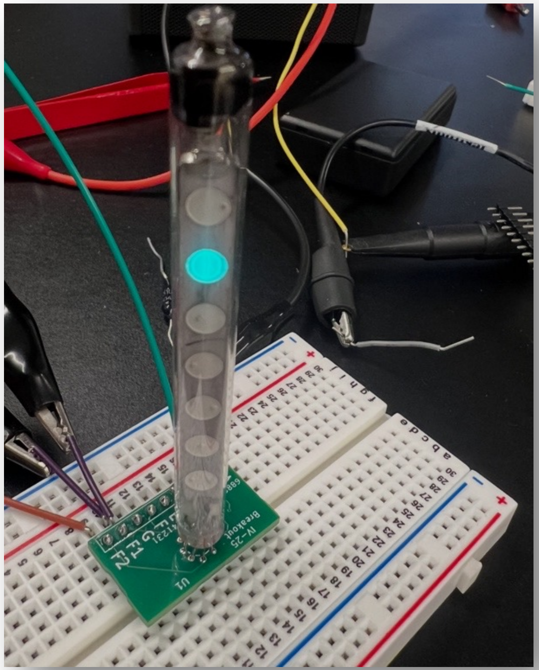
Lecture 3

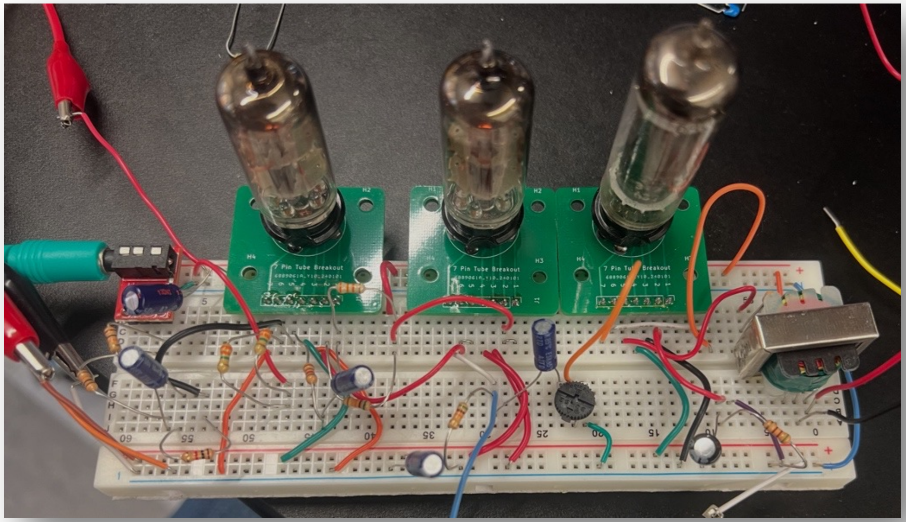
Tube Electronics and Early Transistors

Labs this Week

- Lab 3: Control a Vacuum Fluorescent Display



- Lab 4: Tube Audio Amplifier

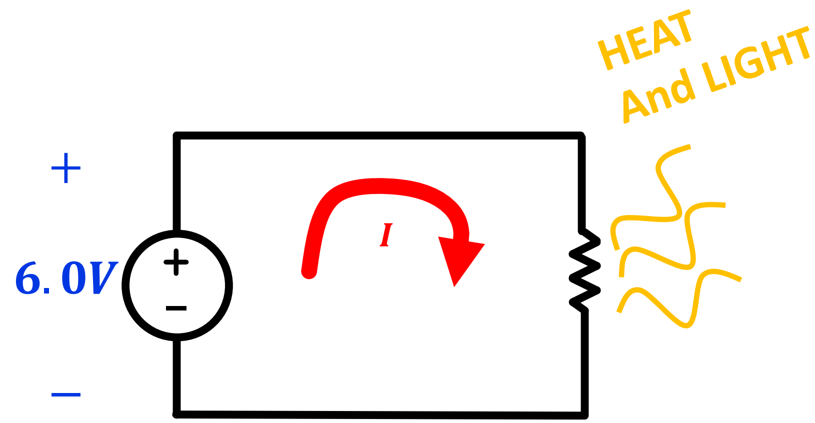


Thermionic Emission, aka “the Edison Effect”

- Early lightbulbs were awful (lasting minutes or hours)
- During experiments to improve light bulbs, lots of weird things were observed.
- People shoved electrodes into the lightbulb to try to make filament last longer….
  - Currents would flow one way and not the other…
  - Largely ignored since what’s the use in that???
- Edison did patent this, but he’d patent literally anything if he could

Beginnings of Vacuum Tubes

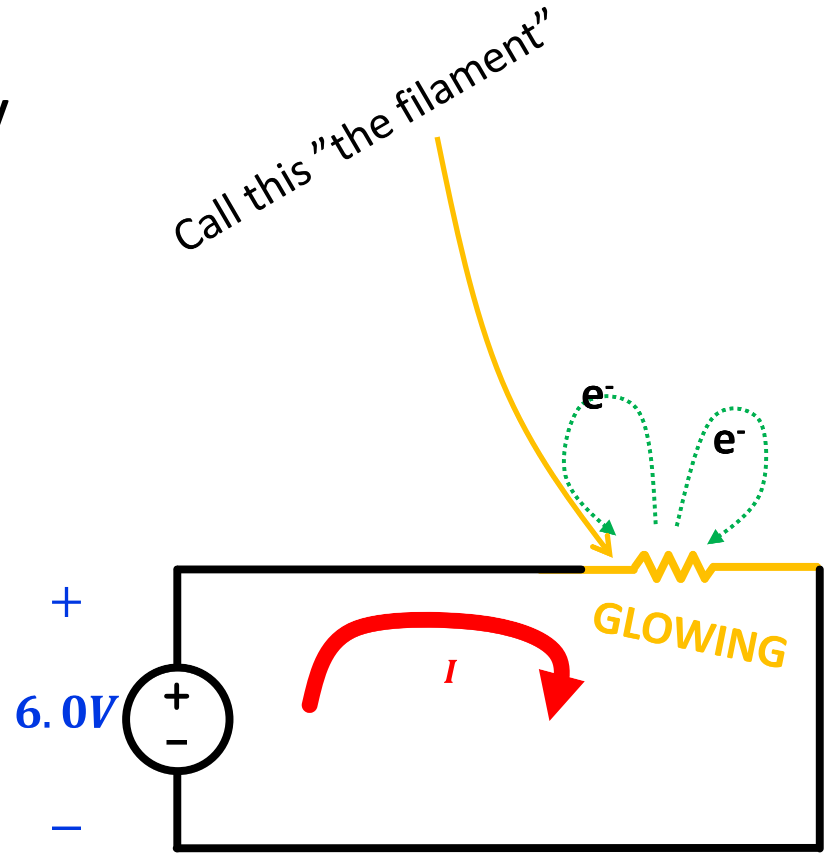
- When you apply a voltage across a resistive material, energy is released. That energy doesn't fly away right away so it stays stuck in the material
- Free energy confined to material warms it up
- Do this enough and material will glow….that's the idea behind a lightbulb



$P = VI$

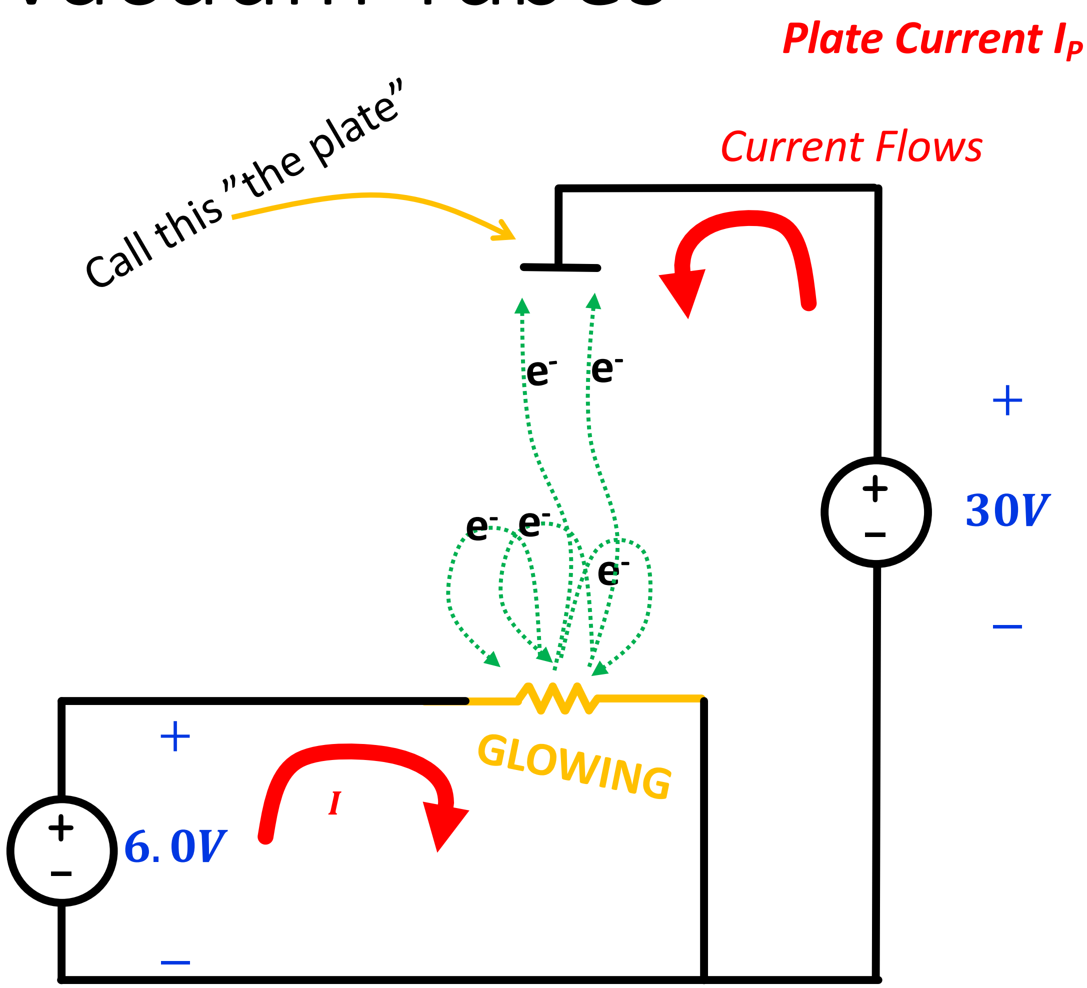
Beginnings of Vacuum Tubes

- When there's enough energy present in a material, electrons can start to be ejected from it.
- In most metals, the particles with the freedom to jump are electrons
- Normally they'll fly off and then fly back down



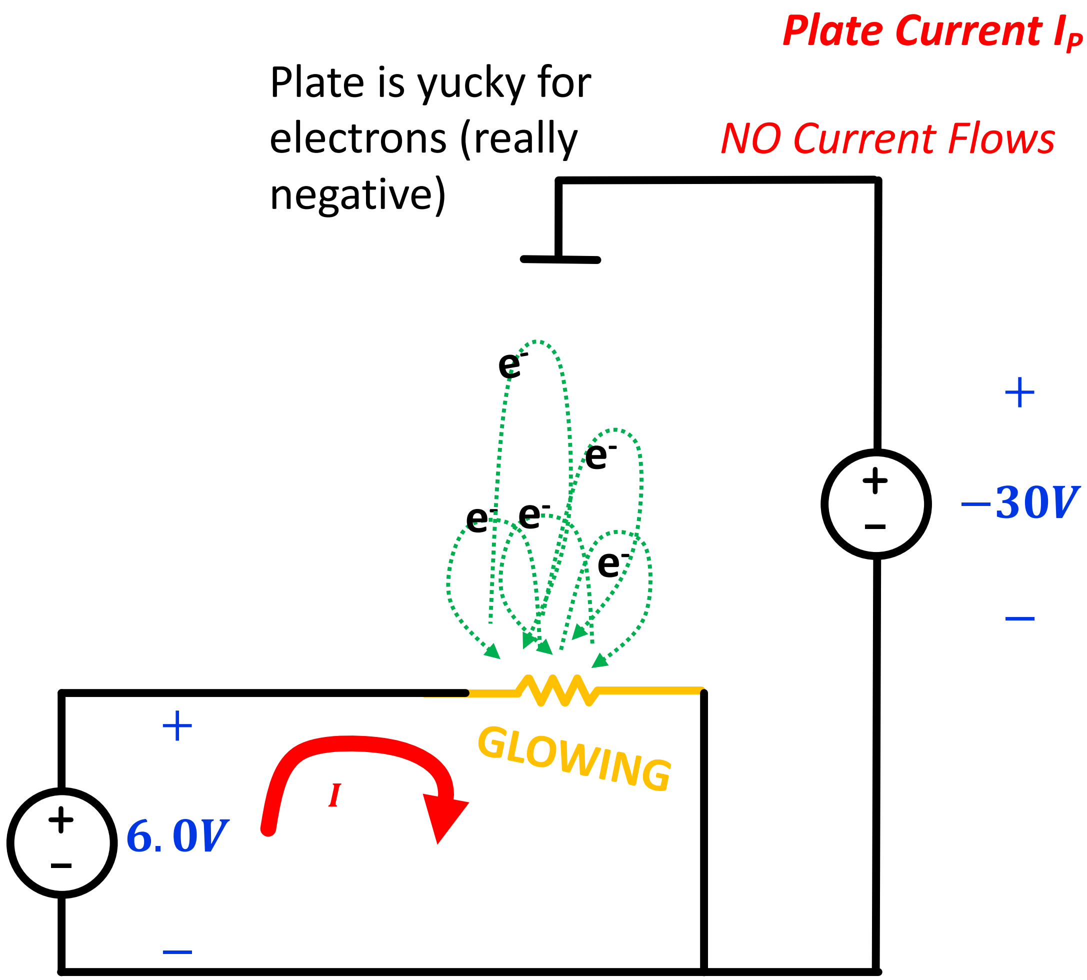
Beginnings of Vacuum Tubes

- If you add a second electrode with a positive voltage near the filament…
- Some electrons will be energized enough and attracted enough to flow to it!
- Current will flow!



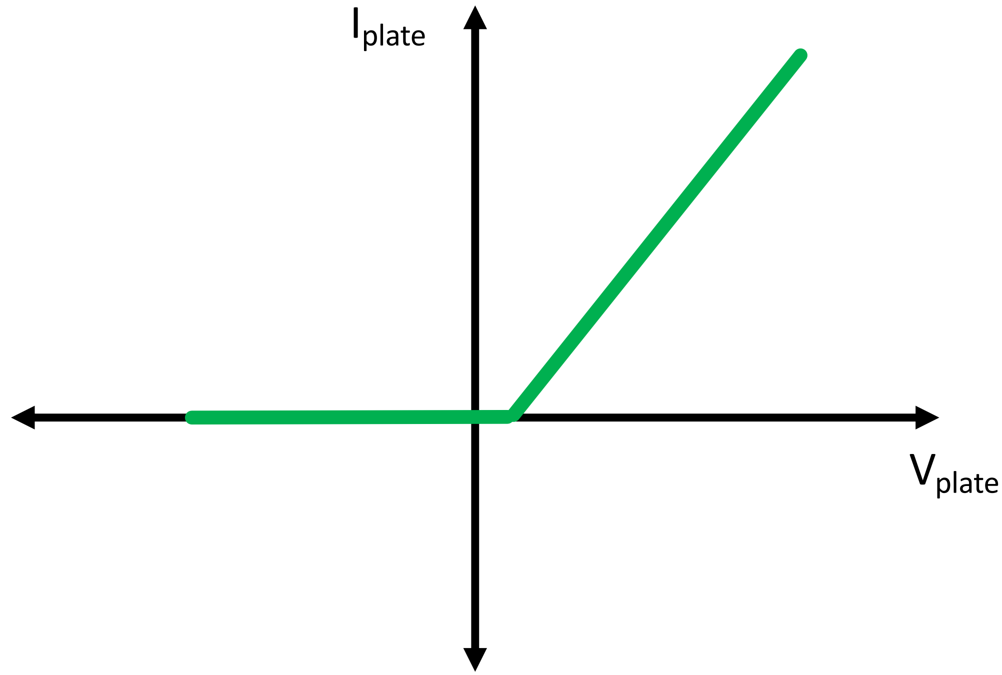
Beginnings of Vacuum Tubes

- If you bias the plate negatively the electrons won't flow
- Weird behavior

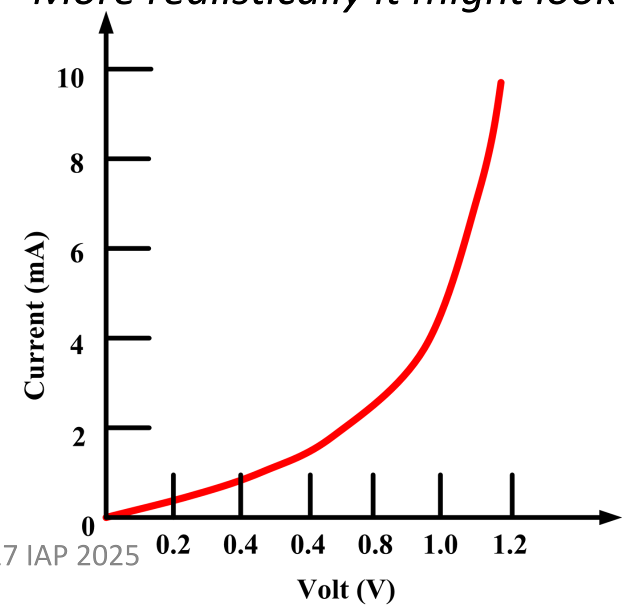


Plot it Out!

- What does this look like?
- …
- NON-LINEAR
- A diode!
- One way electrical valve



More realistically it might look like:

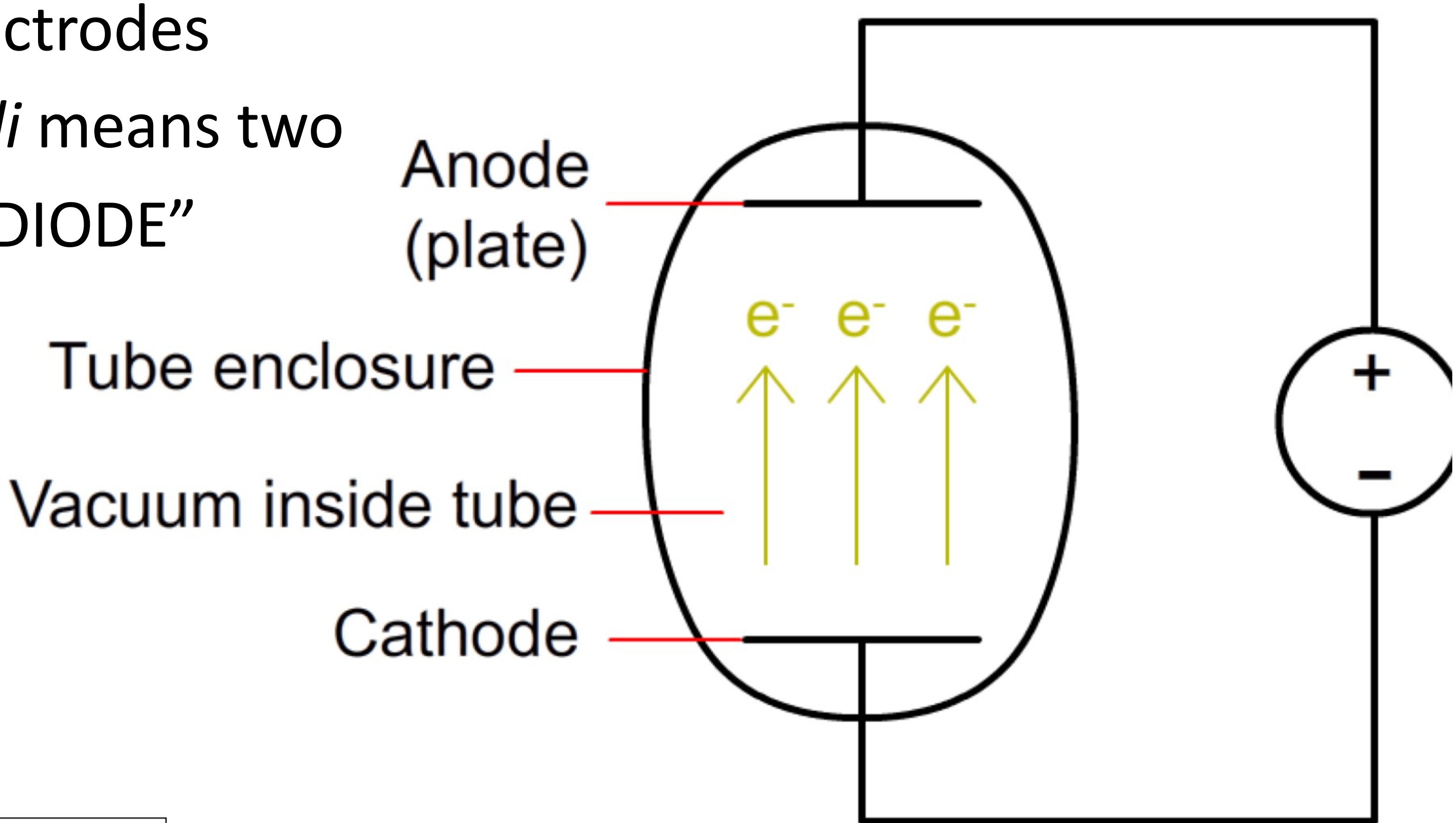


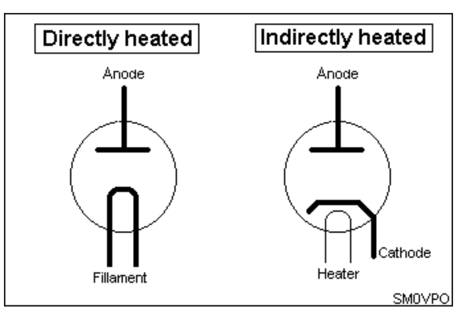
Discovered Several Times

- Fleming in England thought the rectifying behavior was very similar to one-way valves in fluid/pipes…so called it a “Valve”…a term that the English would use for all vacuum tubes in the future (”valve amplifier”)
- Fleming was the first to realize this behavior could be put towards usage as a detector
- The vacuum tube diode on its own didn’t immediately take off. Coherers and Crystal detectors were working ok and the tube diode on its own wasn’t much better (also bleeding edge tech)

Diode

- Two Electrodes
- Greek *di* means two
- Call it "DIODE"

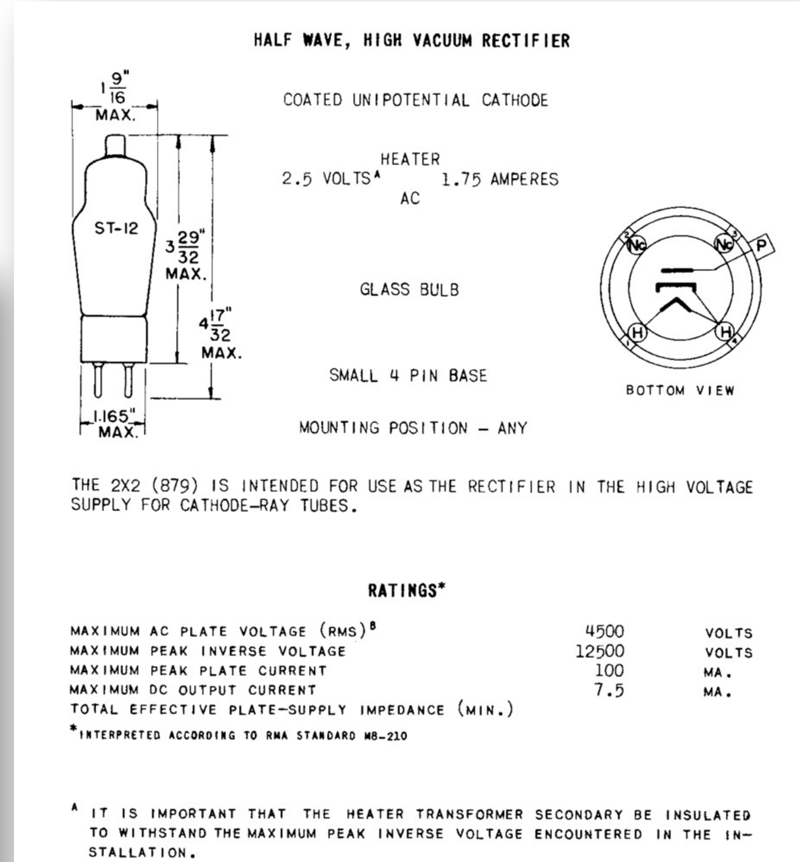




http://213.114.131.21/begin/tube0.htm

https://www.engineering.com/ElectronicsDesign/ElectronicsDesignArticles/ArticleID/16337/Vacuum-Tubes-The-World-Before-Transistors.aspx

Type 879 Tube



HALF WAVE, HIGH VACUUM RECTIFIER

1 9/16" MAX.

ST-12

3 29/32" MAX.

4 17/32" MAX.

1.165" MAX.

COATED UNIPOTENTIAL CATHODE

HEATER
2.5 VOLTS[A] AC 1.75 AMPERES

GLASS BULB

SMALL 4 PIN BASE

BOTTOM VIEW

MOUNTING POSITION – ANY

THE 2X2 (879) IS INTENDED FOR USE AS THE RECTIFIER IN THE HIGH VOLTAGE SUPPLY FOR CATHODE-RAY TUBES.

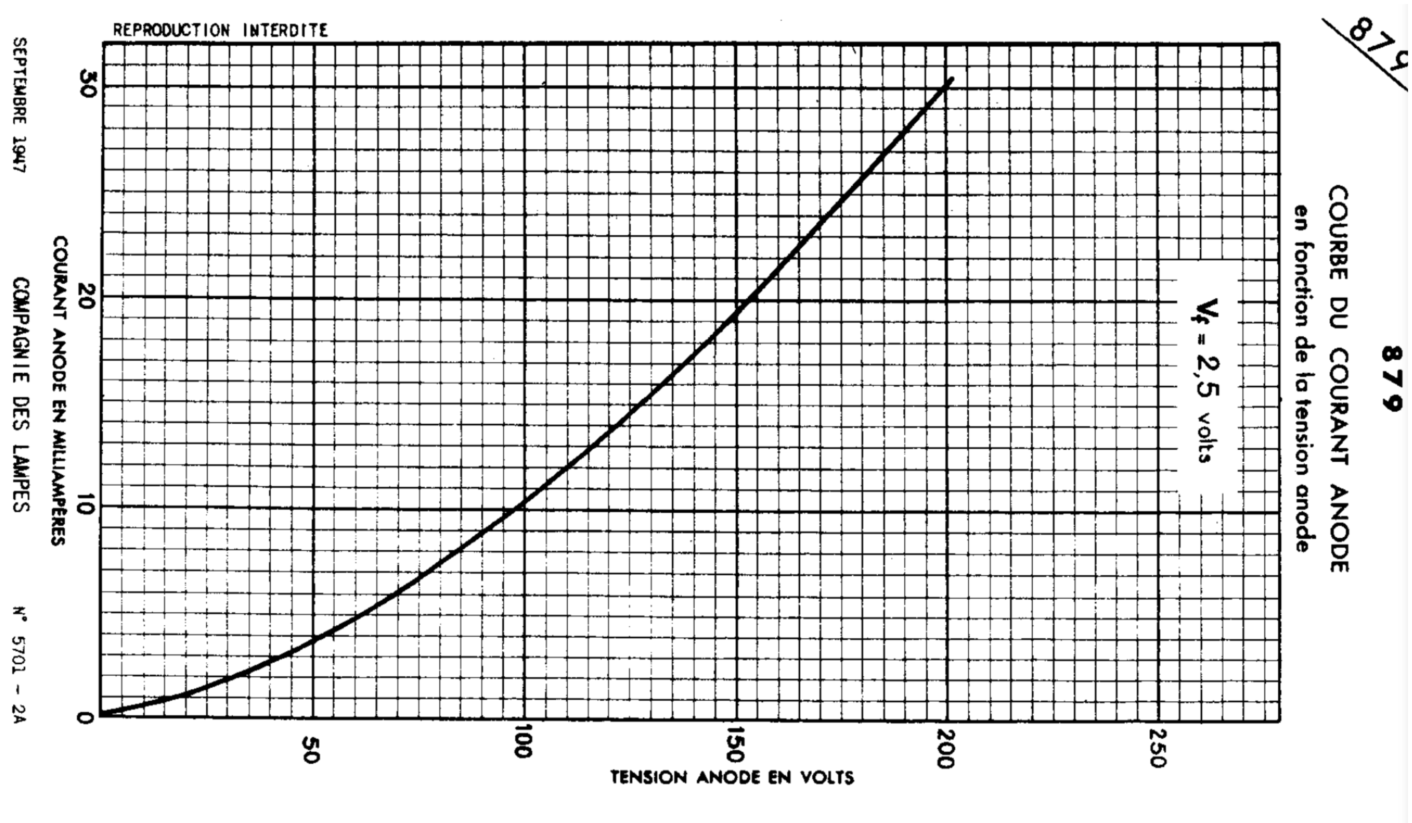
RATINGS*

MAXIMUM AC PLATE VOLTAGE (RMS)[B]	4500	VOLTS
MAXIMUM PEAK INVERSE VOLTAGE	12500	VOLTS
MAXIMUM PEAK PLATE CURRENT	100	MA.
MAXIMUM DC OUTPUT CURRENT	7.5	MA.
TOTAL EFFECTIVE PLATE-SUPPLY IMPEDANCE (MIN.)		

*INTERPRETED ACCORDING TO RMA STANDARD M8-210

[A] IT IS IMPORTANT THAT THE HEATER TRANSFORMER SECONDARY BE INSULATED TO WITHSTAND THE MAXIMUM PEAK INVERSE VOLTAGE ENCOUNTERED IN THE INSTALLATION.

