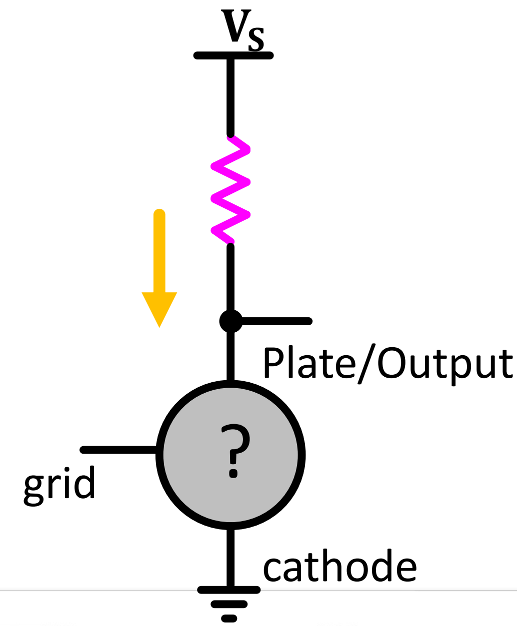
Or really kinda like this:

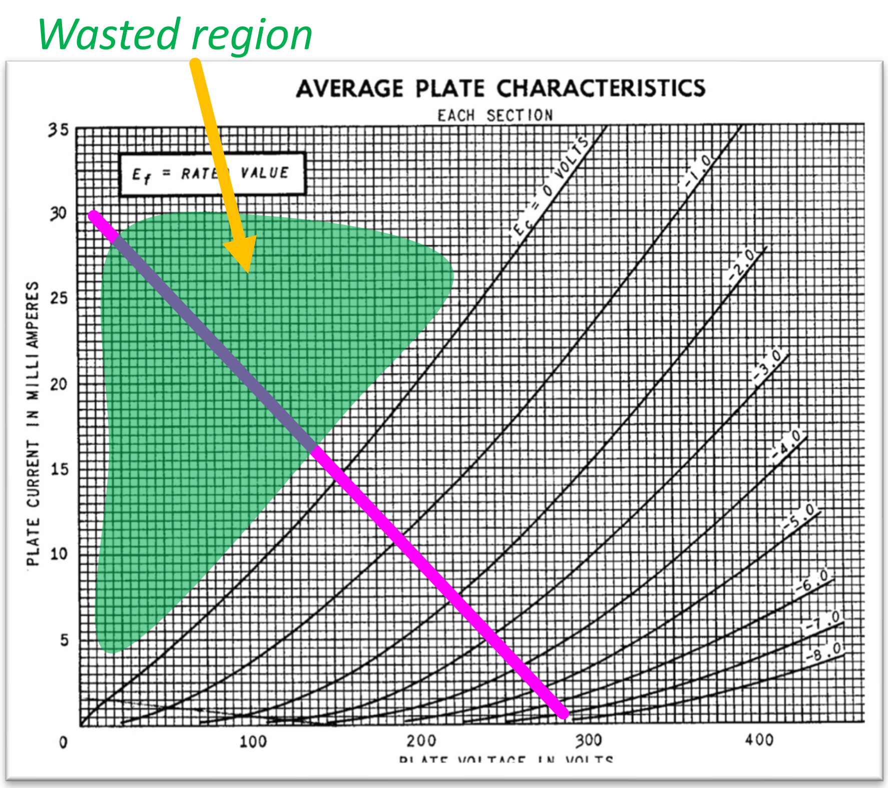


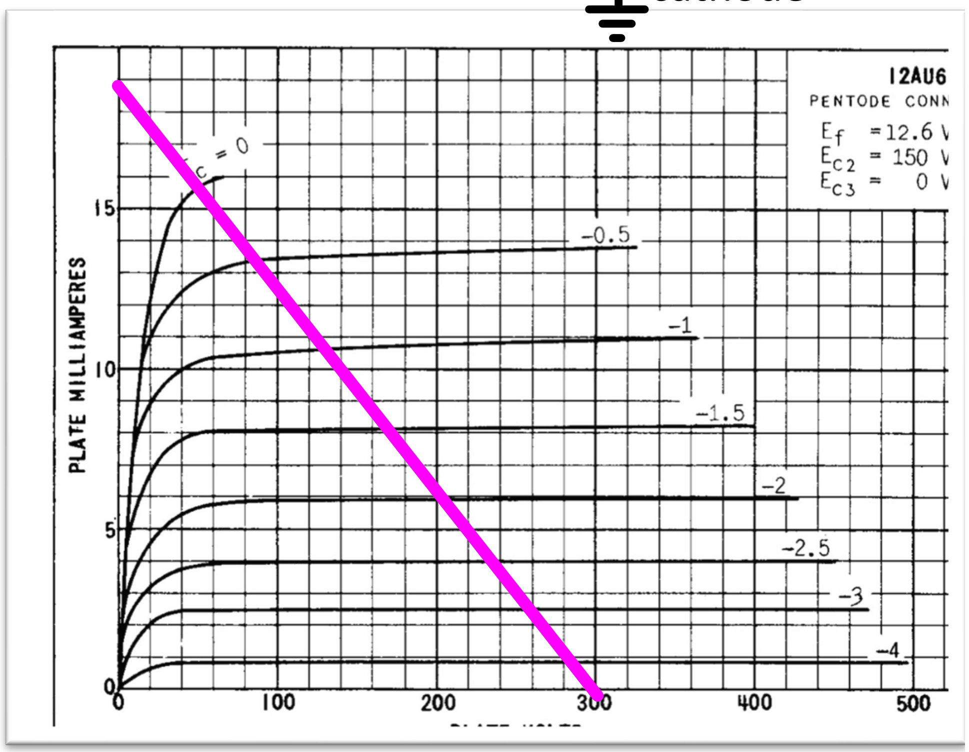
And this is nice…you basically got a voltage controlled current source…not a voltage controlled current source with parasitic shunt resistor like a triode had.

Remember Load Lines

- Pentodes opened up for use a whole different region of the I-V space...
- so you could much larger voltage/power swings into loads







Downsides of Pentodes

- More Noise (so not necessarily good for things like detection/demodulation)...so triodes with low gain would still have uses in the front-end of some circuits
- Higher Output impedance (very flat in plate current for varying plate voltage)…though this is also a benefit in a lot of situations and since these act like current sources it doesn’t matter as much
- Required a Different way to engineer...kinda weird...everyone had been designing circuits with triodes that are like variable resistors...pentodes are weirder

Next Time

- Look more at Pentodes and other -odes
- Look at feedback
- Radio Circuits

- Lab 5 (out now) build an oscillators build an oscillator with pentodes.