Lecture 2

Tube and Early Transistor Electronics

Review: By 1890:

- Multiple types of large-scale information transmission networks were appearing/had appeared:
  - Telegraphy (digital low-data-rate over wire)
  - Telephony (analog higher-data rate over wire)
  - "Radio"/Wireless (not sure yet...hopefully do both without wire)
- In all cases you had to deal with a system like this:

| Transmitter | —— *Information* ——→ | Receiver |

- In all cases, at the receiver end, you had to deal with information that was:
  - Not directly consumable*
  - Small in amplitude/power

*meaning a human couldn't use this form of energy inherently like we can with speech. We have no real "electro-sensor" organs

Review: By 1890:

- Fixing these two problems required:
  - Not directly consumable. → **Detection!**
  - Small in amplitude/power. → **Amplification!**
- **Detection** refers to extraction of information into a consumable form from the transfer medium (some form of transducer)
- **Amplification** refers to the generation of larger-power signals based off of smaller-power signals

Review: By 1890:

✅ • Telegraph (wired) networks were widespread:
  - Electromagnetic (relay-based) amplification and detection

• Telephone networks (wired) were growing:
  - Transmit analog data over distance
✅* • Relatively short-distance networks
  - Early analog amplifiers using electromagnetic and carbon/metal interactions could provide some amplification to recover loss

• "Radio" technology beginning to appear:
❌ • Radio waves operated *at much higher frequencies* than the prior two electromagnetic forms of communication
  - Previous technologies for amplification and detection were useless at radio-frequencies ☹
  - Needed to develop true "electronics" not "electromechanical things"

*carbon amplifiers were annoying and unreliable

Review: Situation with Radio

First attempt to use radio waves to convey information involved:

- Generate a carrier wave(s) of a particular frequency (one that could be reliably transmitted and picked up

- Encode information in the amplitude of that carrier wave (Amplitude Modulate)

- (Fail to) Profit (at first)

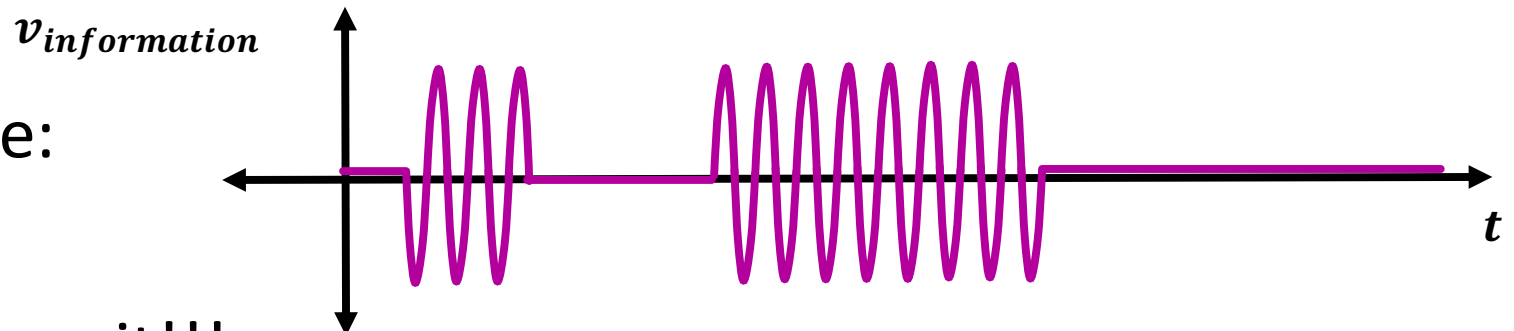# Encode Info with Amplitude of Carrier

- Start with: $v_{carrier}$
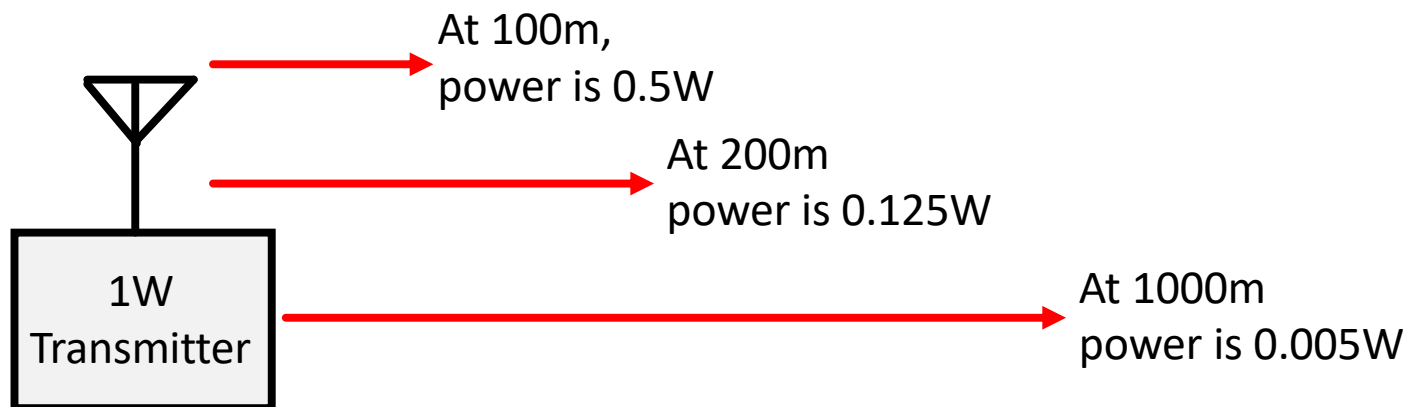
- And with: $v_{information}$

  "1" "N/A" "0" "N/A"

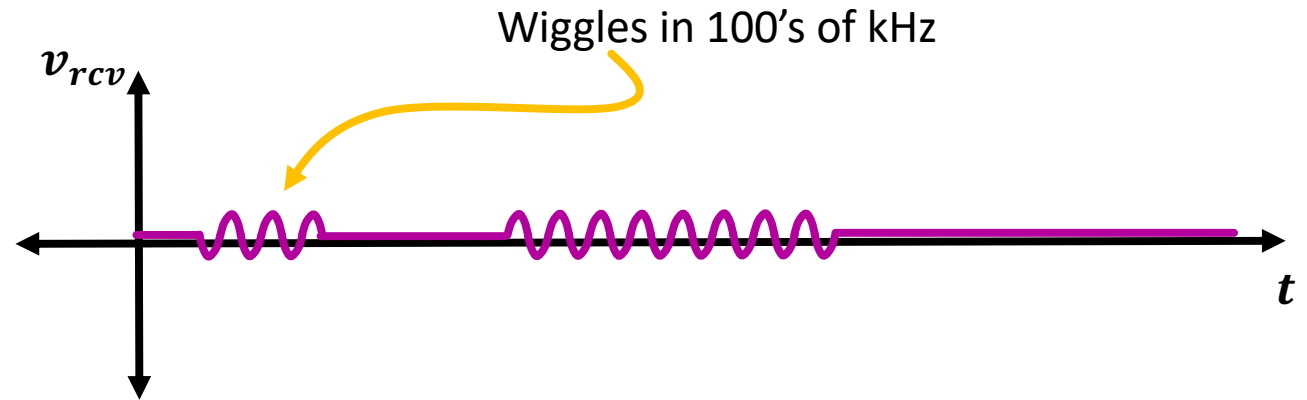- And make: $v_{information}$
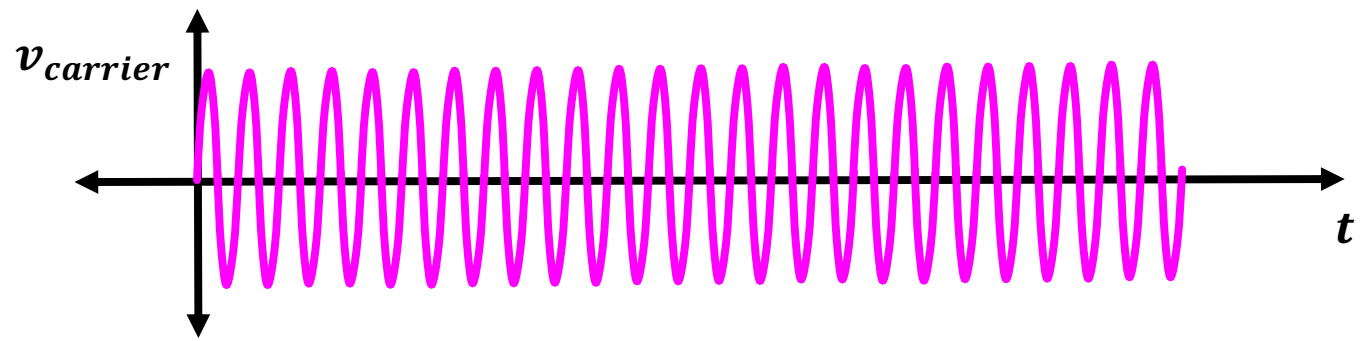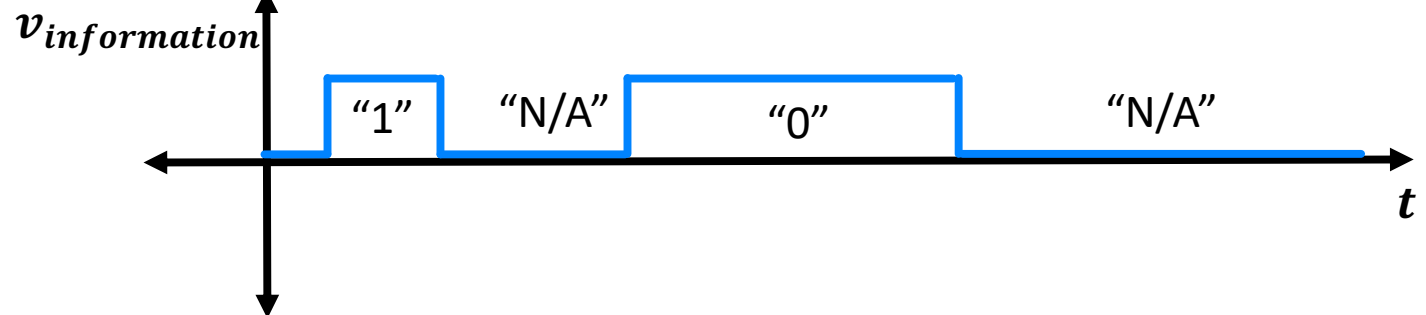
- Then transmit!!!

The Radio Wave Propagates

- Amplitude goes way down, following inverse square law ($\propto {}^1\!/_{d^2}$)…in other words signals get small very quickly!
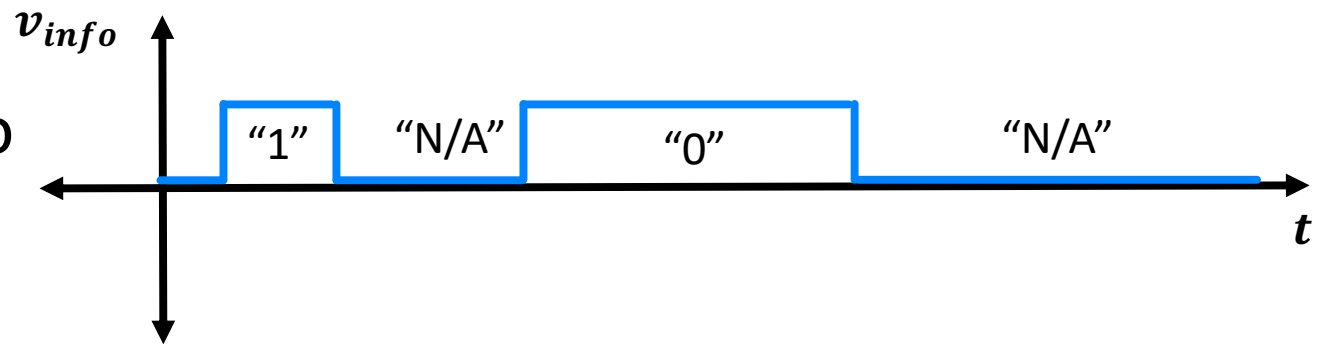
At 100m, power is 0.5W

At 200m power is 0.125W

1W Transmitter

At 1000m power is 0.005W

The Situation on the Receiver Side

Wiggles in 100's of kHz

- You receive this:

v_{rcv}

t

- How do you turn it back into this?:

v_{info}

"1"   "N/A"   "0"   "N/A"
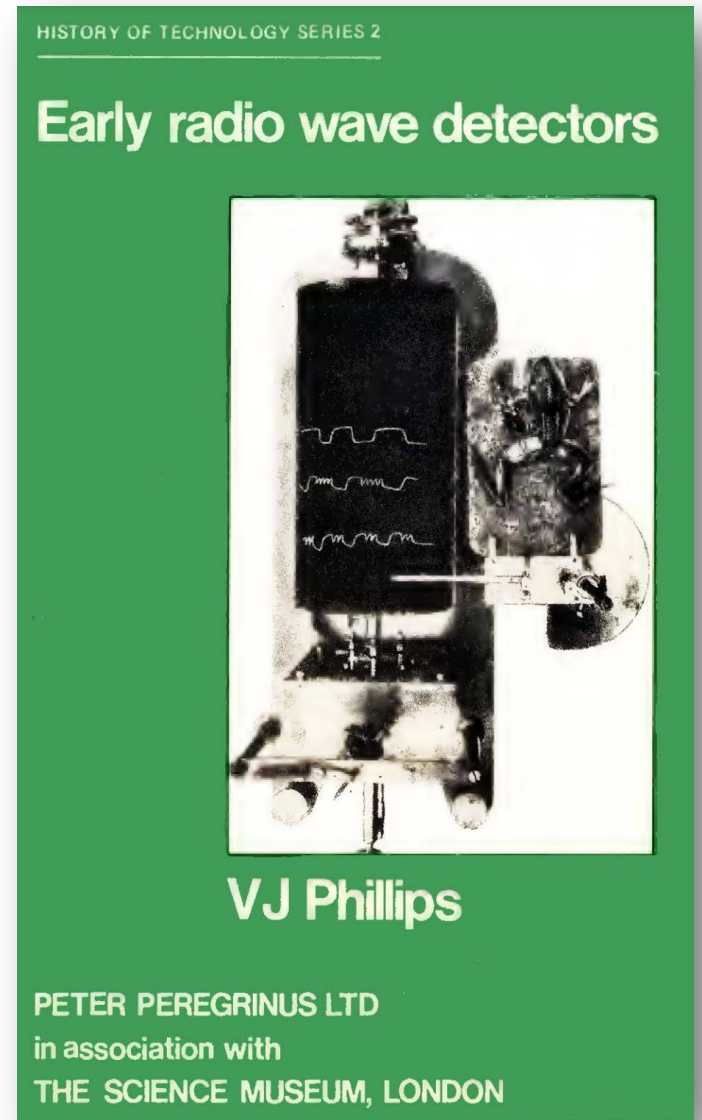
t

- Must Detect and (if needed) Amplify!!!

Early Radio Detection

- First of the two tasks to get "solved"
- Turns out there are a massive number of phenomena that have some degree of responsiveness to radio-wave frequency phenomena! Some solutions:
  - Spark Gap
  - Coherers
  - Electrolytic
  - Magnetic
  - Thin-film and Capillary
  - Thermal
  - Ticklers, tone-wheels
  - Miscellaneous:
    - Frog-legs and brains

Early Radio Wave Detectors (V.J. Phillips) included in supplementary readings for lecture 02

Great Book

- 238 juicy pages on early radio detectors.

HISTORY OF TECHNOLOGY SERIES 2

Early radio wave detectors

VJ Phillips

PETER PEREGRINUS LTD
in association with
THE SCIENCE MUSEUM, LONDON

Frog Leg Detector

- Jam tuned receiver circuit output into dead frog

- Metal-flesh contact did some demodulation/rectification*

- Signal would depolarize neurons/muscle circuit

- Leg kicked…moved pencil or something

- Profit
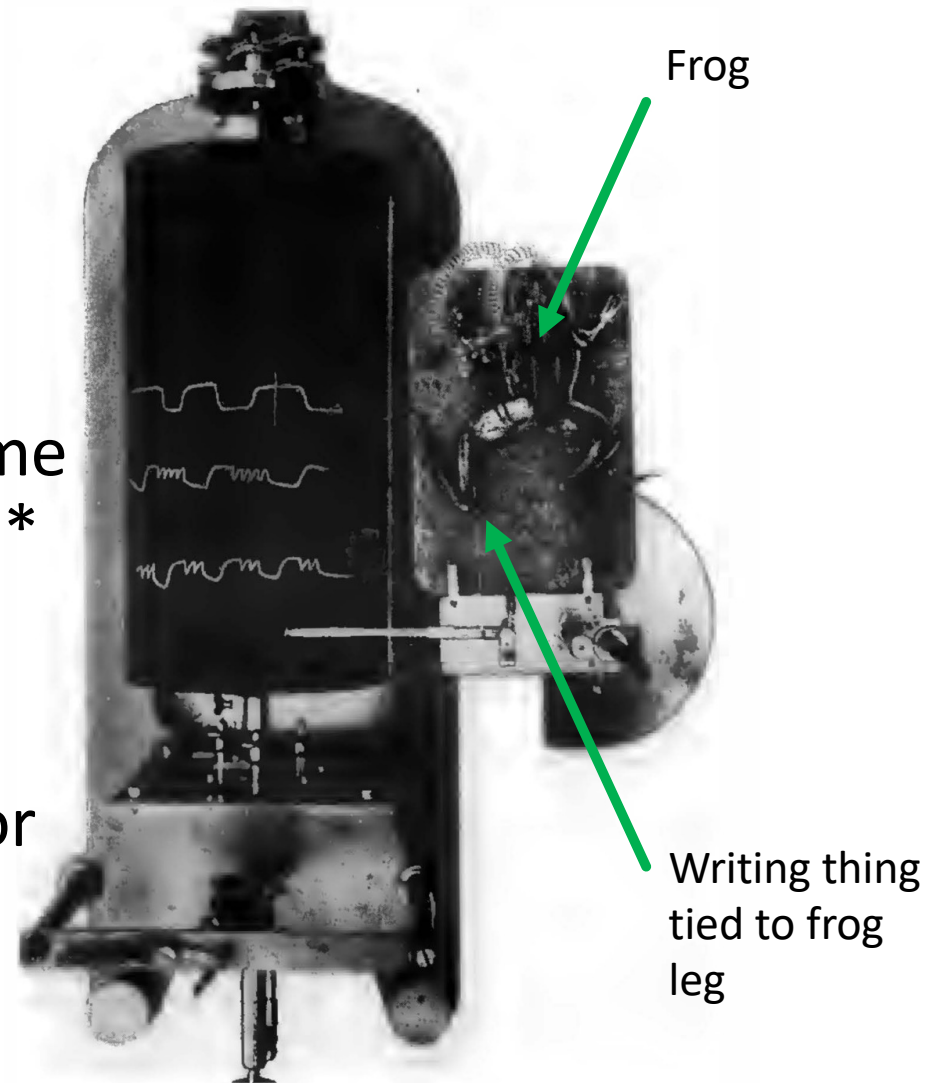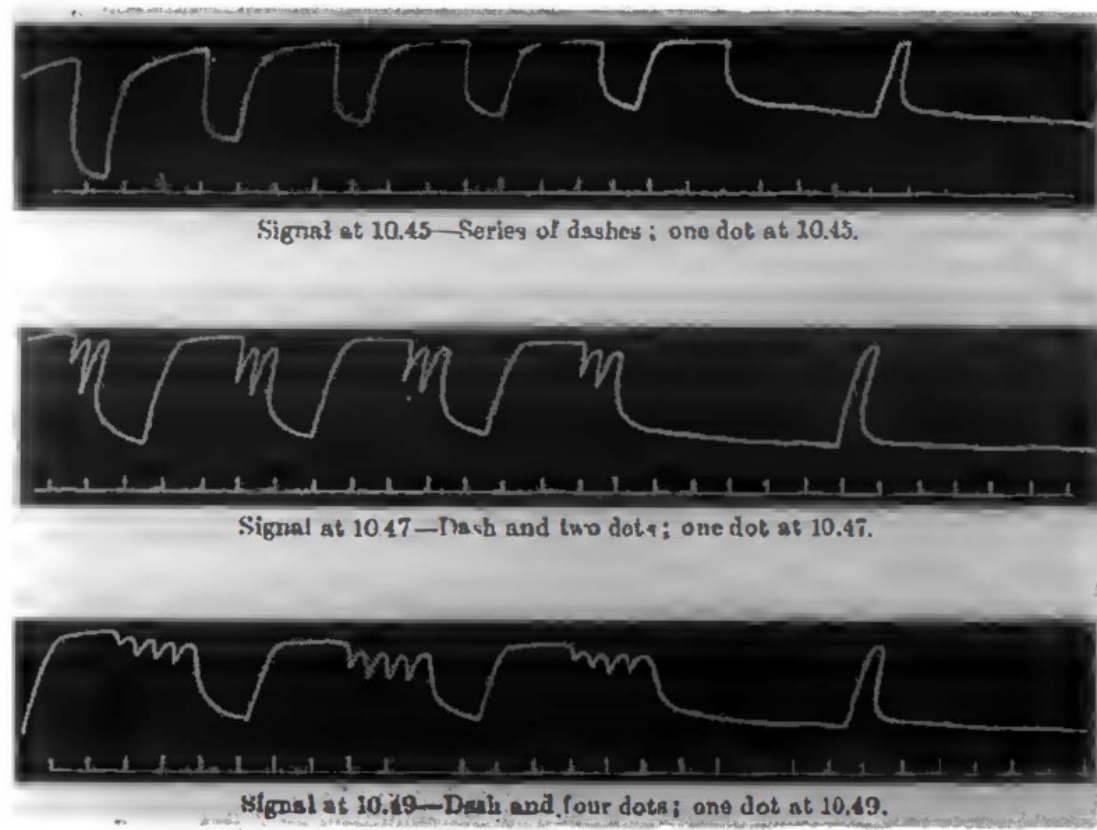
Frog

Writing thing tied to frog leg

Fig. 9.14   *Professor Lefeuvre's physiological receiver using electrical effects in a frog's leg*
[Fleming, J.A.: *Principles of electric wave telegraphy and telephony*
[Longmans, 1916 p.547]

*talk about in a bit

Actually worked (lol)

- How About That:

Signal at 10.45—Series of dashes ; one dot at 10.45.