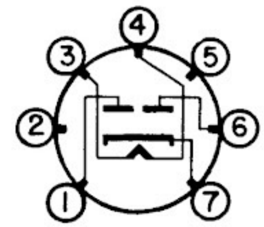
I-V Relationship for 879 Tube



In French because that's the only datasheet I could find for it with curves

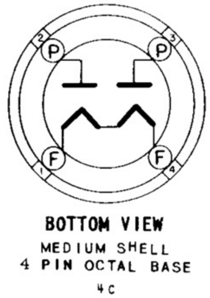
Early Tubes

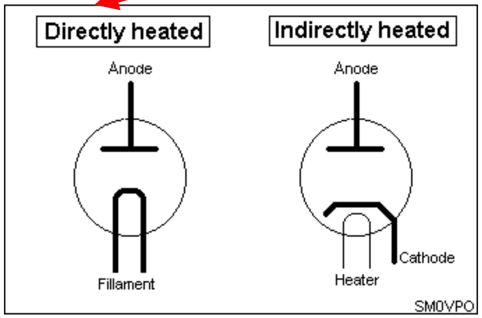
6X4...dual rectifier diode with indirectly heated cathode



- The earliest tubes used the filament <u>directly</u>

Type 80...dual rectifier directly heated cathode

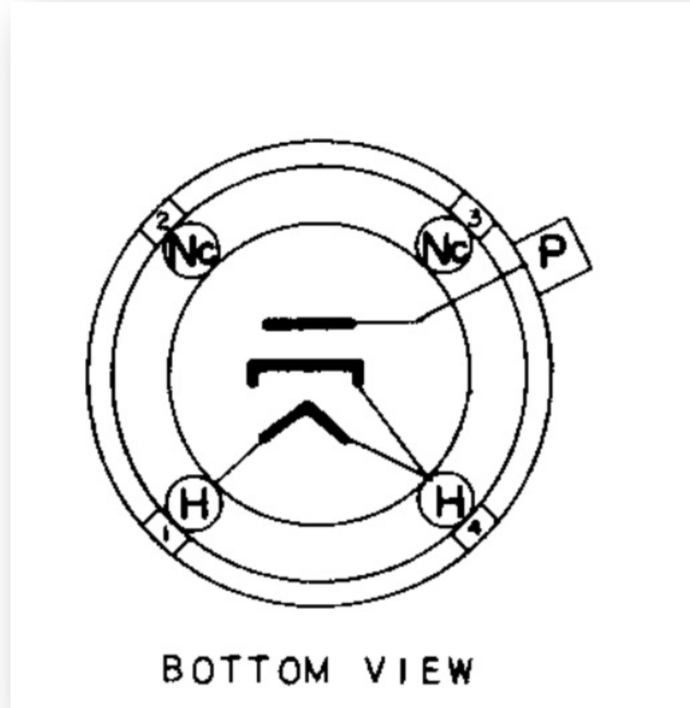




- Could lead to some issues...a good heater wasn't necessarily a good electron emitter...plus electrical noise issues...many later diodes would have the heater and the the cathode electrically separated...
  - In that case the heater indirectly warmed up the cathode...it still emissed electrons, it just wasn't what was making the heat

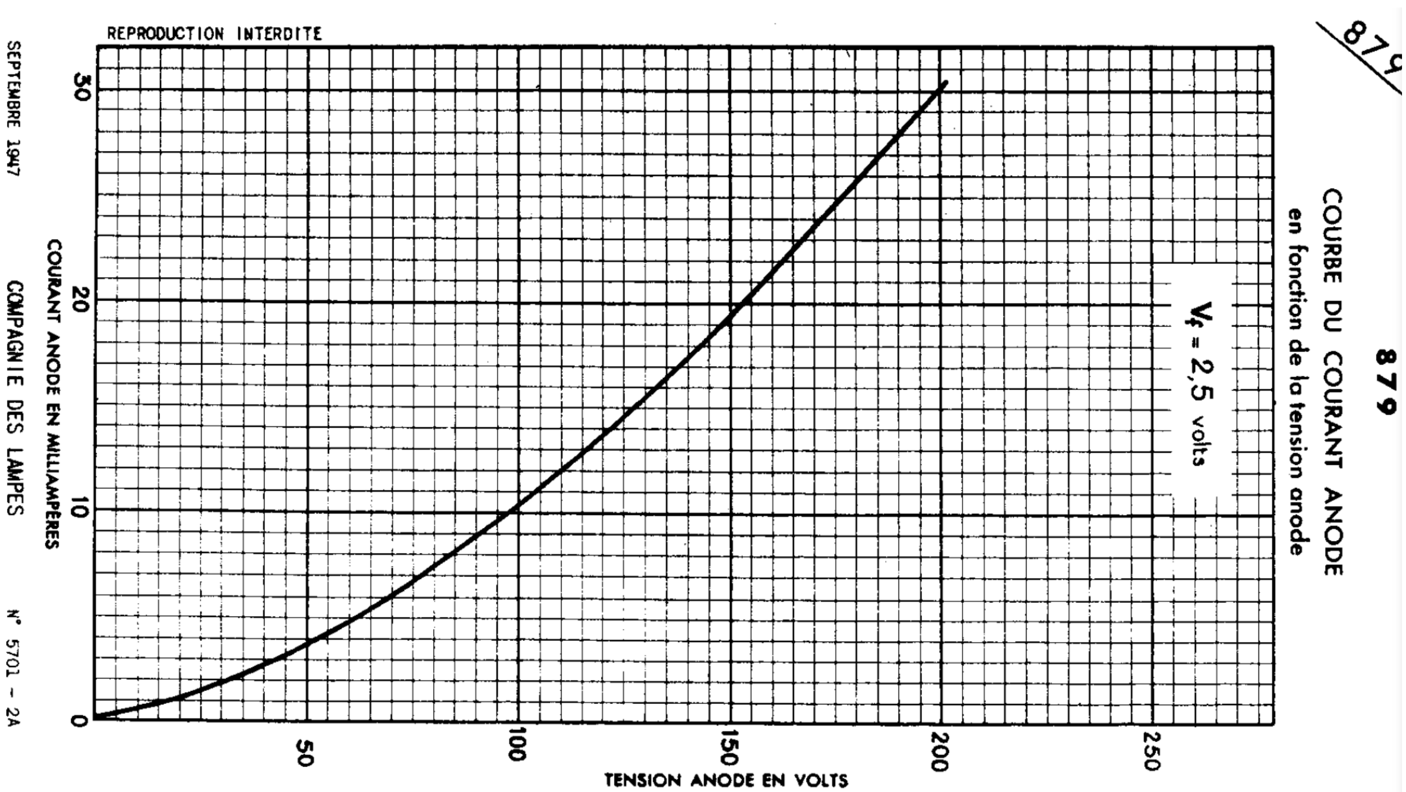
Type 879: Correction

- Four Pins on Tube:
  - Two for filament
    - One pin also connected to separate piece of metal that gets heated
  - Two other pins are no-connection…they are there for structural reasons.
  - The “Plate” is the cap at the top



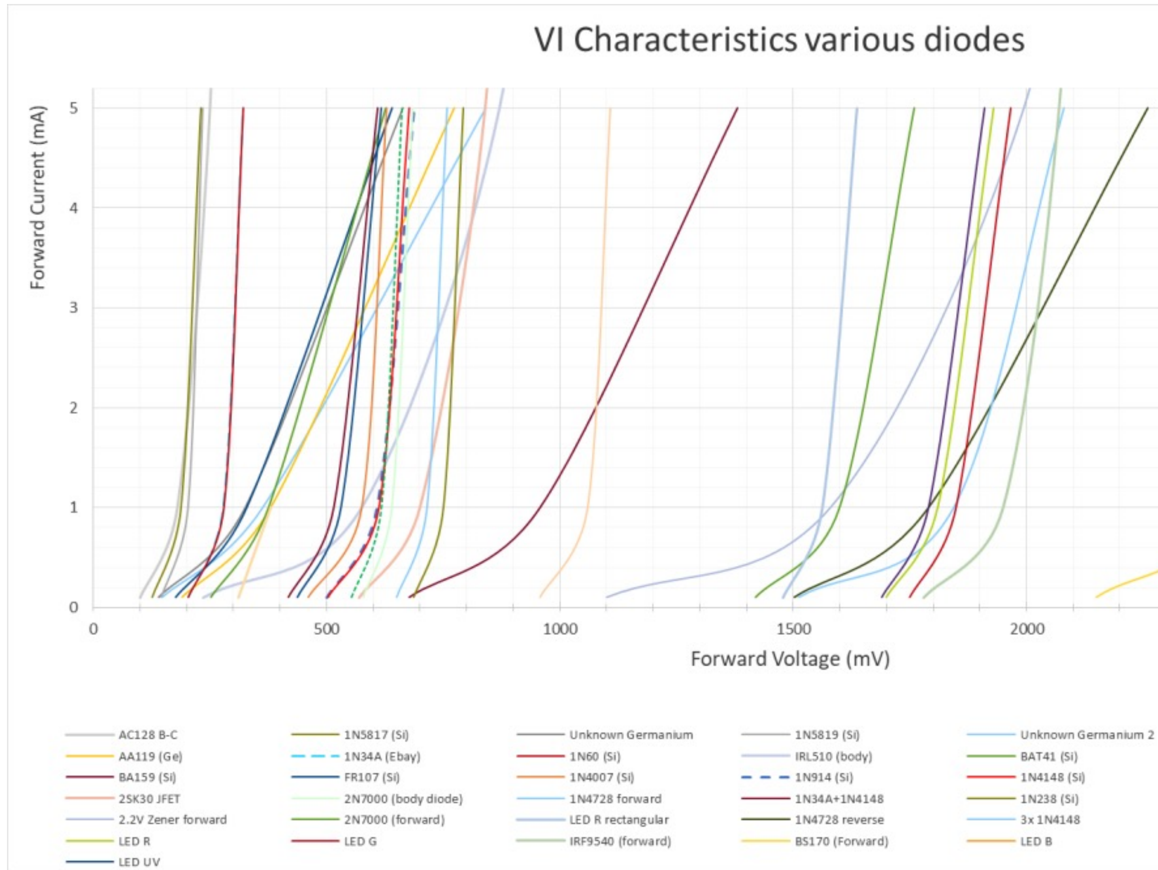
I-V Relationship for 879 Tube

- The Early Tube Diodes did in fact exhibit non-linearity, but the scale over which they exhibited it, left something to be desired.

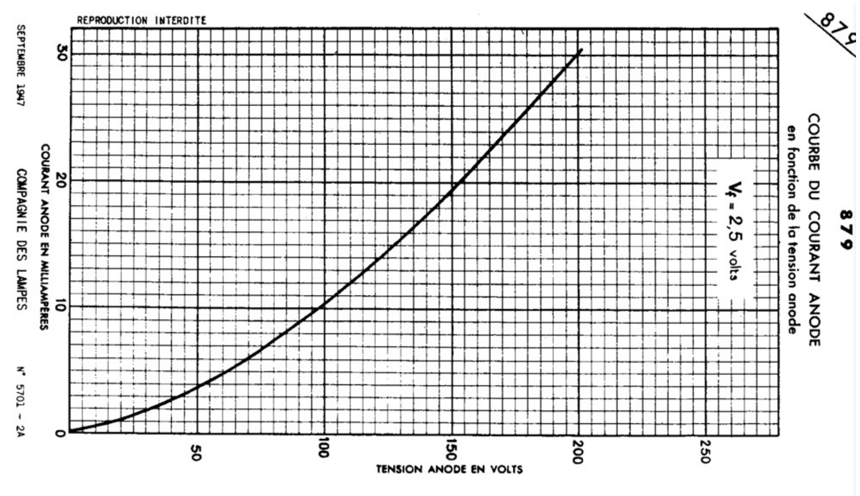


Compare to I-V curves of Semiconductors/Crystals

- Crystal detectors exhibited significant non-linearity/kinks at very low voltages (100’s of mV) not 10’s or 100’s of V like tube diode



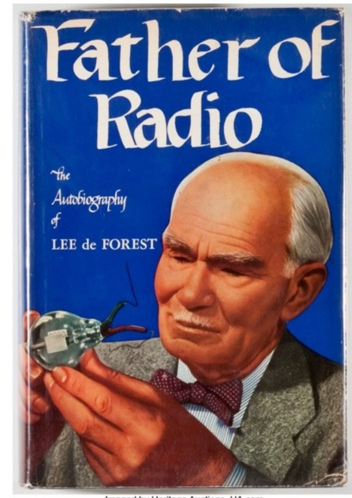
The Tube Diode



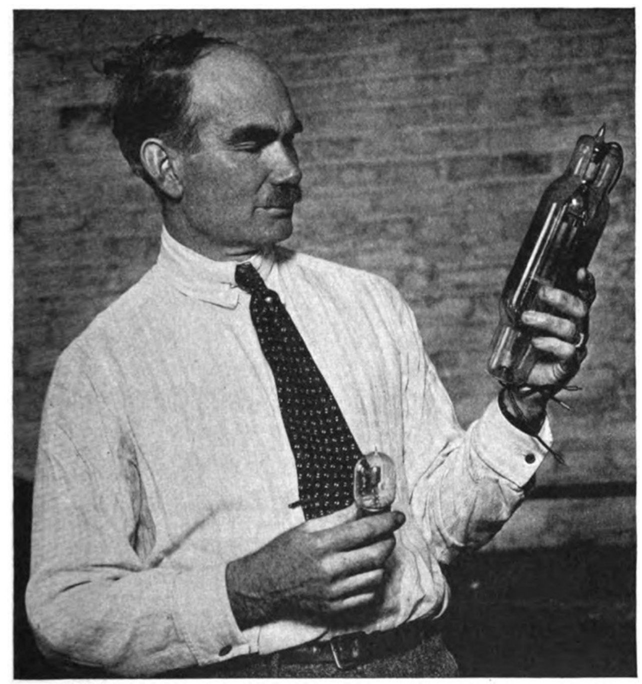
- Just gave non-linearity, not amplification...
- So it wasn’t really solving the radio detector/amplification problem
- Though its non-linearity was useful in early radio transmitters for its mixing/non-linearity
- And in early power supplies!!!
- But not necessarily as detectors
- So people continued to tinker...

Lee De Forest

- First person to put a third wire into a thermionic tube
- He had like a dozen companies that failed and always seemed to become best friends with shysters and conmen/conwomen
- Sued lots of people
- Declared himself to be “father of radio” later in life
- But it is largely established that he invented the “triode” which he called the “audion”
- Had no idea really how it worked



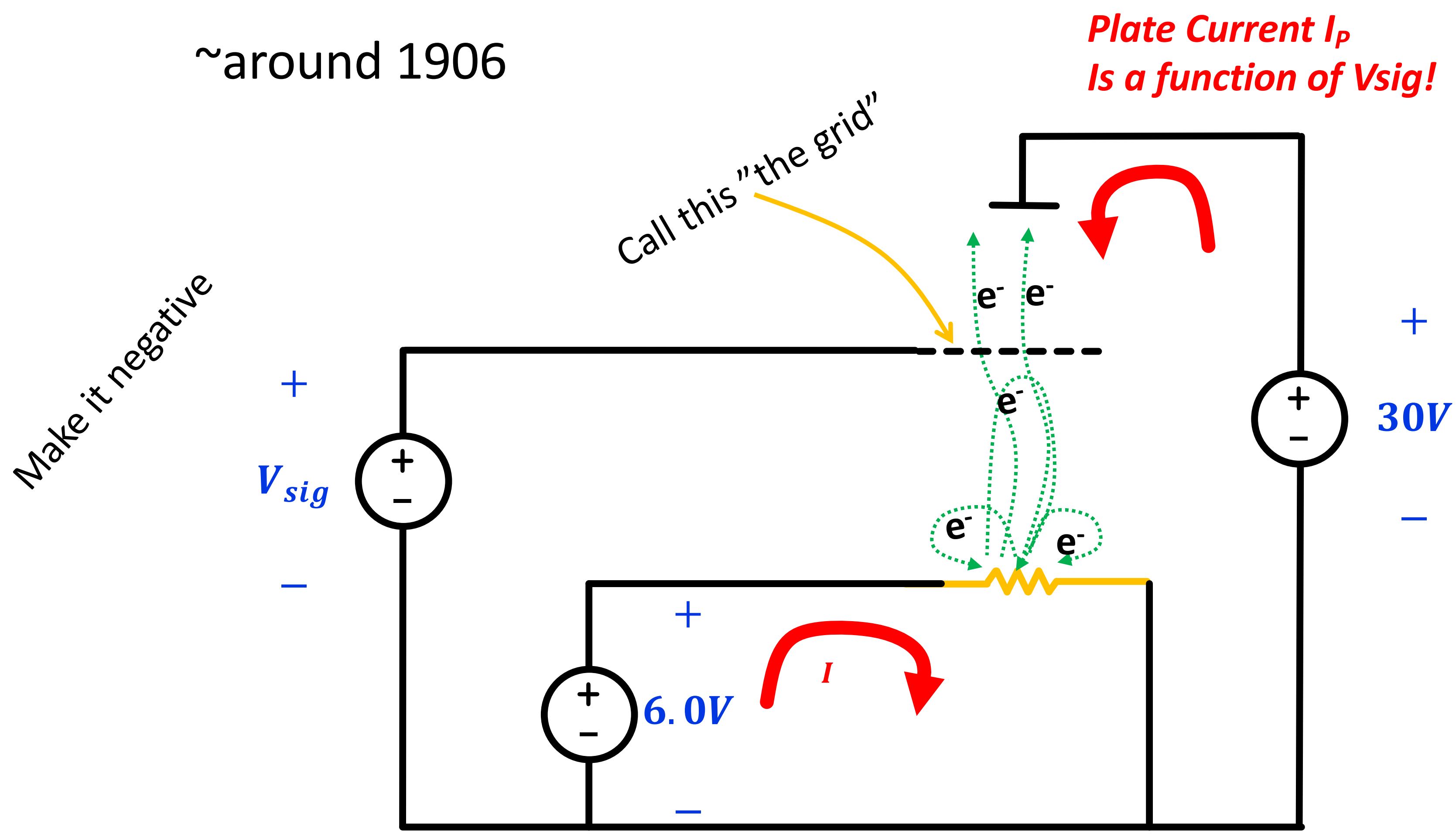
Imaged by Heritage Auctions, HA.com



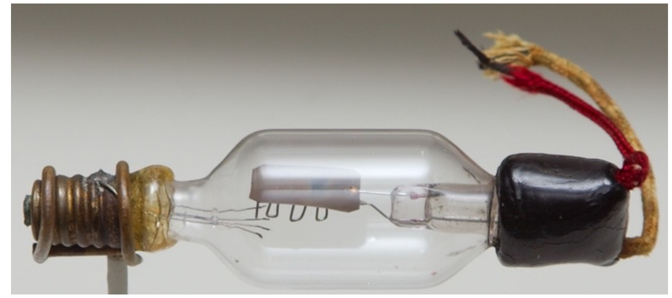
https://en.wikipedia.org/wiki/Lee_de_Forest

Add another Electrode to the Diode

~around 1906



Early "Audions"



- Assumed it would be a kinda sorta good detector and that was their initial application. (weren't used for amplification)
- De Forest assumed that the mechanism of action was the flow of ions so thought that you needed to have a poor vacuum for the thing to work
- This really wrecked early audions' capability to amplify

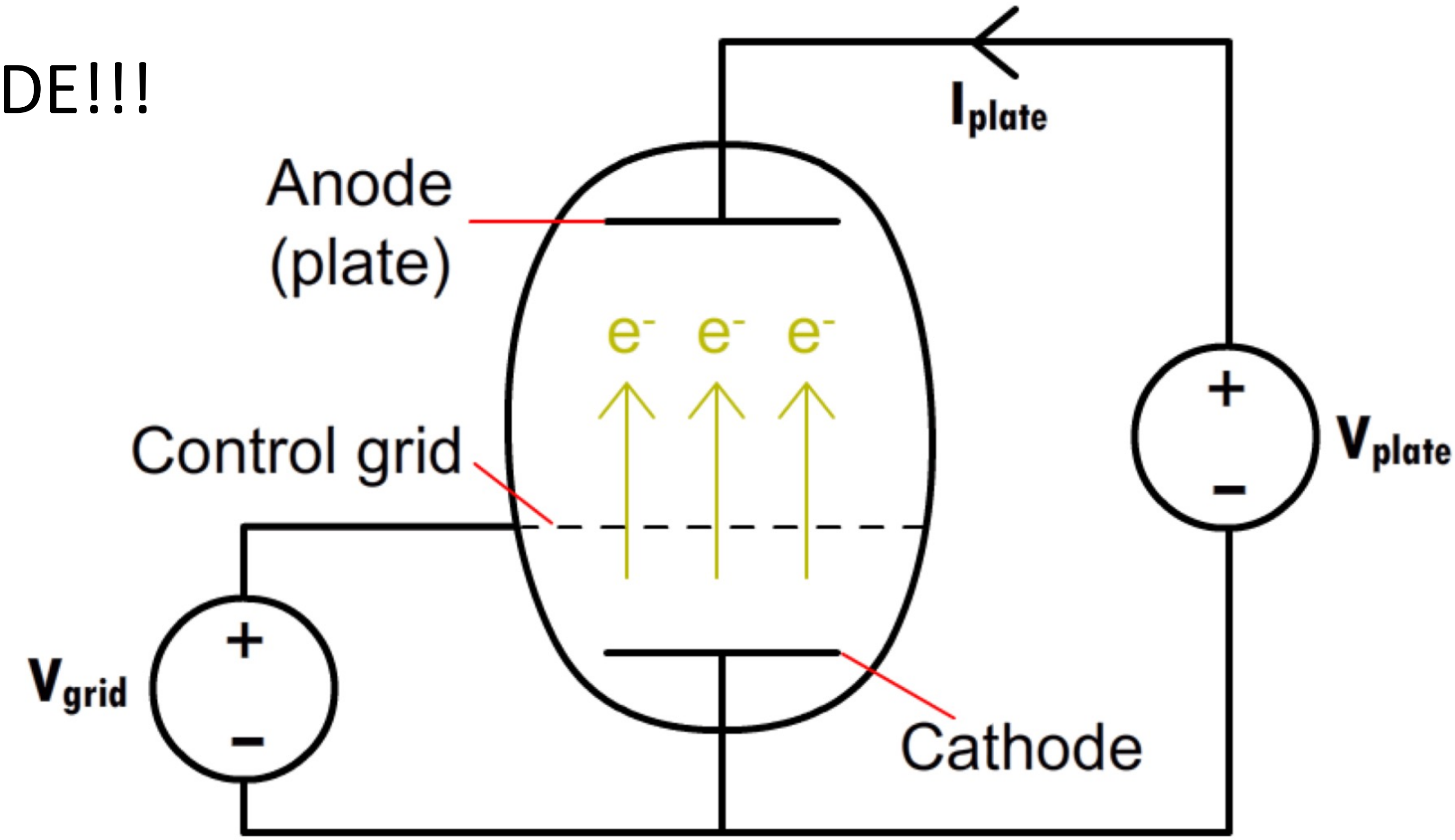
https://en.wikipedia.org/wiki/Triode

Irving Langmuir

- When working at General Electric he realized you really needed to pump down the tubes to a good vacuum.
- Won Nobel Prize later on for work on how oil films organize
- Once he pumped the tubes down, he suddenly was able to get both really good non-linear behavior ***AND*** the ability to amplify somewhat decent amounts
- Named it the “pliotron”, but this basically became the first actual working “triode” in the modern sense

Add another electrode

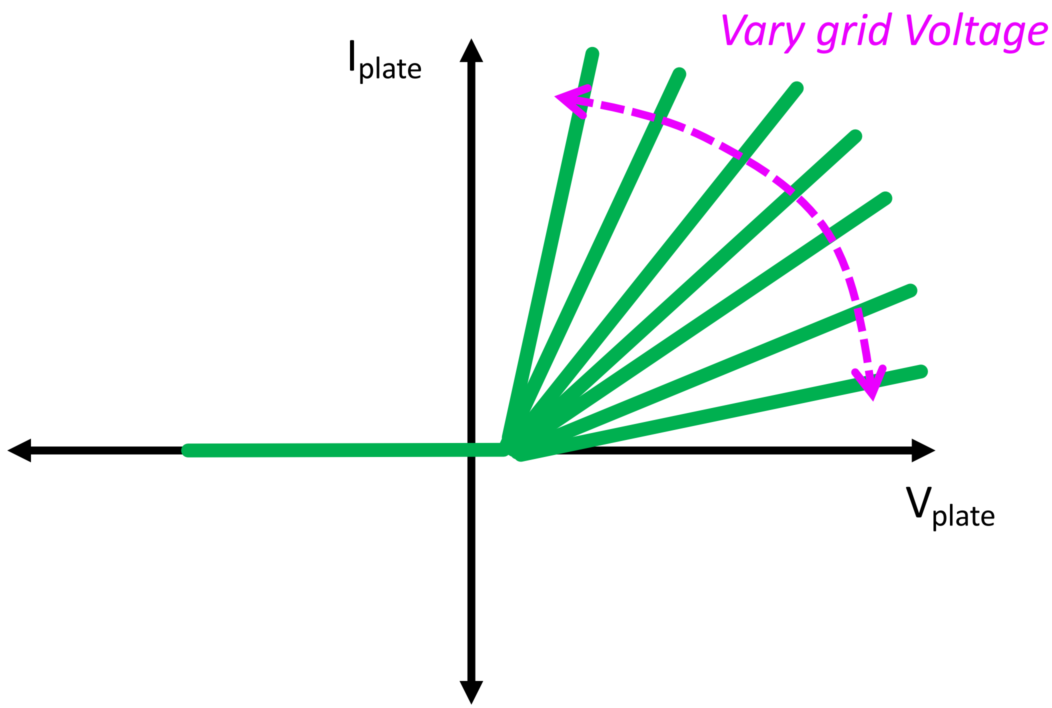
TRIODE!!!



https://www.engineering.com/ElectronicsDesign/ElectronicsDesignArticles/ArticleID/16337/Vacuum-Tubes-The-World-Before-Transistors.aspx

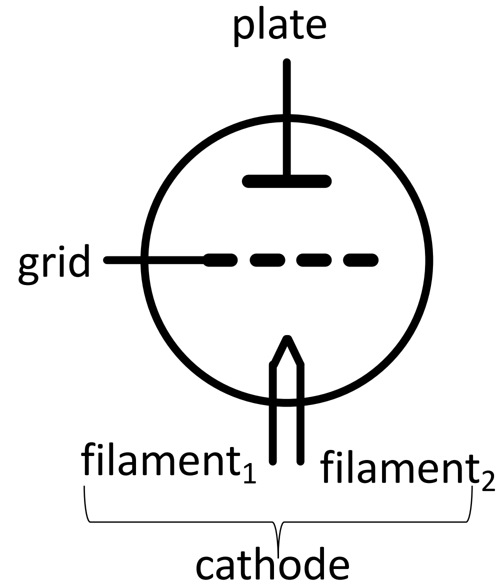
Result:

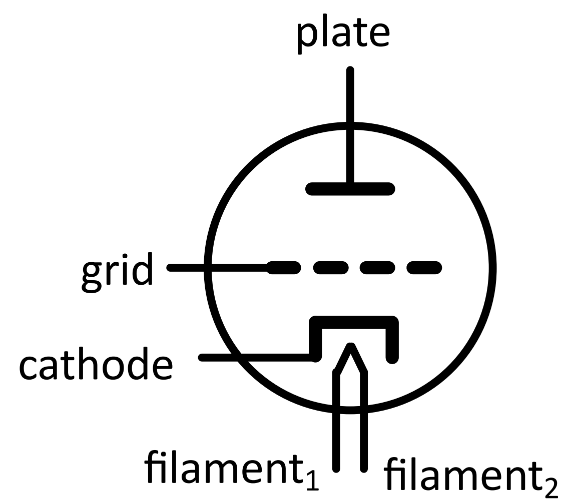
- A bunch of curves
- Which were selectable via the third electrode



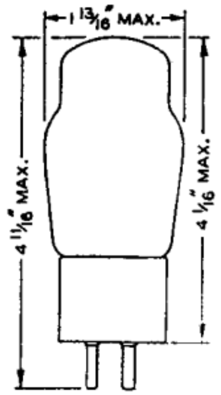
Triode Pins

- Your most basic Triode has four pins:
  - Anode (Plate)
  - Grid
  - Two for Cathode filament
- Having the filament double as the cathode was electrically annoying, so they developed the indirectly heated cathode to keep the two electrically isolated:
  - Often the filaments aren't even drawn for simplicity sake (but they need to be powered)



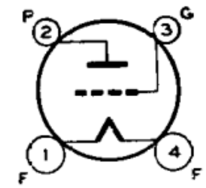


Example Early Triode (Type 26)

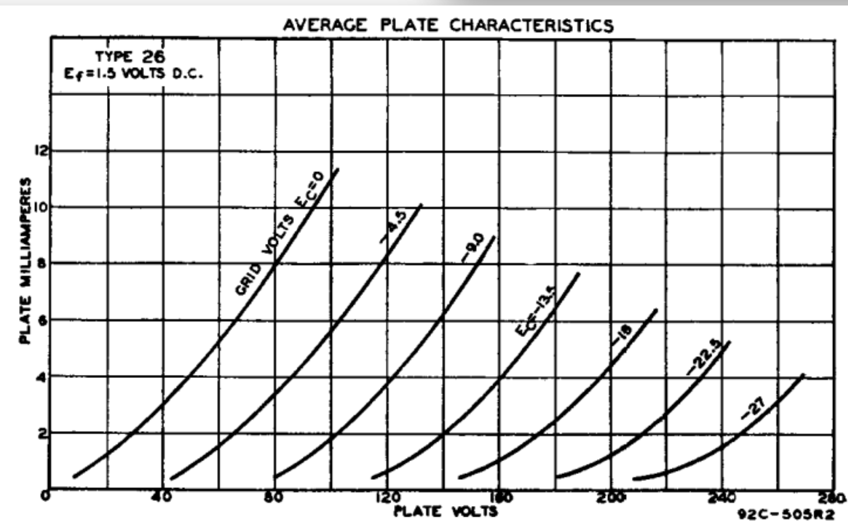


RCA-26

AMPLIFIER

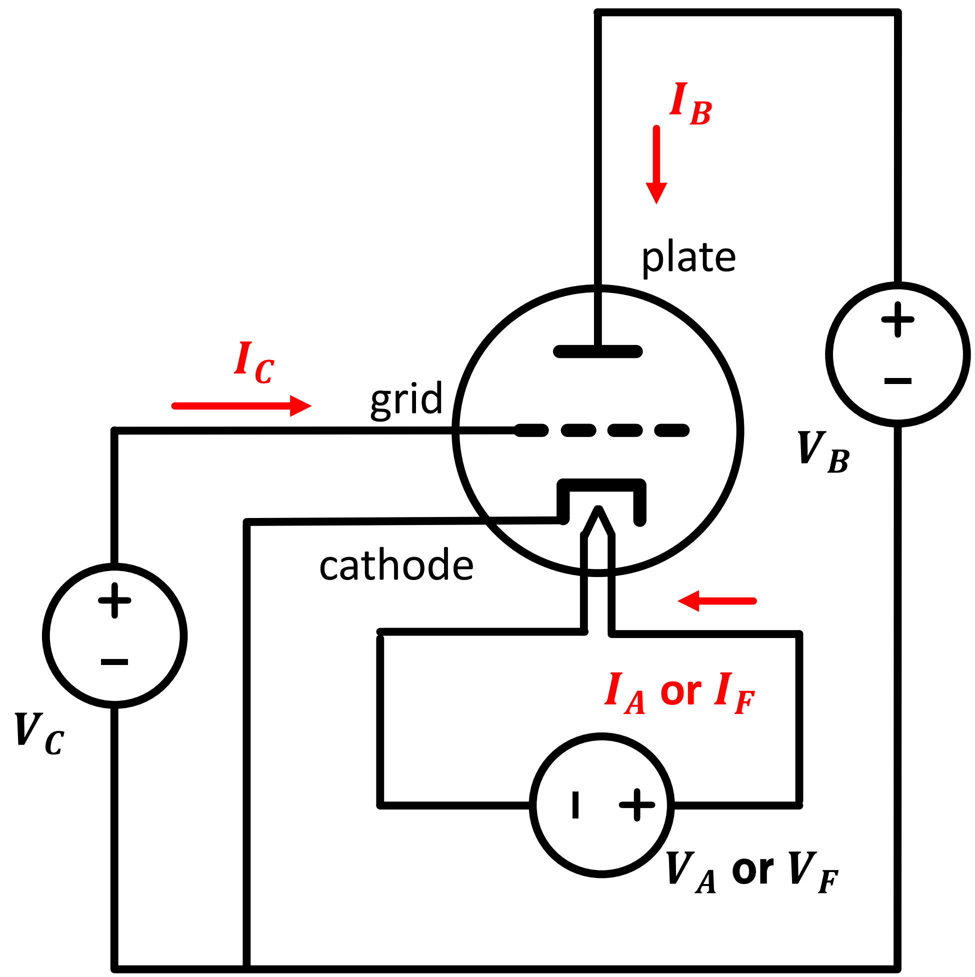


The 26 is an amplifier tube containing a filament designed for operation on alternating current. This tube is for use as an r-f or a-f amplifier in equipment designed for its characteristics. The 26 is not ordinarily suitable for use as a detector or power output tube.



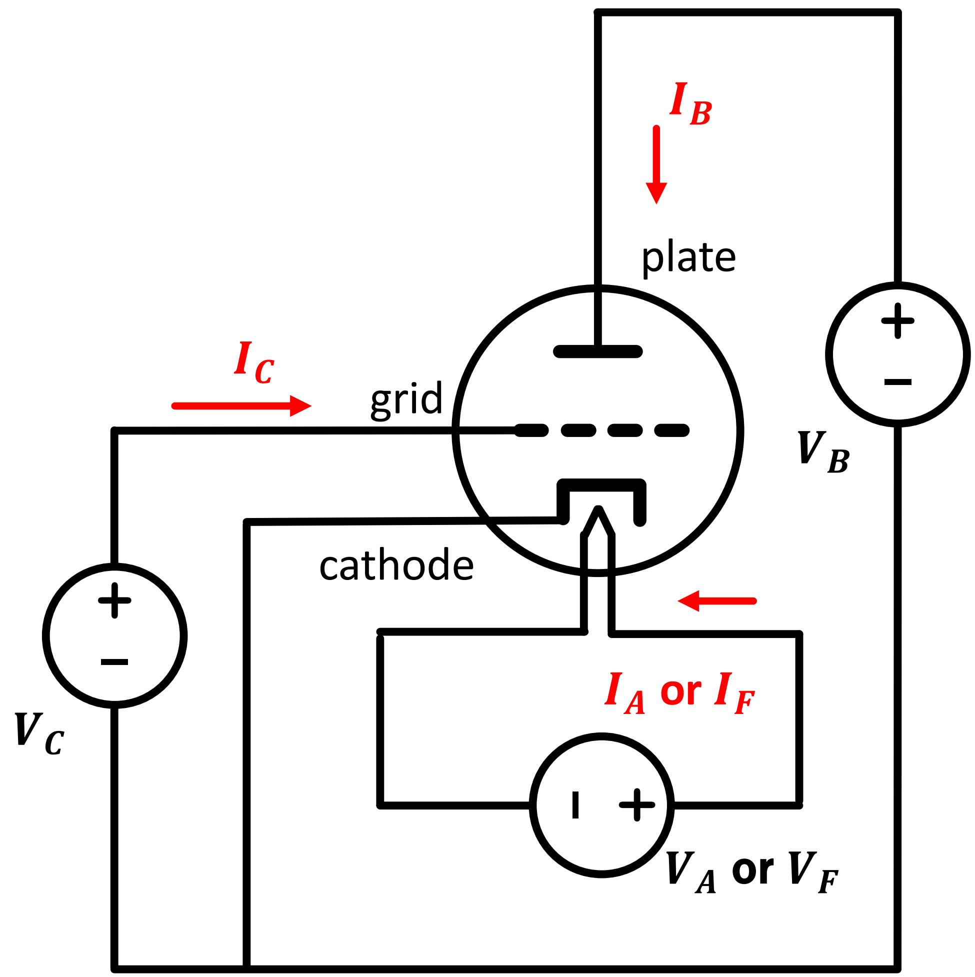
Basic Triode Setup

- At most basic, you need three separate voltage sources to drive a triode:
  - V_A to run your filament (usually relatively low)
  - V_B To set your plate voltage relative to the cathode
  - V_C To set your grid voltage relative to the cathode



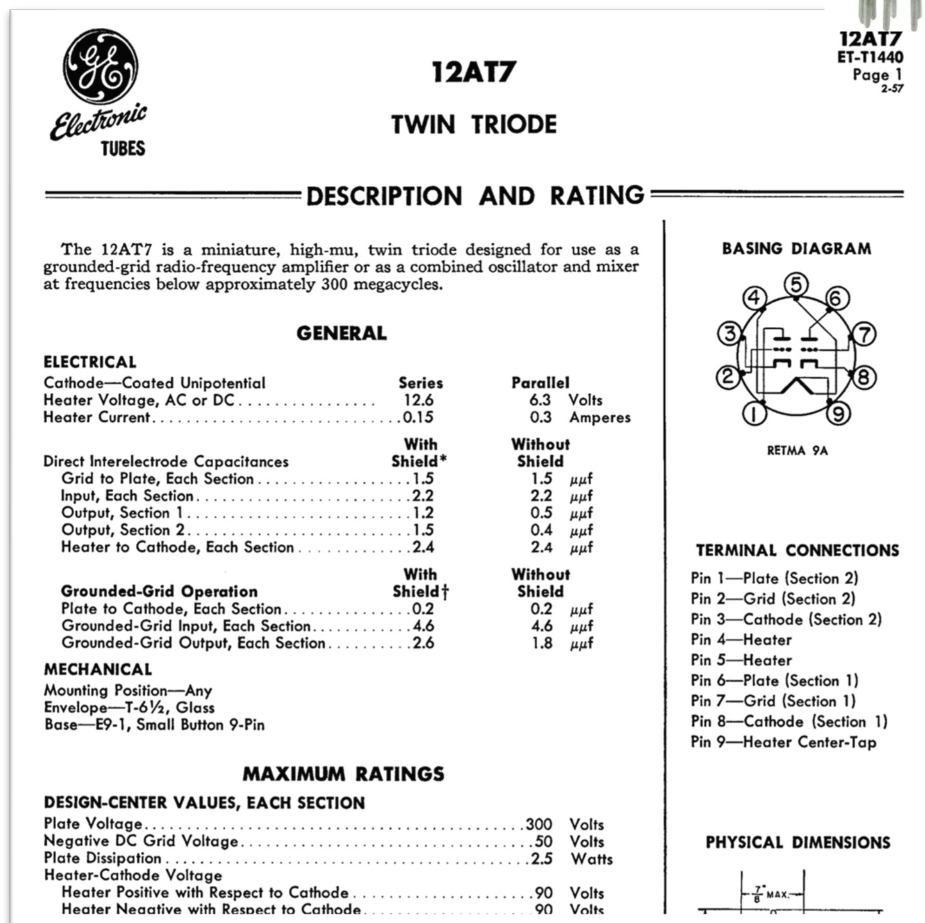
Basic Triode Setup

- Early systems could therefore need at least three different voltage levels (or more), so possibly three different batteries!
- In practice, V_C would usually be derived from V_B through the circuit



Let’s Study a Triode Tube: 12AT7 High-Mu Twin Triode

- Developed in 1940s/50s (much later triode)
- Two independent triodes
- Share a common heater
- Relatively High-Gain tube (up to a gain of 100)
- Still used in a lot of preamps for audiophiles today



GE Electronic TUBES

12AT7

TWIN TRIODE

12AT7
ET-T1440
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DESCRIPTION AND RATING

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

GENERAL

ELECTRICAL

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

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

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

MECHANICAL

Mounting Position—Any
Envelope—T-6½, Glass
Base—E9-1, Small Button 9-Pin

MAXIMUM RATINGS

DESIGN-CENTER VALUES, EACH SECTION

Plate Voltage	300	Volts
Negative DC Grid Voltage	50	Volts
Plate Dissipation	2.5	Watts
Heater-Cathode Voltage		
Heater Positive with Respect to Cathode	90	Volts
Heater Negative with Respect to Cathode	90	Volts

BASING DIAGRAM

RETMA 9A

TERMINAL CONNECTIONS

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

PHYSICAL DIMENSIONS

Aside: Notation

- Older schematics/docs have some weirder notation for some things:

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

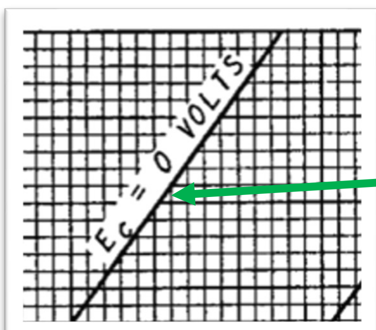
Frequency was quantified in cycles per second (often just shortened to "cycles" up until the SI standardization in 1960 when it was replaced with *Hertz*

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	$\mu\mu f$
Output, Section 1	1.2	0.5	$\mu\mu f$
Output, Section 2	1.5	0.4	$\mu\mu f$
Heater to Cathode, Each Section	2.4	2.4	$\mu\mu f$

"micro micro" is the same as pico (and technically correct since $10^{-6} \cdot 10^{-6} = 10^{-12}$)

TRANSCONDUCTANCE (G_m) IN MICROMHOS

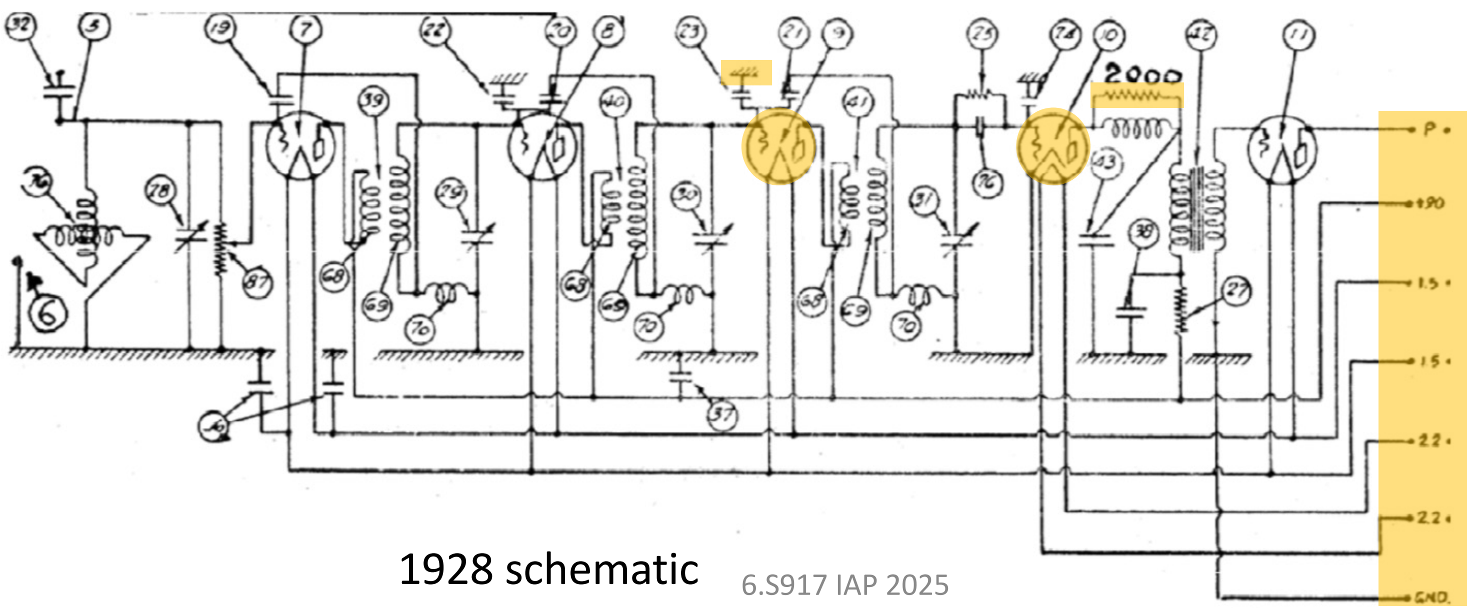
Conductance (the inverse of Resistance) was generally quantified using the "Mho" which is "Ohm" spelled backwards. Symbol was ℧ which is an Omega upside down. In 1971 for whatever reason people thought changing this to Siemens was a better idea (it wasn't). Symbol for Siemen is S.



Usage of "E" to denote voltages rather than "V" is very common. E comes from "electromotive force"

Schematics Could Be Weirder Too

- Tube symbols were kinda weird for a while
- Ground would be drawn all over the place, or put at the top of a schematic
- Resistors were sometimes a lot more zigzags than today
- Tube circuits also just required *a lot* of voltages compared to today so there's and they tended not to do abbreviated V_{CC} type linkers, just disgusting long lines



1928 schematic

Parts were weird too

- Actual resistors looked very similar to modern 1/4W resistors (resistor color code came about in the 1920s/30s)

- Capacitors could be kinda weird:
  - Could have their own color code
  - Could be made of paper and bees wax
  - Not trustworthy components from modern perspective

Tubes Need to Heat Up!

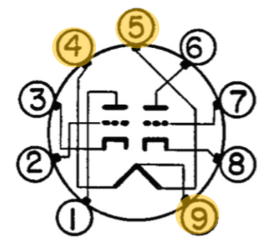
GENERAL

ELECTRICAL

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

- Most of power consumed by tube goes to its heater
- Electrons don't start jumping until the filament gets hot enough.
- *That takes a bit of time from turn-on*
- Here's me turning on a two-stage audio amp (using 12AT7 tubes!):

BASING DIAGRAM



RETMA 9A

TERMINAL CONNECTIONS

Pin 1—Plate (Section 2)
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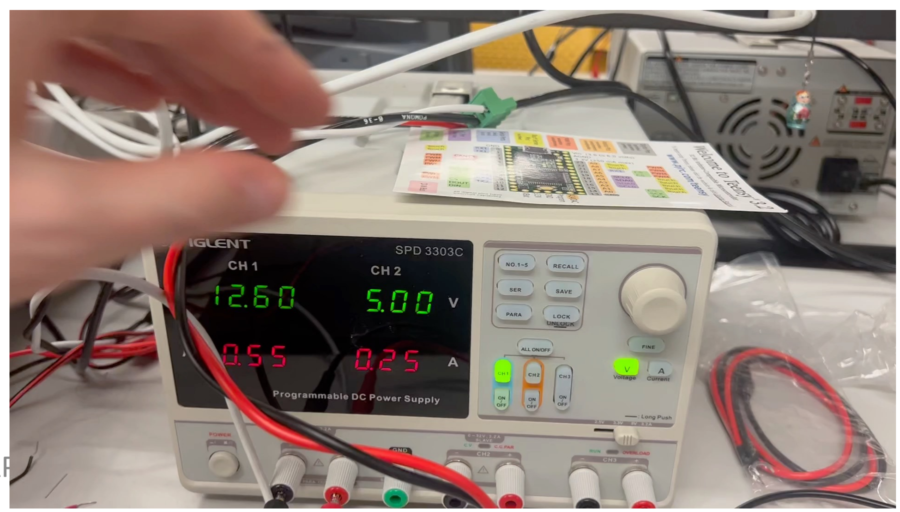
Pin 9—Heater Center-Tap



*the "12" in "12AT7" referred to the approximate heater supply voltage

Classic Inaccuracy in Old Movies

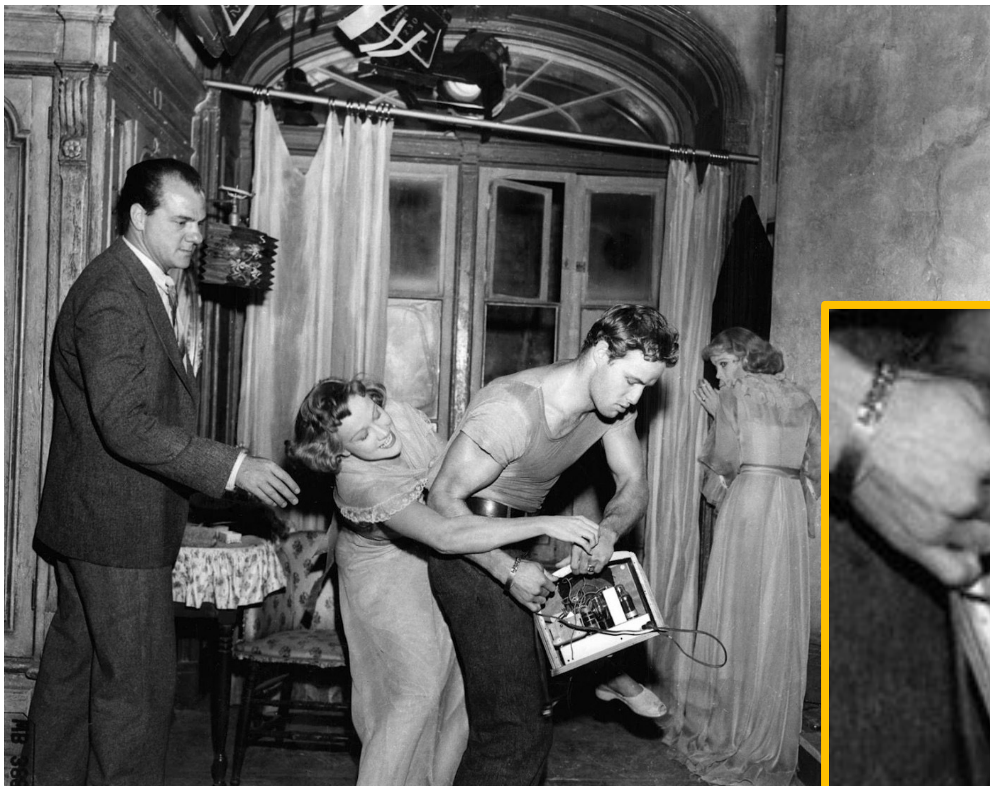
- Any piece of tube equipment would take 15 to 30 seconds to warm up and start running.
- In movies where they show a radio (or something else) turn on they'll often ignore this since that would probably distract the audience who don't care enough to have properly represented electronics and are instead focused on less important things like story or character development

1951's *A Streetcar Named Desire* film adaptation is one example of many*

*@33:31 and then again at @38:20

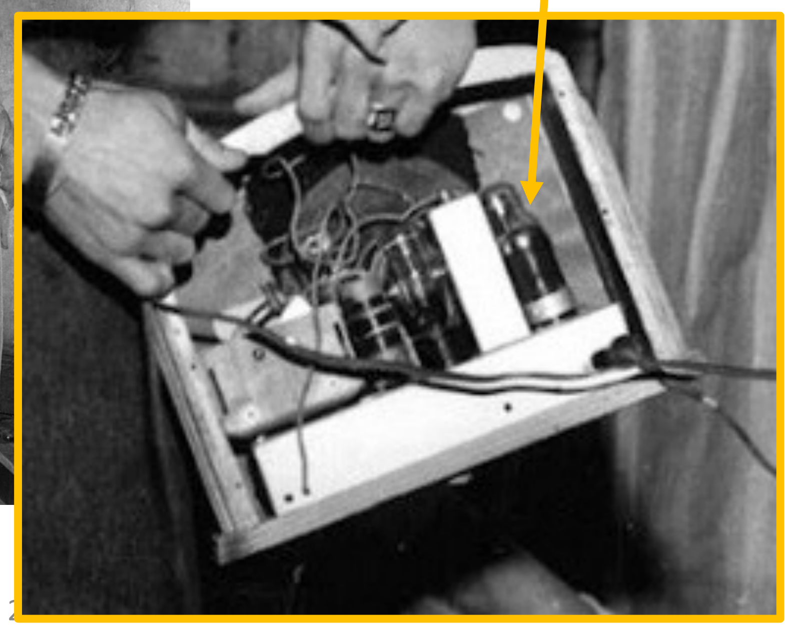
Film was in 1951, Joe

- Transistors were invented in late 1947. Technically it was possible that that was a transistor radio



Behind the scenes photo from film

Clearly a tube radio



https://sydneyweiner3.medium.com/the-sopranos-music-and-control-in-a-streetcar-named-desire-995c551ad80e

Data Sheet Basics

12AT7
ET-T1440
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CHACTERISTICS AND TYPICAL OPERATION

CLASS A_1 AMPLIFIER, EACH SECTION

Plate Voltage	100	250	Volts
Cathode-Bias Resistor	270	200	Ohms
Amplification Factor	60	60	
Plate Resistance, approximate	15000	10900	Ohms
Transconductance	4000	5500	Micromhos
Plate Current	3.7	10	Milliamperes
Grid Voltage, approximate			
Ib = 10 Microamperes	−5	−12	Volts

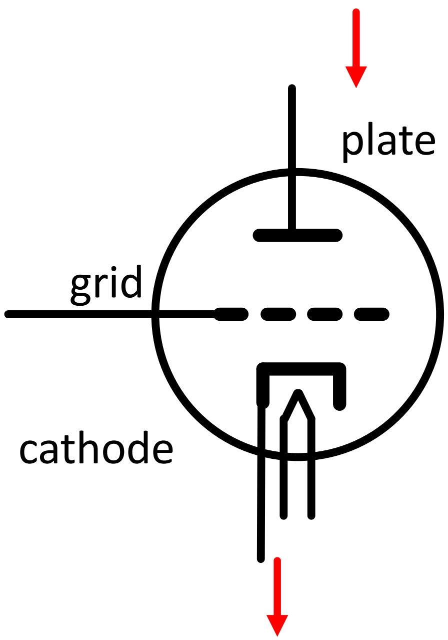
* With external shield (RETMA 315) connected to cathode of section under test.

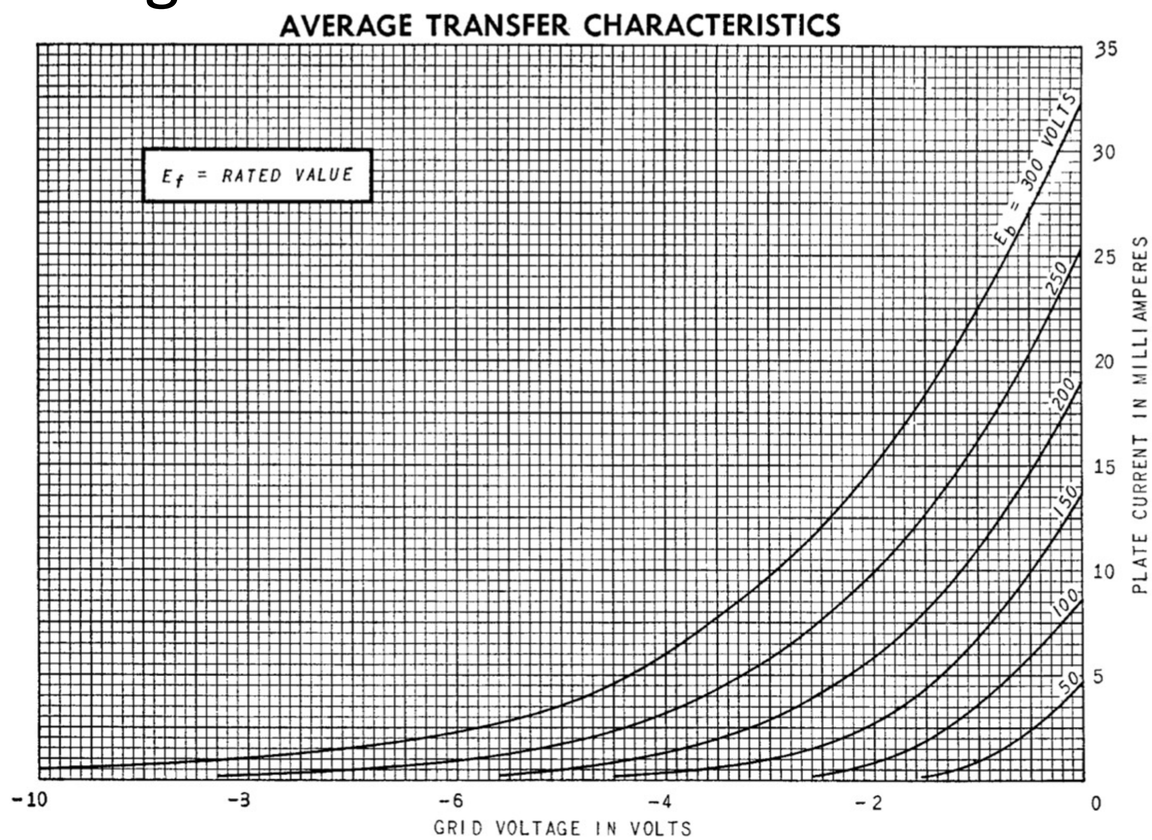
† With external shield (RETMA 315) connected to grid of section under test.

- What is "Typical" Operation?
- The values above give the engineer a rough idea of some characteristics of the triode, however they are very "rough"
- The true nature of the triode operation comes from studying the I-V curves!

12AT7 Curves

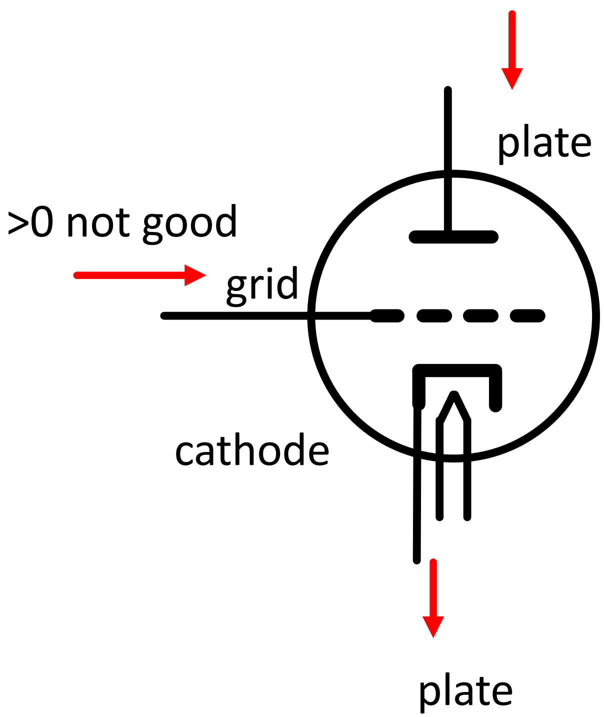
- Plate current as a function of grid voltage for specific plate voltages

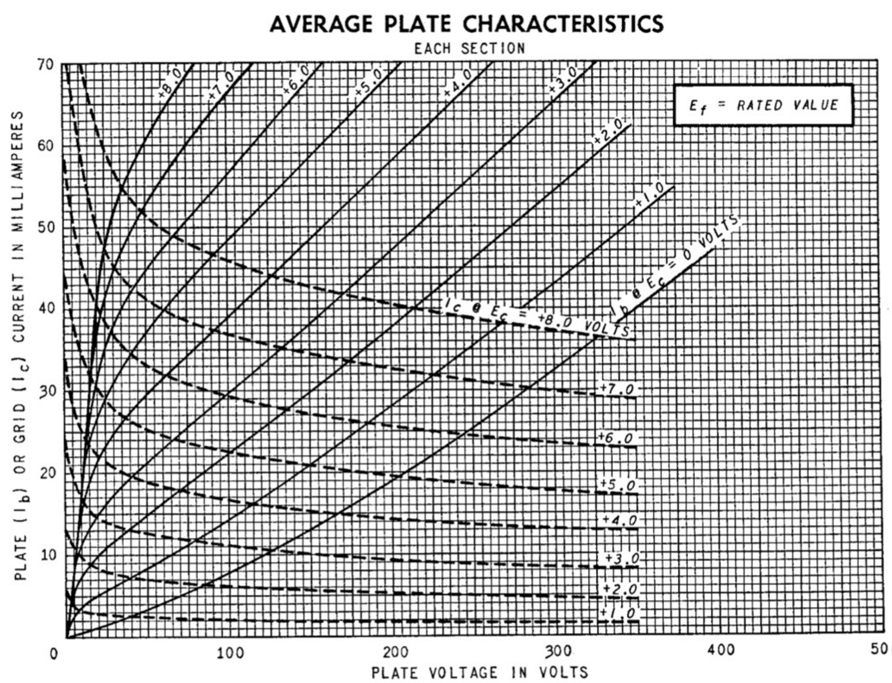




12AT7 Curve 1

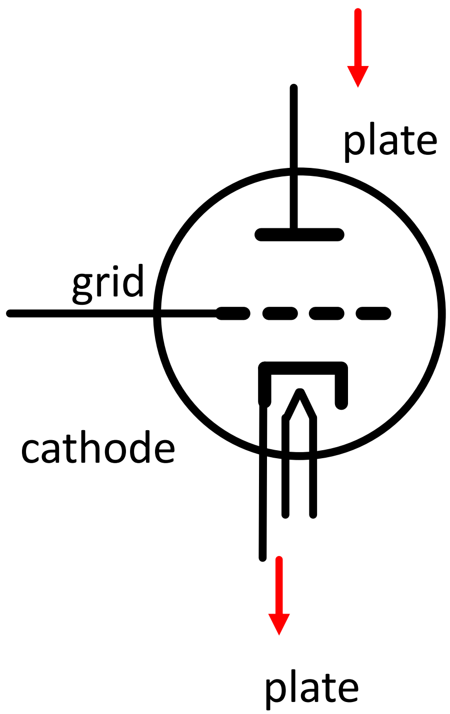
- Plate Currents (and grid currents) for when the grid is at a positive voltage
- Will try to ignore this if possible in this class.
- Not widely used since it could burn out grid

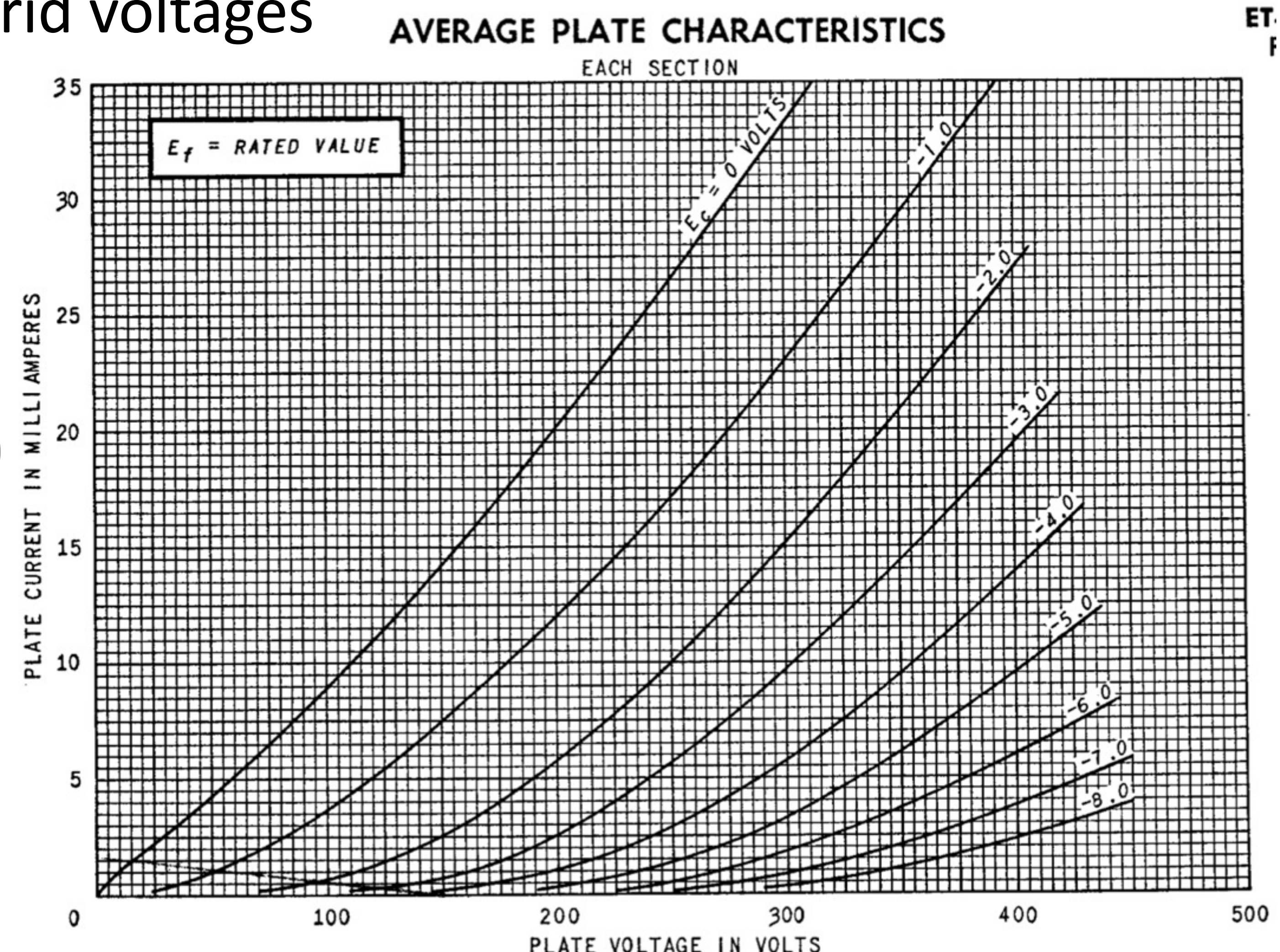




12AT7 Curve 2

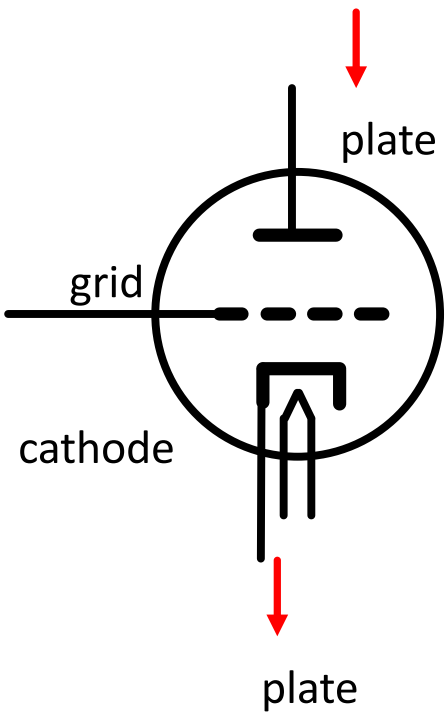
- Plate current as a function of plate voltage for specific grid voltages