Signal at 10.47—Dash and two dots ; one dot at 10.47.

Signal at 10.49—Dash and four dots ; one dot at 10.49.

How Did Frog Leg Detector Work?

- Life had already encountered the problem of needing to amplify and detect signals about 500 million years ago

- Developed Neurons communicate with one another (and to muscles) using a very robust amplification system very similar to what we eventually developed for digital electronics

Hodgkin-Huxley

- Not developed and formalized until 1950s (1963 Nobel Prize)

- Not really "verified" until protein X-ray crystallography in early 2000's

- Cell membrane is a non-linear amplifying detector

Extracellular Medium

C_m $g_n(t,V)$ g_L I_p

E_n E_L

Intracellular Medium
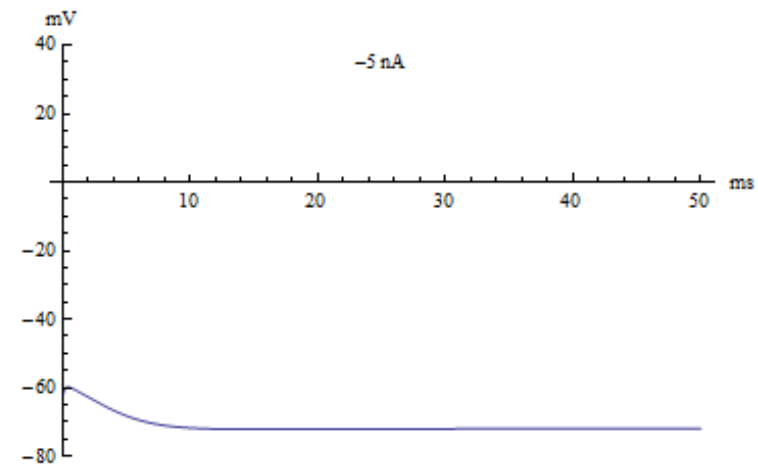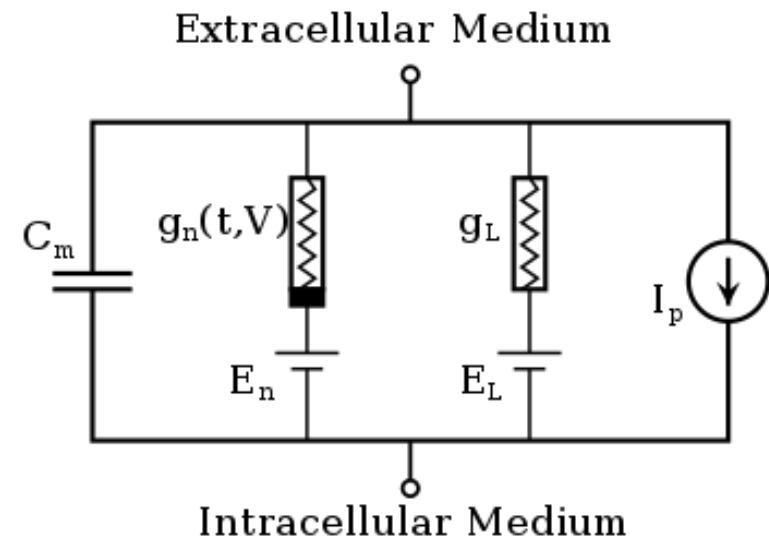
Small signal will cause positive-feedback "firing" of neurons

Early Radio Detectors

- Spark Gap
- Coherers ⬅ *WINNER (for a while)*
- Electrolytic
- Magnetic
- Thin-film and Capillary
- Thermal
- Ticklers, tone-wheels
- Miscellaneous:
  - Frog-legs and brains

I've included *Early Radio Wave Detectors* by V.J. Phillips as extra reading on course site under lecture 02. Covers all these detectors *in depth.*
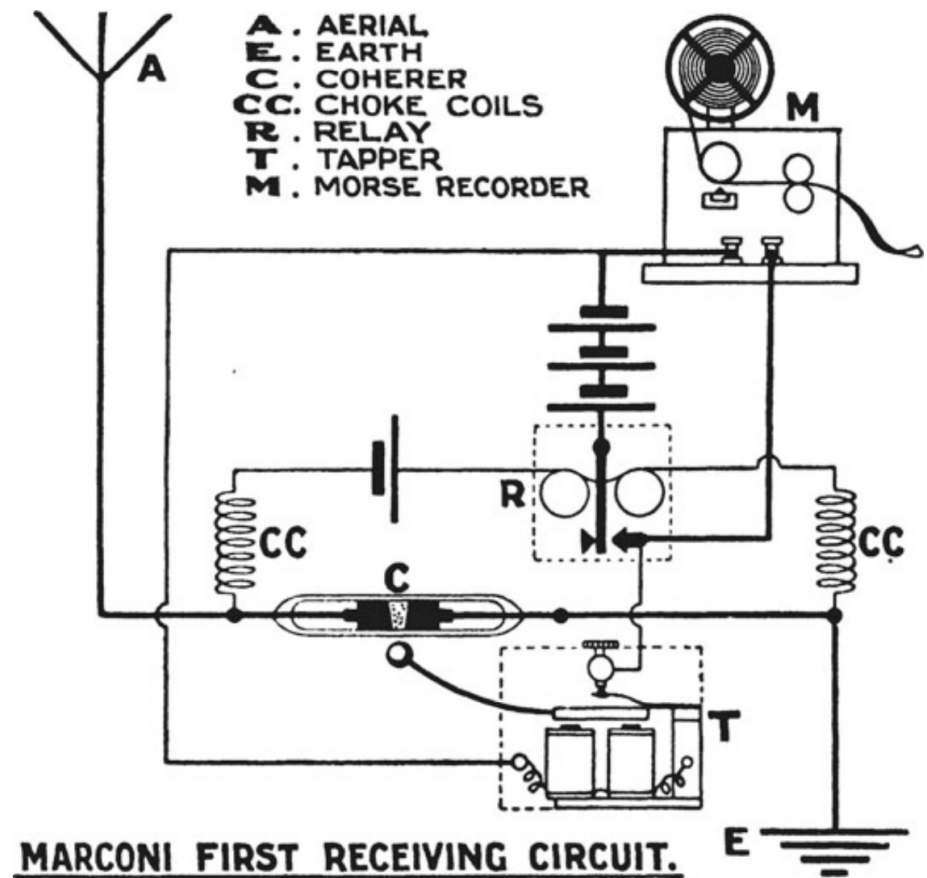
Edouard Branly's Coherer

- An evacuated tube with two electrodes
- In between the electrodes were a bunch of metal filings
- Normally filings didn't conduct
- When exposed to high frequency (RF range), they "cohered"
- Suddenly you could conduct
- Remained cohered after signal was applied

V_B
Local Battery (as big as you want)

$i_N(t)$

buzzer
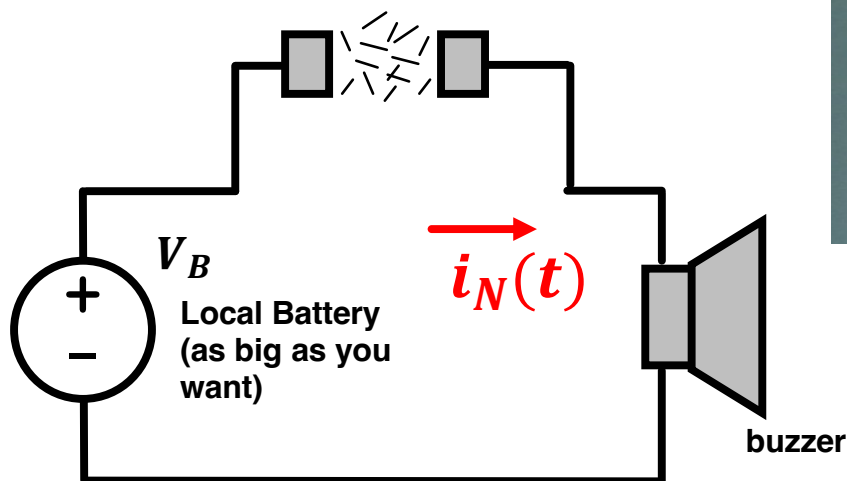
Annoying problem...only ever detect one signal

Incorporate into Circuit

- Coherence would happen on exposure to high-frequency signal

- Coherer would start to conduct local DC circuit

- Make punch on paper or ring a bell or something

- Flow of current would cause relay to fire and tap the coherer to shake the filings loose again ("decohere")

- Ready for another incoming signal

A . AERIAL
E . EARTH
C . COHERER
CC. CHOKE COILS
R . RELAY
T . TAPPER
M . MORSE RECORDER

MARCONI FIRST RECEIVING CIRCUIT.

"Wireless Telegraphy, vol. 1 and 2" (R. Stanley, pub: Longmans, Green & Co, New York, 1919)
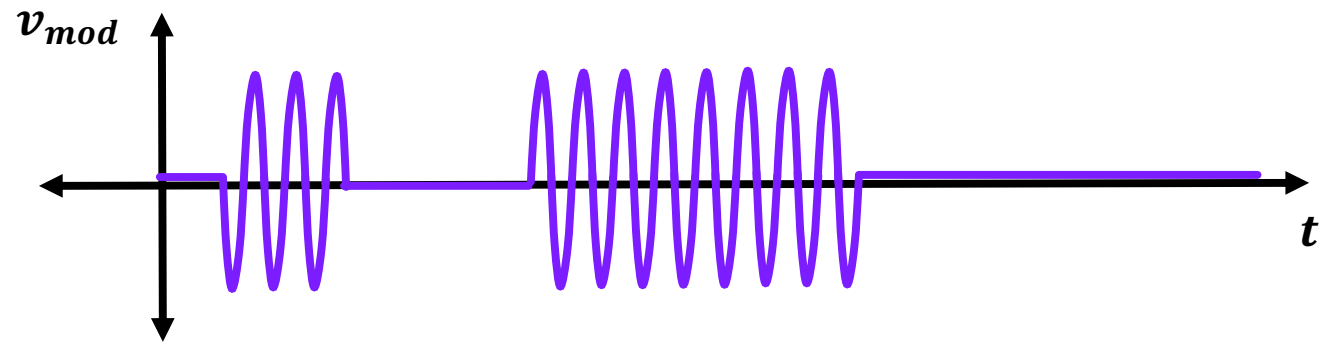
What *Was* the Coherer?

- The coherer was the first radio-compatible detector and was in use for about 20 years or so. Eventually it got replaced by the vacuum tube.

- Nobody really knew how it worked though (like seriously)...theory/experiments caught up in late 20th century*

*couple readings 2000's included in supplemental reading on Coherence phenomenon
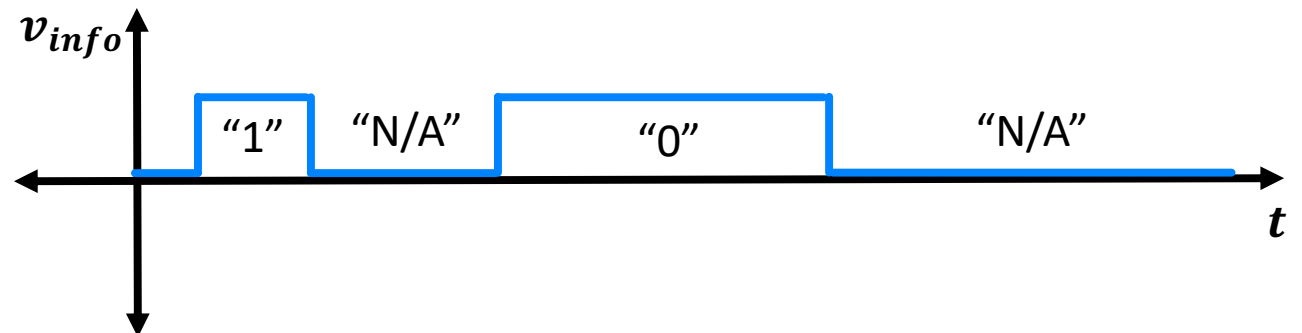
Encode Info with Amplitude of Carrier

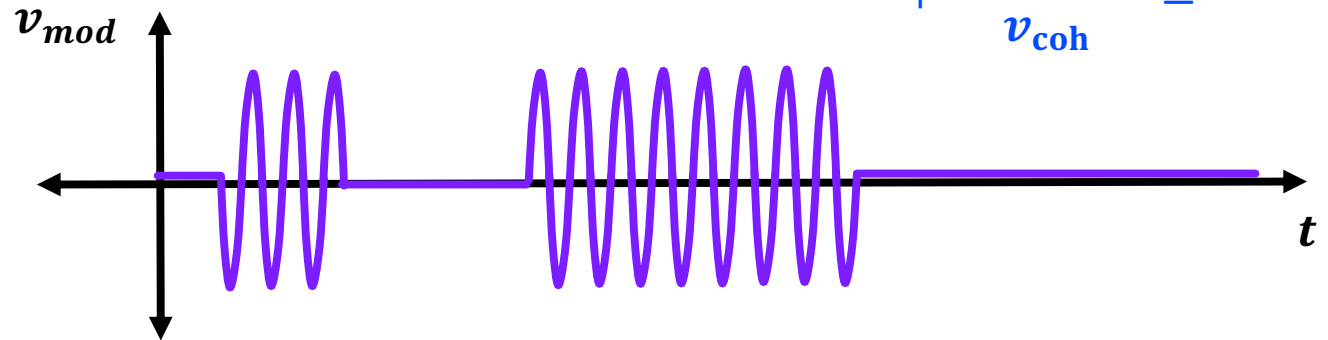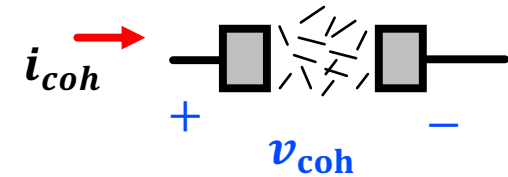- Coherer could handle this:

- Relatively slow transitions

- Yes/No Amplitude
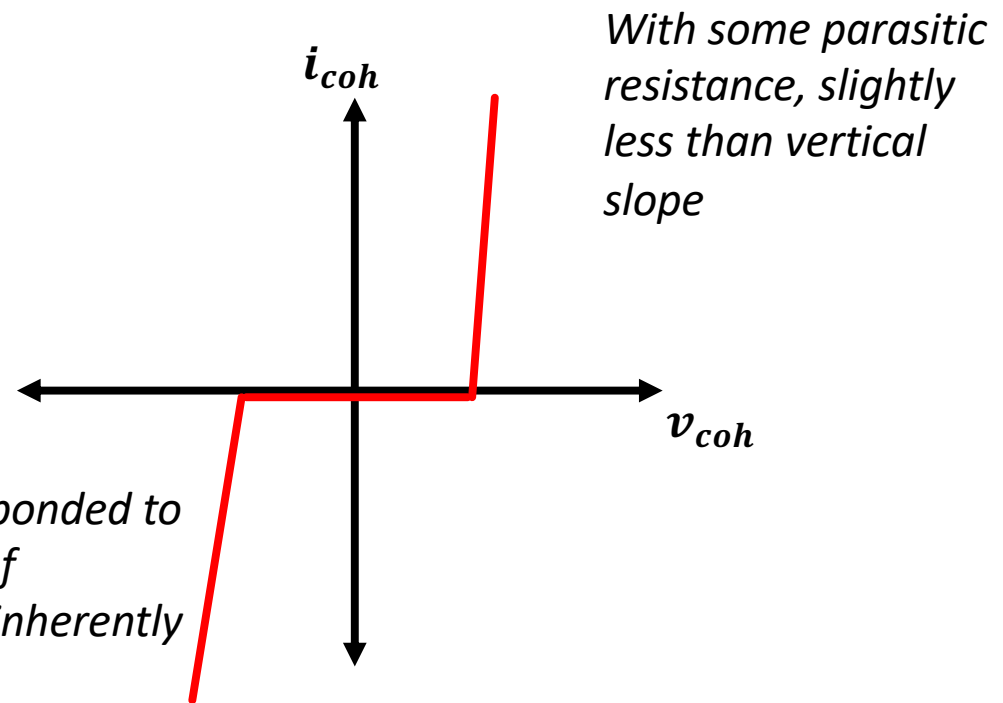

v_{mod}

t

Demodulate to:

v_{info}

"1"   "N/A"   "0"   "N/A"

t

Input-Output of Coherer

i_{coh}

$+$ v_{coh} $-$

v_{mod}

t
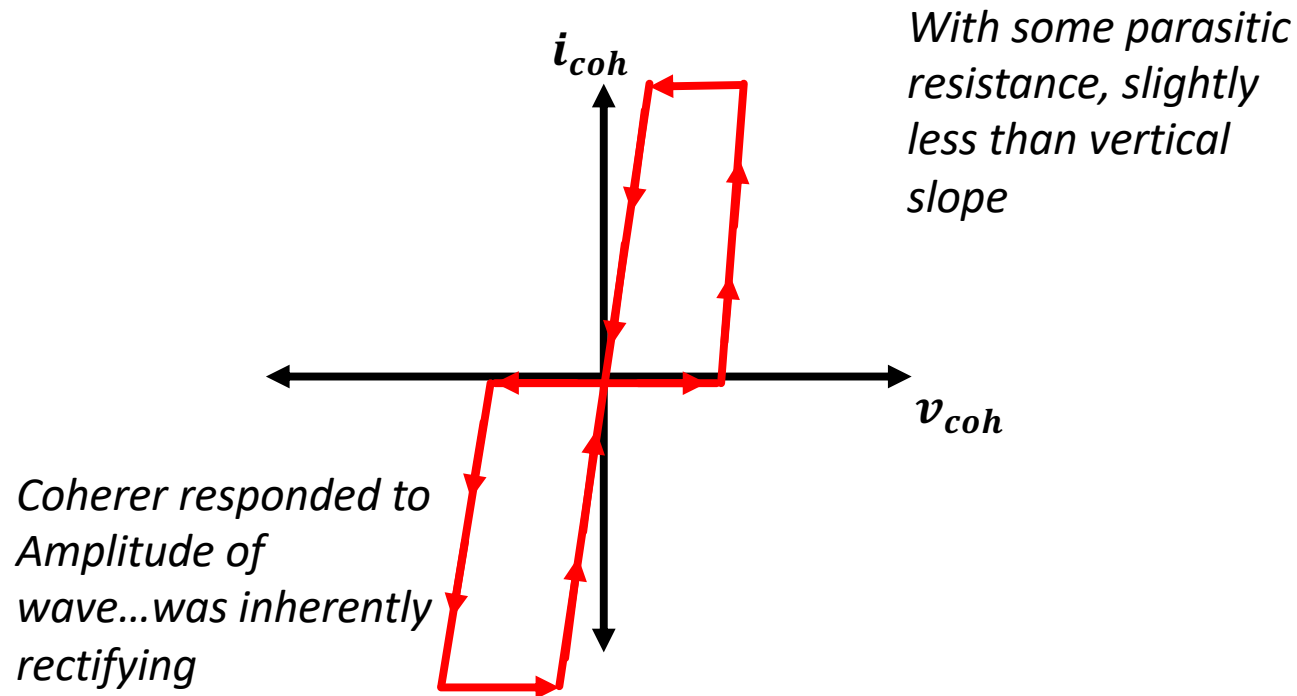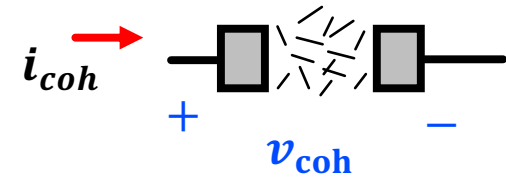
- The coherer looked really weird, but this is exactly what was needed.