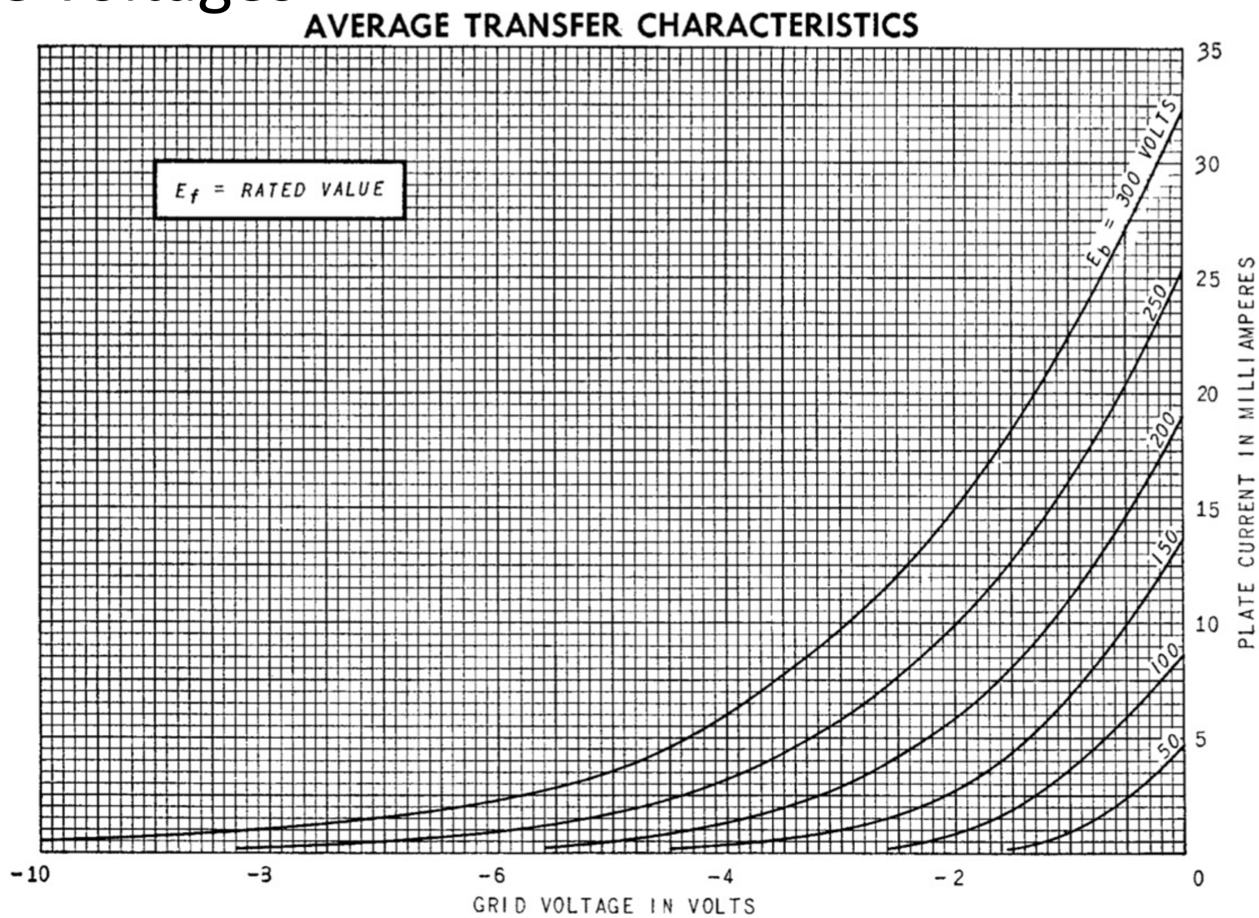




12AT7 Curve 3

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



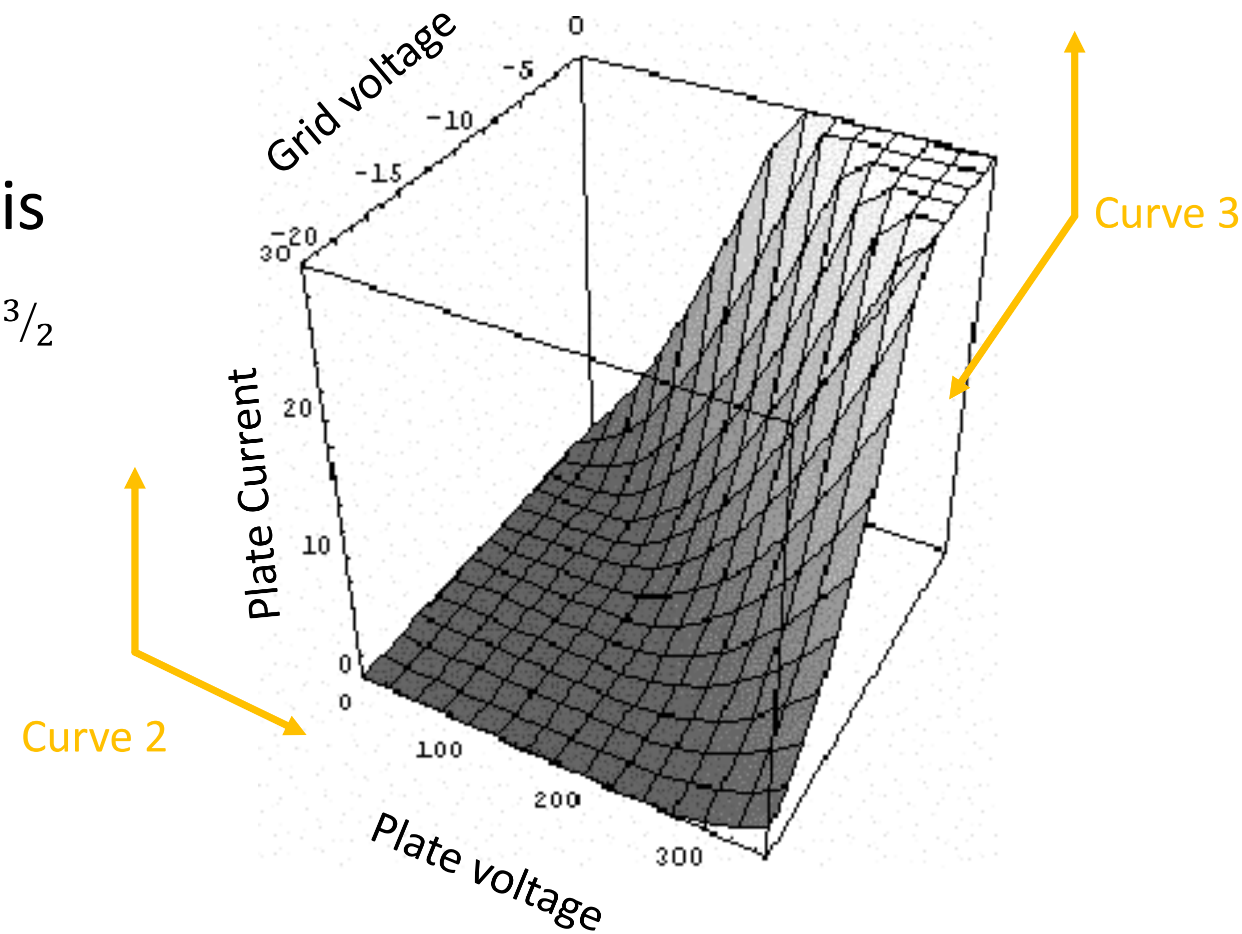


All together

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

- The general rough pattern is

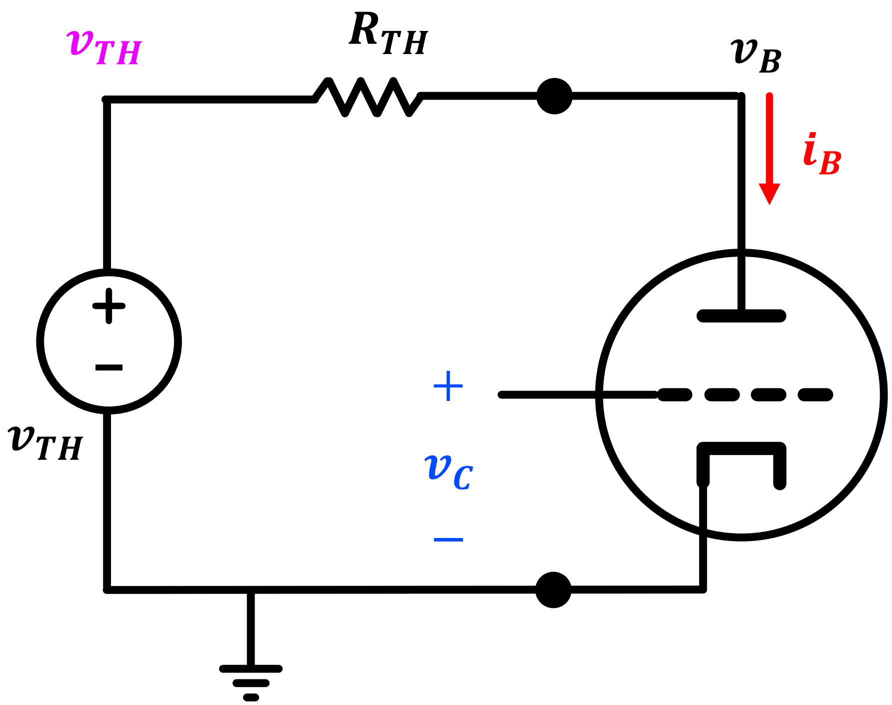
$$I_b = P\left(V_c + \frac{V_b}{\mu}\right)^{3/2}$$



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

Generic Thevenin and Triode

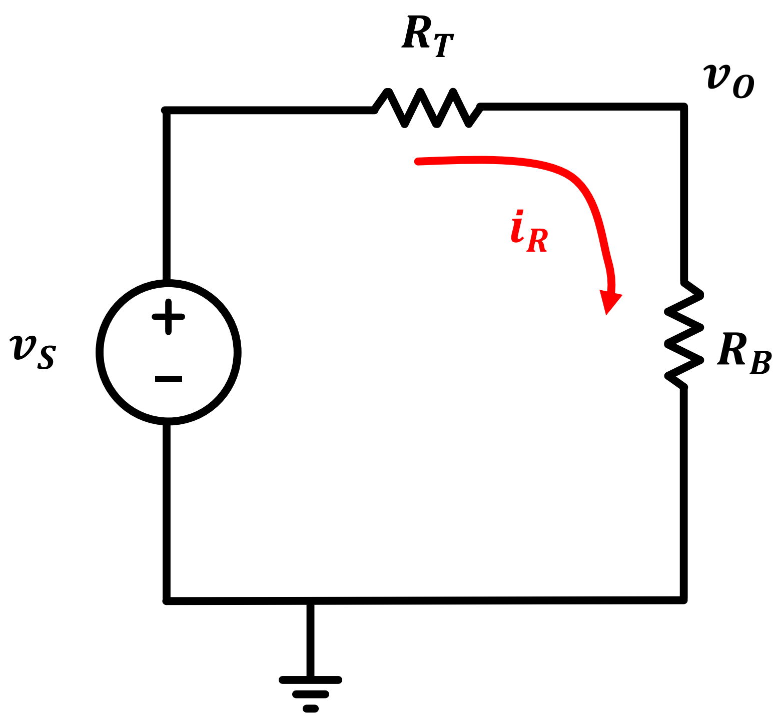
- So let's analyze:



- Unfortunately, trying to solve for how this type of device would be integrated into a standard circuit is hard.
- There is no nice closed form solution of $v_B(v_c, v_{TH})$. Instead you either need:
  - to run simulations
  - Use Load-Line Analysis with collected data
  - And/Or a small signal model

Load Line (Graphical) Analysis

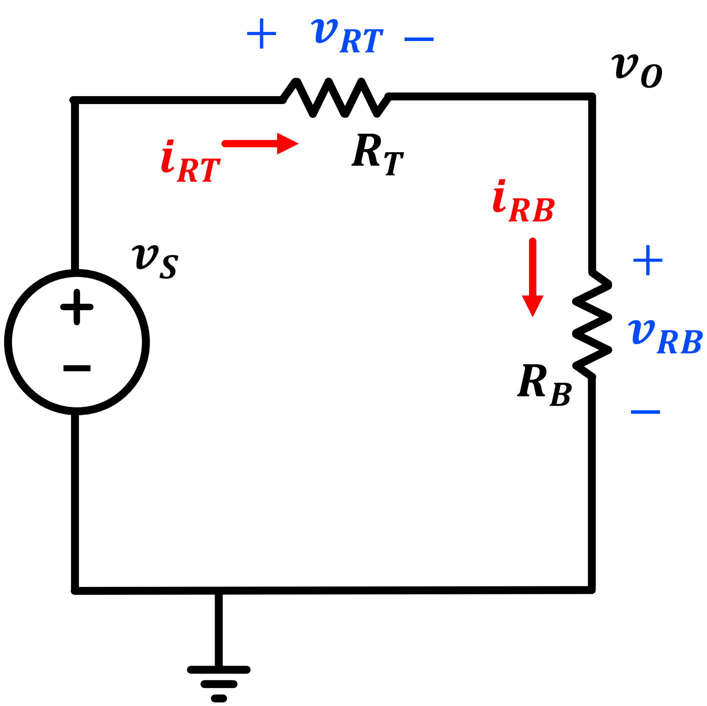
- Yes we know the answer to this is $v_o = v_s \frac{R_B}{R_T + R_B}$
- But let's think about this circuit a different way

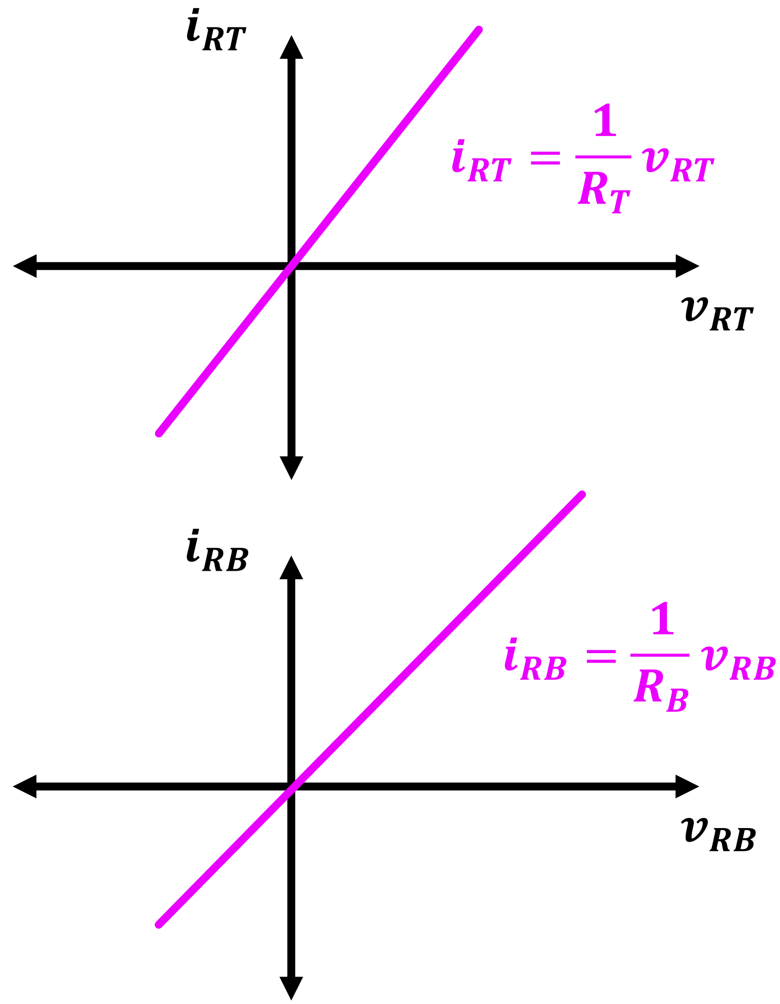


- Let's plot what both R_T and R_B want/require of the common voltages and currents in this circuit!

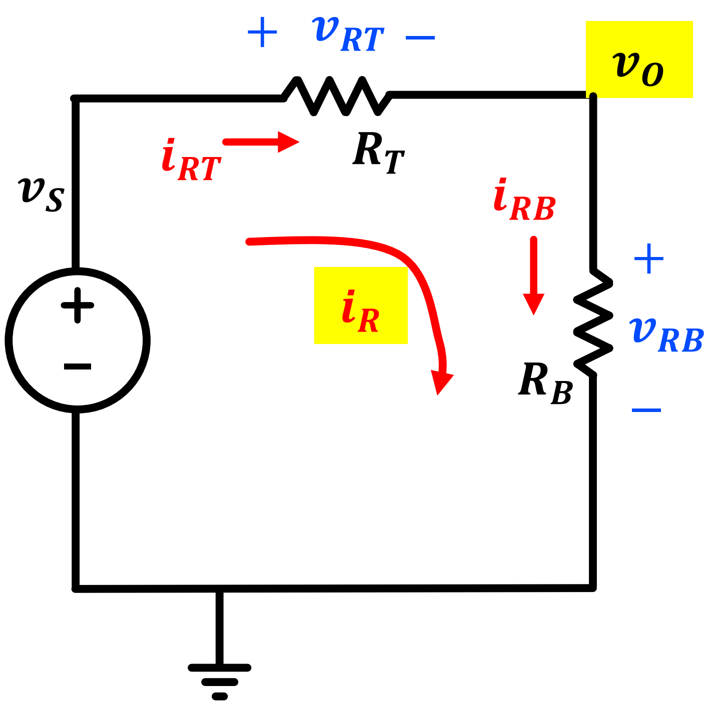
Load Line Analysis

- Let's plot what the resistors want individually…for example:





Let's merge those plots in terms of "global" variables



$$i_{RT} = i_{RB} = i_R$$

$$v_{RT} = v_S - v_O$$

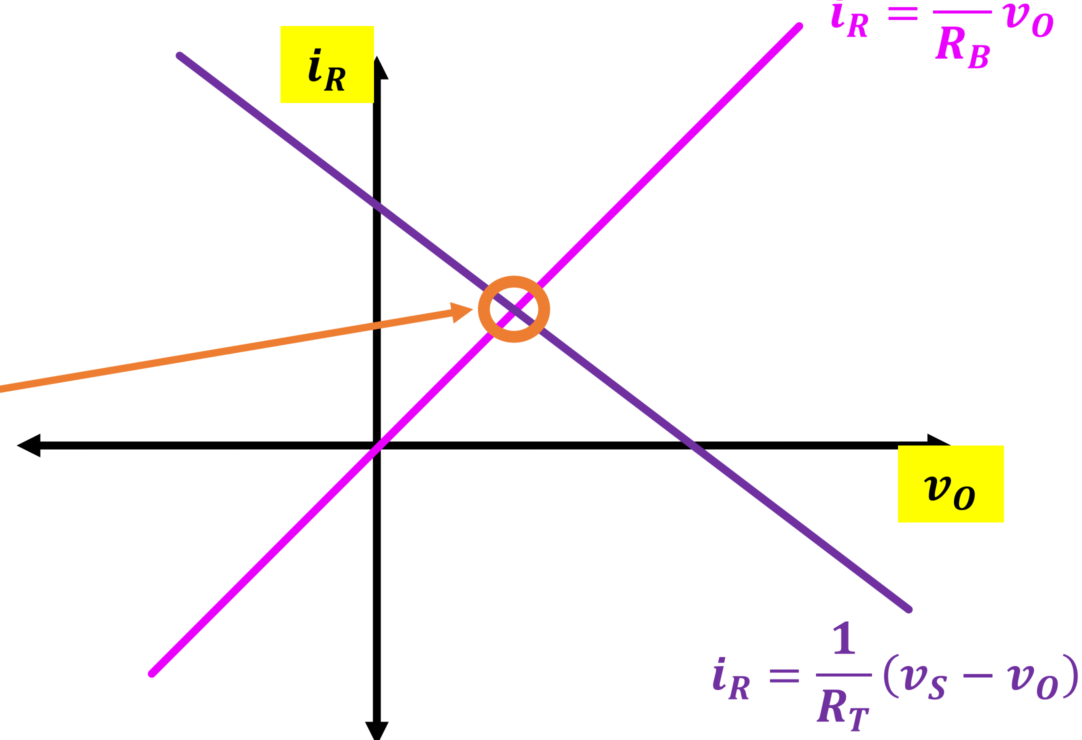
$$v_{RB} = v_O$$

$$i_{RT} = \frac{1}{R_T} v_{RT}$$

$$i_{RB} = \frac{1}{R_B} v_{RB}$$

$$i_R = \frac{1}{R_T}(v_S - v_O)$$

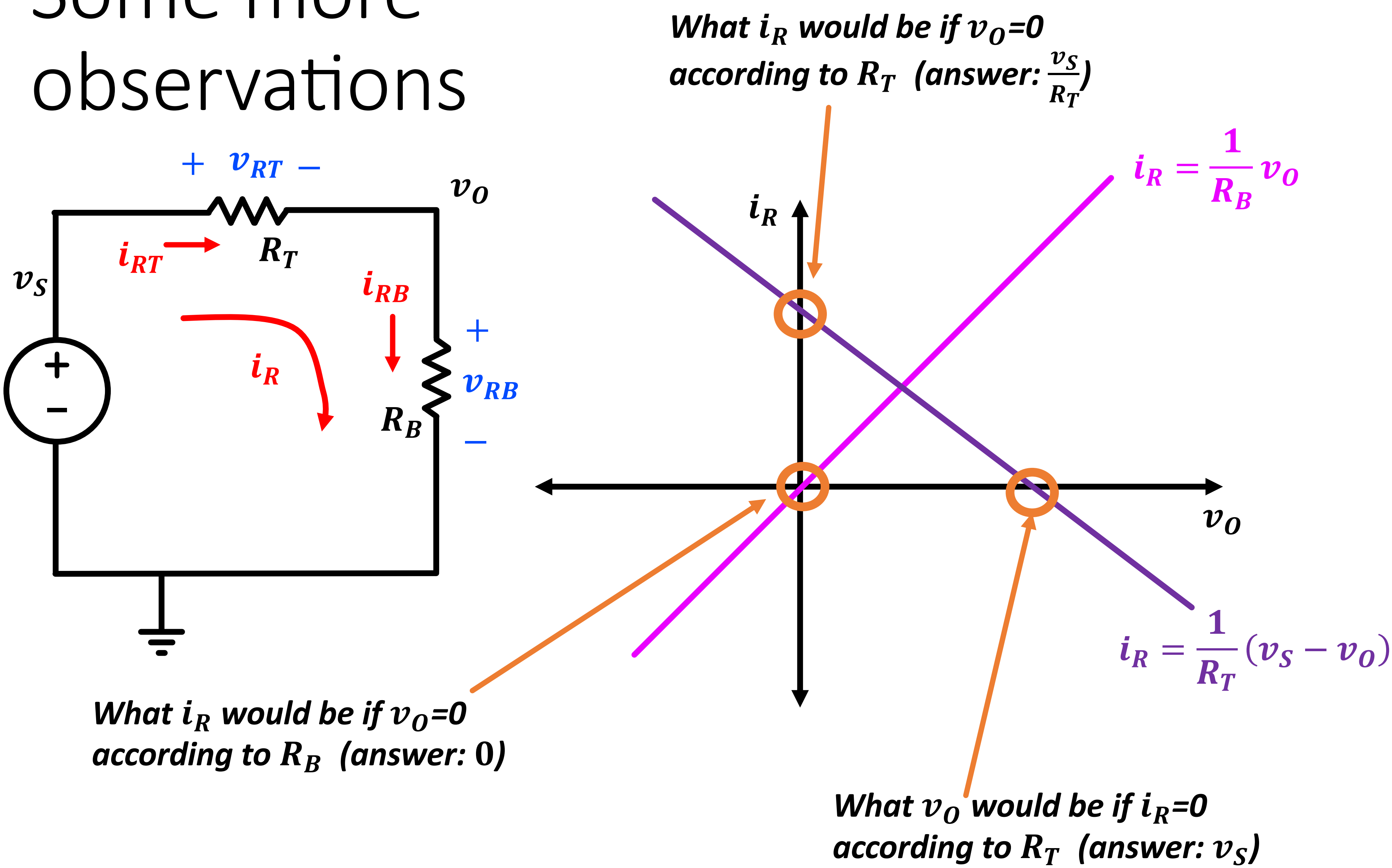
$$i_R = \frac{1}{R_B} v_O$$



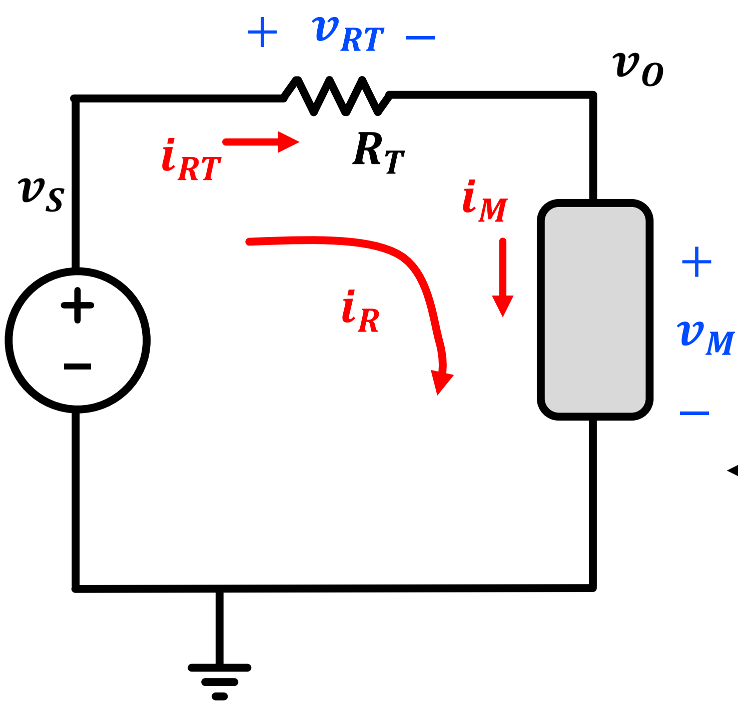
Condition that satisfies both constraints….
Only one that happens!

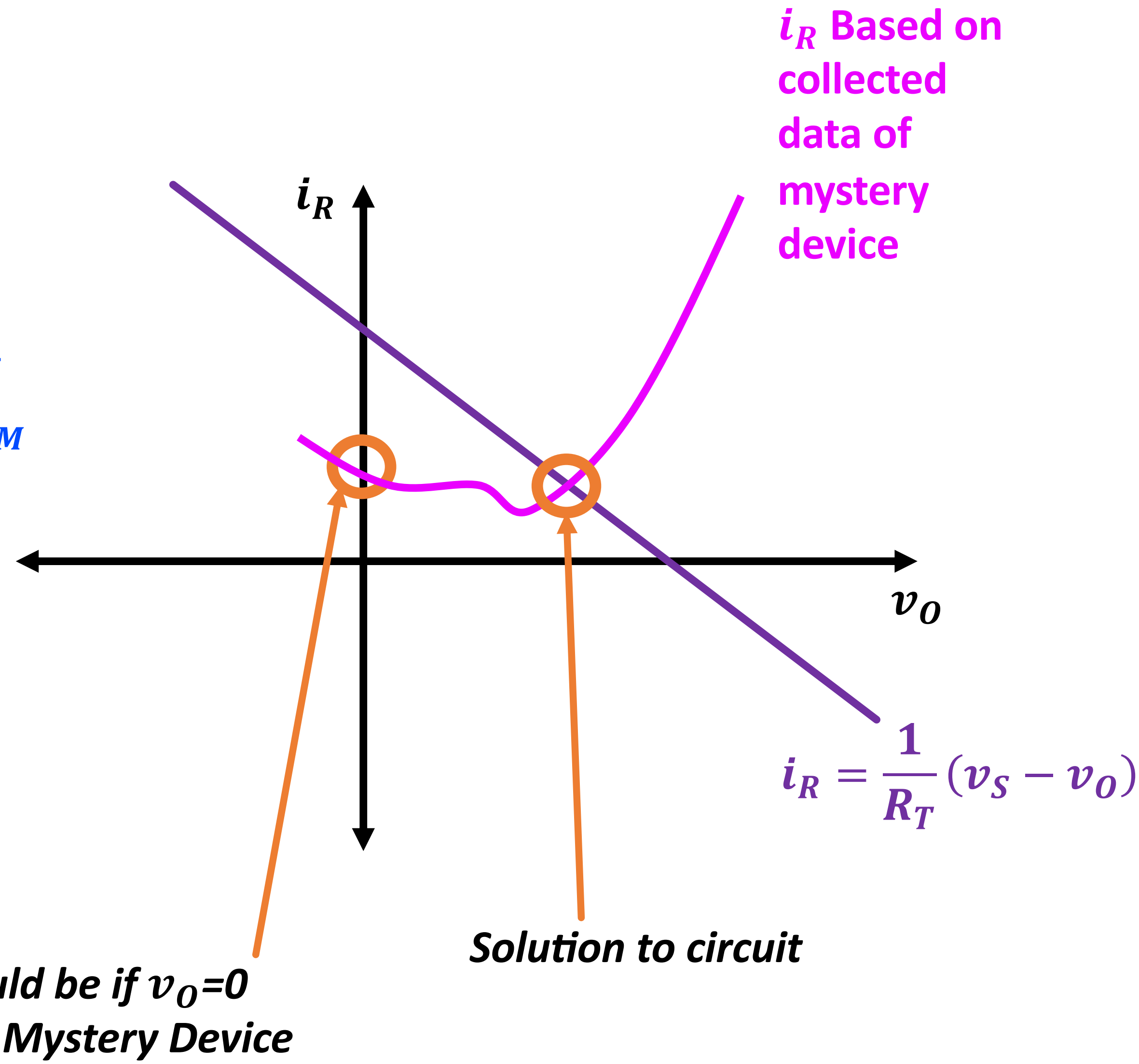
Same answer as: $v_o = v_S \frac{R_B}{R_T + R_B}$

Some more observations



Generalize Load Line





Even if we don't have pretty equation for device, we can use overlapping load lines to solve circuit

Basic Triode Setup

- At most basic, you need three separate voltage sources to drive a triode:
  - V_A to run your filament (usually relatively low)
  - V_B To set your plate voltage relative to the cathode
  - V_C To set your grid voltage relative to the cathode

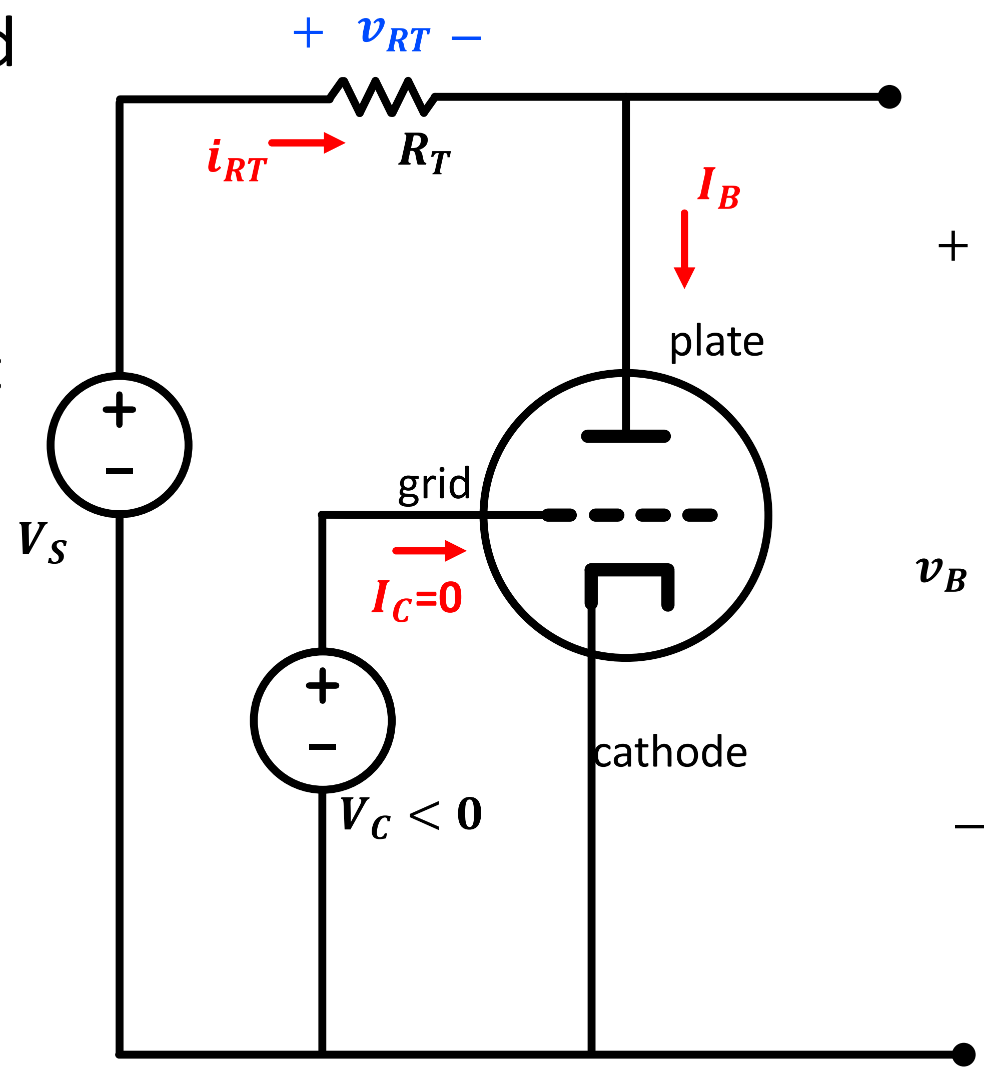
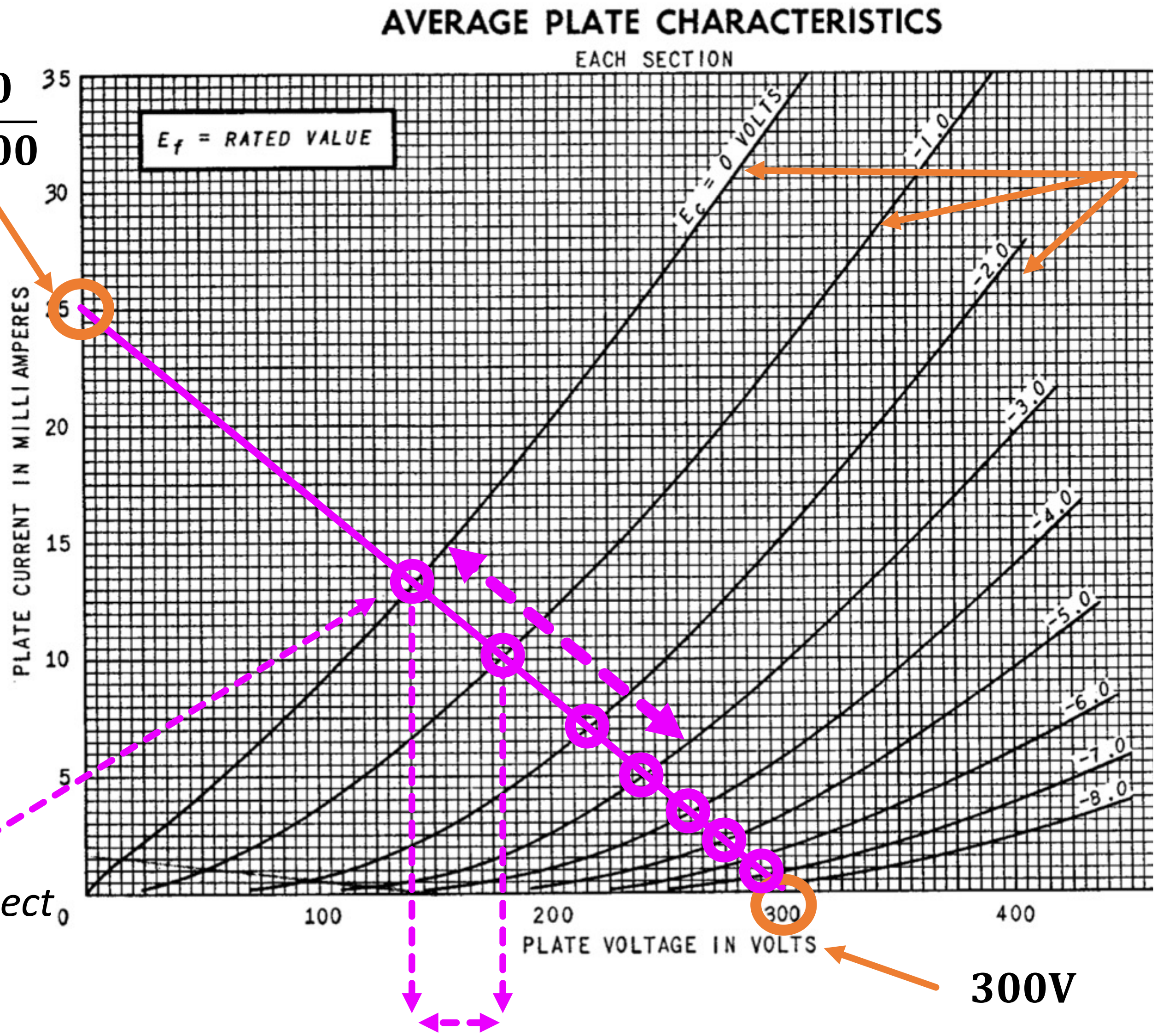


Plate Characteristics

If we set $R_T = 12000\Omega$ and $V_S = 300\ \mathrm{V}$

$$25\ \mathrm{mA} = \frac{300}{12000}$$



These are plate current for different grid voltages

300V

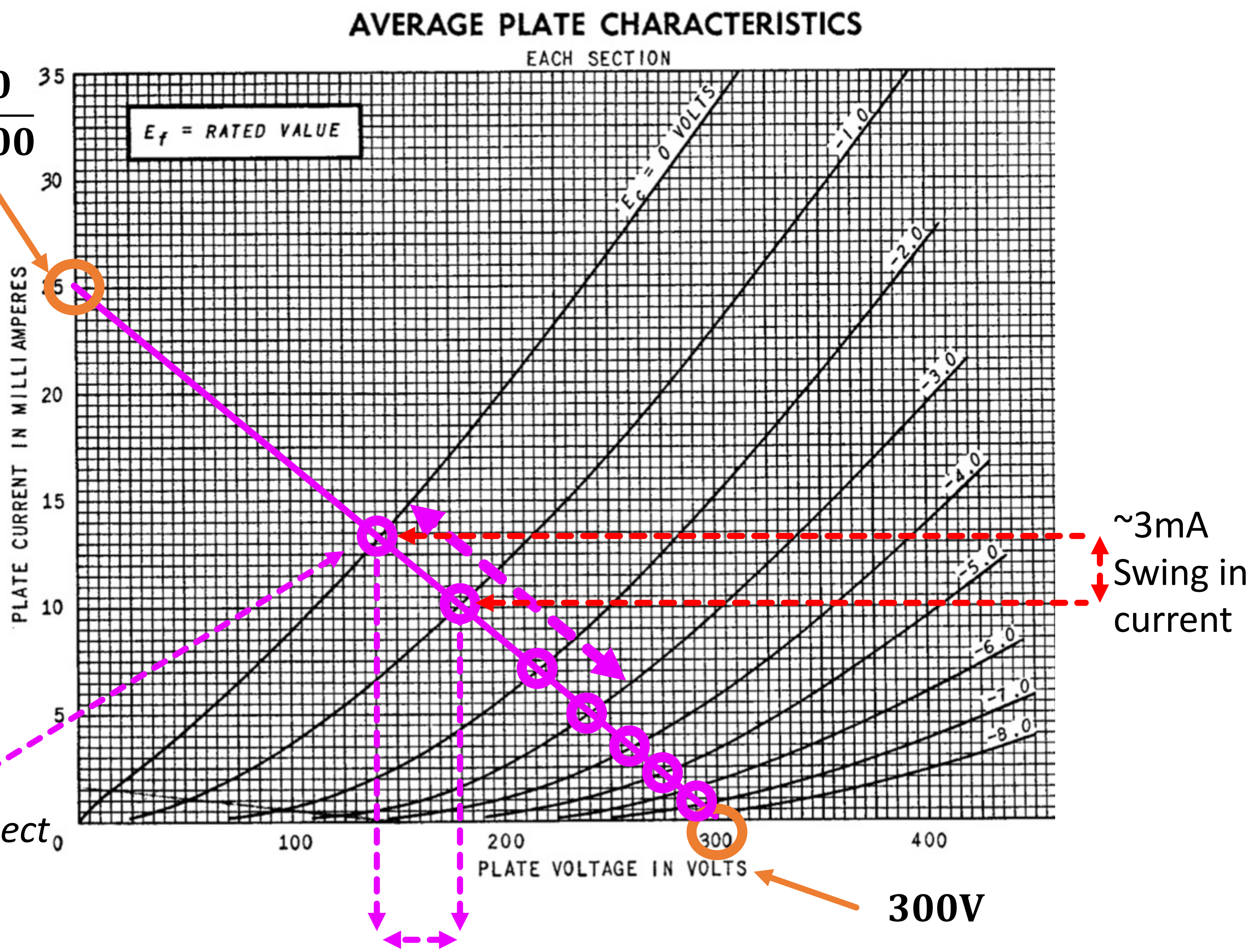
Where we intersect for each V_C trace is the circuit solution for that voltage

1 V grid swing is about 40V plate swing (gain of 40)

Plate Characteristics

If we set $R_T = 12000\Omega$ and $V_S = 300\text{ V}$

$$25\text{ mA} = \frac{300}{12000}$$



Where we intersect for each V_C trace is the circuit solution for that voltage

1 V grid swing is about 40V plate swing (gain of 40)

Critical Coefficients

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

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

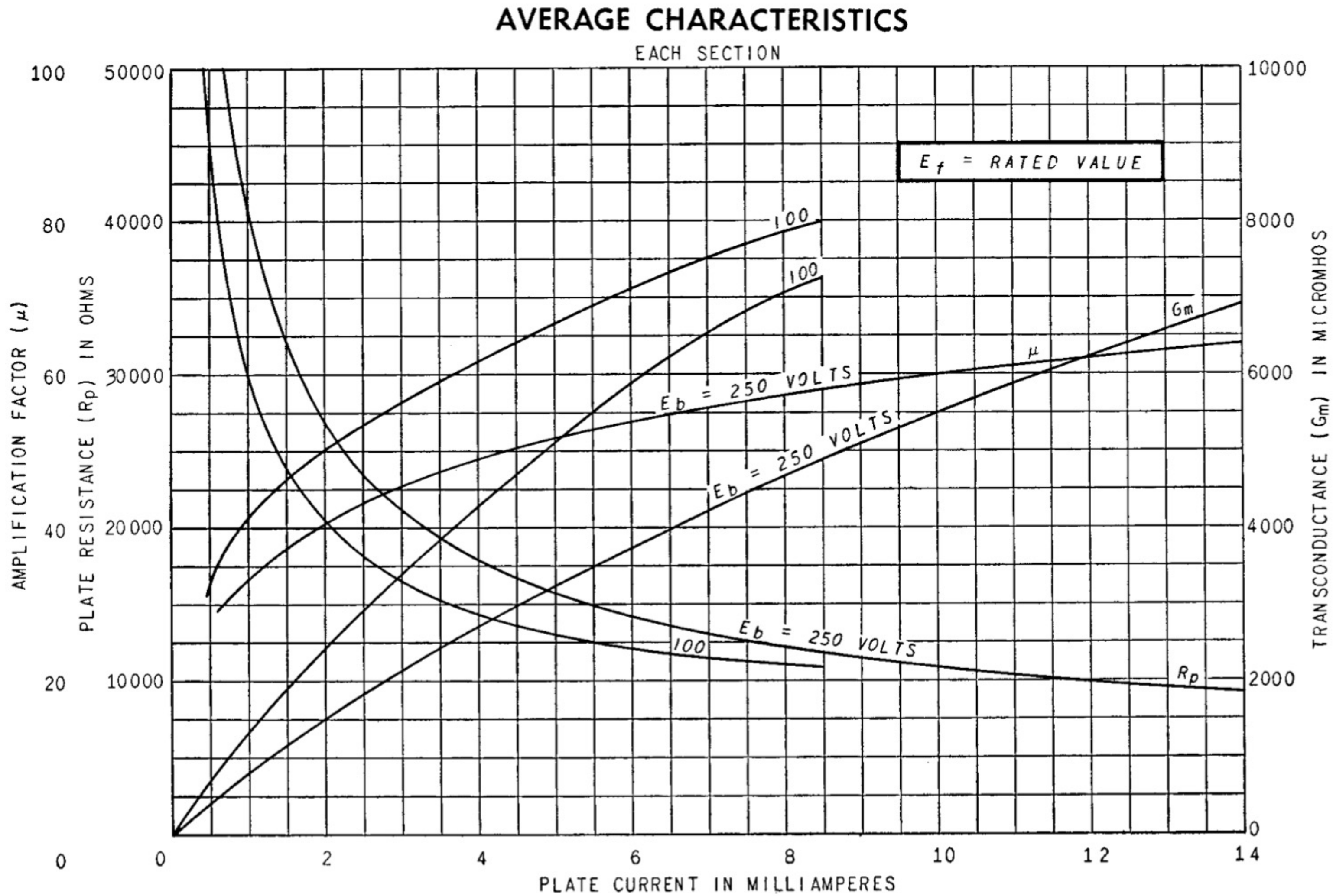
Voltage amplification factor: The factor by which the grid changes the voltage at the plate. (unitless)

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)

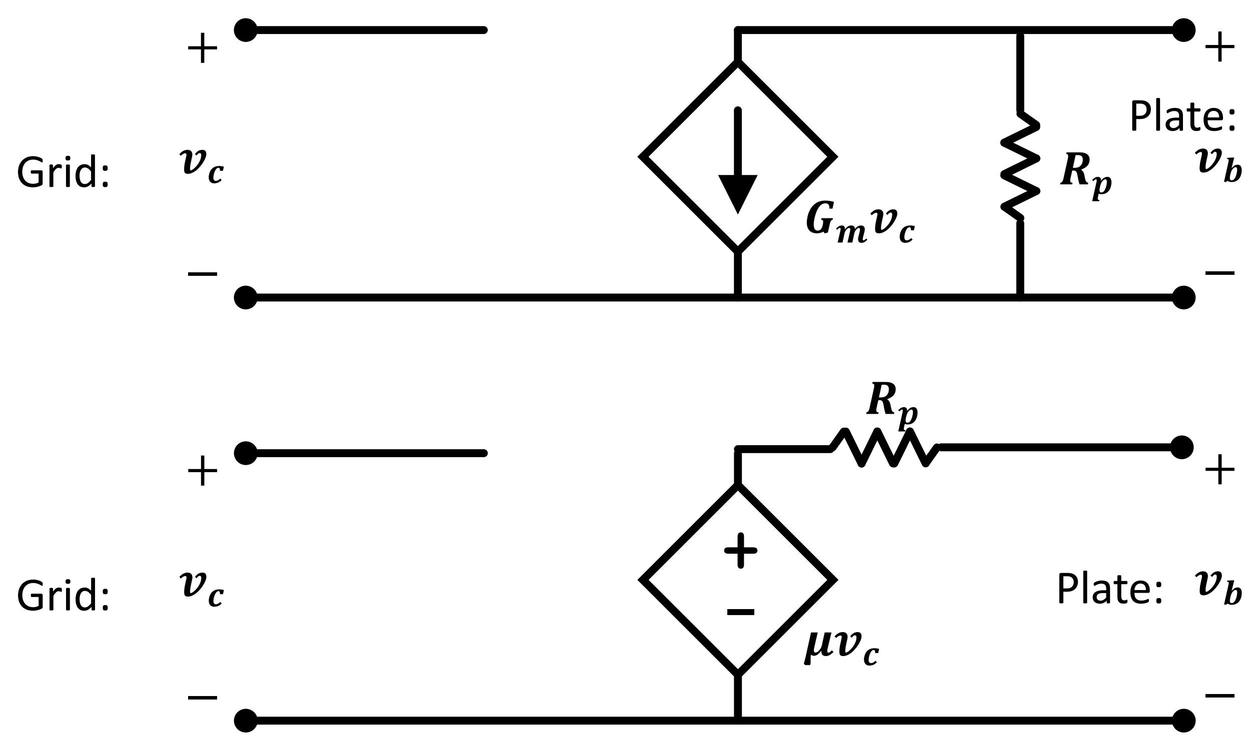
- These numbers are extracted from the values and slopes of the transfer function plots

There's also these:



Triode Small Signal Model (Low Frequency)

- Assuming V_C is negative, I_C will be negligible (nA). Can generate two small signal models therefore:



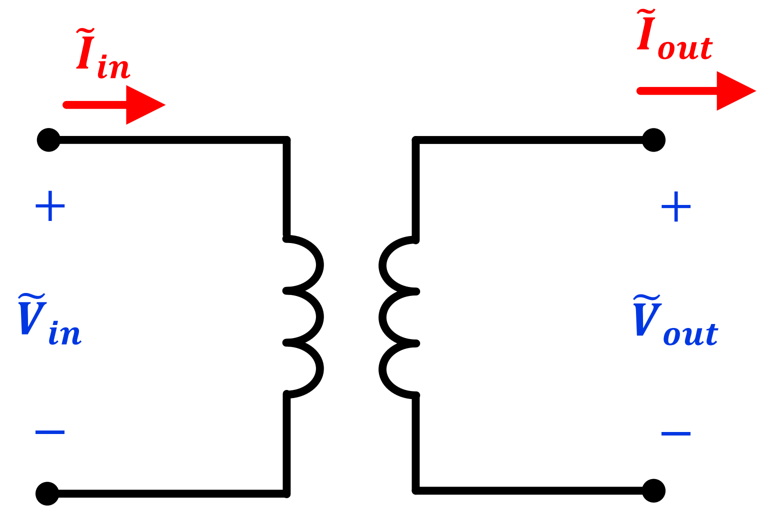
Continue studying Tube circuits on Thursday

- Do a few tube circuits on Thursday to support Week 2 Lab
- But before that...another technology that supports Tube Circuits a lot are transformers…need to go over them!

The Transformer

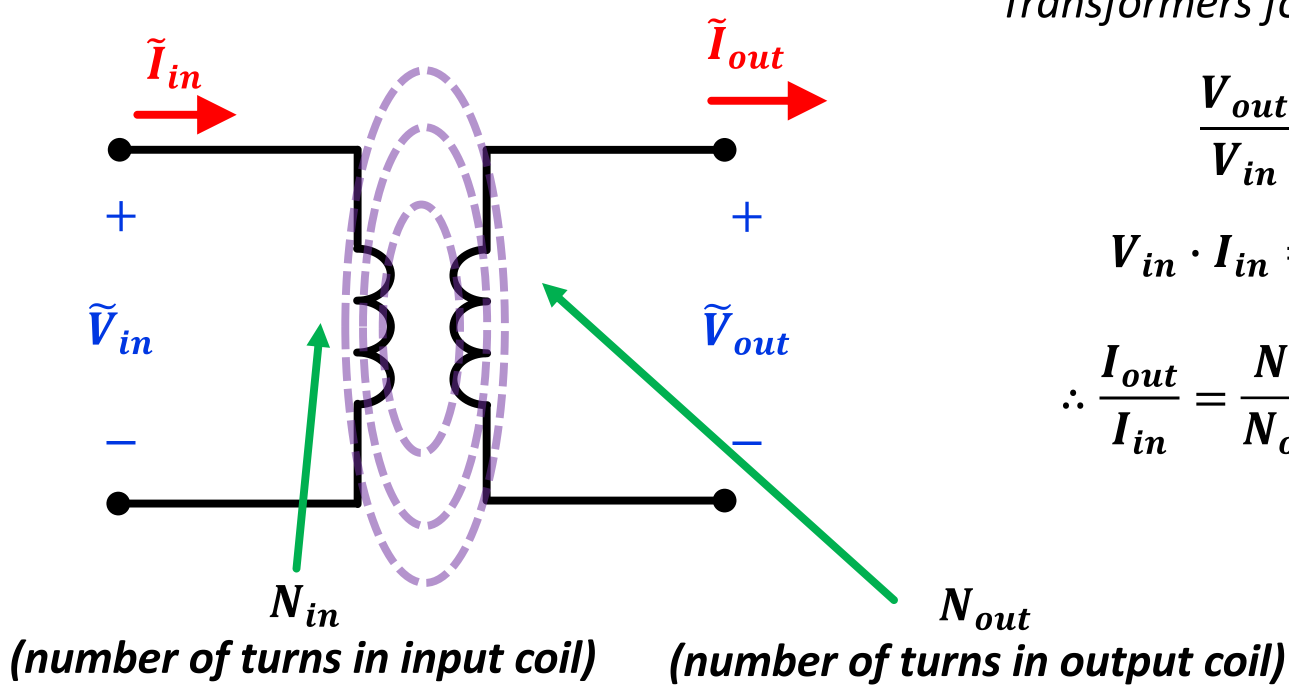
- In 2025, transformers are easier to forget than they were 100 years ago.

- In early electronics, they were everywhere, though so understanding their uses is important



The Transformer

- Two magnetically-coupled coils, one is the input, and one is the output.
- The voltage and current into the input influence the voltage and current out
- You can vary the relative ratios of the coils to step "up" or "down" current/voltage



Transformers follow these rules:

$$\frac{V_{out}}{V_{in}} = \frac{N_{out}}{N_{in}}$$

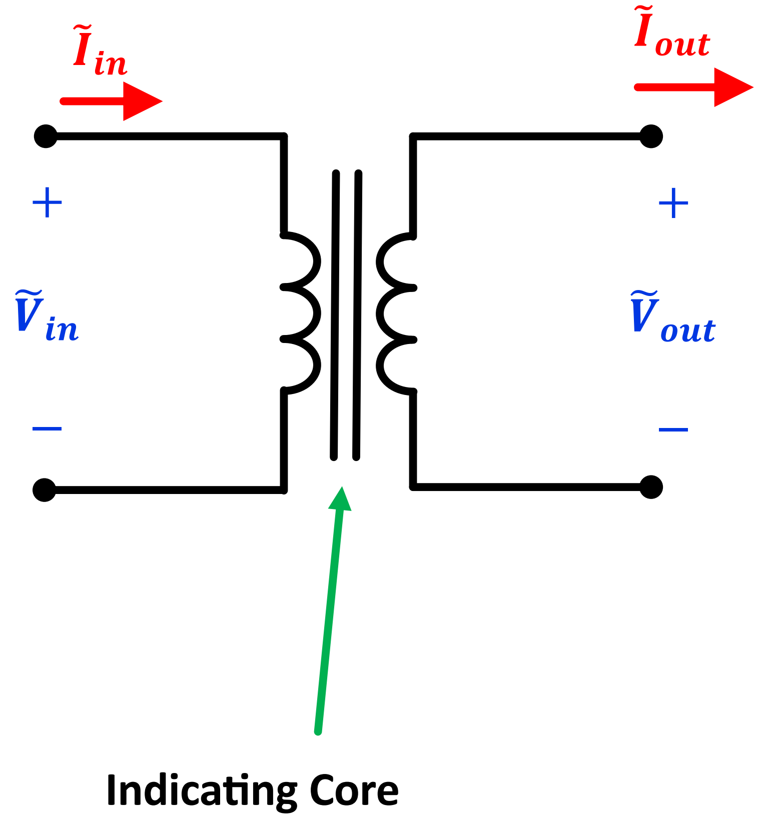
$$V_{in} \cdot I_{in} = V_{out} \cdot I_{out}$$

$$\therefore \frac{I_{out}}{I_{in}} = \frac{N_{in}}{N_{out}}$$

In reality, there's usually a bit of loss, but honestly not that much (usually >95% efficient)

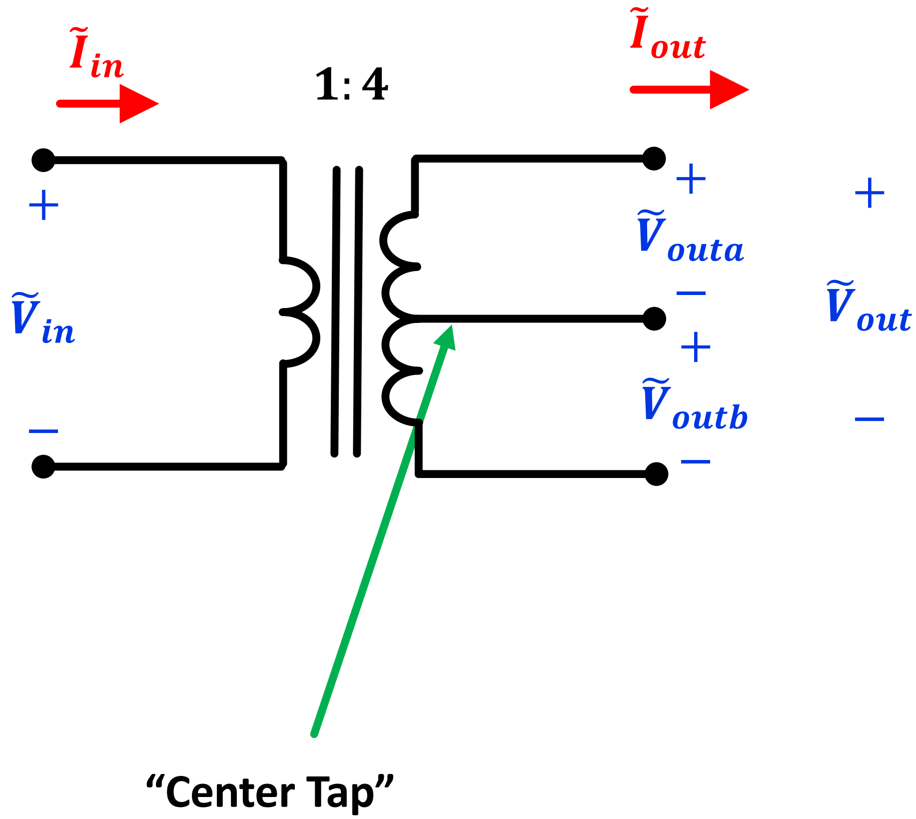
Cores

- Transformers will sometimes have cores of ferrite or mu metal or something to improve or modulate coupling of the fields. If core present will see double lines



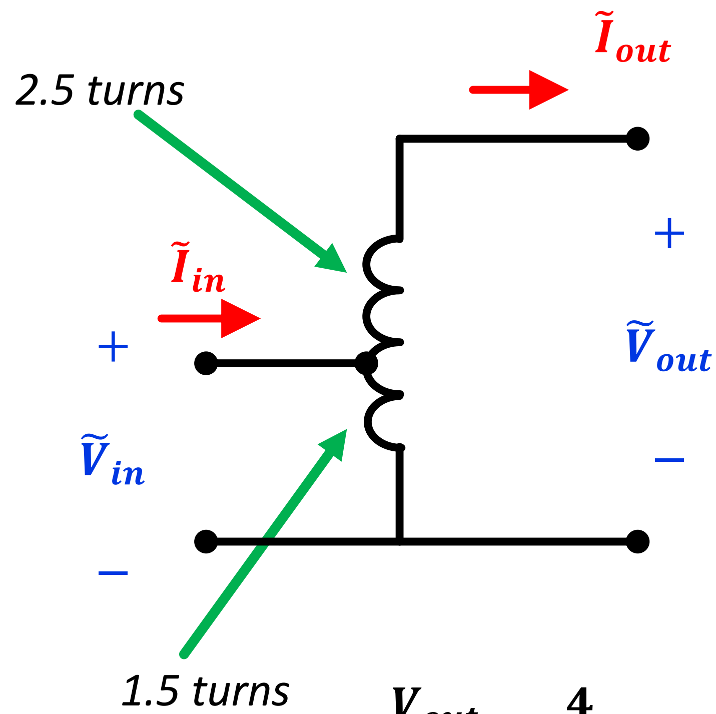
Taps

- Transformers may often have multiple taps to get sub-coils



Can also have transformer be one continuous coil

- Called an auto-transformer
- Works the same
- Lacks the electrical isolation you get from true transformer



$$\frac{V_{out}}{V_{in}} = \frac{4}{1.5}$$

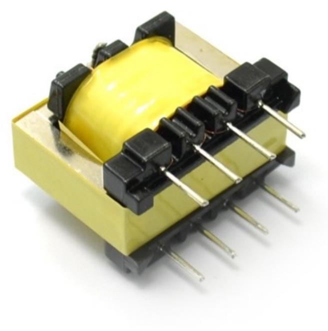
$$V_{in} \cdot I_{in} = V_{out} \cdot I_{out}$$

What Do Transformers Look Like?