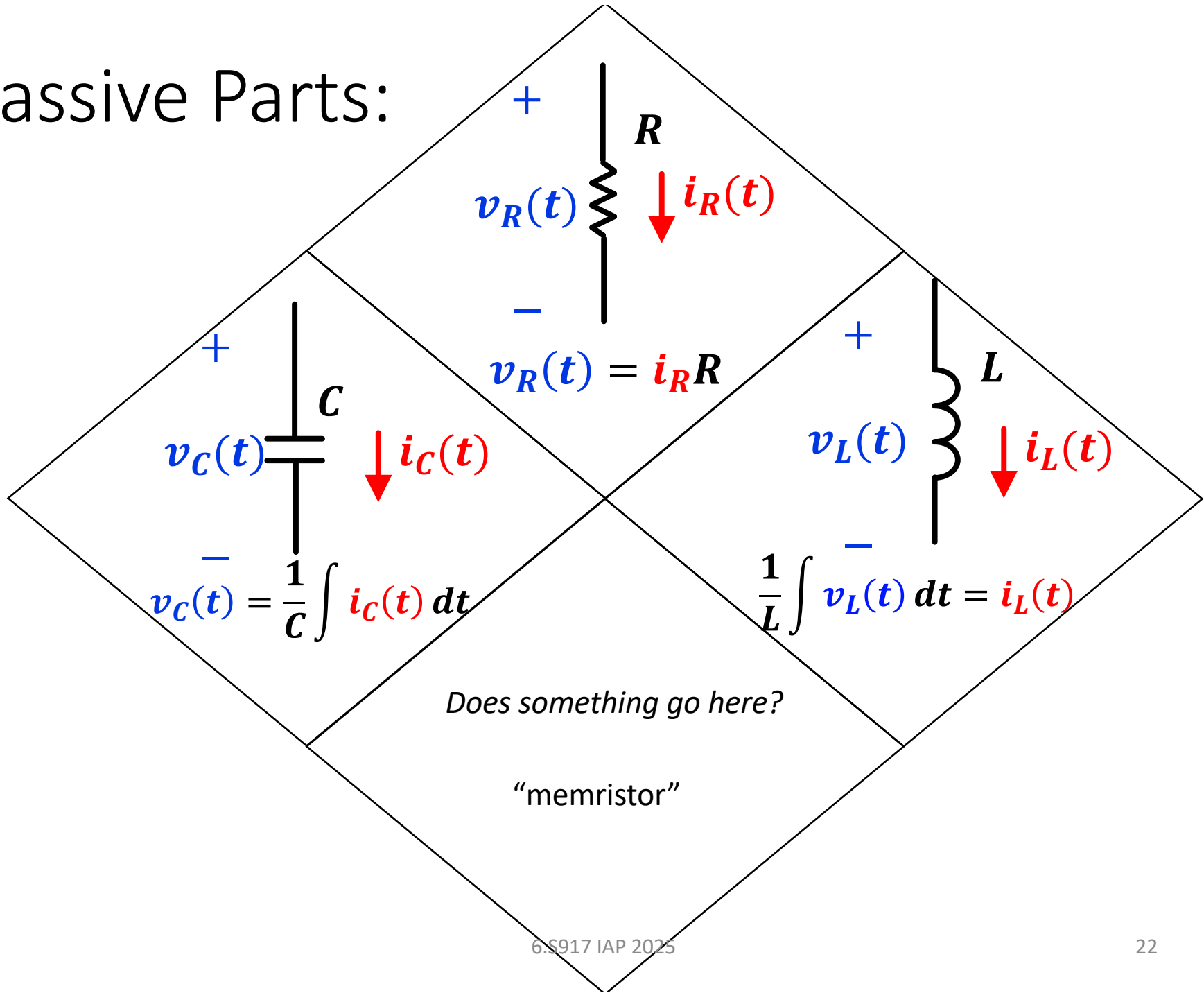- The only downside was that it would get "stuck on" and needed to be tapped

i_{coh}

With some parasitic resistance, slightly less than vertical slope

v_{coh}

Coherer responded to Amplitude of wave…was inherently rectifying

Input-Output of Coherer

- Coherer had memory/hysteresis

i_{coh}

$+$ v_{coh} $-$

i_{coh}

With some parasitic resistance, slightly less than vertical slope

v_{coh}

Coherer responded to Amplitude of wave…was inherently rectifying

Passive Parts:

$$v_R(t) = i_R R$$

$v_R(t)$, $i_R(t)$, R

$+$ $-$

$$v_C(t) = \frac{1}{C}\int i_C(t)\,dt$$

$v_C(t)$, $i_C(t)$, C

$+$ $-$

$$\frac{1}{L}\int v_L(t)\,dt = i_L(t)$$

$v_L(t)$, $i_L(t)$, L

$+$ $-$

Does something go here?

"memristor"

Passive Parts:

$+$

R

$v_R(t)$ $i_R(t)$

$-$

$$v_R(t) = i_R R$$

$+$

C

$v_C(t)$ $i_C(t)$

$-$

$$v_C(t) = \frac{1}{C}\int i_C(t)\,dt$$

$+$

L

$v_L(t)$ $i_L(t)$

$-$

$$\frac{1}{L}\int v_L(t)\,dt = i_L(t)$$

$+$

M

$v_M(t)$ $i_M(t)$

$-$

$$\int v_M(t)\,dt = M(t)\int i_M(t)\,dt$$
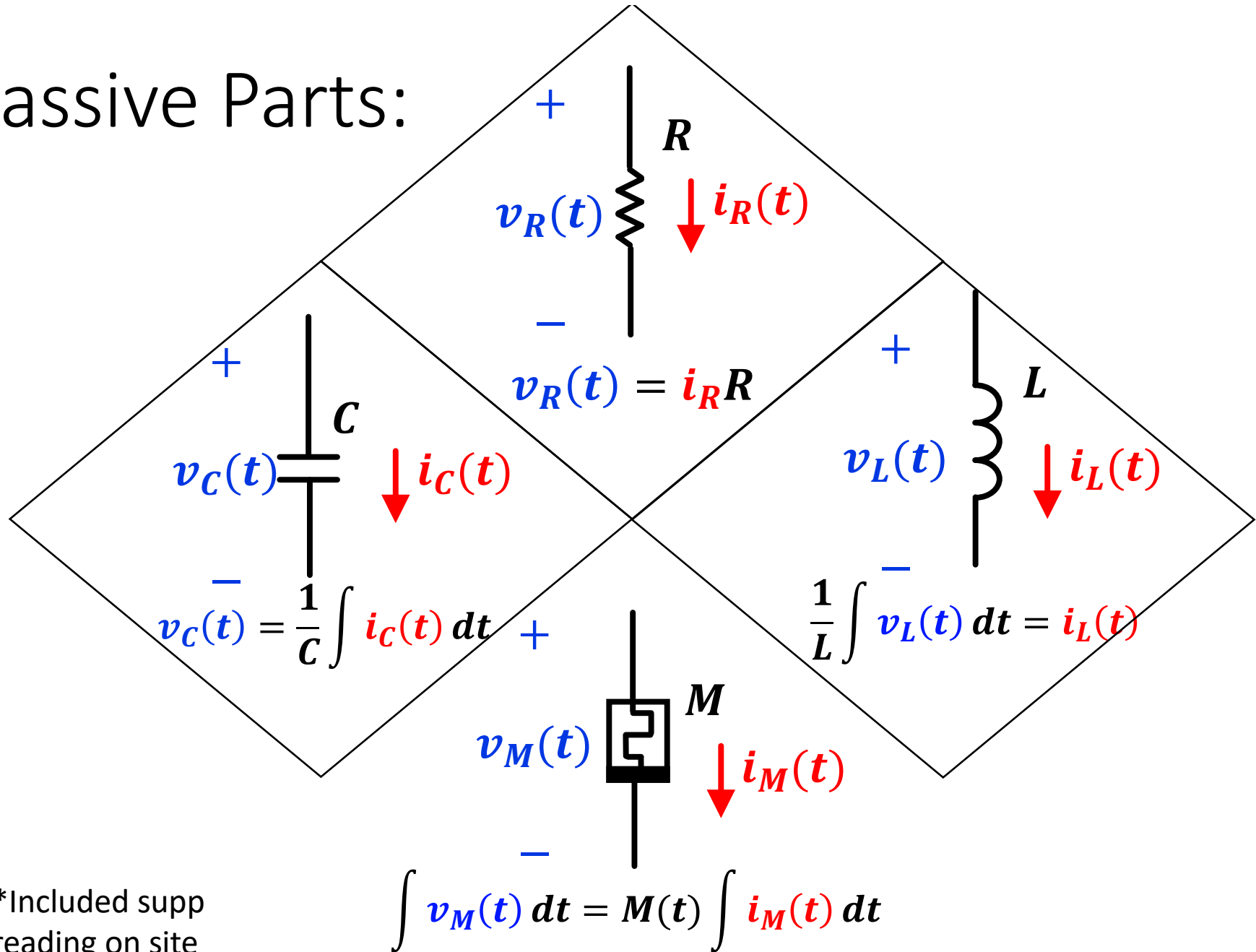
*Included supp
reading on site

Argument to be Made…

- Its resistance was a function of its history
- Coherer was first memristive device
- It was also investigated in the 1940's 1950's as the foundation for an actual memory device for computation, though dropped in favor of other technologies.

"From Branly Coherer to Chua Memristor" (Chapter 1 from *Fractional Dynamics, Anomalous Transport and Plasma Science*) included in supplemental reading

Coherer

- The Coherer took the presence of high frequency signals and transformed its state (resistance)

- That resistance could then be used to drive a circuit locally to indicate to human via noise, light, etc...

- Only good for low-data rate information streams (morse/digital code).

  - Coherence was largely a non-linear ON/OFF phenomenon (cohesion relative to amplitude)

  - *Not limitation of coherence phenomenon itself* but by the fact that it had memory (stayed cohered after signal) and therefore had to get shaken electromagnetically with tapper greatly limited bandwidth

- Needed something that could do the same thing but faster...give use the presence of audio-rate analog variations in the amplitude of the signal carrier

Note on Terminology

- The Coherer became *THE* way to reliably detect radio waves for quite a while.

- ...So much so that follow-on technologies would be named with respect to it.

- Diodes (which we'll see soon) were called things like "crystal coherer's" or just "coherers"
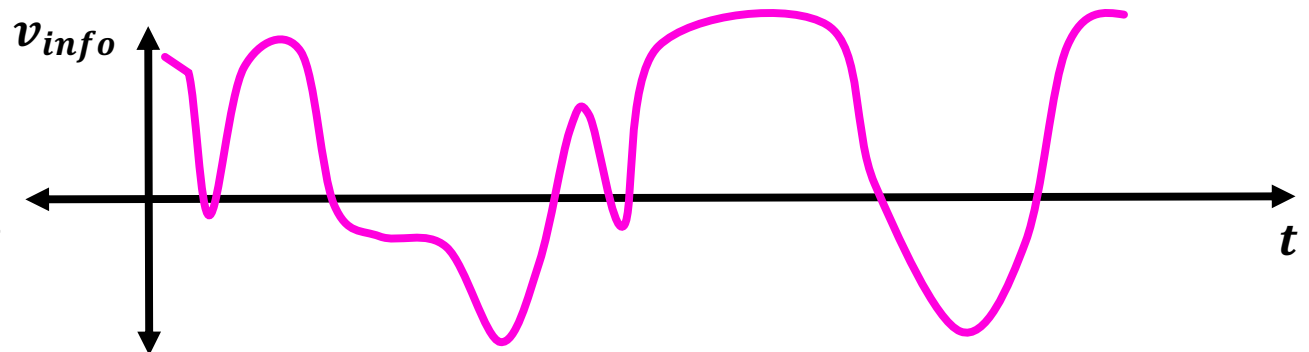
Encode Info with Amplitude of Carrier

- Wanted something that could handle this:

- Faster transitions

- Analog amplitude

- The tapping needed by a coherer, is a mechanical action...could not keep up with 1000's of Hz of audio signal nor the varying amplitudes (coherer was digital)
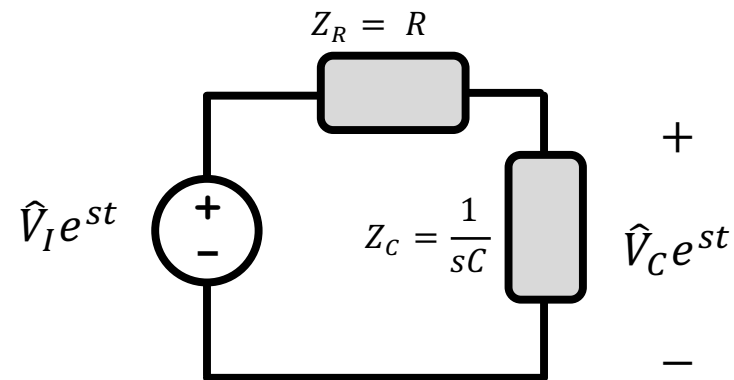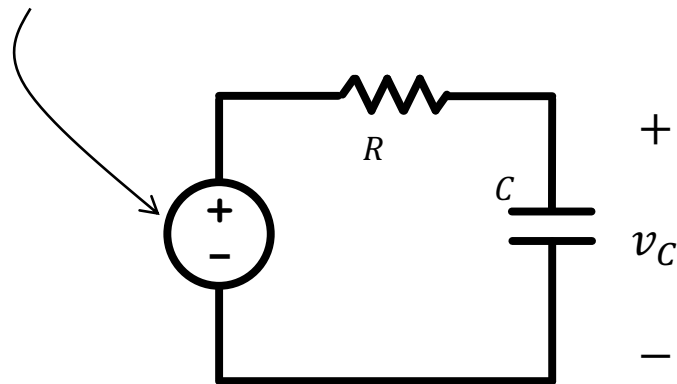
v_{mod}

t

Demodulate to:

v_{info}

t
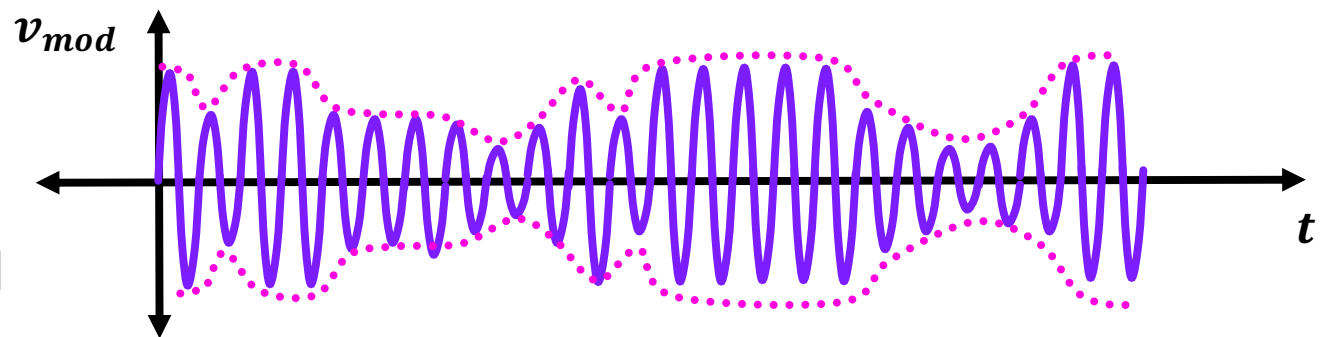
What *did* we have working well in 1890?

- We could filter reasonably well
- Linear components (R's, C's, and L's) could be put into combinations to filter out (or in) signals based on frequencies. "Low pass" circuit below:

$$v_I(t) = V_I \cos(\omega t + \phi_I)$$

R

C

$+$

v_C

$-$

$Z_R = R$

$\hat{V}_I e^{st}$

$+$

$-$

$Z_C = \dfrac{1}{sC}$

$+$

$\hat{V}_C e^{st}$

$-$

Non-Linear Manipulations (Aside)

- In order to appreciate why coherers or diodes (upcoming) can mathematically do what we need to do, we should look at some math.

The Math of Modulation

- When an AM signal is created we start with the carrier:

$$v_c(t) = A_c \cos(2\pi f_c t)$$

- The information ("message") signal that we care about can be generalized as a sine wave as well*:

$$v_m(t) = A_m \cos(2\pi f_m t)$$

- Amplitude modulation is created by multiplying the two signals together such that:

$$v_t(t) = v_c(t) \cdot (1 + m \cdot v_m(t))$$

Modulation index
(should be <1)

*and from Fourier theory we can argue that any more complicated signal is just a sum of what we do here using every relevant sine signal at the appropriate frequency
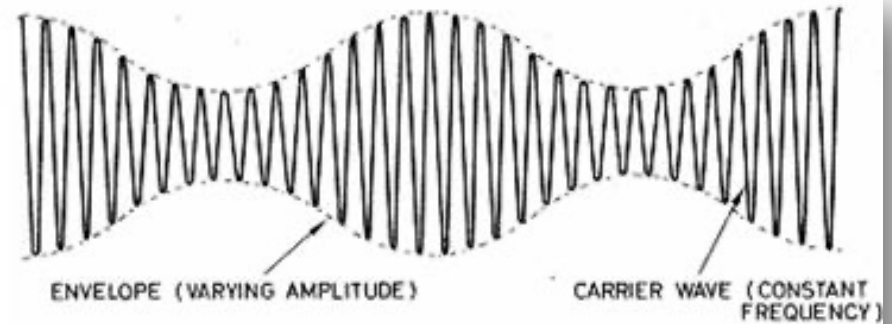
The Math of Modulation (cont.)

- Using this multiplication

$$v_t(t) = v_c(t) \cdot (1 + m \cdot v_m(t))$$

- Leads to:

$$v_t(t) = A_c \cos(2\pi f_c t) \cdot (1 + m \cdot A_m \cos(2\pi f_m t))$$

- If we remember this identity:

$$\cos(a) \cdot \cos(b) = \frac{\cos(a - b) + \cos(a + b)}{2}$$

- That leads to:

$$v_t(t) = A_c \cos(2\pi f_c t) + \frac{1}{2} \cdot (\cos(2\pi(f_c - f_m)t) + \cos(2\pi(f_c + f_m)t))$$

This combination of waves is what is transmitted in AM

*and from Fourier theory we can argue that any more complicated signal is just a sum of what we do here using every relevant sine signal at the appropriate frequency

ENVELOPE (VARYING AMPLITUDE)   CARRIER WAVE (CONSTANT FREQUENCY)

Figure 1 - Time domain of an AM signal
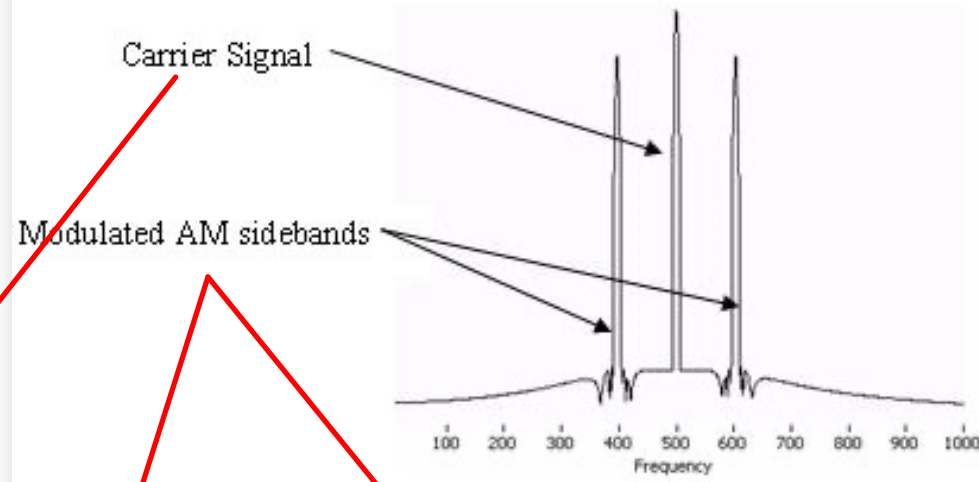
Carrier Signal

Modulated AM sidebands

Figure 2 – Frequency domain of an AM signal

$$v_t(t) = A_c \cos(2\pi f_c t) + \frac{1}{2} \cdot (\cos(2\pi(f_c - f_m)t) + \cos(2\pi(f_c + f_m)t))$$

https://knowledge.ni.com/KnowledgeArticleDetails?id=kA03q000000YGEbCAO&l=en-US

Wait a Second…how could you even make AM in the first place…how do we multiply two signals?

- I'm talking as if these AM signals were even available already? But how were we able to do this?
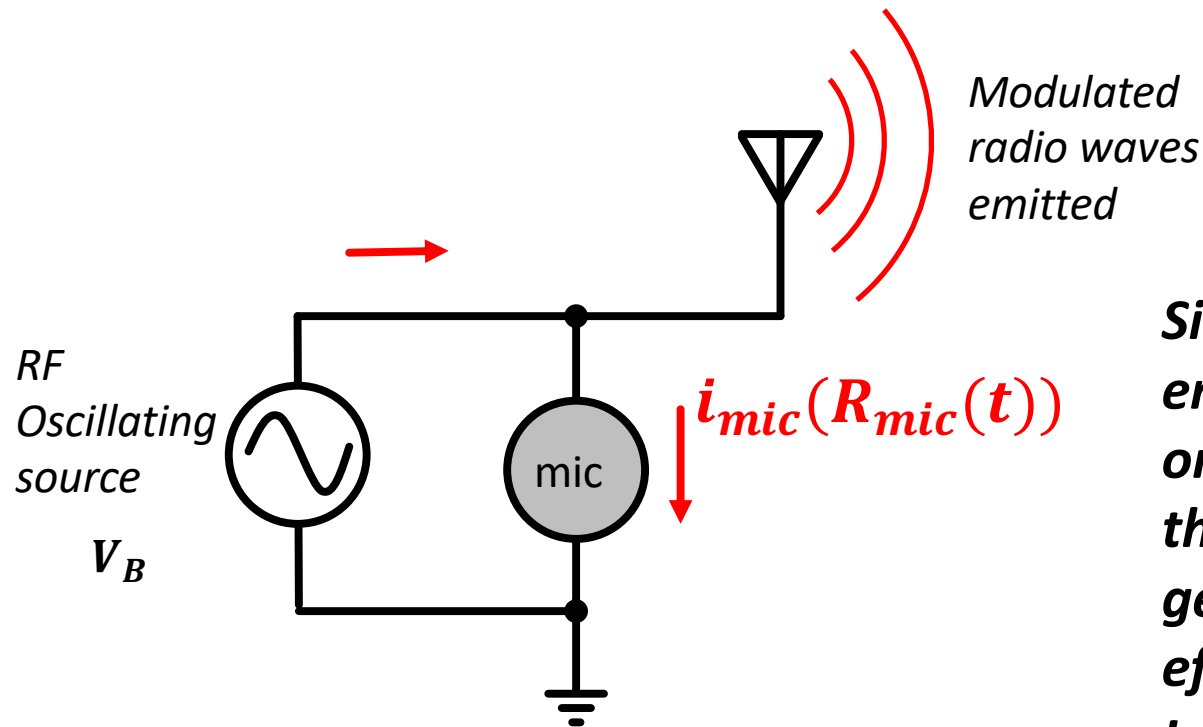
$$v_t(t) = v_c(t) \cdot (1 + m \cdot v_m(t))$$

- If we have only linear circuit components there's no way to multiply two voltages or a voltage or a current!!!