- Vary based on purpose:

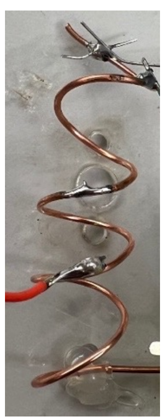
Power Transformer:

Audio Transformer:



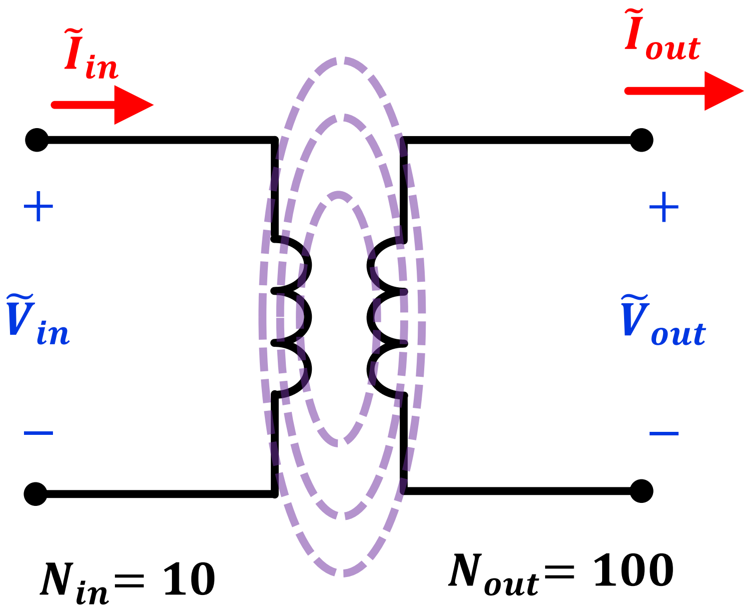
Tunable inter-stage transformer:

Auto-transformer from Lab 2 radio:



Are Transformers Amplifiers?

- Example:



$$V_{out} = \frac{N_{out}}{N_{in}} V_{in} = 10V_{in}$$

Sure looks like an amplifier…voltage go big!

Because of $V_{in} \cdot I_{in} = V_{out} \cdot I_{out}$ there is actually no power gain and that's usually what we want when we talk about amplifiers…amplifier should modulate a larger power source based off of input signal. Output signal is based on the power of input signal here ONLY!

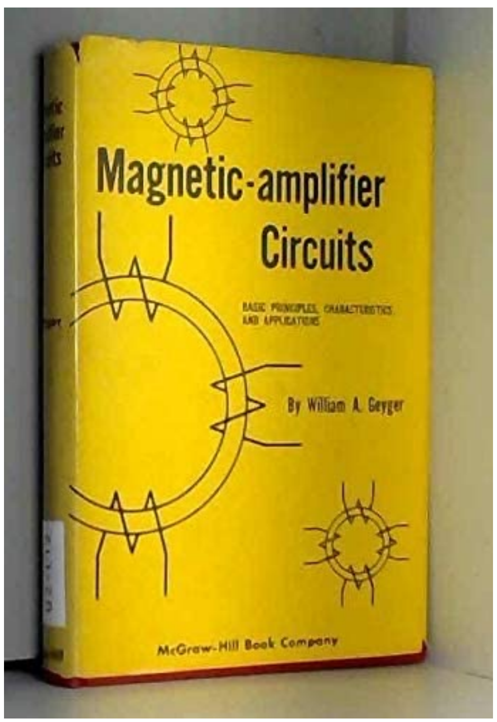
$$I_{out} = \frac{N_{in}}{N_{out}} I_{in} = 0.1I_{in}$$

$$P_{in} = P_{out}$$

<u>SO NO!</u>

Aside: Magnetic Amplifiers

- Through an unrelated technology, using multiple coils on common core, you can use transformers as amplifiers, (called saturable core amplifiers), but that is a specialty field that we're not talking about.

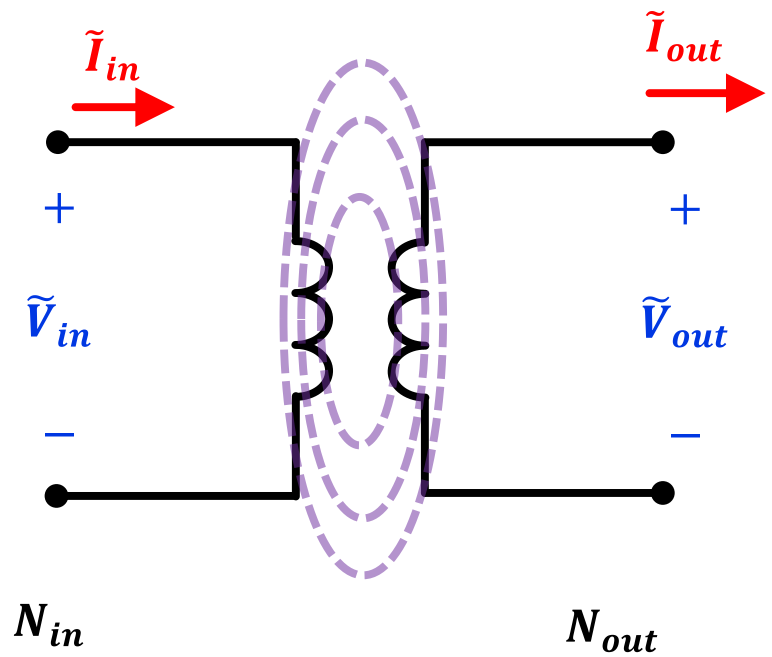


- Germans used "mag amps" in their V2/A4 rocket guidance system
- Some mag amps saw use in specific high-power applications into 60's but that's it
- OK end of aside

The Transformer

- OK, so what can we use the transformer for? We can't amplify

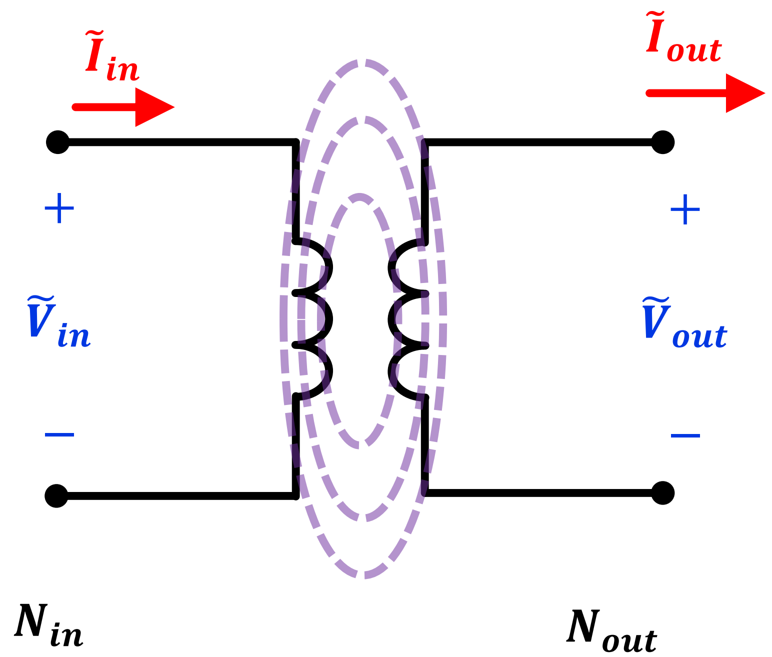
- Several big uses:
  - Power conversion
  - Impedance Matching
  - Electrical Isolation
  - Phase Inversion



The Transformer

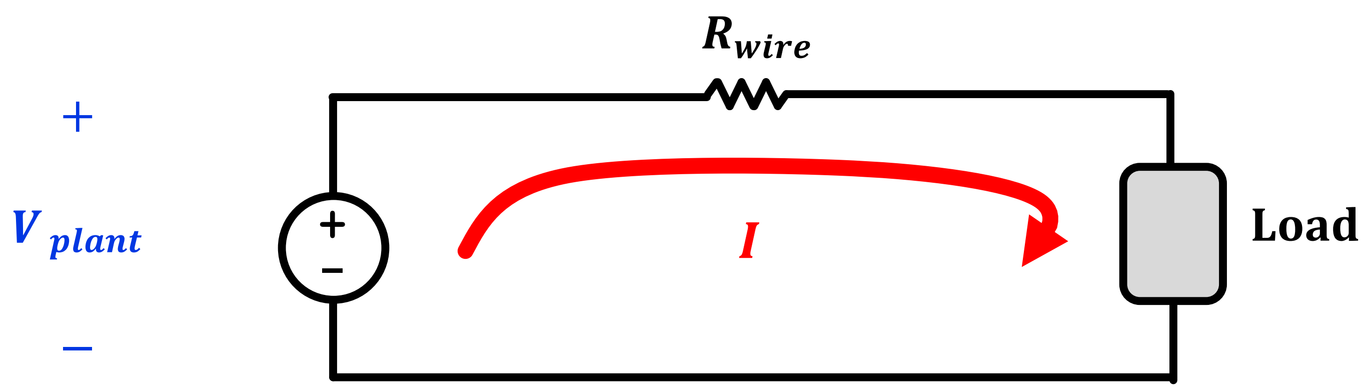
- OK, so what can we use the transformer for? We can't amplify

- Several big uses:
  - ***Power conversion***
  - Impedance Matching
  - Electrical Isolation
  - Phase Inversion



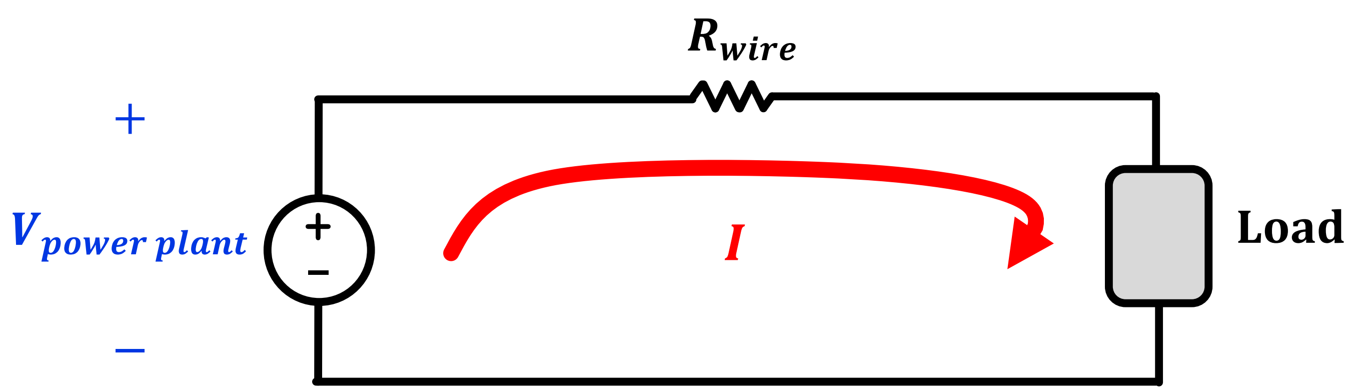
Transformers: Power Supply

- In parallel with tube development, came the development of the electrical grid.
- AC won out over DC as far as power distribution and the reason for that was transformers!
- Consider the power distribution problem:
  - The load is connected to the power source via non-ideal wire which can be modeled as $\boldsymbol{R_{wire}}$.
  - Since $\boldsymbol{P} \propto \boldsymbol{V_{plant}} \cdot \boldsymbol{I}$ as we need to deliver more and more power down stream, if we achieve this by increasing current since $\boldsymbol{P_{loss}} \propto \boldsymbol{I^2 R_{wire}}$ loss will go waaaay up:



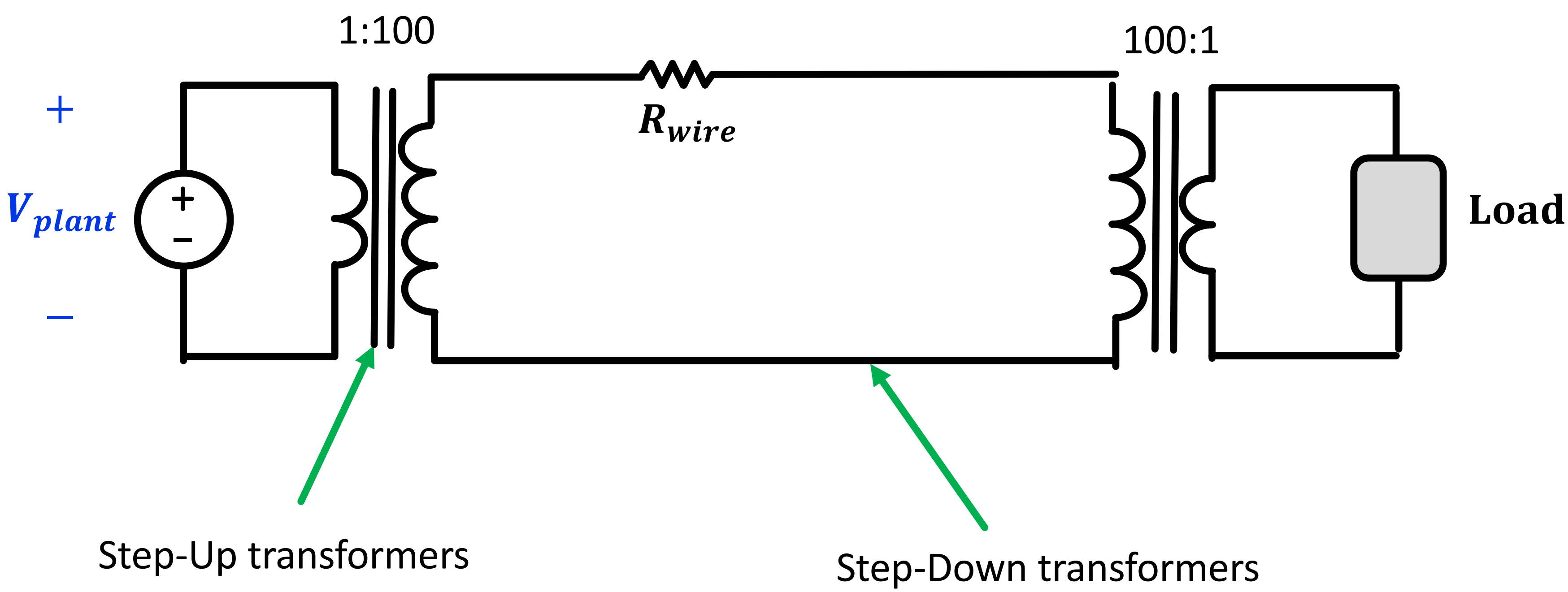
Power Supply Voltage Conversion

- Lowering $\boldsymbol{R_{wire}}$ requires making the wires really good (big, pure copper,…$$$)
- Instead of delivering lots of power using low-voltage high current systems, do the opposite: <u>high-voltage, low current</u>.
- That way, very little $\boldsymbol{I^2 R_{wire}}$ loss happens
- But most systems actually want to work off of low voltage high current. How to fix?



Solution

- Use AC for our power. Lets us use transformers!
- Use transformers to step up voltage to very high voltage (low current) for transport, then on consumer side, step back down



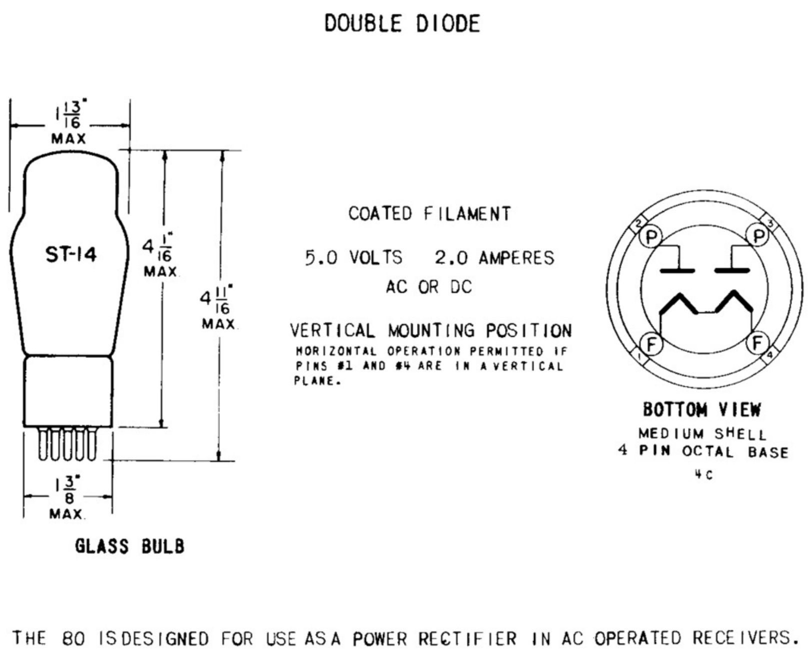
Vacuum Tube Diodes also helped out here!

- Original argument for DC was that many systems actually worked off of DC. If your electrical system was in AC, then a lot of systems wouldn't run
- Conversion to DC from AC requires some sort of non-linearity in the flavor of rectification (just like in AM decoding)
- Transformers and then Tube diodes* (which could handle decent amounts of power) allowed transforming AC into DC in a relatively safe manner

*other rectifying devices which we covered really couldn't handle the powers needed

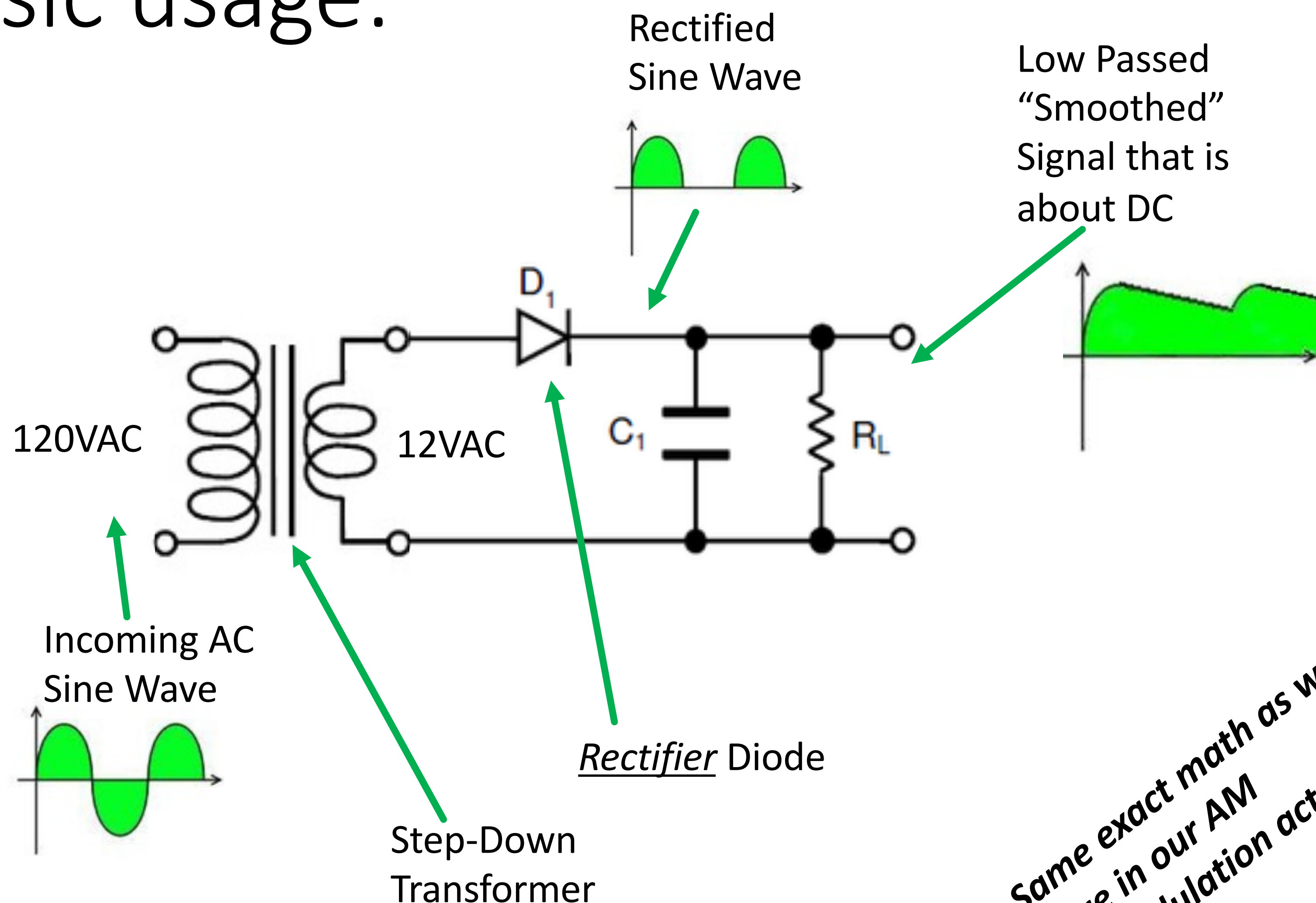
Type 80 Tube

- First wide-spread standardized double-diode for power rectification!



http://www.r-type.org/exhib/aaa0296.htm

Basic usage:

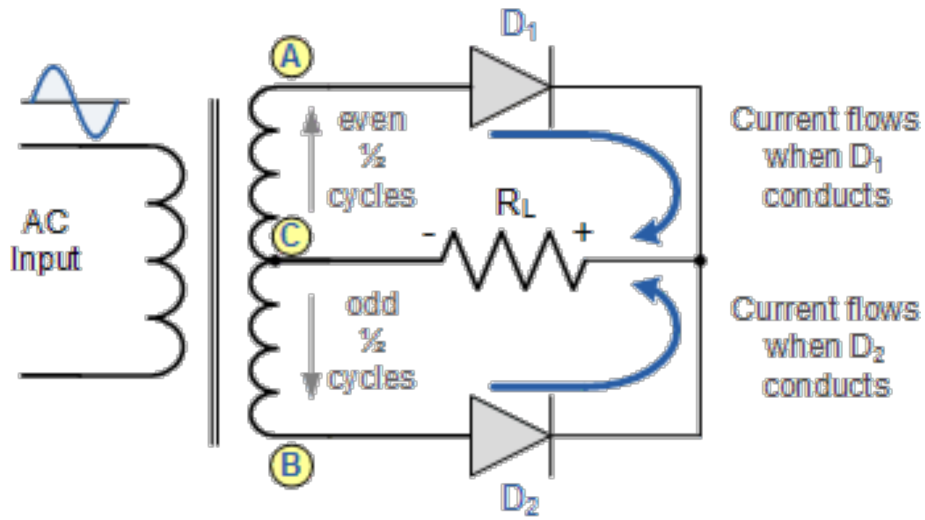


Same exact math as we have in our AM Demodulation actually!

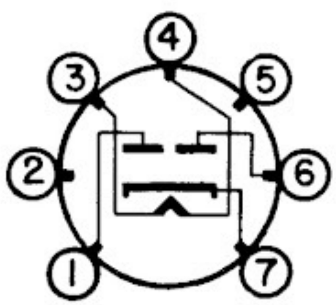
https://wiki.analog.com/university/courses/electronics/text/chapter-6

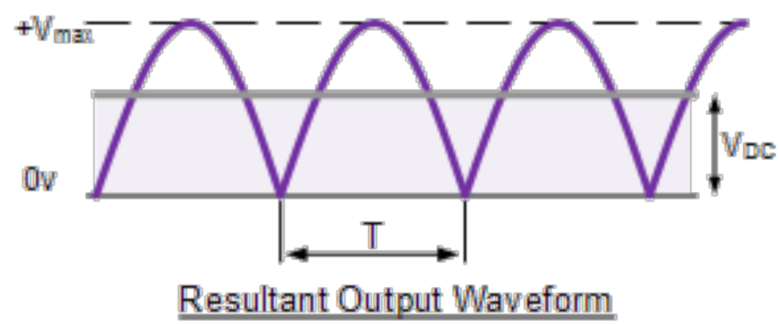
Full Wave Rectifier

- Two diodes with a center-tapped transformer could convert both cycles of AC Waveform



6X4...dual rectifier diode with indirectly heated cathode





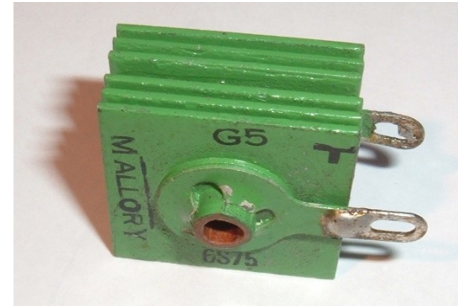
https://www.dnatechindia.com/Full-Wave-Rectifier.html

Mercury Vapor Rectifiers

- Lots of variants...some vacuum tube rectifiers would get filled with mercury vapor to improve current handling.
- Extremely dangerous, but also the most attractive glow you've ever seen in your life.
- You look at it and you feel like Gollum in Lord of the Rings

Type 83 Tube

Rectifiers



Selenium Rectifier

- Vacuum tubes as power supply rectifier diodes were widely used...could convert AC to DC at ~50 to 60% efficiency (high at the time)...most of loss was from filament heating btw.

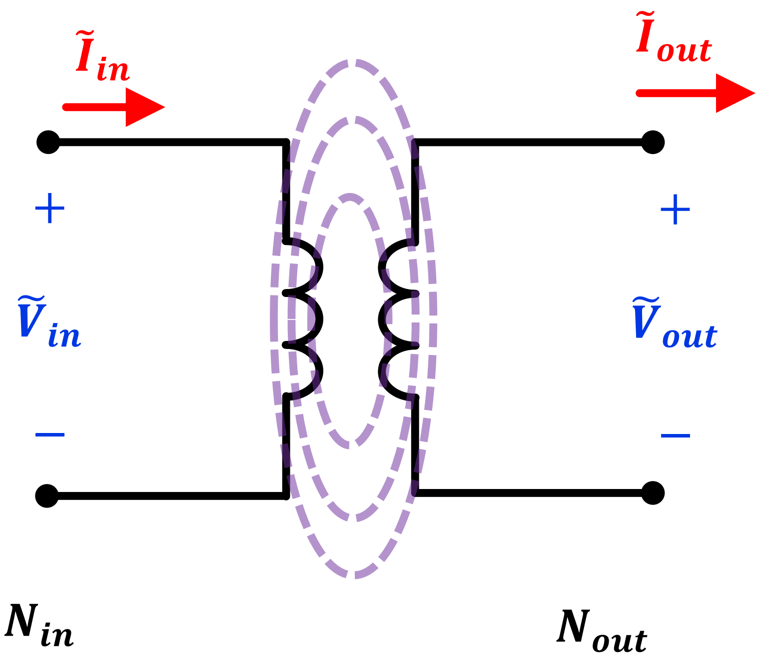
- Eventually replaced with selenium rectifiers and other early semiconductors for the 1940s-1950s until Silicon rectifier diodes became the standard

https://upload.wikimedia.org/wikipedia/commons/2/26/Selenium_rectifier.agr.jpg

The Transformer

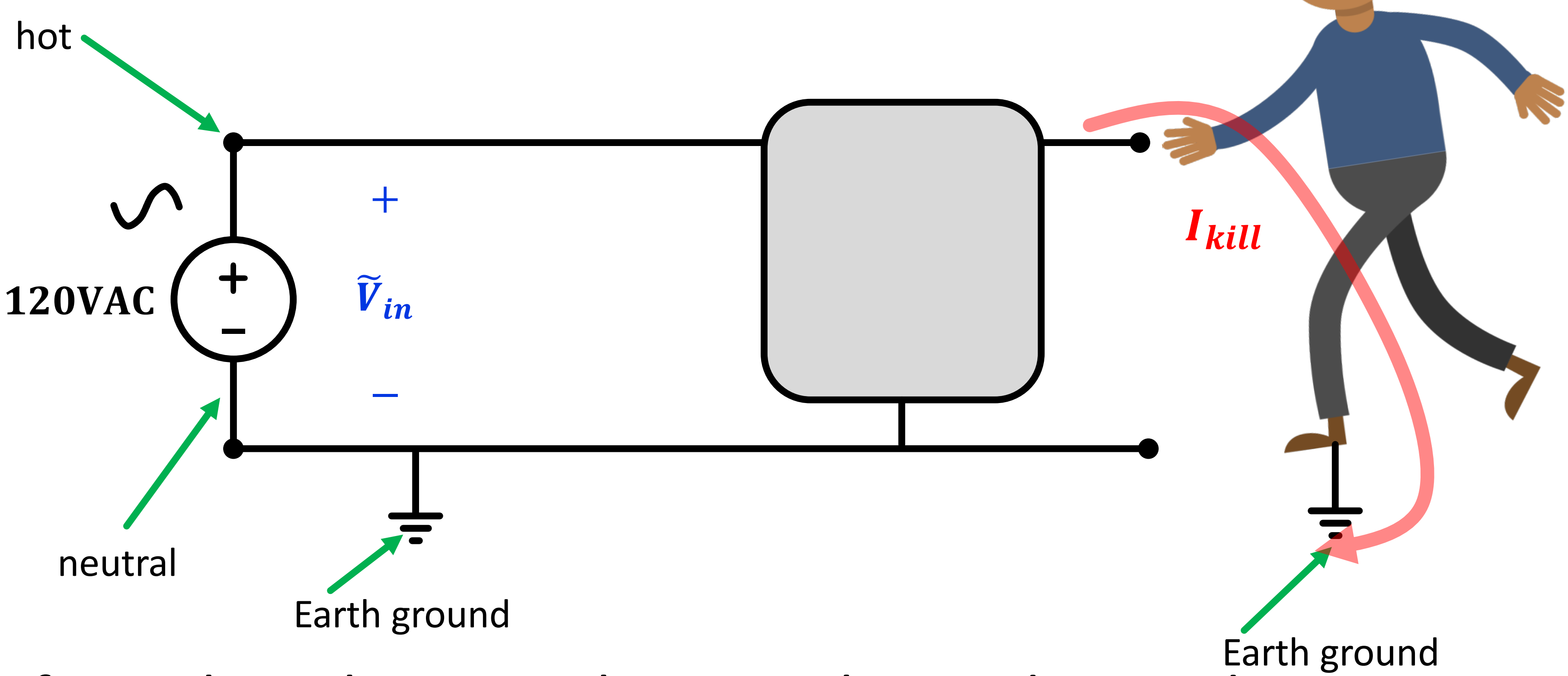
- OK, so what can we use the transformer for? We can't amplify

- Several big uses:
  - Power conversion
  - Impedance Matching
  - **Electrical Isolation**
  - Phase Inversion



Transformers: Isolation

- If we consume AC power directly there is a legit change for electrocution:

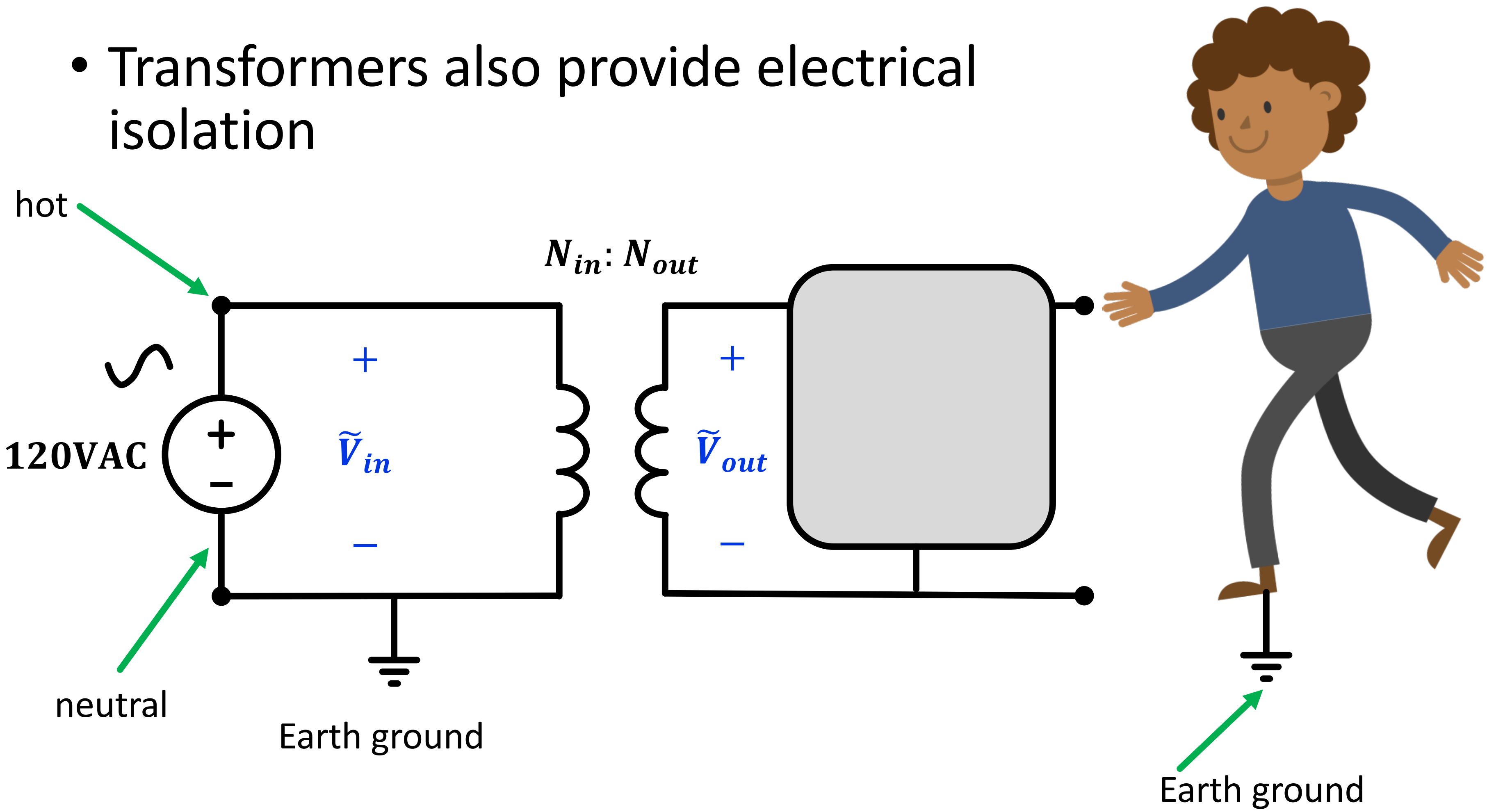


- If you close the circuit between hot and ground, current flows :/

https://www.clipartmax.com/download/m2H7N4d3N4i8H7G6_cartoon-person-walking-png-cartoon-ankaperla-com-group-cartoon/#

Transformers: Isolation

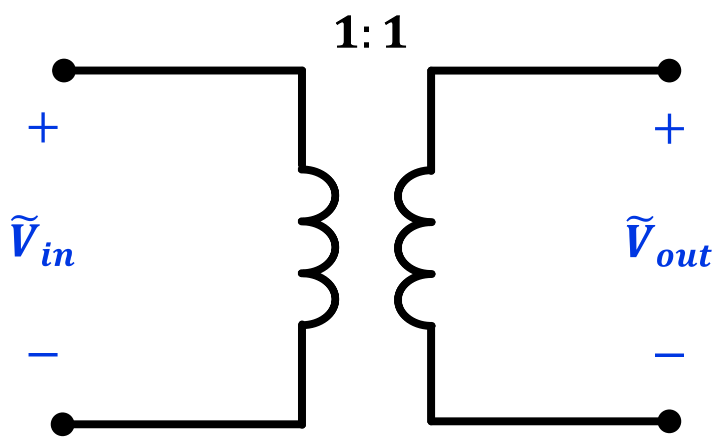
- Transformers also provide electrical isolation



- If you close the circuit between hot and ground, no biggie…in your isolated circuit, your local ground is different!

Transformers: Isolation

- A transformer-ed power supply is electrically quite safe.
- Even if you don't need to step up/down voltage, you'll sometimes see 1:1 transformers that exist solely for the purpose of electrical isolation!



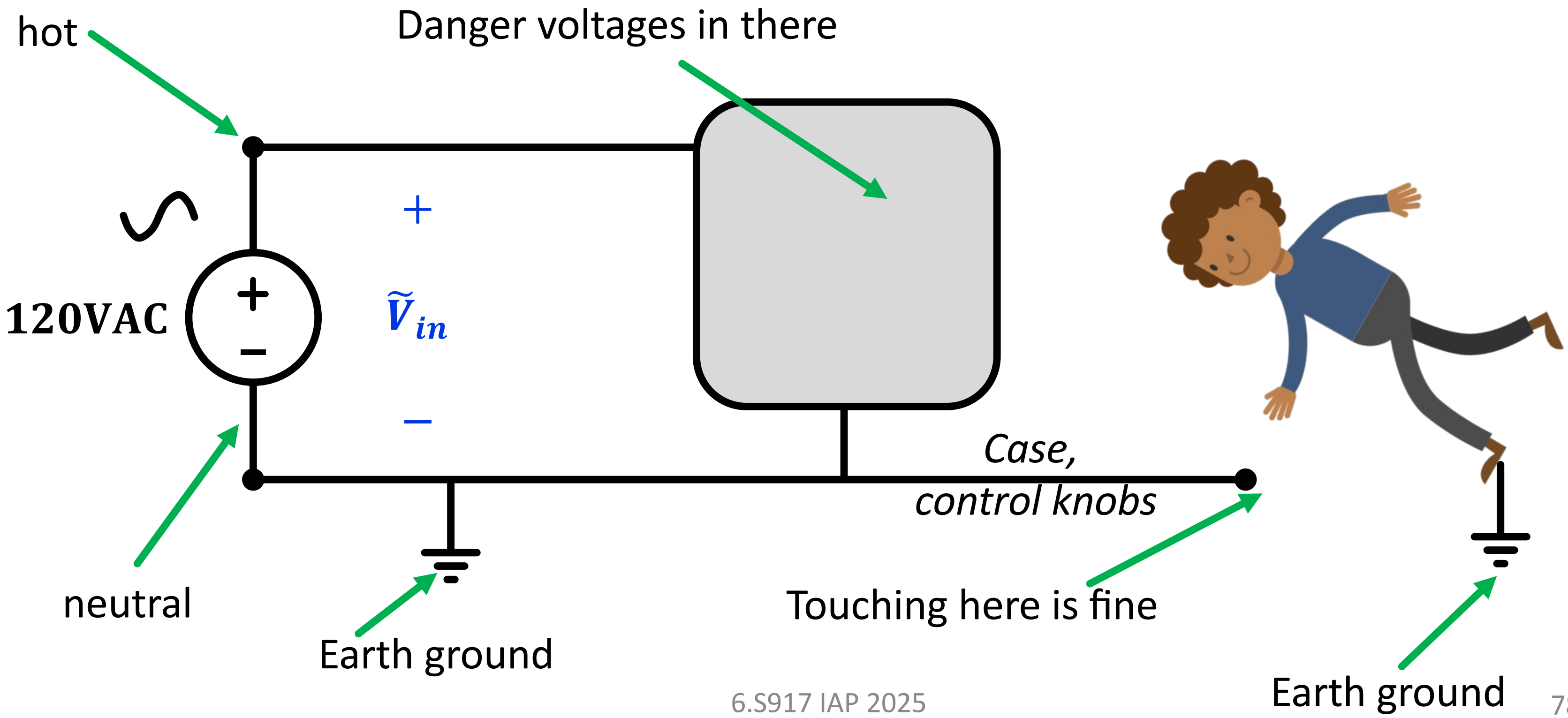
$$V_{out} = V_{in}$$

Isolation and Cost

- Transformers for power conversion are made of metal and are heavy and have copper and iron.
- As a result, they are expensive!
- One of the first things to get “cut” when radios and appliances started to be getting made *en masse* and “budget/discount” models started to appear was the transformer.
- Why spend an extra dollar to avoid electrocution!?
- Assuming everything was set up properly, you’d be fine

Grounding the Chassis!

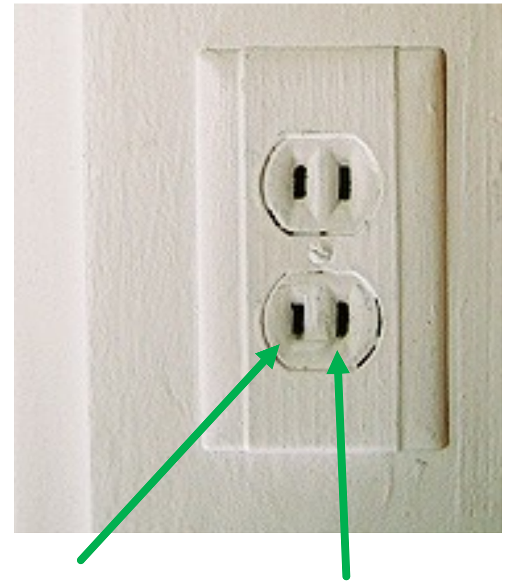
- In creating cheap appliances with no isolation, you'd tie your appliances case/chassis (often metal) to the neutral wire coming from the wall
- The parts of the circuit derived from the "hot" line would ideally be isolated inside the device so as long as you didn't open it up there'd be no fear of electrocution



Unfortunately…

- Up until 1960’s US AC plugs were completely symmetric.
- Other than measuring, there was no way to know which line was neutral and which was “hot”

Older wall US outlet
Note equal size of slots



Neutral or Hot?

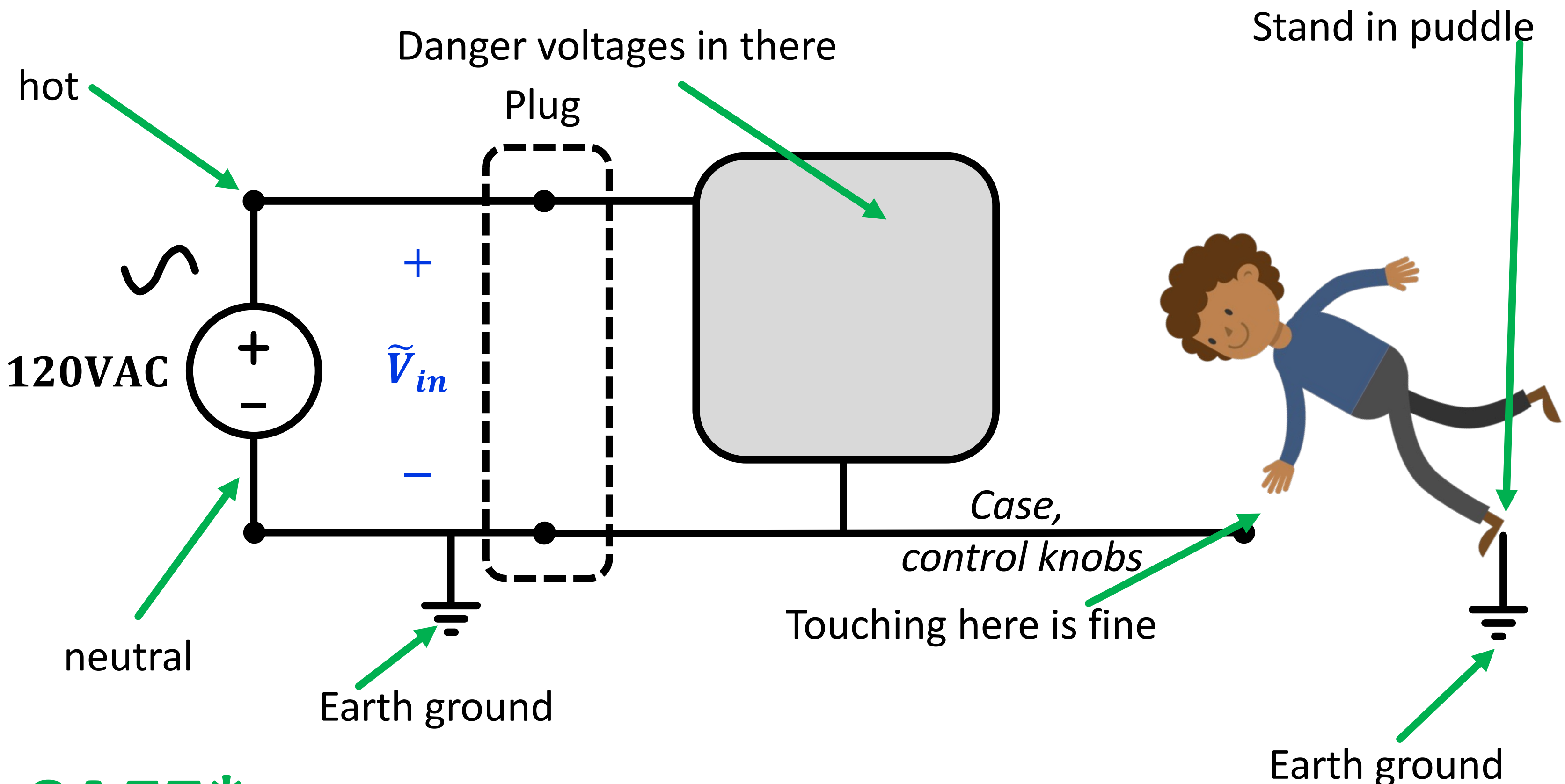
Neutral or Hot?

IUNNO

https://www.houselogic.com/organize-maintain/home-maintenance-tips/should-you-replace-old-wiring/

Flipping a Coin…

- If you plugged in your equipment one way, you would end up with your happy, safe circuit

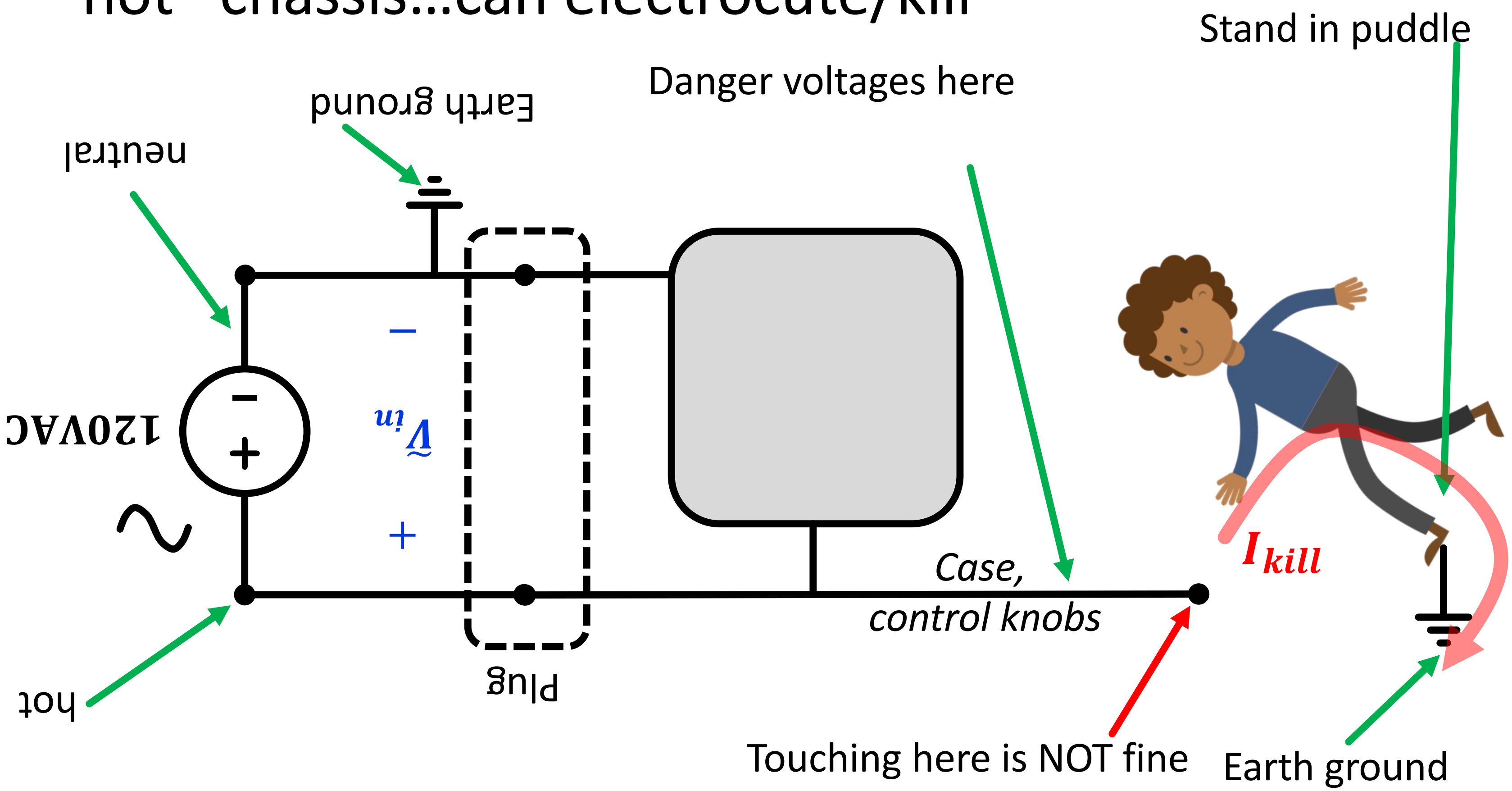


SAFE*

*by standards of the day

Flipping a Coin…

- If you plugged in your equipment the other way, you would end up with a "hot" chassis…can electrocute/kill

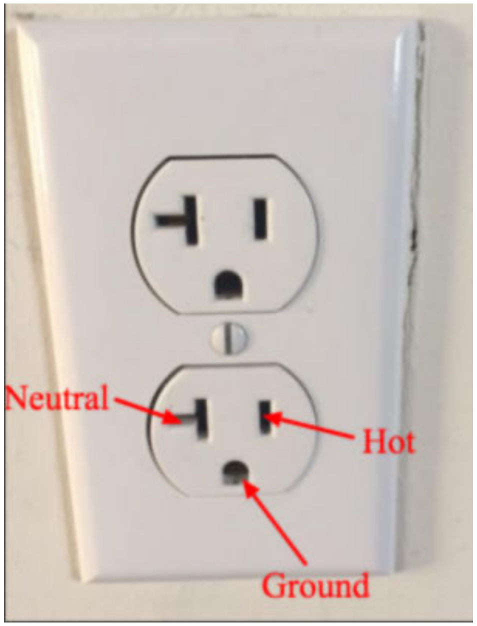


DANGER

Improvements

- 1960s, US started to make slightly better AC safety rules pertaining to plug dimensions and shapes forcing proper orientation

Better
(note prongs have different sizes)

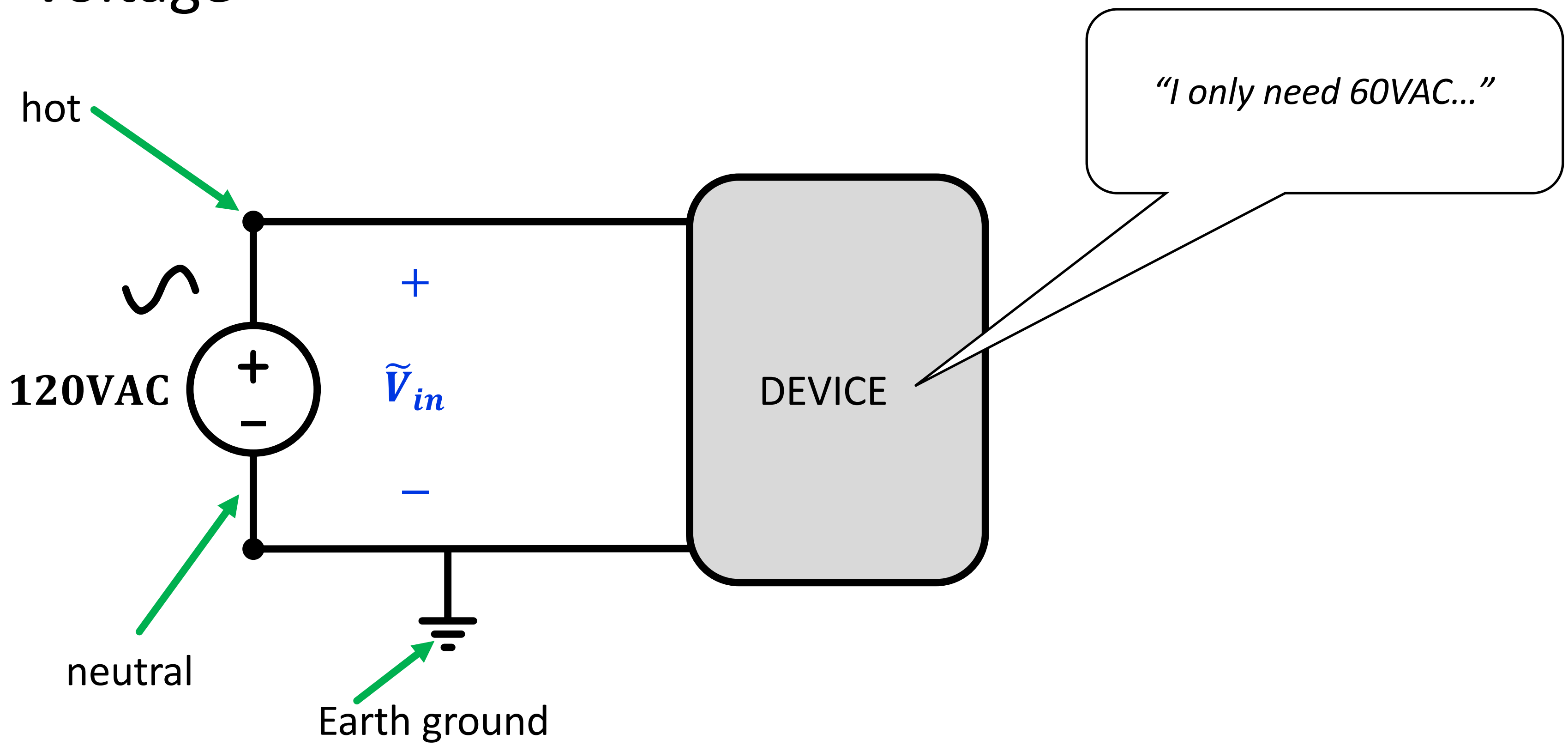


Even better

Best

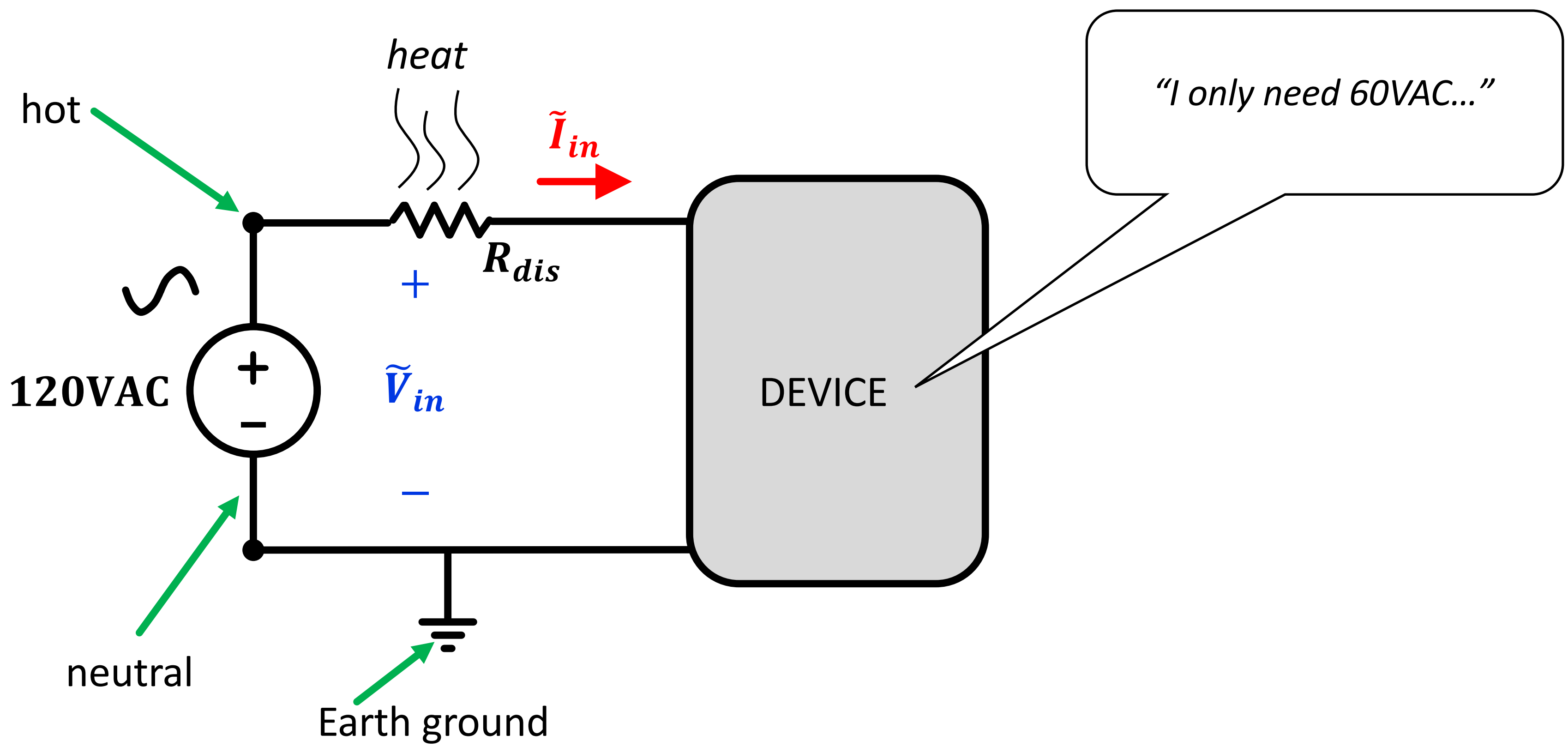
Dropping Voltage without Transformers

- Some early/mid-20th century appliances needed lower voltages than 120VAC line, but didn't have budget to have a transformer to step down the voltage



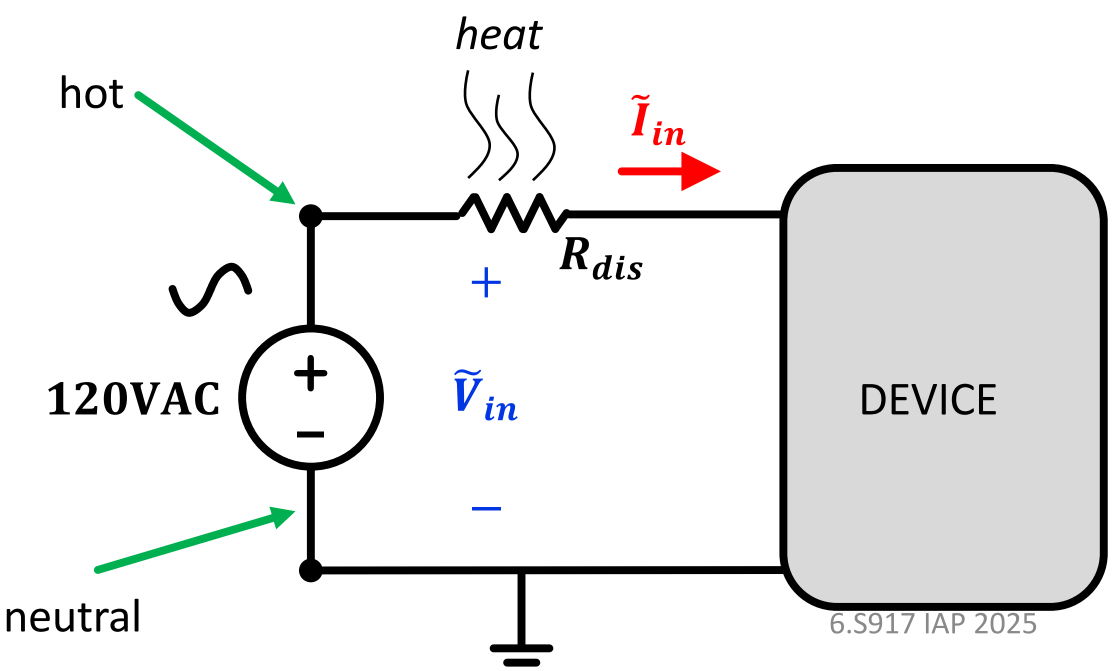
Solution: Drop it with In-Series Resistor

- Cook off excess power with resistor
- Many systems needed an amp or more
- If you needed to drop 60VAC that'd be 60W!
- Too much to dissipate inside device



Solution: Cook it off in power cable!

- Embed AC power cable with in-series heat-dissipating resistor and keep it stretched out.
- If you bunch it up, though Good luck
- Came to be known as “curtain-burners”
- They would coat them in asbestos to make more robust to heat, but that of course has other issues



Restoring Antique Appliances

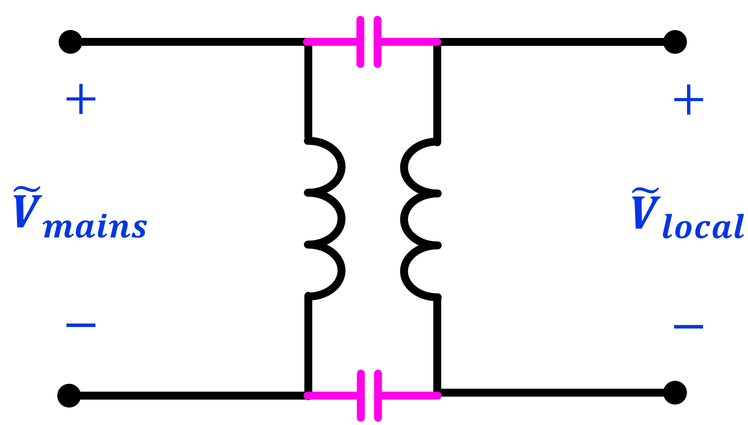
- If you find an old radio or fan or mixer or whatever, and want to restore it, you'll need to:
  - Rewire it so that a hot-chassis is impossible
  - Potentially add a modern power supply to more safely drop voltage as needed
  - Also do a whole bunch of other things!

Interesting Issue

- I get a slight electrical tingle from my macbook when I touch the chassis and a grounded object
- That would suggest there must be some path or lack of isolation or something.
- But we're in the modern era and things are safe, correct?
- There's no more hot chassis(es)?