Early Microphones could do this

- Make a variable resistor based on incoming sound waves

cone

carbon granules

mic

$R_{mic}(t)$
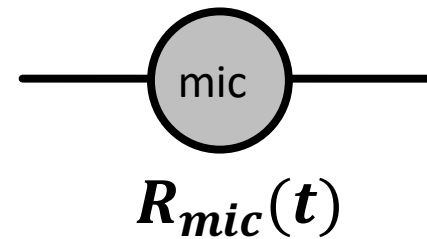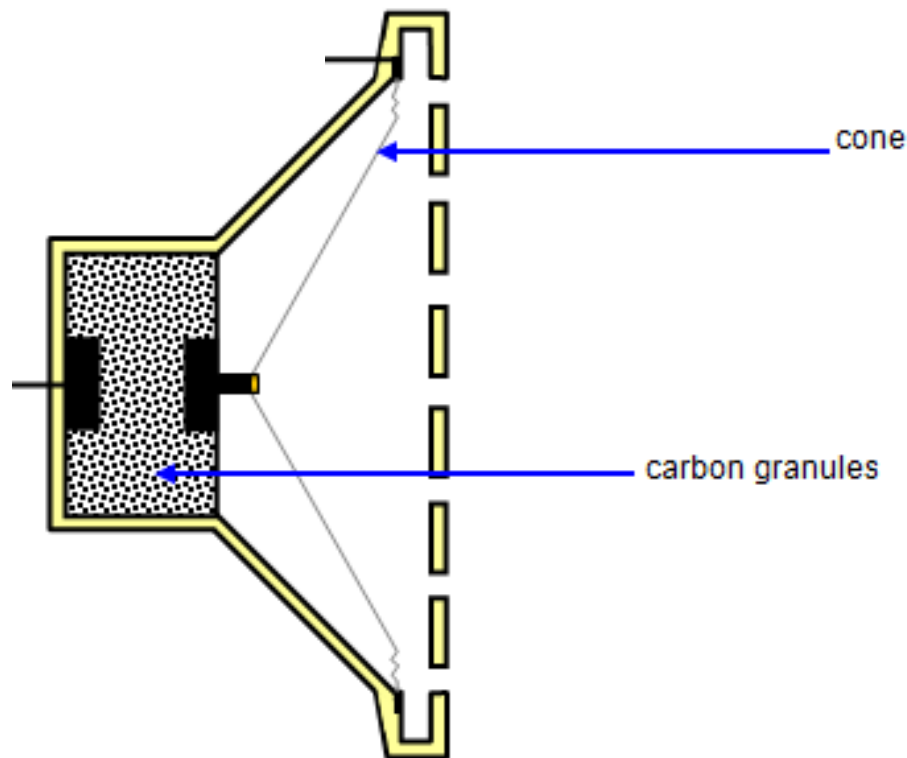
Put it into a circuit like this:

Modulated radio waves emitted

RF Oscillating source

V_B

mic

$i_{mic}(R_{mic}(t))$

Since the audio signal was embedded not in a voltage or a current, but rather in the resistance, you would get the multiplication effect directly from Ohm's Law!!!
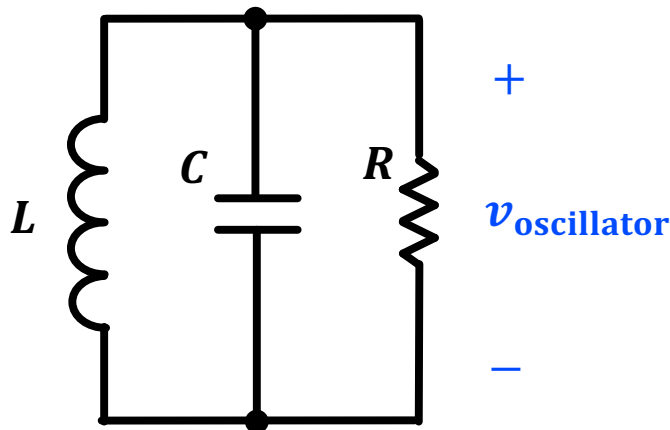
But also wait a second…where was _this_ coming from?

RF
Oscillating
source

V_B

mic

$i_{mic}(R_{mic}(t))$

Modulated
radio waves
emitted
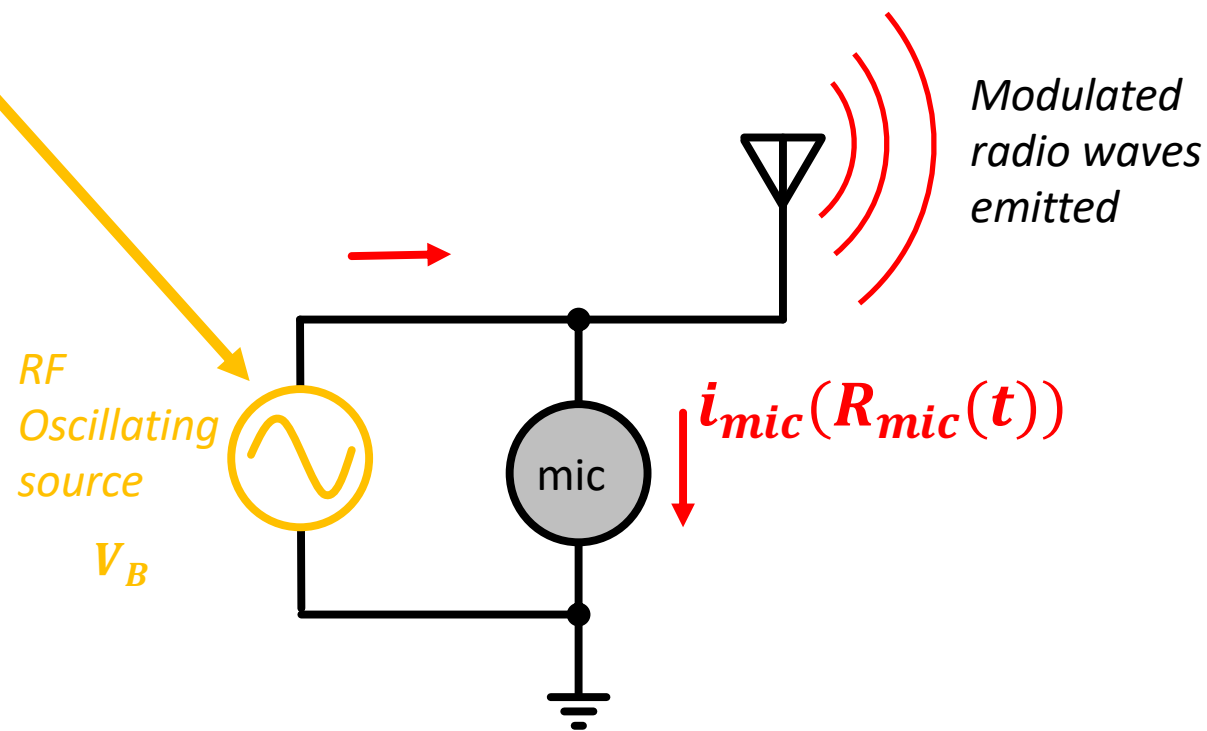
Wait a Second...how would you make an oscillation at high frequency in 1890?

- Well by this point they had R's, L's and even pretty good C's

- They could build circuits like this...and these circuits have 2nd order diff eq's to describe them.

$$0 = LC\frac{d^2v(t)}{dt^2} + RC\frac{dv(t)}{dt} + v(t)$$

- *Natural* solution to such a circuit has roots at:...

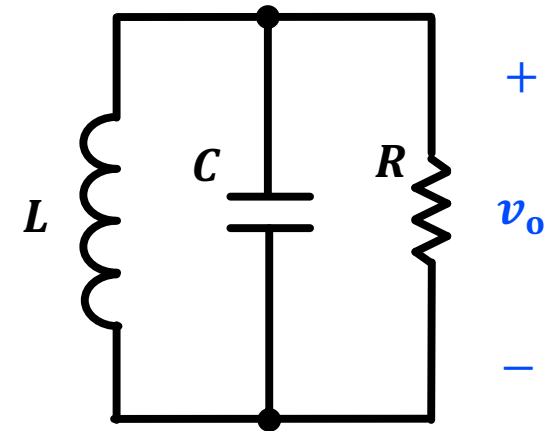$$s_{1,2} = -\frac{1}{2RC} \pm \frac{1}{2}\sqrt{\left(\frac{1}{RC}\right)^2 - \frac{4}{LC}}$$

$+$

$v_{\text{oscillator}}$

$-$

L C R

These Roots are Critical

$$s_{1,2} = -\frac{1}{2RC} \pm \frac{1}{2}\sqrt{\left(\frac{1}{RC}\right)^2 - \frac{4}{LC}}$$

- These roots can go three ways…two ways we don't care about (critically damped and overdamped)

$$\left(\frac{1}{RC}\right)^2 - \frac{4}{LC} = 0 \qquad \left(\frac{1}{RC}\right)^2 - \frac{4}{LC} > 0$$
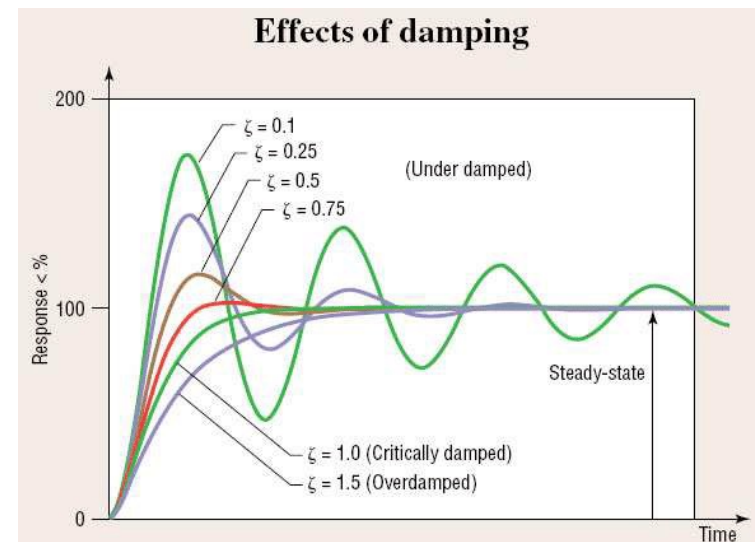
- Underdamped, though is interesting…

$$\left(\frac{1}{RC}\right)^2 - \frac{4}{LC} < 0$$

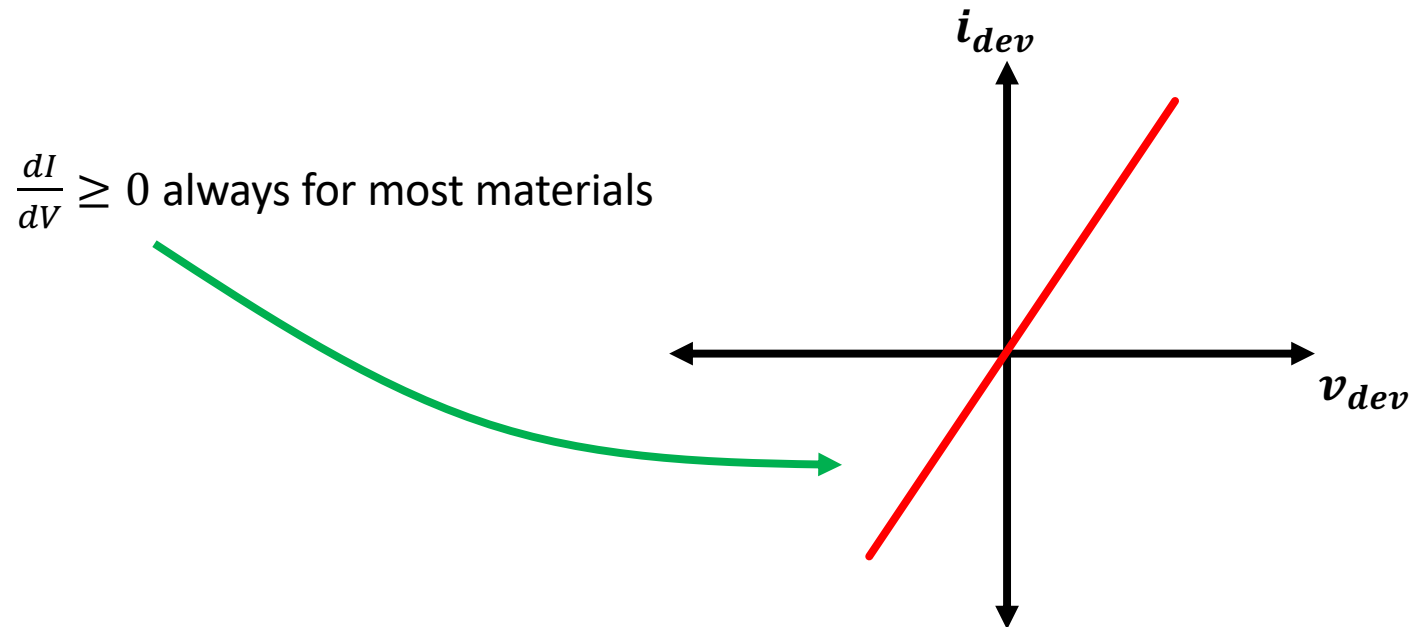- Gives us two complex conjugate roots and these give us oscillation:

The Oscillation

- It will take on (roughly) form: $v(t) = V_I e^{\alpha t} \sin(\omega_o t)$

- ω_o based on $1/\sqrt{LC}$ and some minor stuff

- α based on the $-\dfrac{1}{2RC}$ term of the root.

- Normally this dooms us to a decaying oscillation since R can only be positive.
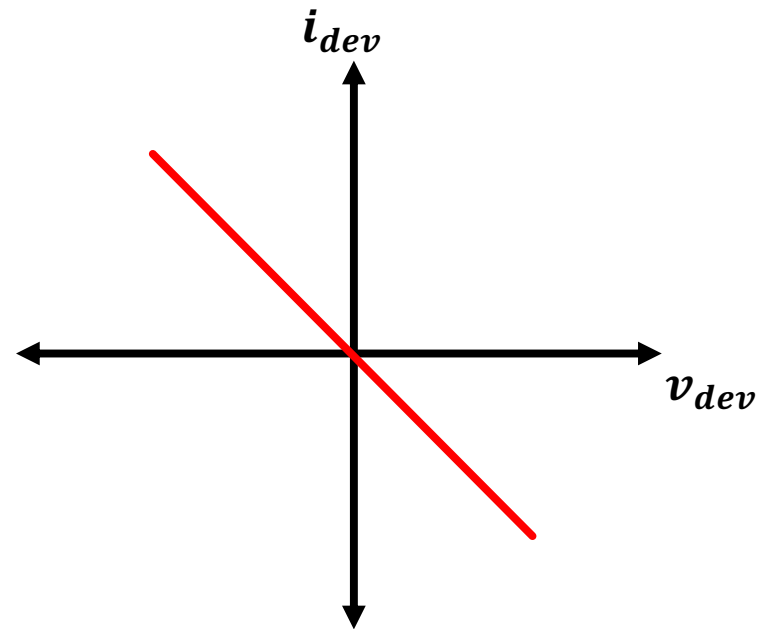
- But does it have to be?

Effects of damping

$\zeta = 0.1$
$\zeta = 0.25$
$\zeta = 0.5$ (Under damped)
$\zeta = 0.75$

Steady-state

$\zeta = 1.0$ (Critically damped)
$\zeta = 1.5$ (Overdamped)

Response < %

Time

Resistance?

- What makes an R positive?

$\frac{dI}{dV} \geq 0$ always for most materials

- It's all about the slope of v across a device to I through the device.

Resistance?

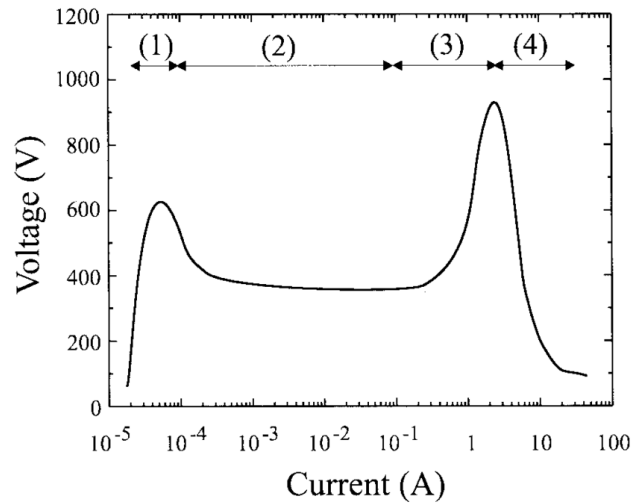- Is there anything in existence that looks like this?

- Well amazingly yeah there are things…they don't look like this "forever" but will in certain regions of their I-V curve.

- One of these that was discovered in early 1800s is various flavors of gas discharge lamps

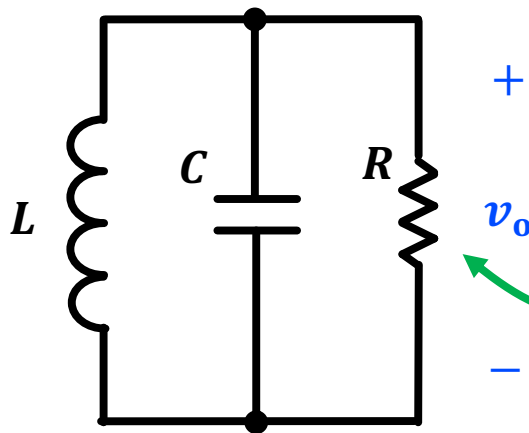# Neon Gas Discharge Lamp

- I-V curve of Neon discharge tube:

$\frac{dI}{dV} < 0$ in these regions

Rotate it/flip it so V and I line up
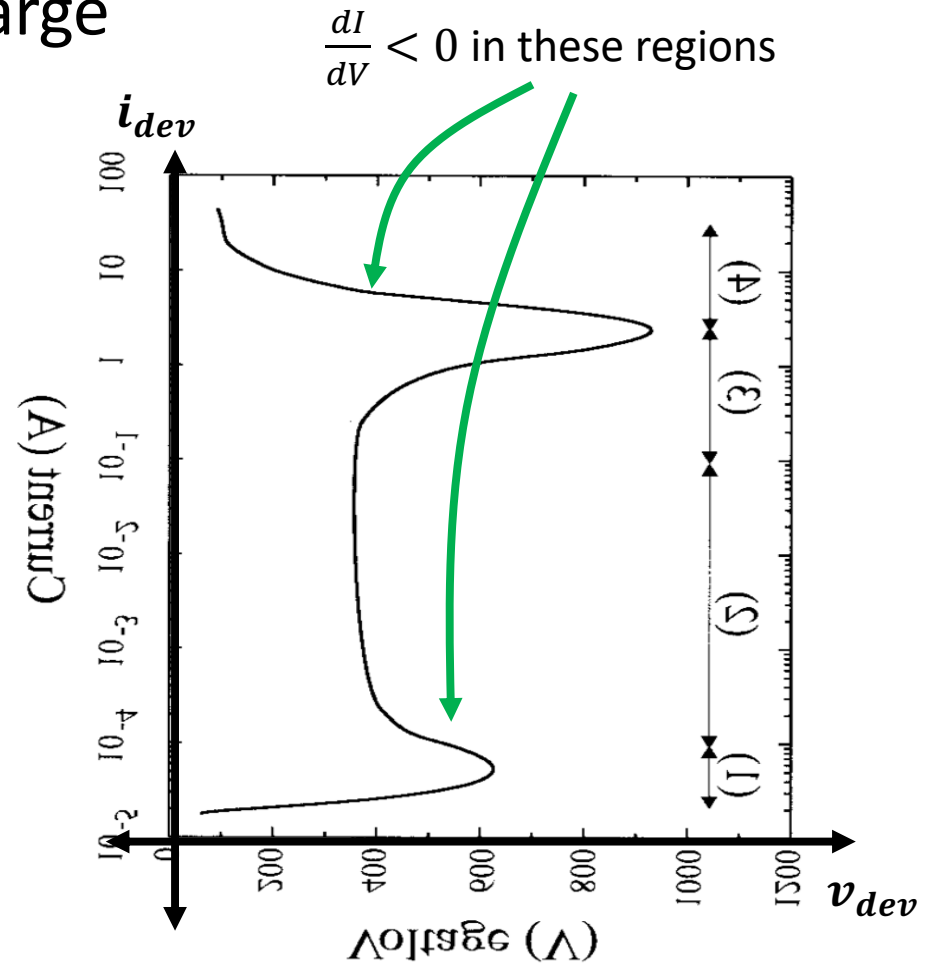
So they could make full oscillators

- Circuits that actually want to oscillate and stay oscillating (with a little help)

$+$

v_o

$-$

Replace that with a gas discharge tube and they could get reasonable oscillations at controllable frequencies

Anyways…back to *de*modulation

- We now know how we could make audio-AM signals at RF frequencies using 1890s technology.

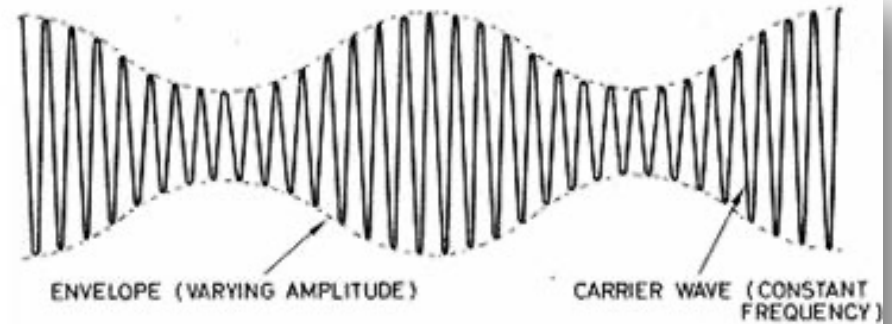- But how could we demodulate the modulation? Unfortunately that was harder.

ENVELOPE (VARYING AMPLITUDE)   CARRIER WAVE (CONSTANT FREQUENCY)

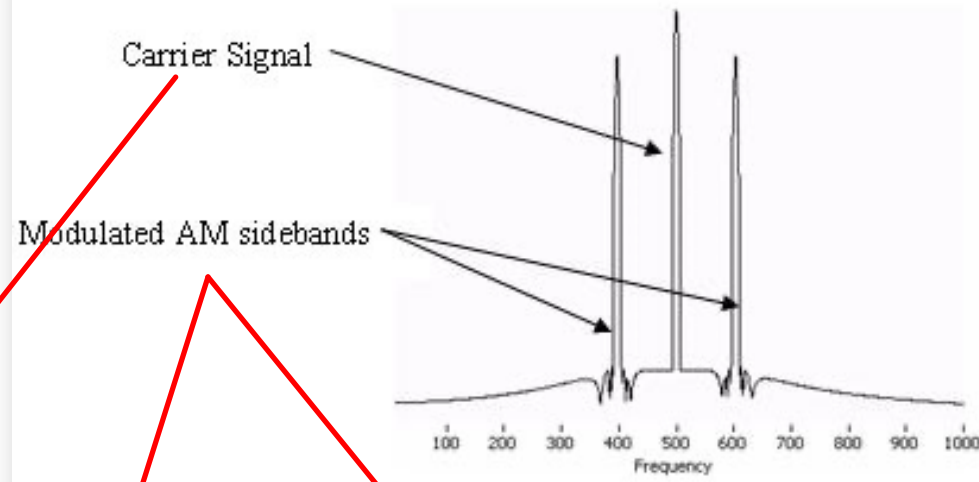Figure 1 - Time domain of an AM signal

Carrier Signal

Modulated AM sidebands

Figure 2 – Frequency domain of an AM signal

$$v_t(t) = A_c \cos(2\pi f_c t) + \frac{1}{2} \cdot (\cos(2\pi(f_c - f_m)t) + \cos(2\pi(f_c + f_m)t))$$

https://knowledge.ni.com/KnowledgeArticleDetails?id=kA03q000000YGEbCAO&l=en-US

The Math of AM Demodulation

- If this is what we capture out of the sky:

$$v_t(t) = A_c \cos(2\pi f_c t) + \frac{1}{2} \cdot (\cos(2\pi(f_c + f_m)t) + \cos(2\pi(f_c - f_m)t))$$

- We want to have some sort of circuit allow us to perform operations that will let us get back to a signal that looks like this:

$$v_{rec}(t) \propto A_m \cos(2\pi f_m t)$$

- If we can do that, we're golden…but the only way to do that is to be able to use trig identities again:

$$\cos(a) \cdot \cos(b) = \frac{\cos(a - b) + \cos(a + b)}{2}$$

The Math of AM Demodulation

- If on the reception side we could somehow get this to happen:
$$\cos(2\pi f_c t) \cdot \cos(2\pi(f_c + f_m)t)$$

- The result would be a term that is now only the modulation signal again (our information):

$$\propto \cos\left(2\pi\left(f_c - (f_c + f_m)\right)t\right) = \cos(2\pi f_m t) \ !$$

- But that requires ***multiplication of two electrical signals***…something you can't do with a linear system…need a multiplier

The Math of AM Demodulation

- If we could somehow take the *square* of our incoming AM signal, the FOIL-ing of the resultant math would have a term in there that accomplishes this!

$$v_t(t)^2 = v_t(t) \cdot v_t(t)$$

$$= \left(A_c \cos(2\pi f_c t) + \frac{1}{2} \cdot (\cos(2\pi(f_c + f_m)t) + \cos(2\pi(f_c - f_m)t)) \right)$$

$$\cdot \left(A_c \cos(2\pi f_c t) + \frac{1}{2} \cdot (\cos(2\pi(f_c + f_m)t) + \cos(2\pi(f_c - f_m)t)) \right)$$

- So we need a device that will square for us!!!

- That's annoying…not only do we want a non-linear device, but we need a device that is a particular type of non-linear.

- Damnit

Taylor Series to Rescue

- Think about a Taylor Series
- Model some device described by function $f(v)$ around some point V
- That function can be expressed as:

$$\sum_{k=0}^{n} \frac{f^{(k)}(v)}{k!} (v - V)^k$$

$$= f(V) + f'(V)(v - V) + \frac{f''(V)}{2}(v - V)^2 + \cdots$$

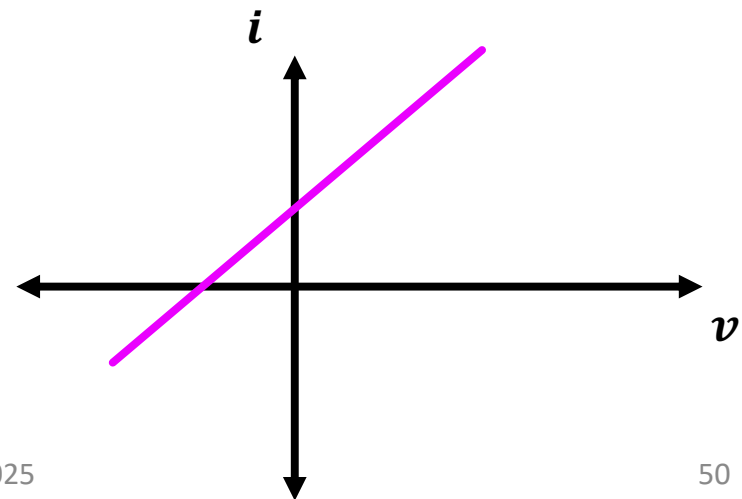**0th order term**   **1st order term**   **2nd order term**   **additional order terms**

Electronics are Boring if you only have Linear Devices

- Linear Devices will expand at most to something like this:

$$= f(V) + f'(\cancel{V})(v - V) + \frac{f''(V)}{2}(v - V)^2 + \cdots$$

Not function of V
(just a constant)

No second order term

A Non-Linear Device

- Non-linear devices will have that and more potentially

$$= f(v) + \boxed{f'(V)}(v - V) + \boxed{\frac{f''(V)}{2}(v - V)^2} \boxed{+ \cdots}$$

Non-constant scalar

Gives us multiplication or in this case a squaring!
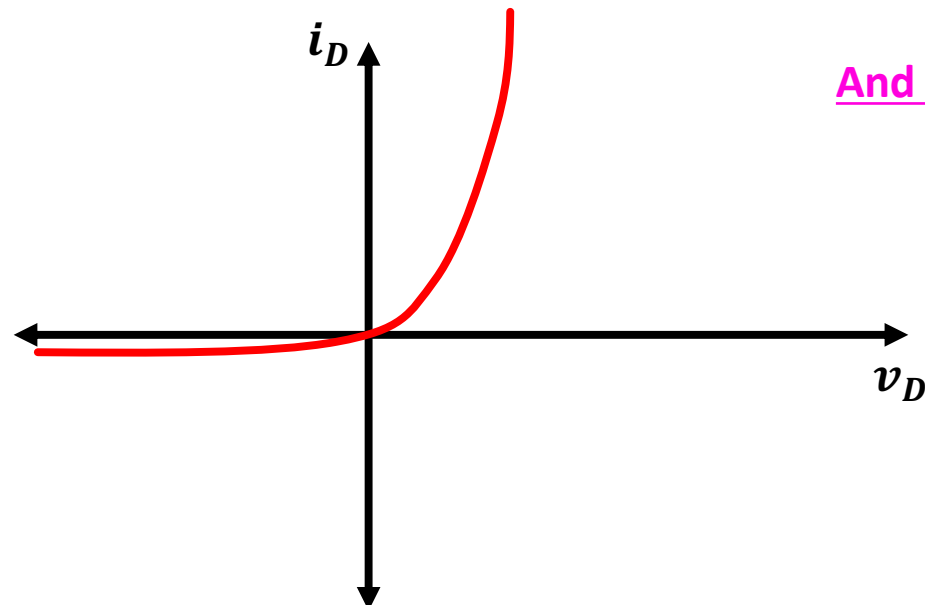
And potentially other crap

Conclusion

- Find a device with ***reliable high-frequency*** non-linearity

- Even if not a pure multiplier or squarer or whatever, if it is non-linear it will likely have some sort of squaring action due to its underlying Taylor Series Expansion!***

- Since multiplication of sinusoids results in sinusoids of differing frequencies, we could then use filters to block all the residue terms that we don't care about and isolate only the sinusoids we want (the ones containing information)

***The more square-like the better in the case of modulation, but it isn't a deal breaker if it departs from that

Both __Modulation__ and Demodulation Benefit

- If we can produce good nonlinear devices, we can easily modulate as well as demodulate:

- On the <u>transmit</u> side you could do:
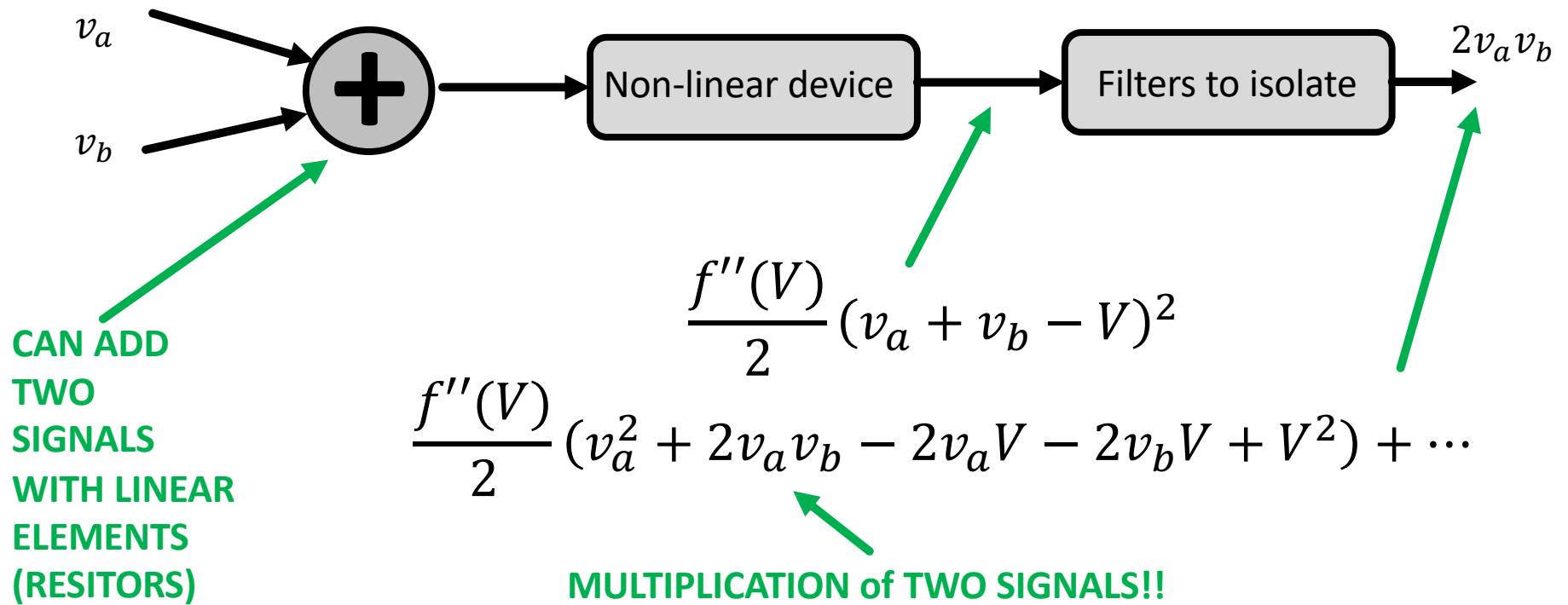
v_a

v_b

$+$ → Non-linear device → Filters to isolate → $2v_a v_b$

CAN ADD TWO SIGNALS WITH LINEAR ELEMENTS (RESITORS)

$$\frac{f''(V)}{2}(v_a + v_b - V)^2$$

$$\frac{f''(V)}{2}(v_a^2 + 2v_a v_b - 2v_a V - 2v_b V + V^2) + \cdots$$

MULTIPLICATION of TWO SIGNALS!!

Both Modulation and <u>Demodulation</u> Benefit

- If we can produce good nonlinear devices, we can easily modulate as well as demodulate:

- On the <u>receive</u> side you could do:

$$v_a v_b \longrightarrow \boxed{\text{Non-linear device}} \xrightarrow{\begin{array}{c} v_a + v_b + \\ v_a v_b + \cdots \end{array}} \boxed{\text{Filters to isolate}} \longrightarrow v_a$$
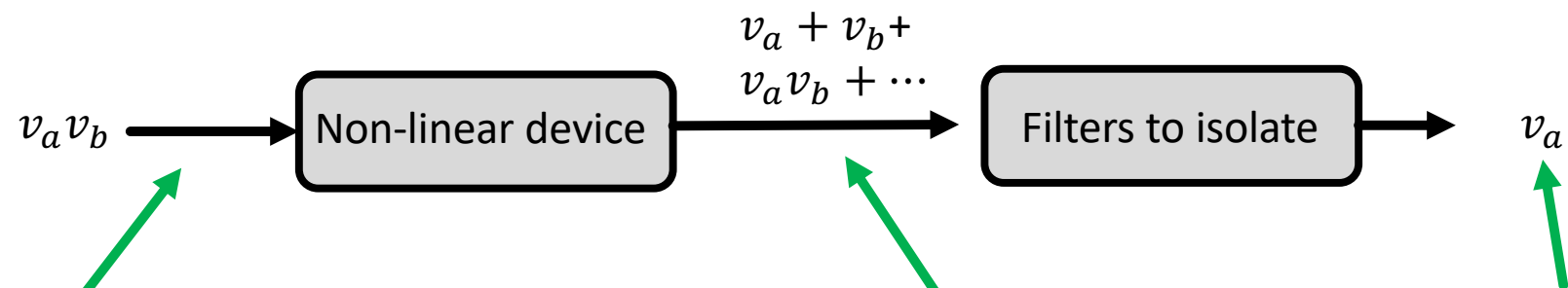
SIGNALS COME IN MIXED TOGETHER

$$\frac{f''(V)}{2}(v_a + v_b - V)^2$$

$$\frac{f''(V)}{2}(v_a^2 + 2v_a v_b - 2v_a V - 2v_b V + V^2) + \cdots$$

So people experimented

- All you needed was something that was reliably non-linear at high frequencies and you could get some demodulation

- One particular non-linearity started to appear quite a bit: rectification

Fourier Theory:

Incoming signal of $v_s(t) = A \sin(2\pi f_o t)$
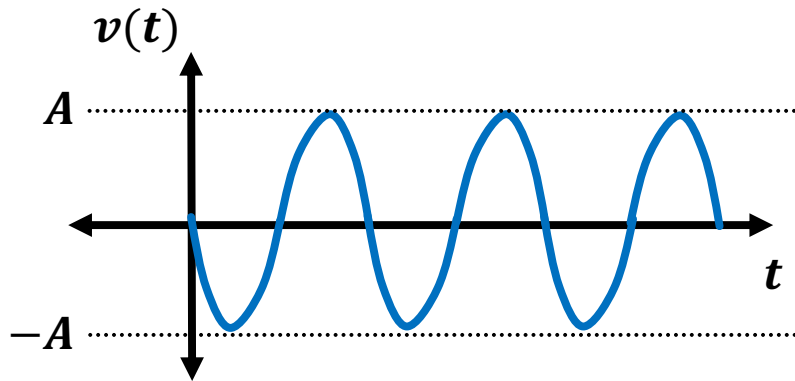
Frequency Spectrum of spike at f_o
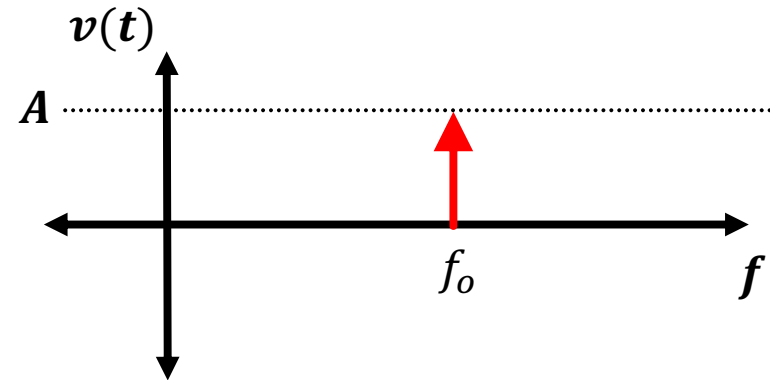
- Not much we can do with this signal…

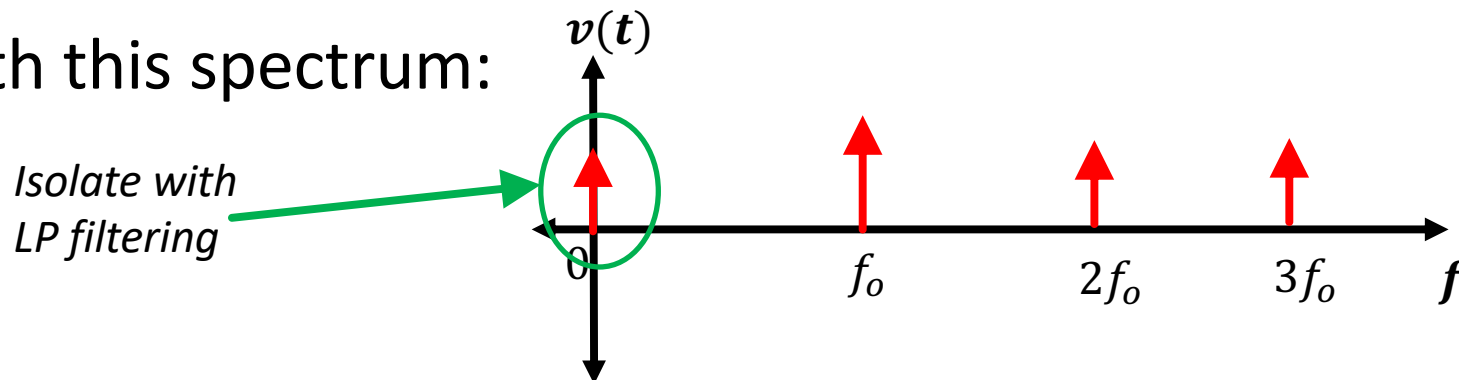- But if we run that signal through a non-linear device that lets only the top half of the sinusoids through…we have something…

Fourier Theory:

- If you rectify the signal, truncate signal's bottom half you get a signal like this:

$v(t)$

A ┈┈┈┈┈┈┈┈┈┈┈┈┈┈┈┈┈┈

t
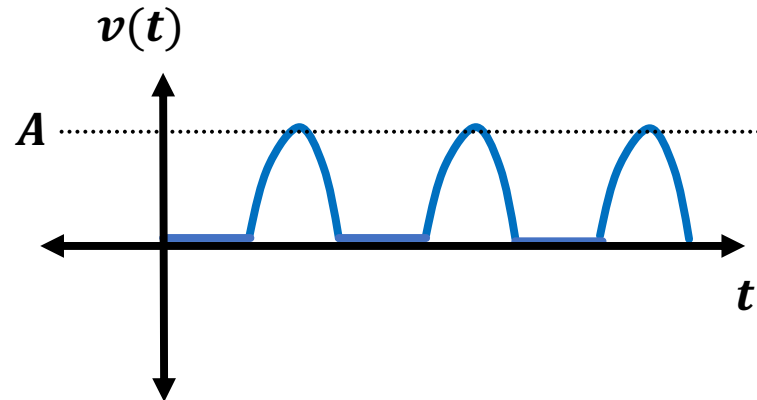
- Which is actually comprised of a sum of sinusoids like this:

$$v_s(t) = \frac{A}{\pi} + \frac{A}{2}\sin(2\pi f_o t) - \frac{2A}{1.3}\cos(4\pi f_o t) - \frac{2A}{3.5}\cos(6\pi f_o t) + \cdots$$

- With this spectrum:

$v(t)$

Isolate with LP filtering

0　　f_o　　$2f_o$　　$3f_o$　　f

Fourier Theory Now with Time-varying A :

- If $A(t)$ could vary with time (at frequencies much lower than carrier), then the following…

Incoming signal of $v_s(t) = A(t)\sin(2\pi f_o t)$
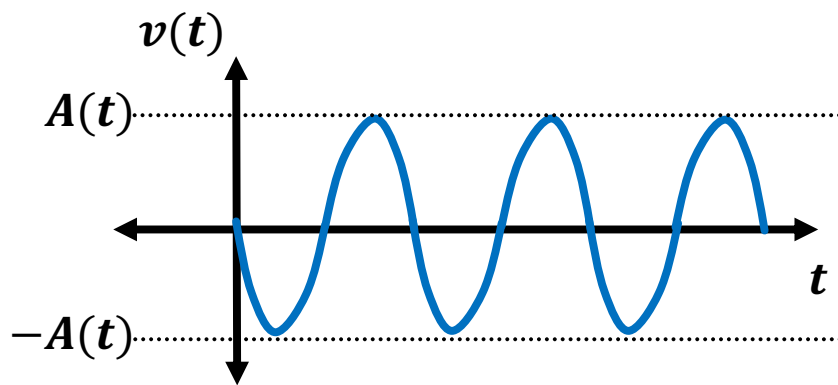
Frequency Spectrum of spike at f_o
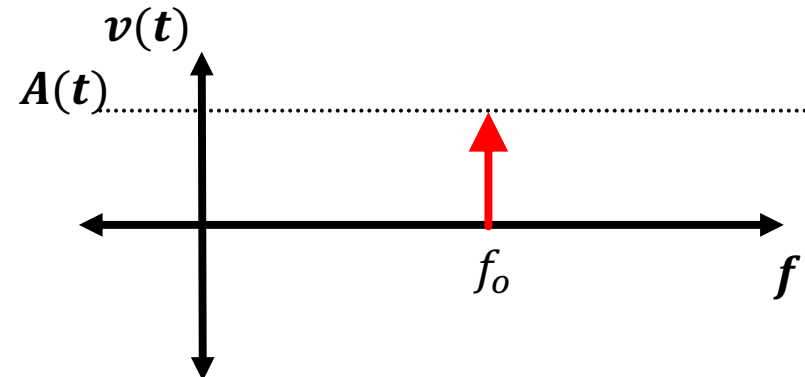
- Run through a rectifying device:…