Where the Leakage Comes From

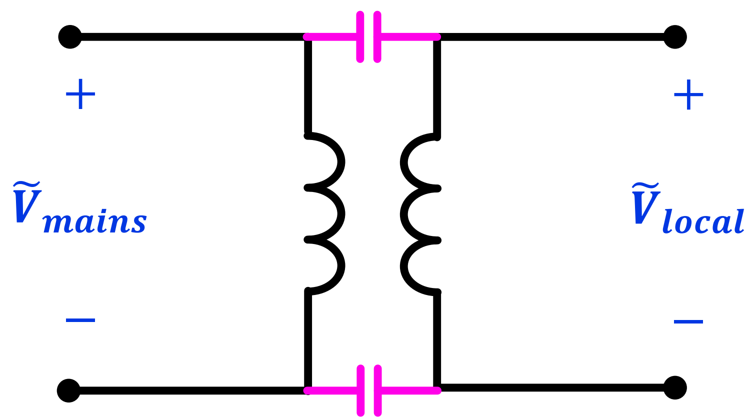
- Modern power supplies run at very high frequencies (100’s of kHz).
- Doing so lets the transformers be much smaller so you save on iron (and other benefits too)
- They do have full “official™” isolation via some transformers, but these types of transformers will have parasitic capacitance between the two windings



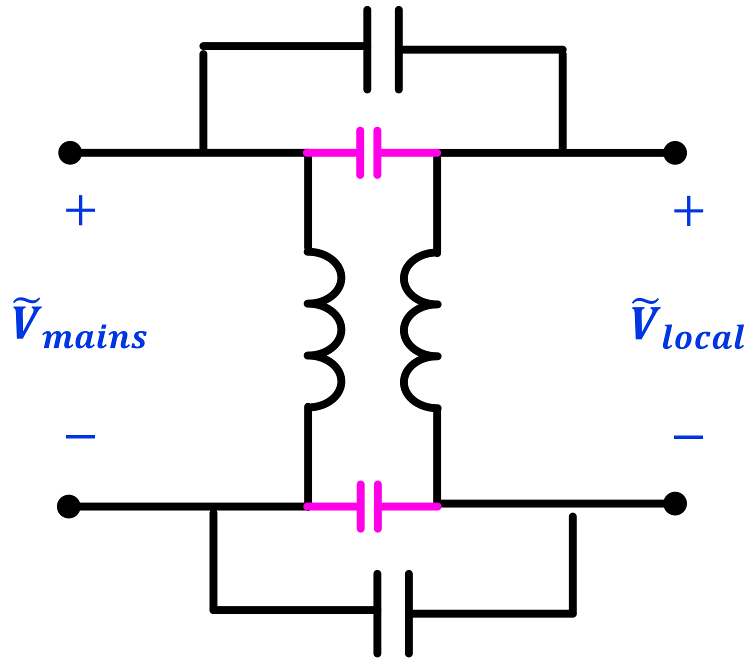
Where the Leakage Comes From

- This parasitic Capacitance is small, but because of its presence and involvement with the inductances of the coils of the transformer you can get some oscillatory action.
- Since C is small that means the frequency the caps and coils like to oscillate at together will be large:
- This high frequency behavior can get everywhere and cause noise

$$f = \frac{1}{2\pi\sqrt{LC}}$$

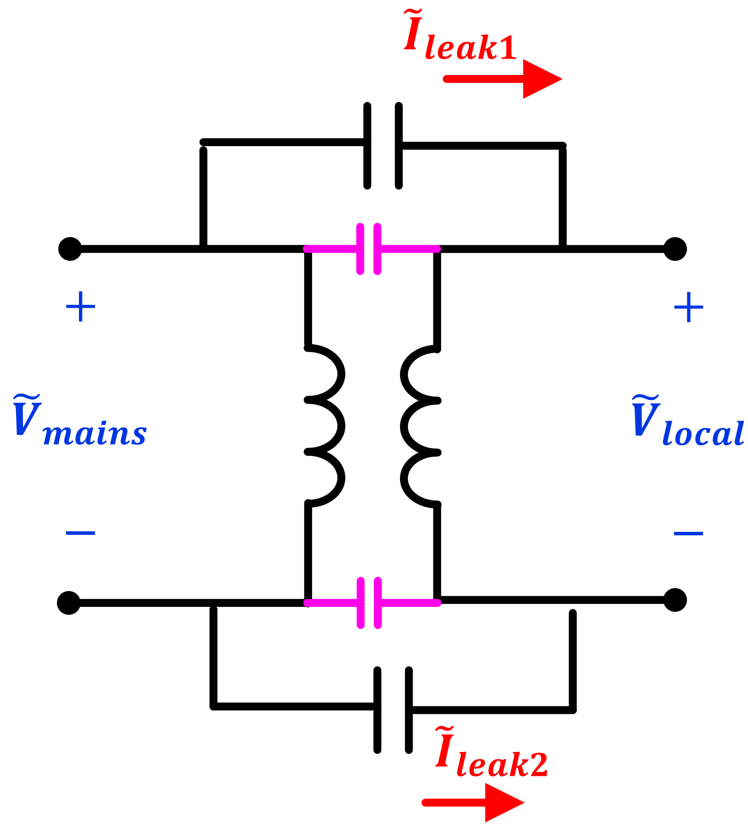


Solution: The Y Capacitor



- Put much larger capacitors (nF) in parallel with transformer
- This C adds (in parallel) with parasitic C, making total C much larger…brings the resonant frequency down $f = \frac{1}{2\pi\sqrt{LC}}$

Issue:



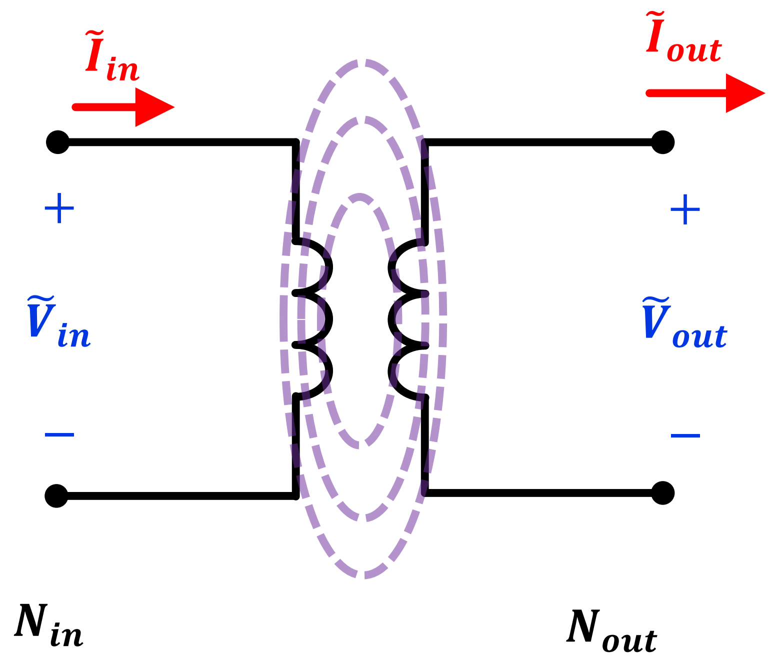
- Bigger capacitors have lower impedances $Z_C = \frac{1}{j\omega C}$
- So now there is a bigger non-isolation path between the “isolated” side and the mains

Issue:

- And this means there is the possibility for leakage current to occur if the polarity of an AC plug is flipped and someone touches earth ground
- Thankfully, this is *highly regulated*. Can't be more than about 50 uA of current
- The Y capacitors must be very good (very high safety rating to avoid failure/shorting).
- But there is some leakage there.
- So my macbook isn't a hot chassis…more like a warm chassis.
- Good discussion:
  - https://electronics.stackexchange.com/questions/216959/what-does-the-y-capacitor-in-a-smps-do

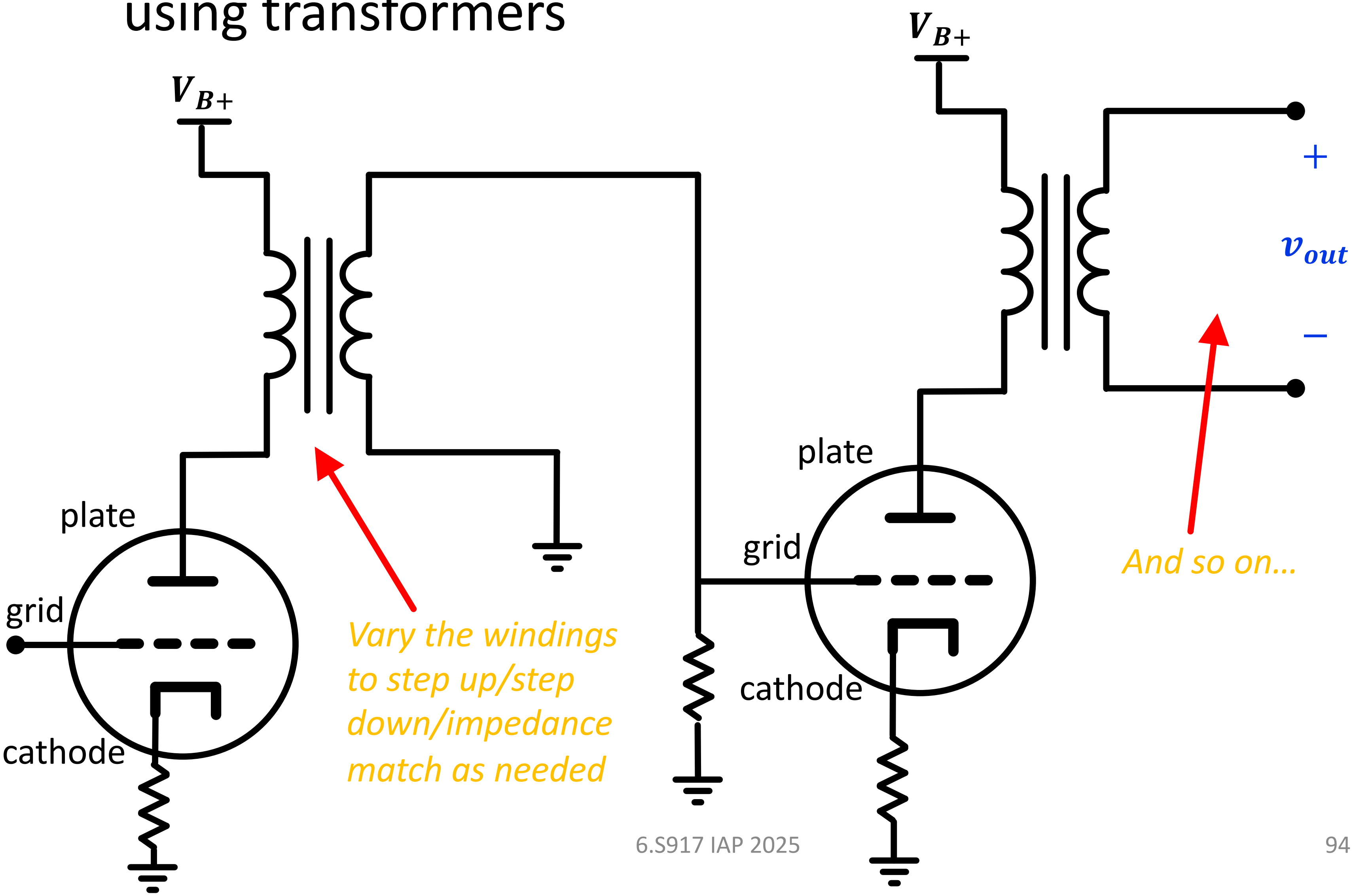
The Transformer

- 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



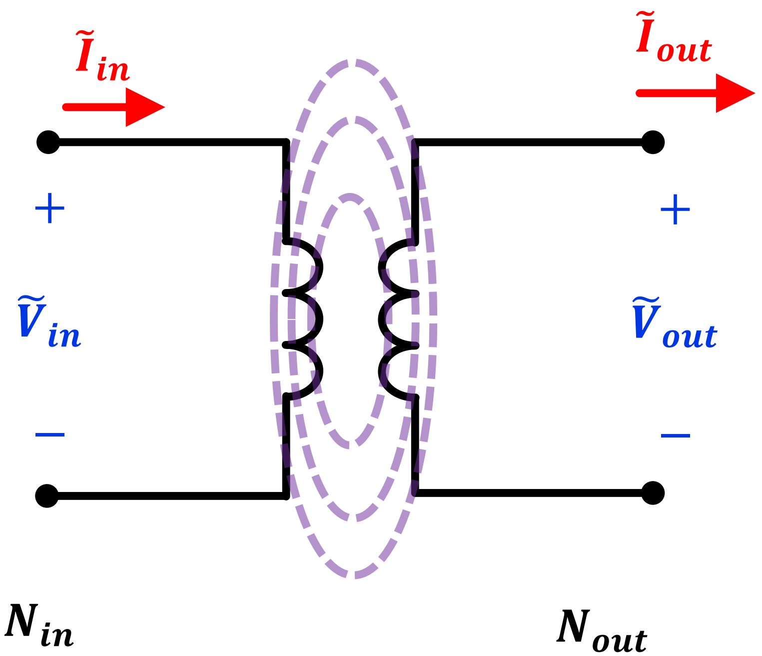
Transformer Coupling

- A triode with a transformer output could kinda create a system with:
  - High input impedance
  - Low(er-ish) output impedance
    - (which is exactly what we want from Op amps for example)

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

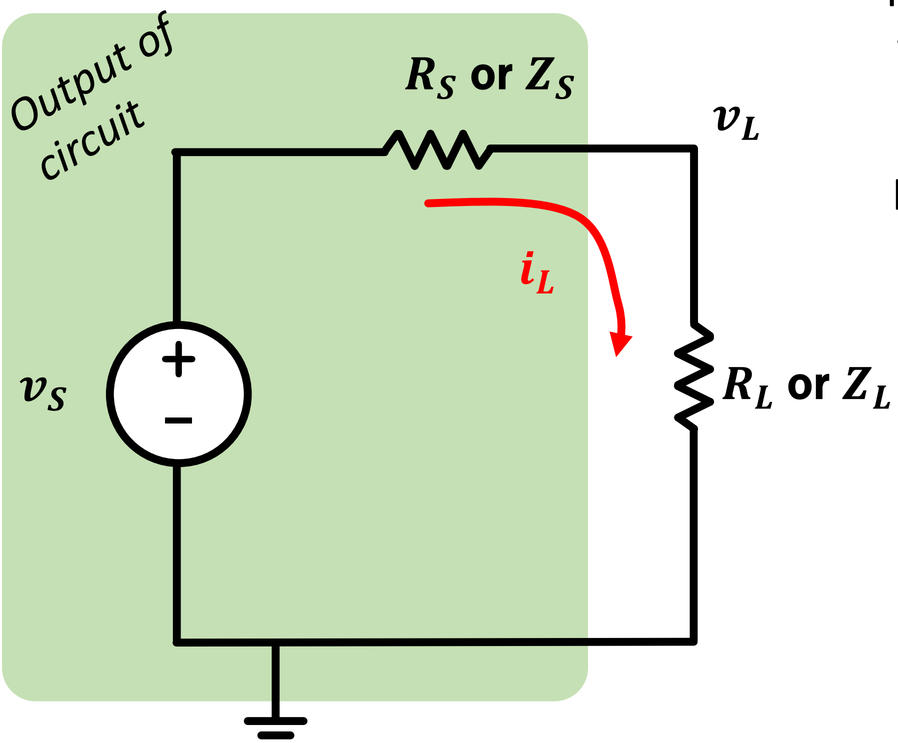
The Transformer

- 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



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:

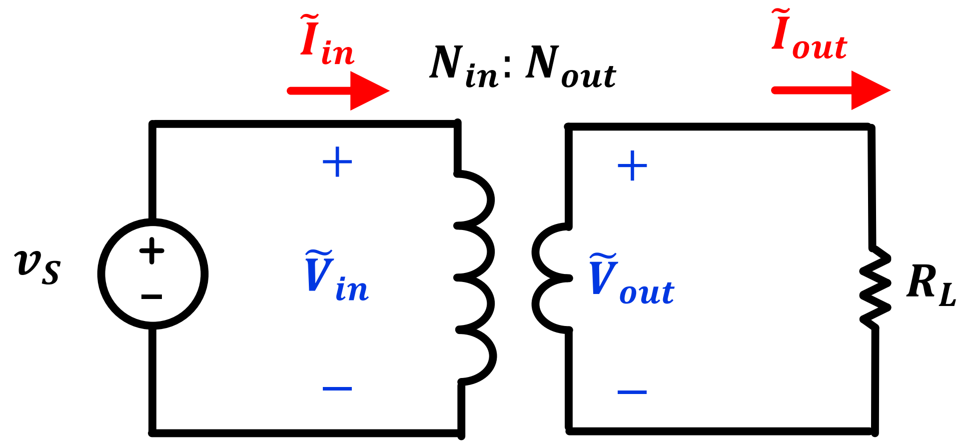
Like before: $\frac{V_{out}}{V_{in}} = \frac{N_{out}}{N_{in}}$

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

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

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

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

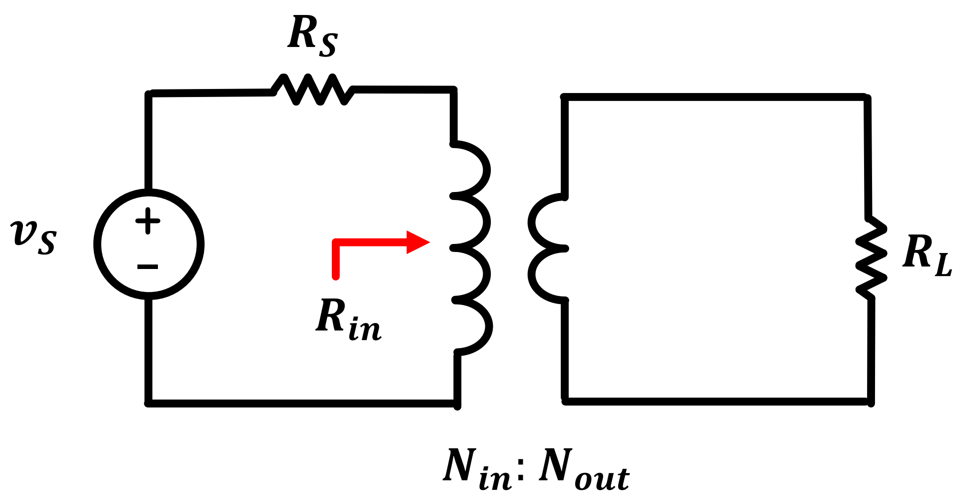


We could define $R_{in} = \frac{V_{in}}{I_{in}}$:

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:



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

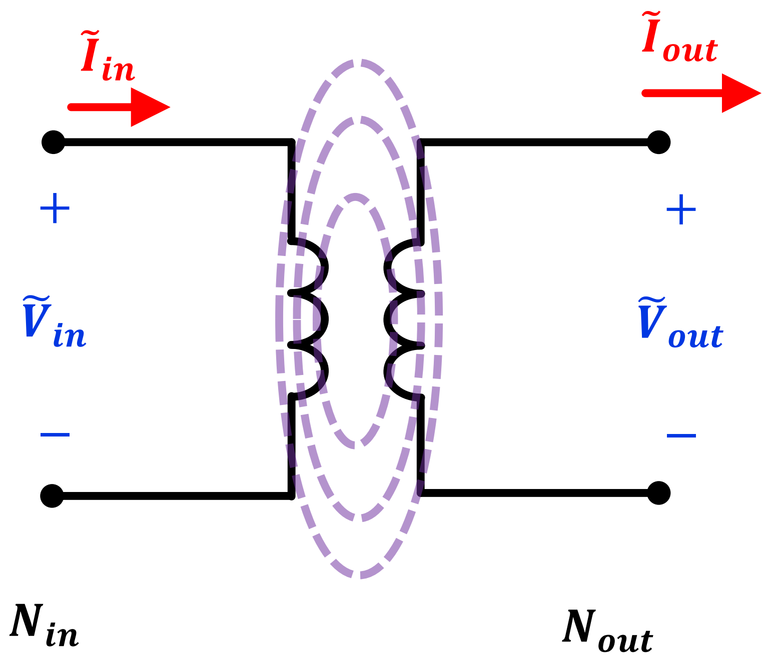
Works more generally for impedance too:

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

- Is R_L too low (like might be the case in a speaker like we'll see in Lab 4)? Use a step-down transformer to increase the effective impedance
- Is R_S too high (like is sometimes the case in an antenna)? Use a step-up transformer to decrease the resistance

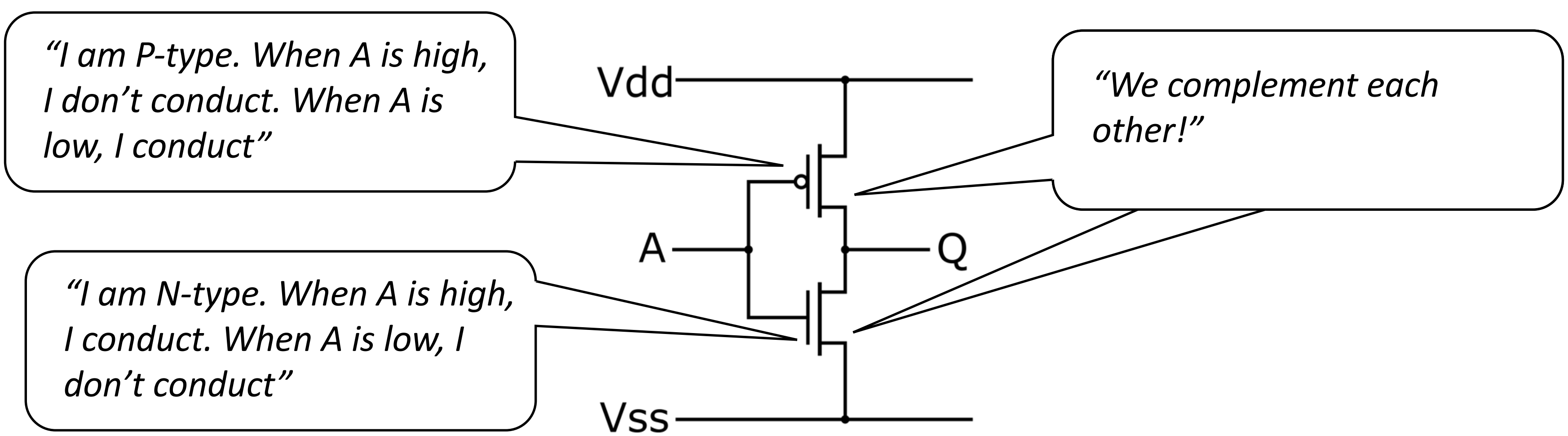
The Transformer

- 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**



Problem: Tubes only have one “type”

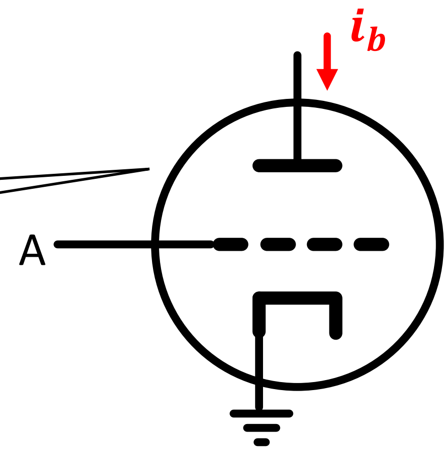
- In the future (1950s) we’ll have N-type and P-type devices, working off of electron and hole charge carriers, respectively
- Allows us to develop amplifiers that work in complementary fashion
- Consider a CMOS inverter for example



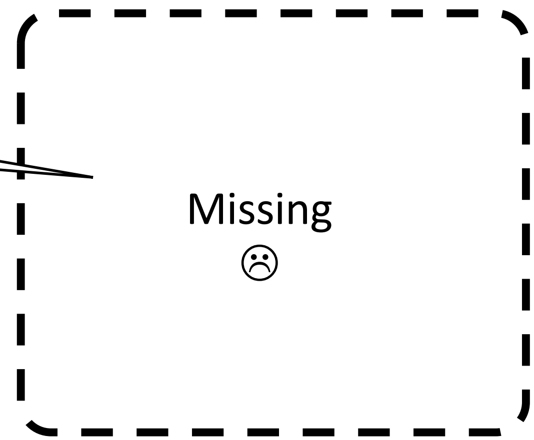
Tubes only have one "type"

- Tubes only work off of electrons as carrier

"I am N-type. When A is high, I conduct. When A is low, I don't conduct"

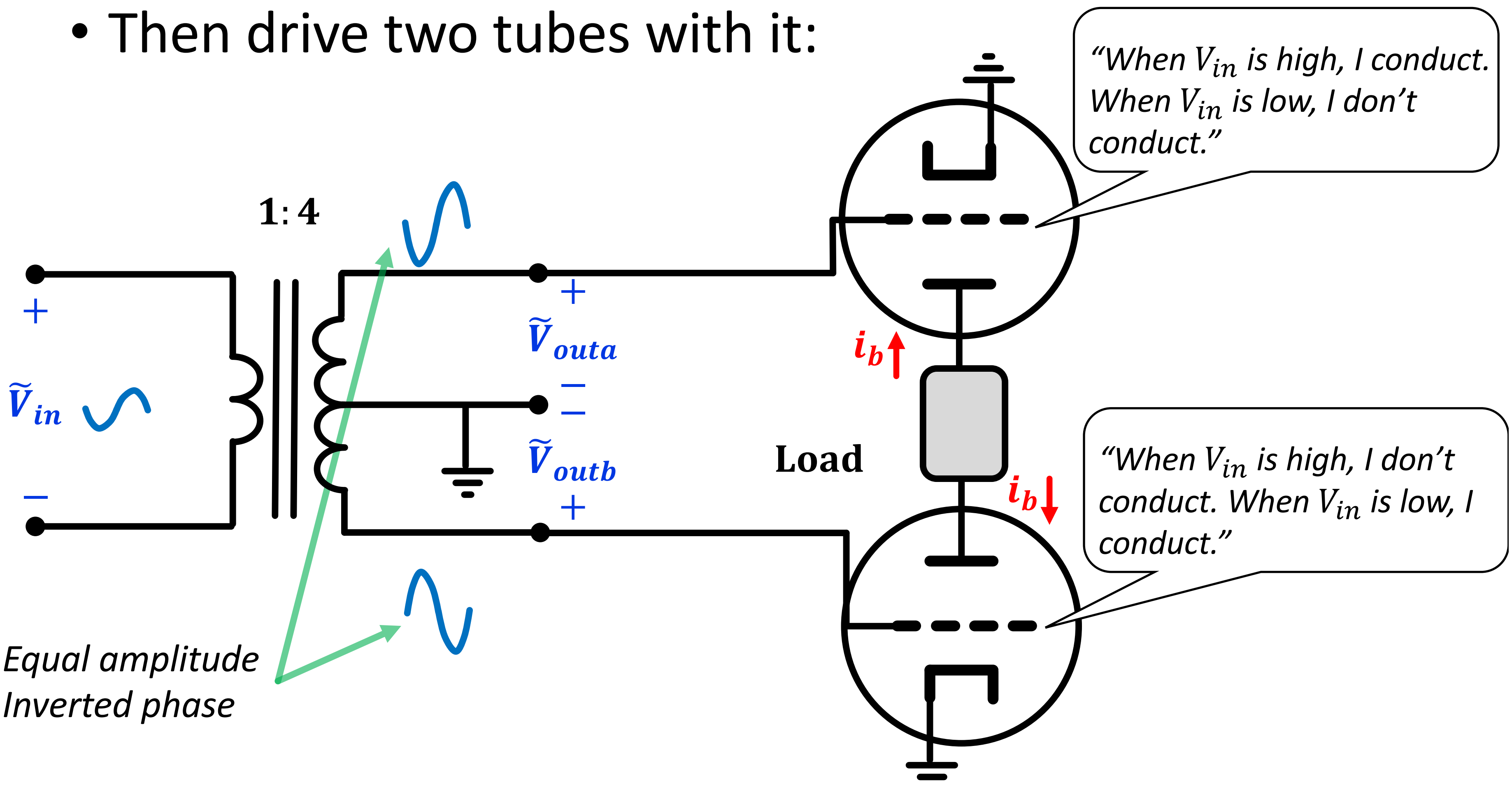


"I am P-type. When A is high, I don't conduct. When A is low, I conduct"

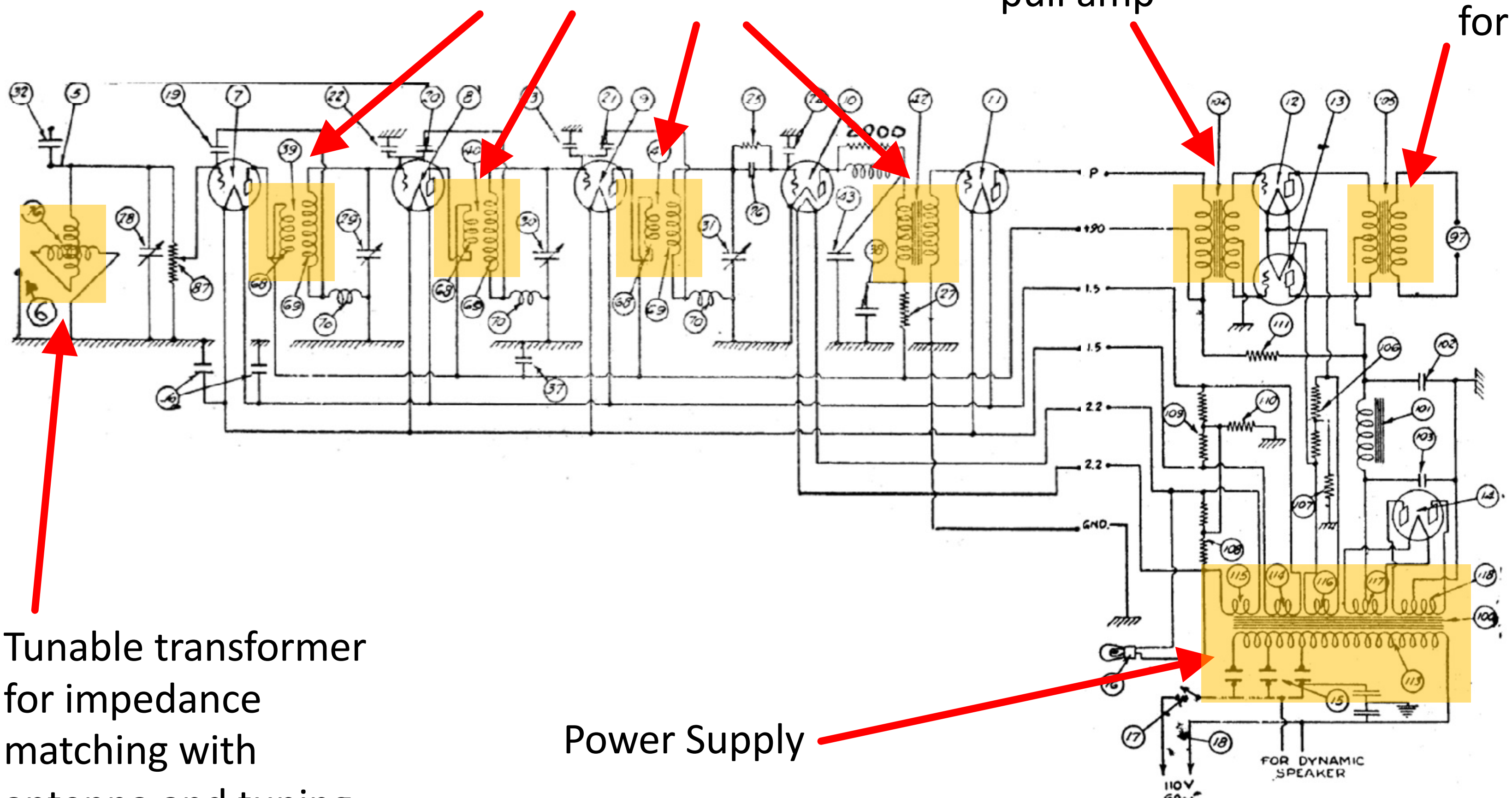


Solution: Use a Transformer

- 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



Next Lecture

- Some More Tube Circuits
- Triode Limitations
- Adding More Electrodes
- Complexity Keeps Increasing...