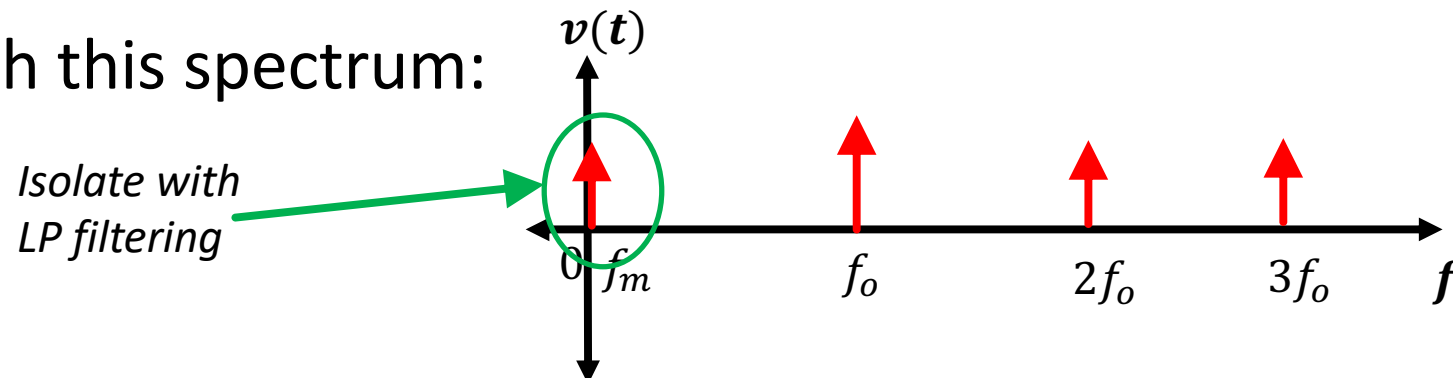# Fourier Theory Now with Time-varying A :

- If you truncate signal's bottom half you get a signal like this:

$v(t)$

$A(t)$ ....

t
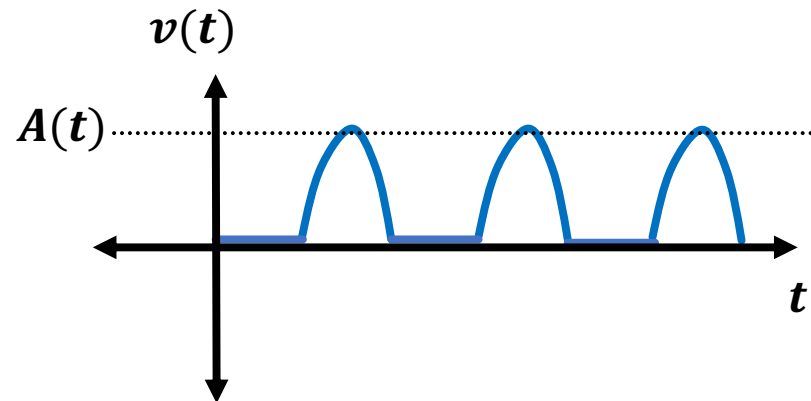
- Which is actually comprised of a sum of sinusoids like this:

$$v_s(t) = \frac{A}{\pi}\sin(2\pi f_m t) + \frac{A}{2}\sin(2\pi f_o t) - \frac{2A}{1.3}\cos(4\pi f_o t) - \frac{2A}{3.5}\cos(6\pi f_o t) + \cdots$$

- With this spectrum:

$v(t)$

Isolate with LP filtering

$0 \quad f_m \qquad\qquad f_o \qquad\qquad 2f_o \qquad\qquad 3f_o \qquad f$

The Search Got refined to "Rectifying Devices"

- Are there places in nature/physics where a device can conduct in one direction and not the other?

- And can these situations behave like this at radio frequencies?

- The search was on…
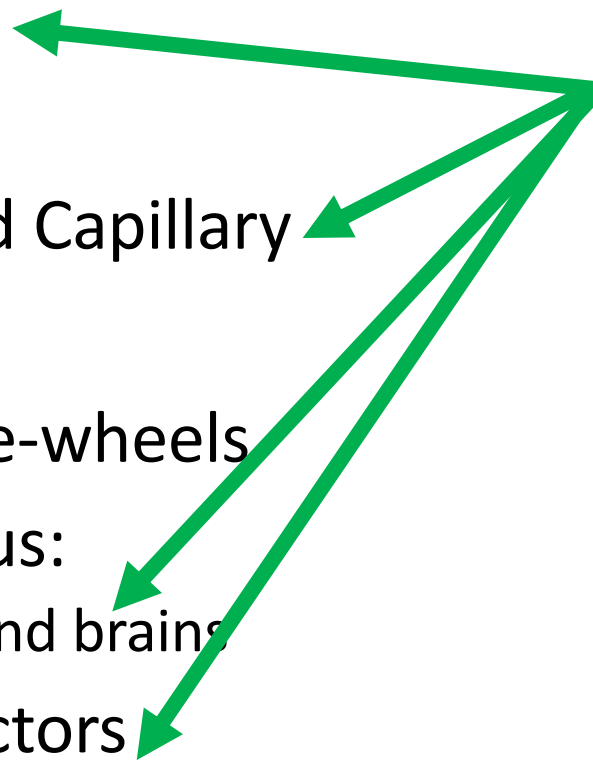 - This V-I relationship:
  - This sort of resistance:

$$R_{rec}(t) = \begin{cases} 0 \text{ if } \boldsymbol{v_{rec}} > 0\text{V} \\ \infty \text{ if } \boldsymbol{v_{rec}} \leq 0\text{V} \end{cases}$$
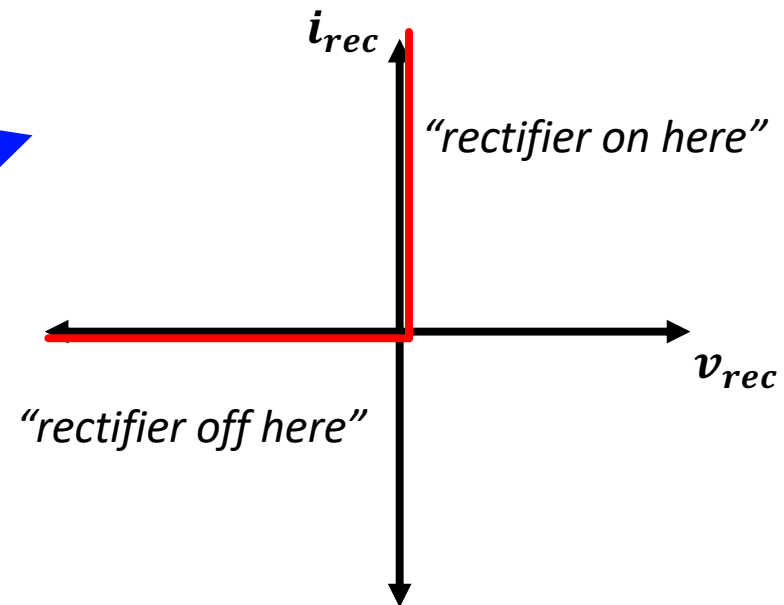
i_{rec}

"rectifier on here"

v_{rec}

"rectifier off here"

Early Radio Detectors

- Spark Gap
- Coherers
- Electrolytic
- Magnetic
- Thin-film and Capillary
- Thermal
- Ticklers, tone-wheels
- Miscellaneous:
  - Frog-legs and brains
- Crystal Detectors

Rectifying Devices

*Included as extra reading on course site under lecture 02

Developments

- Since Coherers worked a lot of research was launched around the interaction of metal contacts with "things".

- Eventually this caused a smart person to investigate how metal and semiconductors worked together…

The Winner: "Crystals"

- Through lots of experimentation and trial an error, Metal-crystal junctions started to pull ahead and work really well

- Metal was metal... nothing new there

- Crystal referred to semiconductors...
  - A lot of weird ones were used early on...
  - Lead-Sulfide (II) aka "Galena" was a popular one by early 1900s since you could basically find it ready-made in the earth*

*Many other semiconductors only appear "hidden" inside other compounds...ex: Silicon largely exists naturally only as Silicon Oxide... need good metallurgy to purify

Jagadish Bose

Bose

- Indian/Bangladeshi researcher Jagadish Bose in Calcutta who developed/refined the crystal device

- Got it working in 1901

- Didn't bother to patent it

- "Diode" wasn't really term yet…instead the device was called a "carbon-mercury-metal coherer"

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

Bose v. Marconi

Bose

- Marconi and his various companies were the first to successfully transmit information over the ocean.

- In 1901 he claims to have achieved first successful transmission of 's' across ocean

- In order to have a detector with enough sensitivity he used an "Italian Navy Coherer"…which was actually a metal-semiconductor junction device he claimed as his own and patented.

Marconi

- Marconi was very cagey about what detectors he actually used… point of controversy ever since*

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

*supplemental reading on site

A Crystal Detector

- Traditional Coherers stuck around for Morse Code, but crystal diode detectors started to become more commonplace for better sensitivity **and for audio**
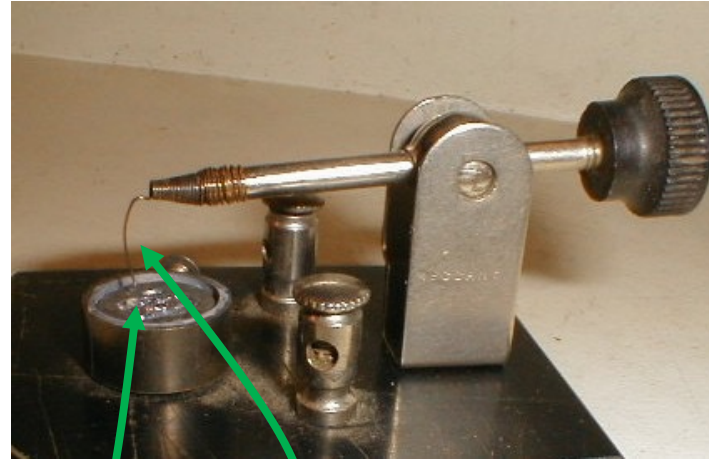
Chunk of galena

Tiny metal wire you'd poke around to get a good metal-semiconductor junction. Wire called a "Cat's Whisker"

- This metal-semiconductor junction formed a point-contact diode

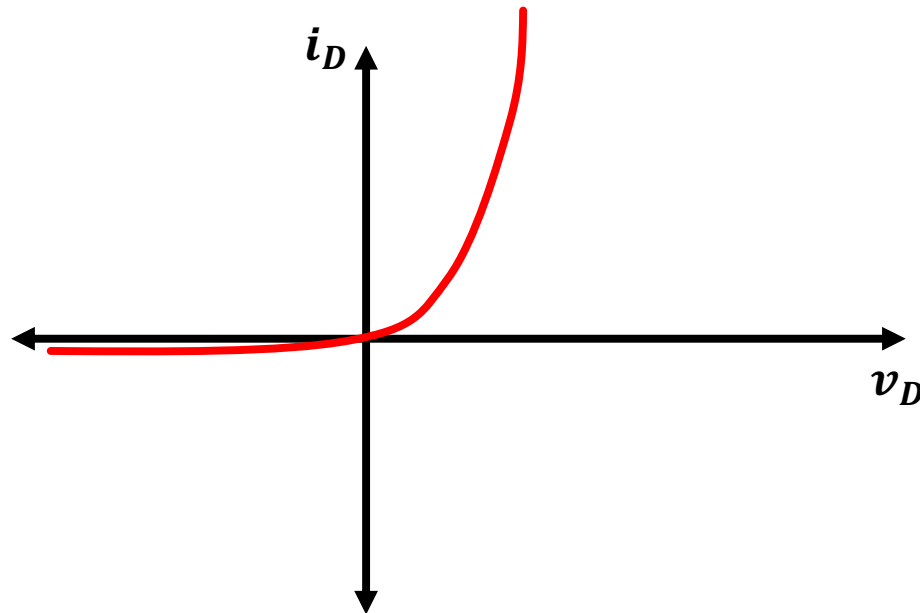- Galena was not uniform…so you'd have to poke around with the whisker
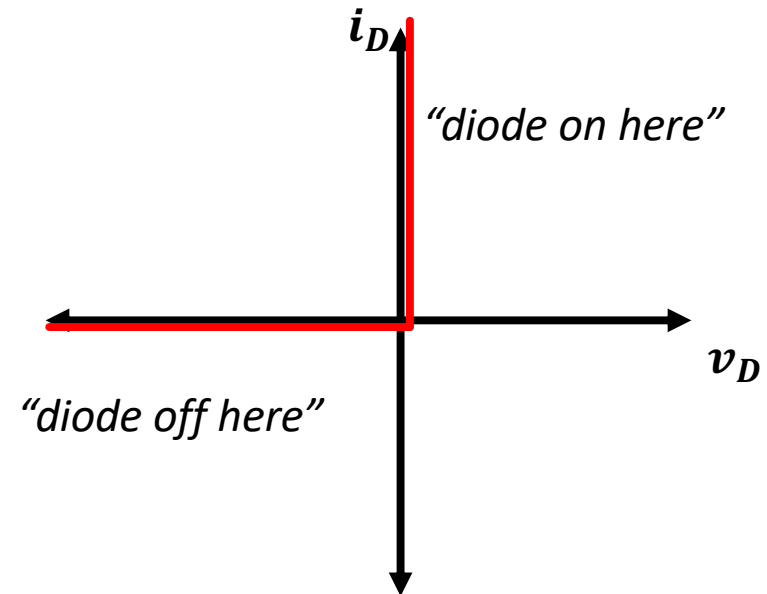
https://en.wikipedia.org/wiki/Crystal_detector

Diode

$+$ v_D $-$

i_D
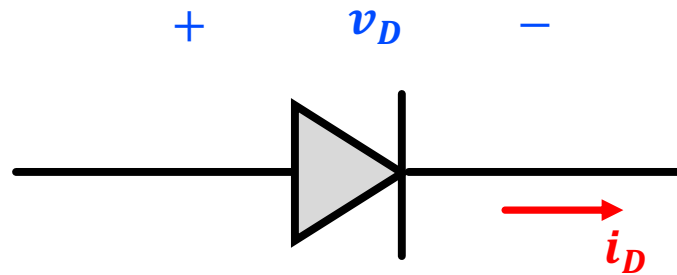
- This metal-semiconductor device is now known to us as a "diode" today. But that terminology didn't arrive until the early 1920s.

I-V characteristics looked like this:

i_D

v_D

Not exactly this, but pretty close:

i_D

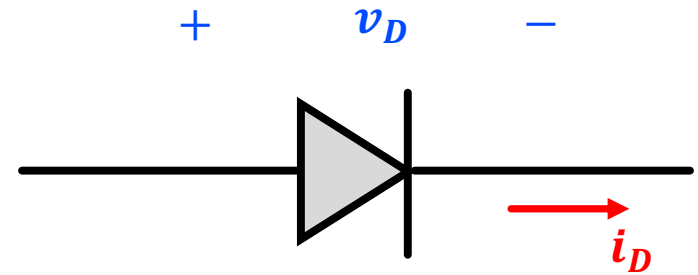*"diode on here"*

"diode off here"

v_D

Germanium Diode

- Modern point-contact diode

- Use in our Lab 02

- Good contact assured at factory with refined germanium rather than you having to poke around on some rando impure chunk of Galena

Chunk of germanium
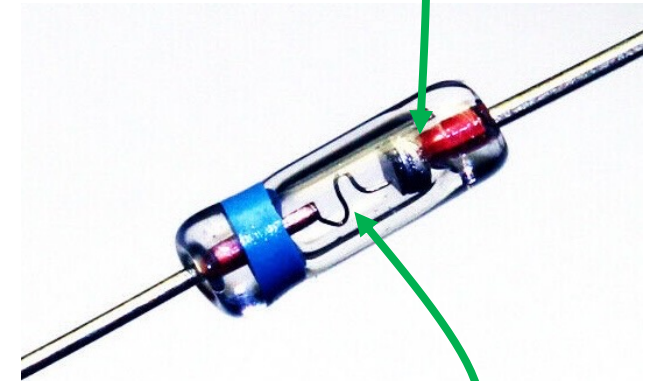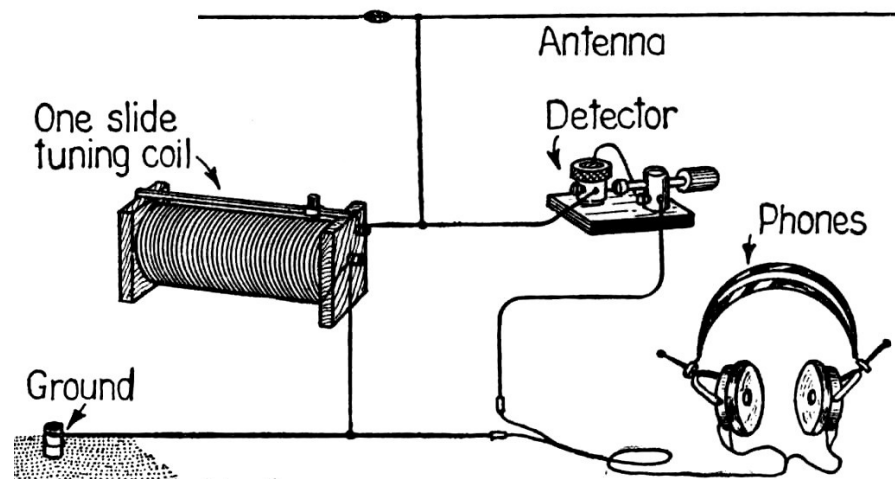

Wire called a "Cat's Whisker"

Note on Diodes in Class

$+$ $\quad v_D \quad$ $-$

i_D

- US diodes have their line in agreement with diode symbol
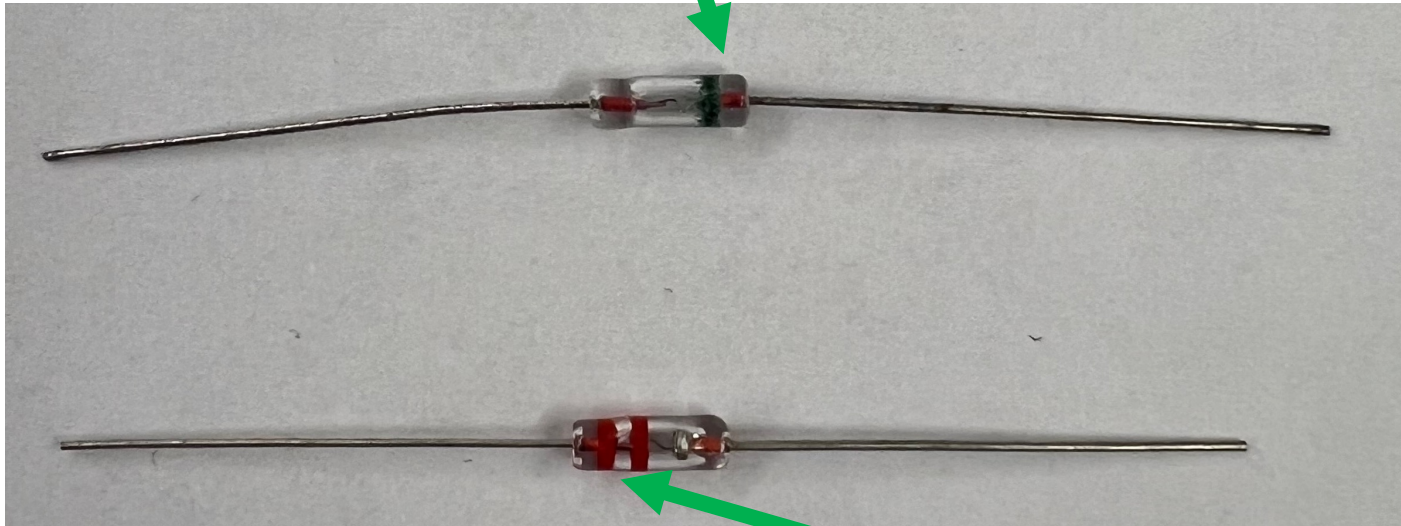
- Soviet Diodes usually do opposite (line on triangle-bottom side)
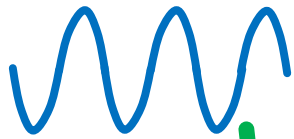
Crystal Radio (~1910)

- Lead Sulfide
- Make a diode from metal-semiconductor junction
- Recover radio signal
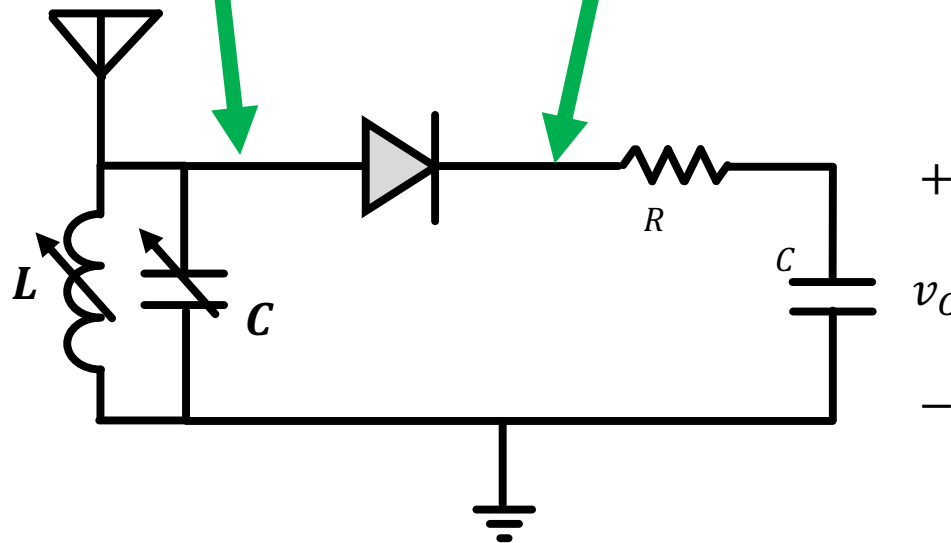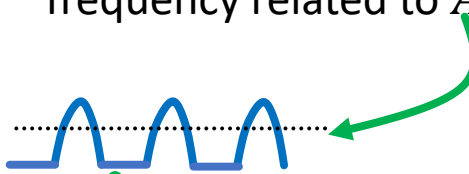- No amplification so headsets only

https://en.wikipedia.org/wiki/Crystal_radio#/media/File:CrystalRadio.jpg

Recovery Circuit

Our chosen frequency. Its A encodes information:

Rectified signal. This signal contains an "offset" component that is very low frequency related to A

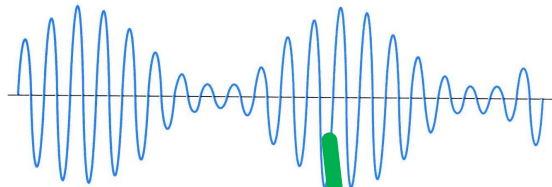Filtered Output is a voltage correlated with A (and only A)!

If A is actually $A(t)$, this output will track over time. All we need is for the frequency content of $A(t)$ to be much lower in Hz than the carrier frequency (which is the case even for audio!)
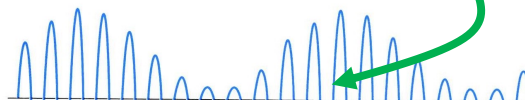
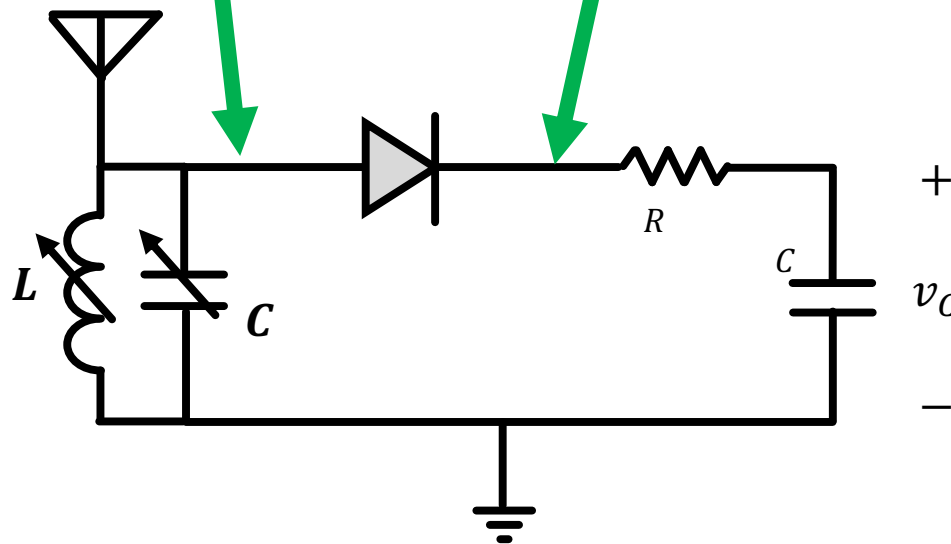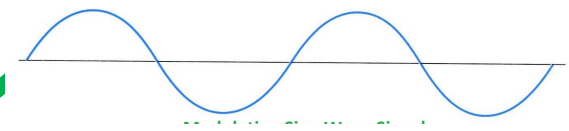- Beautiful!

Recovery Circuit with Time-varying A

Our chosen frequency. Its A encodes information:

Rectified signal. This signal contains an "offset" component that is very low frequency related to A

Filtered Output is a voltage correlated with A (and only A)!
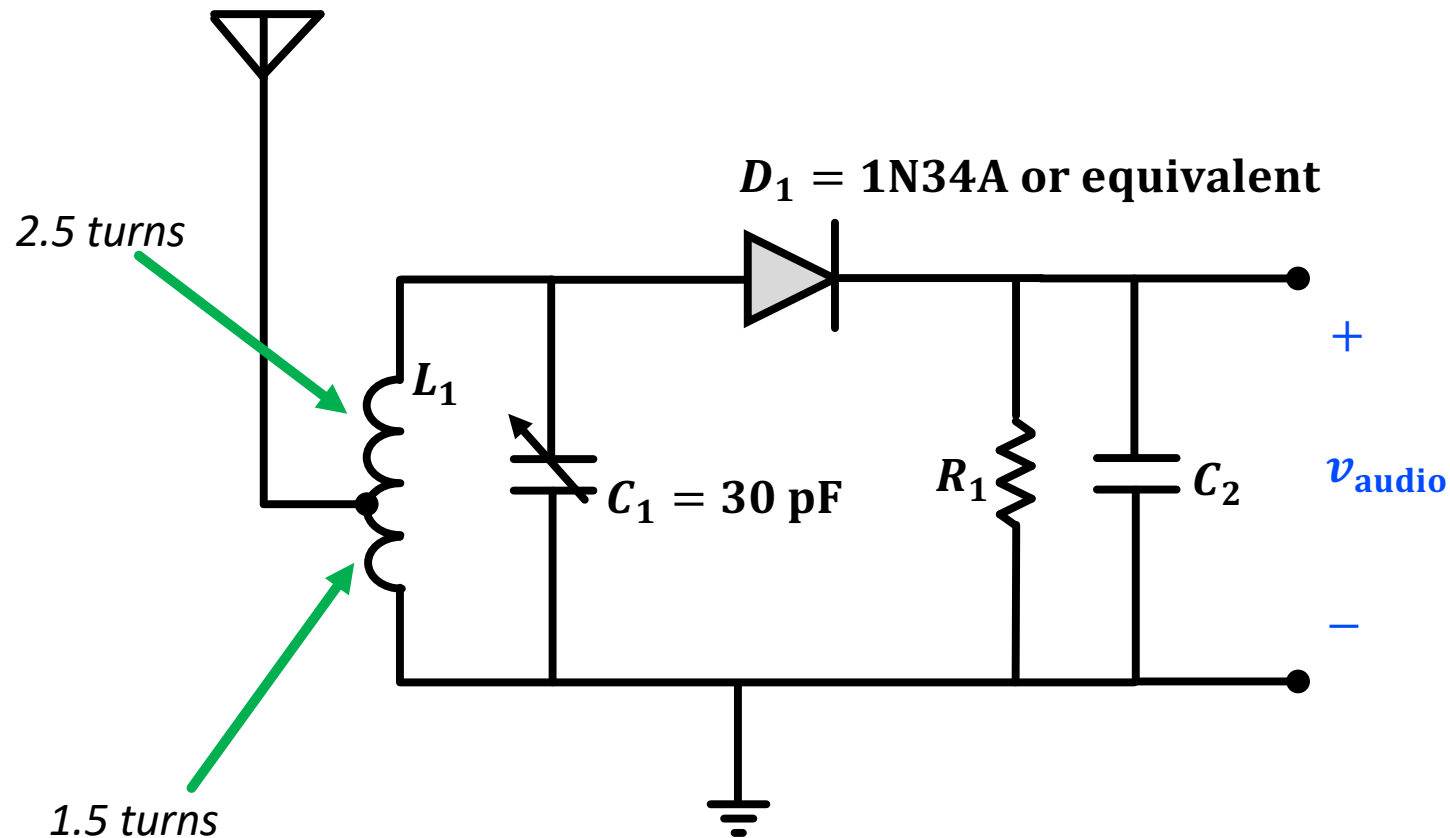
If A is actually $A(\text{t})$, this output will track over time. All we need is for the frequency content of $A(\text{t})$ to be much lower in Hz than the carrier frequency (which is the case even for audio!)

- Beautiful!

Lab 2

- Build a simple FM Crystal Detector

$D_1 = $ **1N34A or equivalent**

2.5 turns

L_1

$C_1 = 30 \text{ pF}$

R_1

C_2

v_{audio}

+

−

1.5 turns

L_1 4 turns of 16 or 18 AWG bare copper around 0.5"
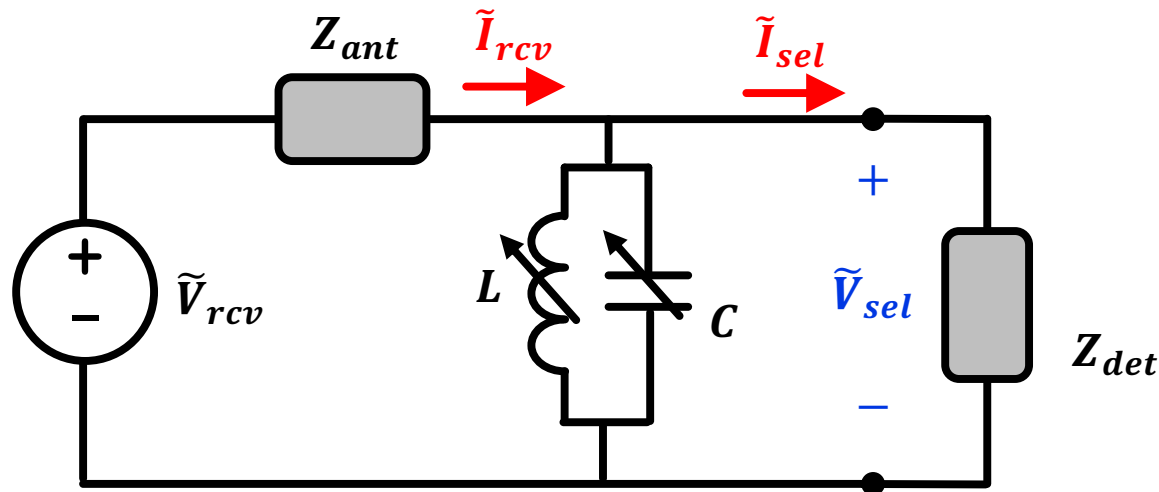form pulled out to about 1" in length

Theory of Operation:
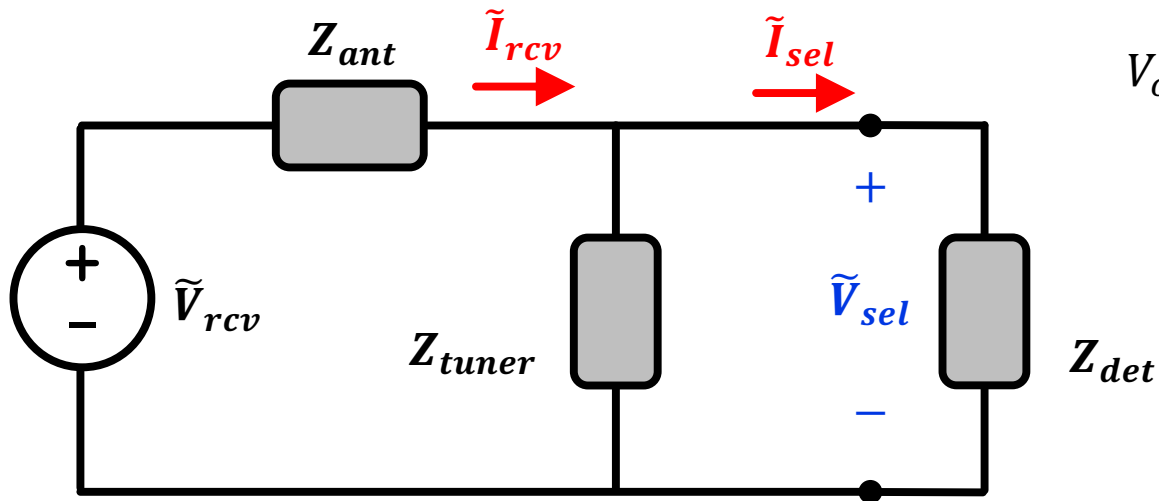
$$V_{out}(s) = V_{in}(s) \cdot \frac{Z_{tuner}}{Z_{tuner} + Z_{ant}}$$

$$Z_{tuner} = \left(\frac{1}{Z_L} + \frac{1}{Z_C}\right)^{-1}$$

$$Z_{tuner} = \left(\frac{1}{j\omega L} + \frac{1}{1/j\omega C}\right)^{-1}$$

$$Z_{tuner} = \frac{j\omega L}{1 - \omega^2 LC}$$

Behavior of tuner parallel LC

Remember $\omega = 2\pi f$

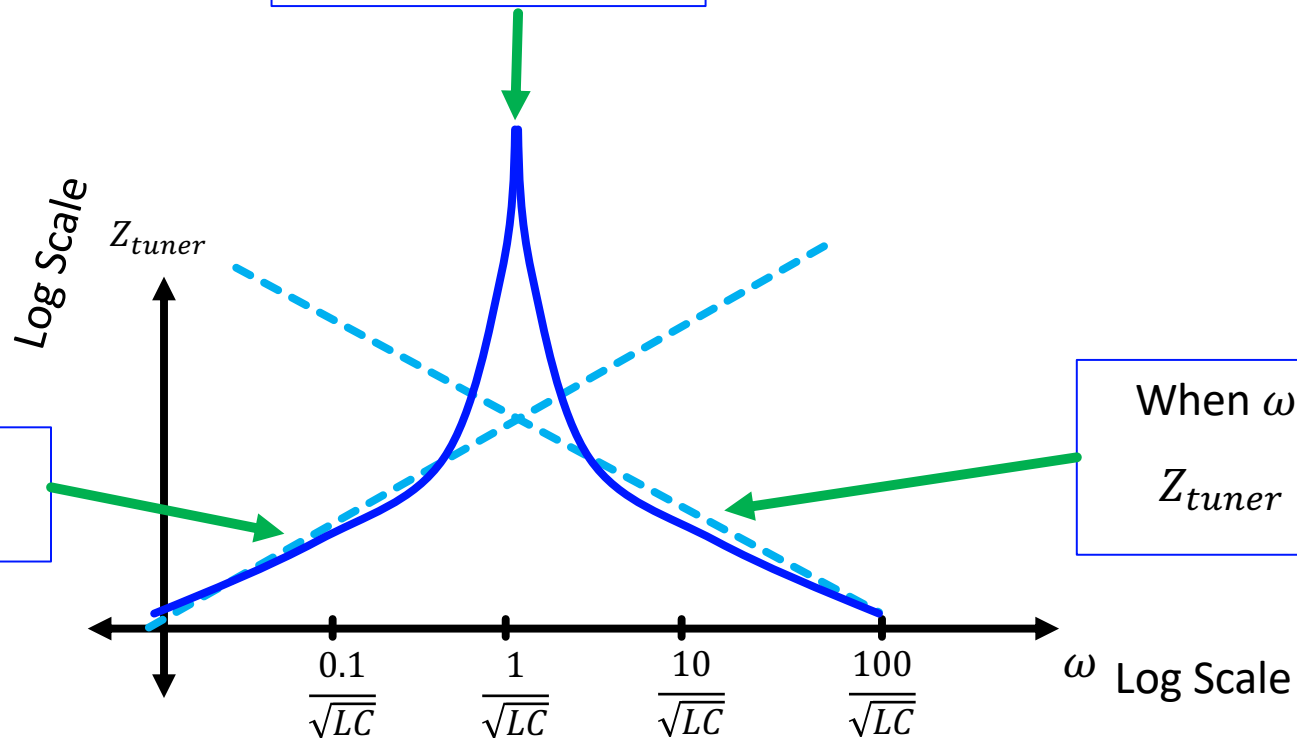$$Z_{tuner} = \frac{j\omega L}{1 - \omega^2 LC}$$

Resonant Frequency:

$$\omega_o = \frac{1}{\sqrt{LC}} \text{ (in radians)}$$

Or

$$f_o = \frac{1}{2\pi\sqrt{LC}} \text{ (in radians)}$$

When $\omega = \omega_o$,
$Z_{tuner} \to \infty$
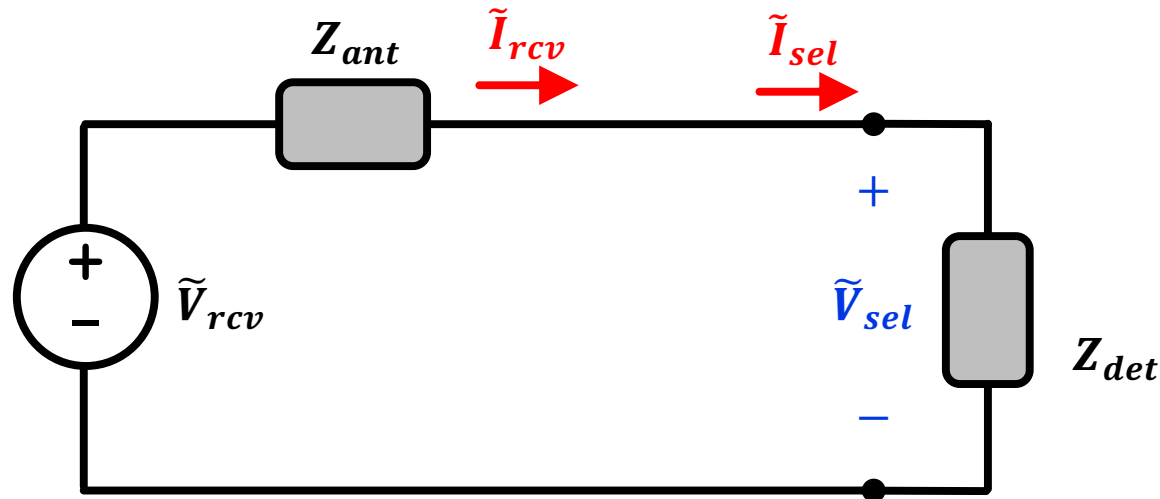
When $\omega \ll \omega_o$,
$Z_{tuner} \approx j\omega L$

When $\omega \gg \omega_o$,
$Z_{tuner} \approx \dfrac{1}{j\omega C}$

Log Scale

Z_{tuner}

$\dfrac{0.1}{\sqrt{LC}}$ $\dfrac{1}{\sqrt{LC}}$ $\dfrac{10}{\sqrt{LC}}$ $\dfrac{100}{\sqrt{LC}}$

ω Log Scale

Conclusion I

- At resonance, the tuner "disappears" so the circuit looks like the following:
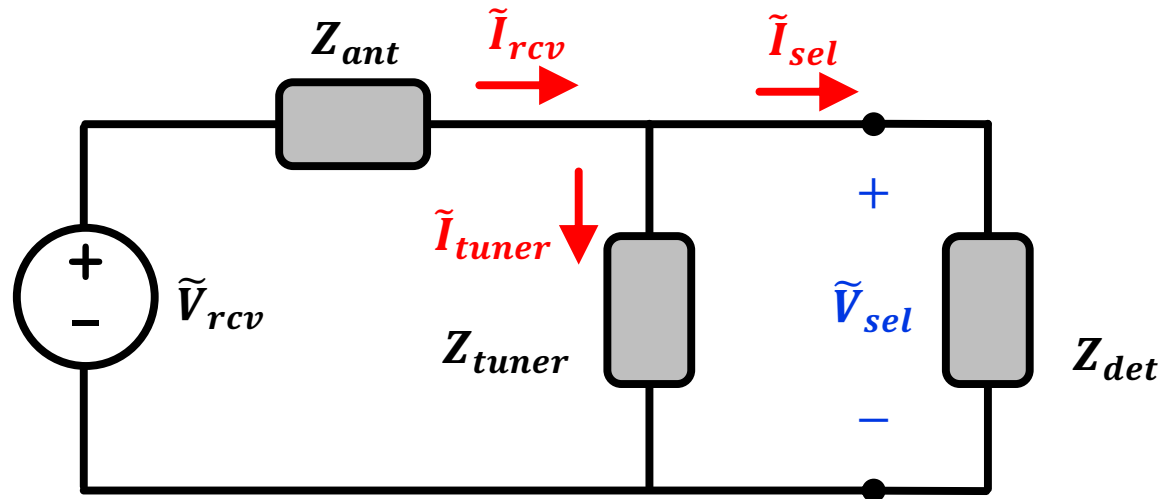

- And importantly all power coming from the antenna will get directed towards the detector.

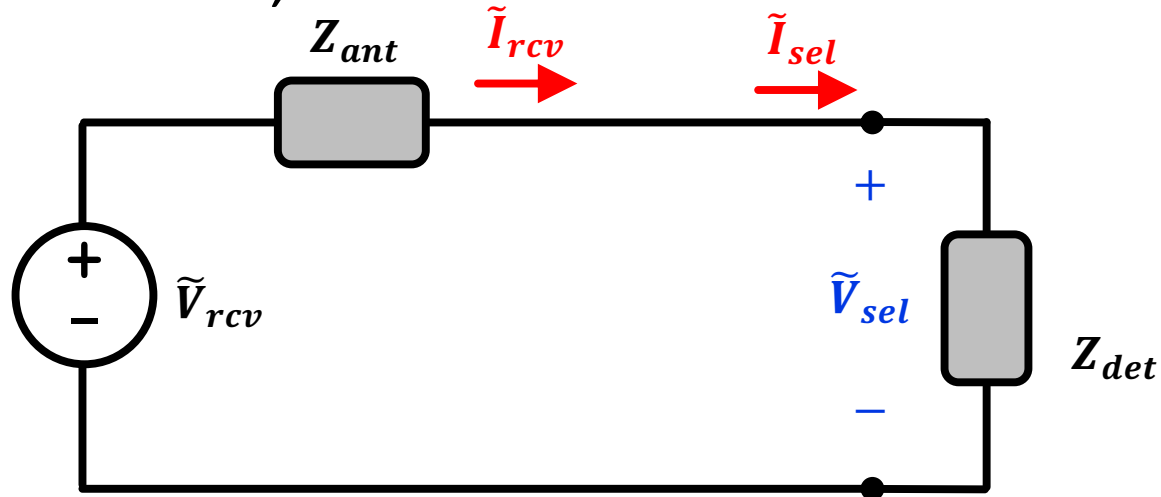$$\tilde{I}_{rcv} = \tilde{I}_{sel}$$

Conclusion II

- At off-resonance, the tuner can't be ignored so the circuit looks like the following:

- The further away from resonance we stray, the lower $|Z_{tuner}|$ and therefore $\tilde{I}_{tuner}$ eats more of $\tilde{I}_{rcv}$, leaving less for $\tilde{I}_{sel}$

- Non-desired signals are blocked

But wait, there's more

- At resonance, our circuit looks like this:

- We want to ensure that the maximum power is delivered to the detector. How to do that?

- We must impedance match!

Review: Impedance Matching

- Concerned with maximizing *power* delivery to load, not voltage*
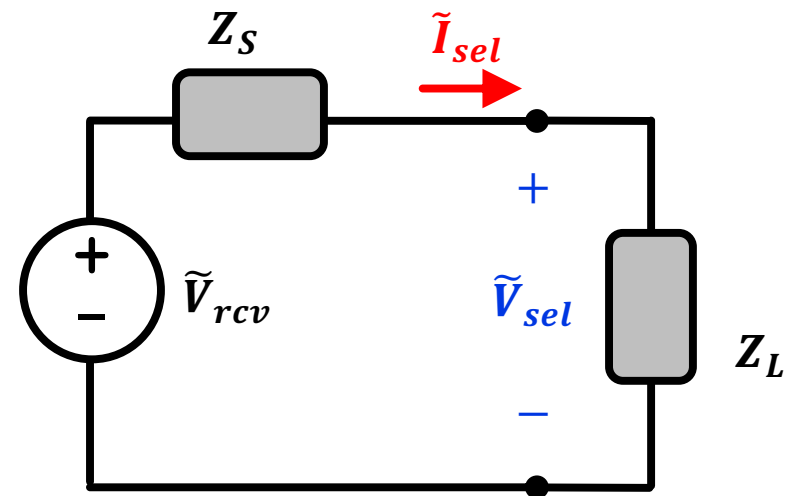
*If voltage is our primary concern (as we often encounter in systems), the general trend is to ensure $|Z_L| \gg |Z_S|$...in that case the voltage divider devolves to $\widetilde{V}_{sel} \approx \widetilde{V}_{rcv}$

Review: Impedance Matching

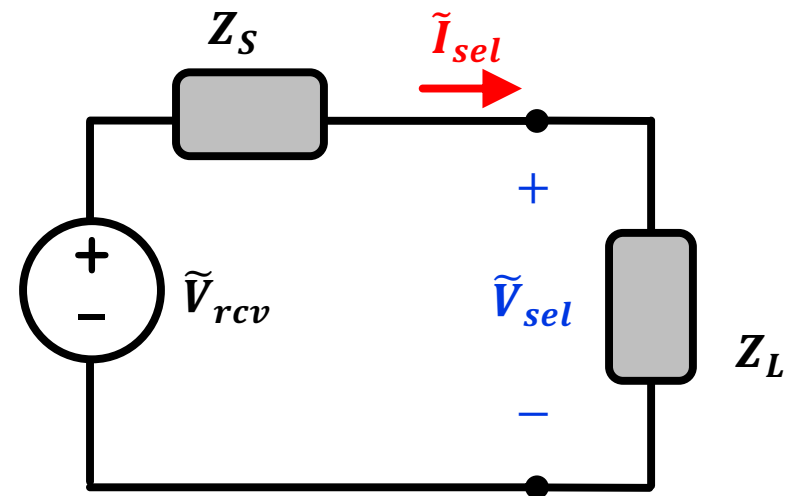- Concerned with maximizing *power* delivery to load, not voltage[1]

- This will happen when the Load impedance is the complex conjugate of the Source impedance $Z_L = Z_S{}^*$ ⟵ Complex conjugate


[1] If voltage is our primary concern (as we often encounter in other systems), the general trend is to ensure $|Z_L| \gg |Z_S|$...in that case the voltage divider devolves to $\widetilde{V}_{sel} \approx \widetilde{V}_{rcv}$.

One way to help this is via the tuning coil

- Instead of using the full amount of coil as we originally showed, use different amounts of it for your entry and exit points of signals

- The coil turns into a auto-transformer and transformers can be used to impedance match (and we will do that often working with tubes!)...more next week

2.5 turns

$\tilde{I}_{out}$

$\tilde{I}_{in}$

$+$

$\tilde{V}_{out}$

$-$

$+$

$\tilde{V}_{in}$

$-$

1.5 turns
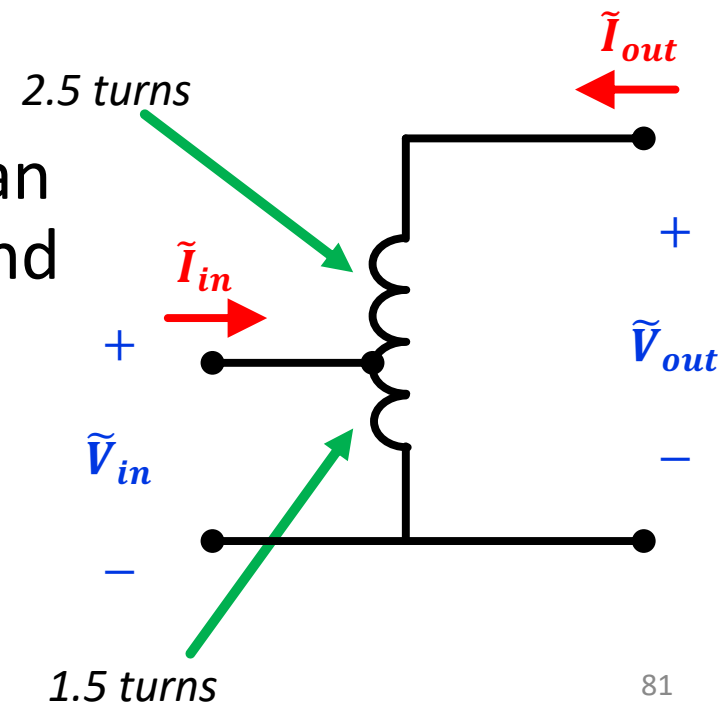
# So we gotta make sure $Z_{ant} = Z_{det}*$

- But WTH is Z_{ant} and WTH is Z_{det} ?

- In order to know that we need to know stuff about the antennas and stuff about the detectors (diode)

- We won't obsess too much about that in this class since it is a deep topic

- The circuit we build is actually pretty good as built...if we wanted to improve it, we'd need to spend more effort on that
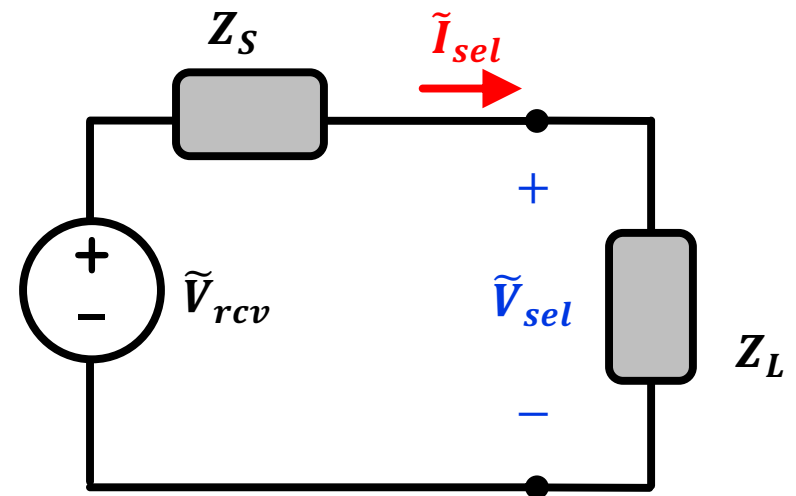
Lab 2: No Active Detection!

- Completely based on energy recovered from signal*

$D_1 = $ **1N34A or equiv.**

2.5 turns

L_1

$C_1 = 30$ pF

R_1

C_2

v_{audio}

+

−

1.5 turns
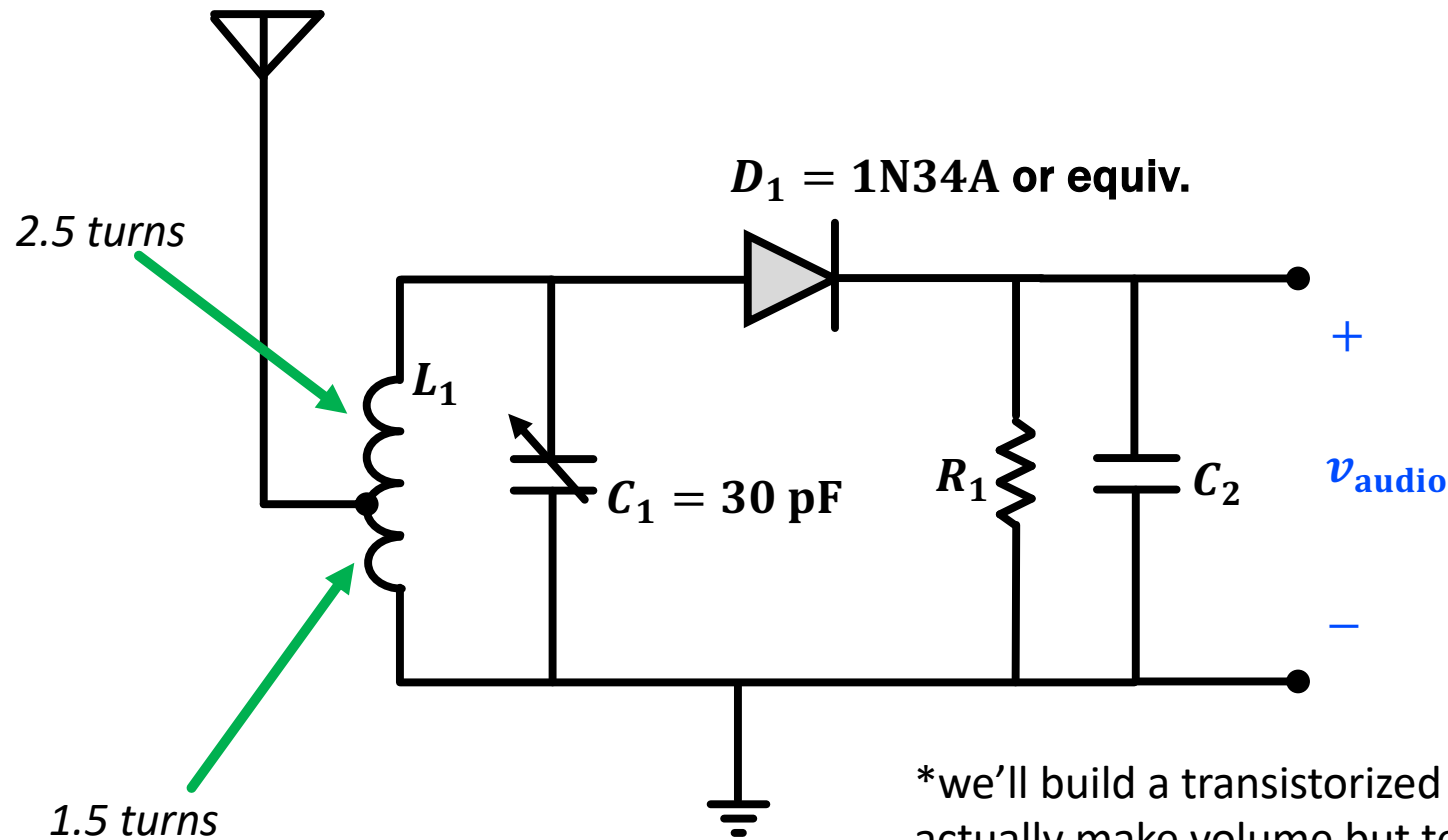
*we'll build a transistorized amp to actually make volume but technically you don't need it if you have a good crystal earpiece

Review: By 1890:

✅ • Telegraph (wired) networks were widespread:
  • Electromagnetic (relay-based) amplification and detection

  • Telephone networks (wired) were growing:
    • Transmit analog data over distance

✅* • Relatively short-distance networks
    • Early analog amplifiers using electromagnetic and carbon/metal interactions could provide some amplification to recover loss

  • "Radio" technology beginning to appear:
❌   • Radio waves operated at much higher frequencies than the prior two electromagnetic forms of communication
    • Previous technologies for amplification and detection were useless at radio-frequencies ☹
    • Needed to develop true "electronics" not "electromechanical things"

*carbon amplifiers were annoying and unreliable

Review: By 1890:

- Fixing these two problems required:
  - Not directly consumable. → **<u>Detection!</u>**
  - Small in amplitude/power. → **<u>Amplification!</u>**
- ✅ **<u>Detection</u>** refers to extraction of information into a consumable form from the transfer medium (some form of transducer)

- ❌ **<u>Amplification</u>** refers to the generation of larger-power signals based off of smaller-power signals

And this is the hole that vacuum tube tech will start to fill

What were the Killer Apps in Electronics throughout recent history?

- A coarse set of categories:
- 1840s-1880s: Telegraphy
- **1880s-1920s: <u>Lighting</u>, Appliances, Things with motors, Telephone**
- 1890s-1940s: Radio, Telephony
- 1940s-1970s: TV
- 1970s-2000s: Gaming Systems, Computers
- 1990s-present: Internet
- 2000s-present: Smart Phones

The Era where Electronics entered People's Lives Personally

- Happened Slowly (cities electrified far sooner than farm areas)…some areas of Appalachia lacked electricity until 1970s

- Mostly limited to electrical or electro-mechanical things
  - Street Lighting → Home Lighting
  - Appliances (fans, heaters, etc)
  - In-house electricity
  - Streetcars

1893 Columbian Exposition

- Approximately 27 million visitors during run (25—40% of US population)

- Like CES, and every companies' product reveal all wrapped into one.

https://interactive.wttw.com/playlist/2017/11/14/dreaming-worlds-fair

Bidding War to Demo Lighting Technology and Other Things

Westinghouse's AC was selected to light fair since he underbid Edison's DC
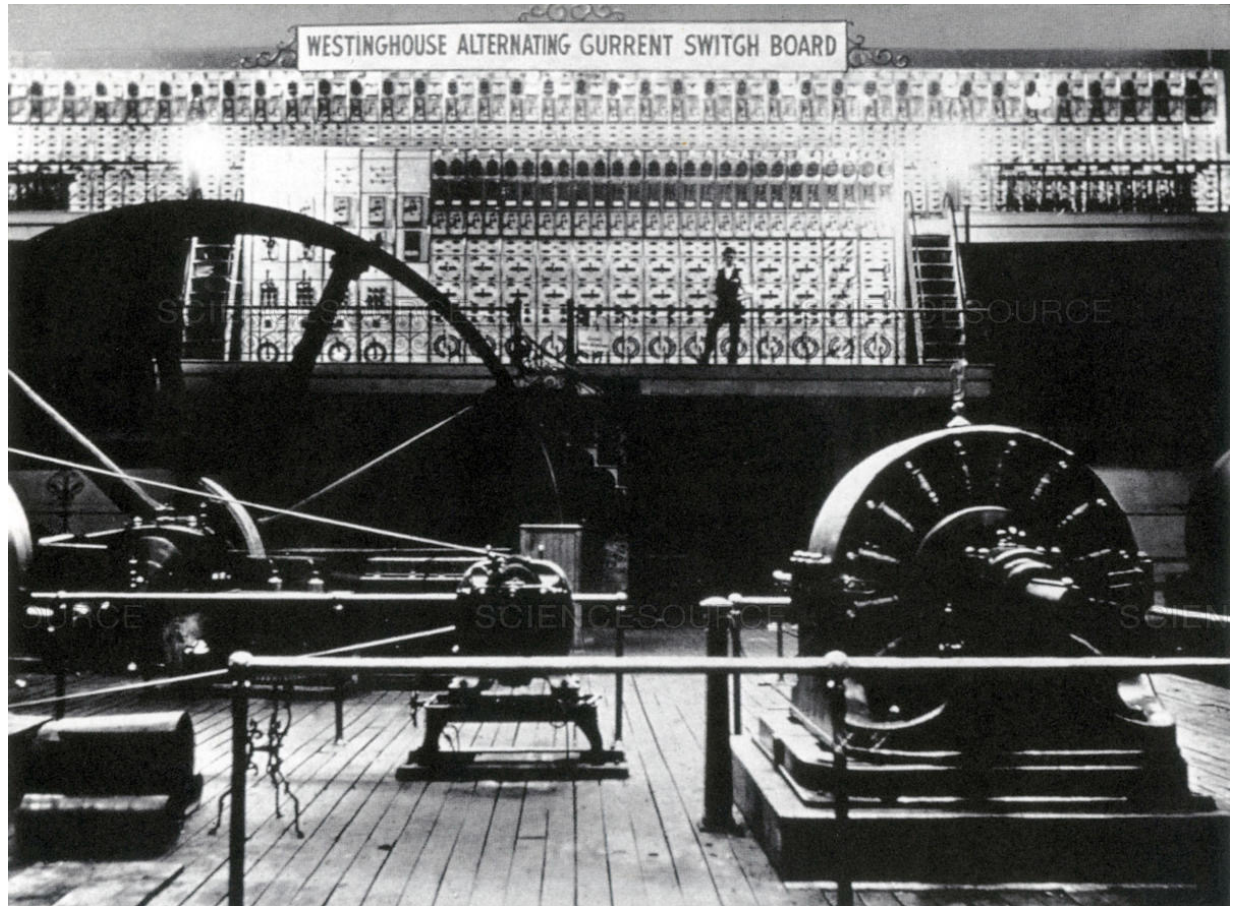
200,000 lightbulbs, hundreds of types of generators, motors, everything…

Built a whole temporary city out of plaster/cheap materials so it would basically "glow" at night!
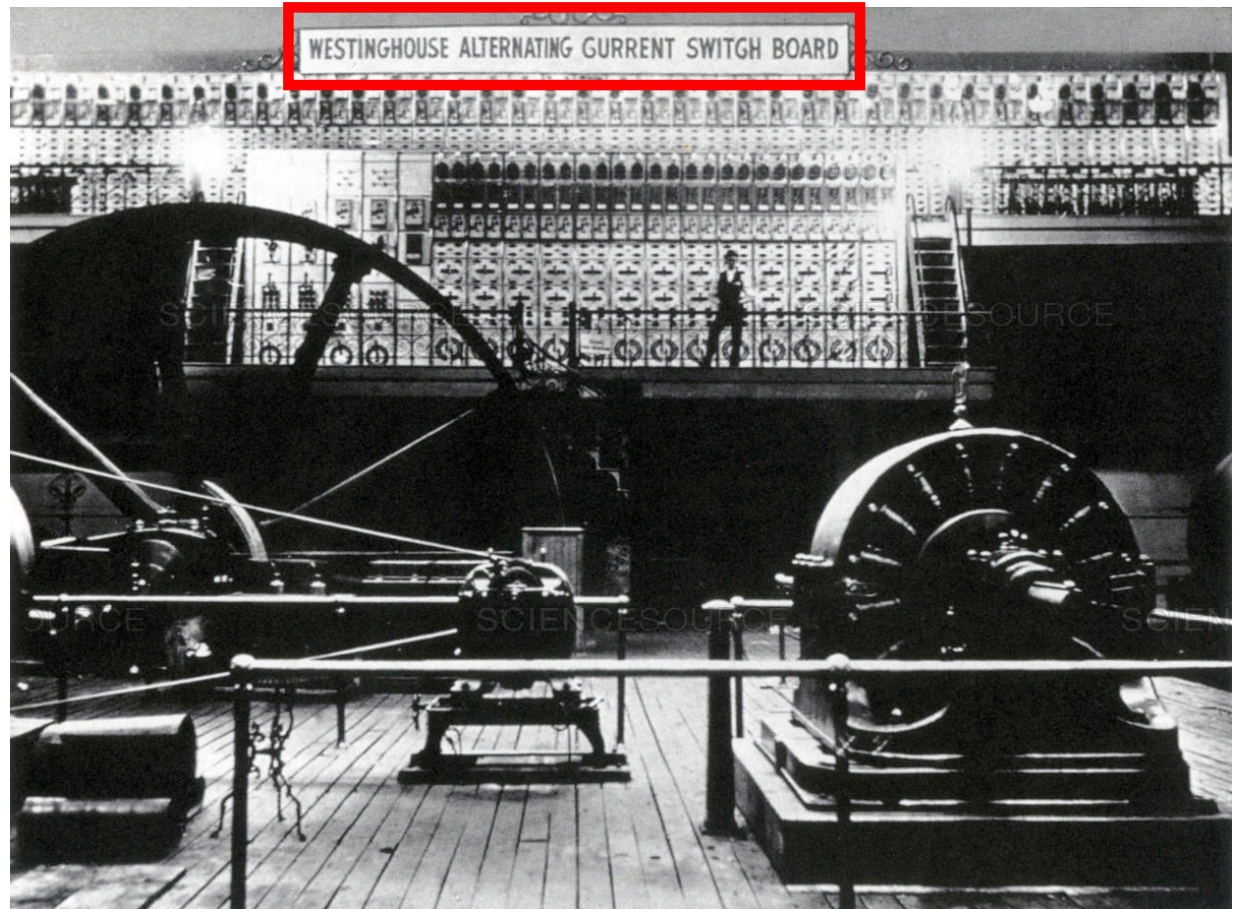
Hall of Dynamos

- Huge Hallway featuring all electrical devices from era

- One of Fair's centerpieces

Corporate Sponsorship

- One of first National Events with Corporate Sponsorship

WESTINGHOUSE ALTERNATING GURRENT SWITGH BOARD

Bidding to Display Technology Still Common Place

https://www.theverge.com/2017/12/4/16734838/microsoft-surface-nfl-deal-extension

Artificial Light

- Street Lights existed for most of 1800s, but were like gas or arc-lamps..basically dirty and dimly lit

- Everything needed to be burned

- Burning causes soot

- Most regular-person buildings were dark colors as a result, because what's even the point

- Electric Light changed all that
  - Didn't have to kill whales all the time (they were mostly gone by then anyways)
  - Didn't need to run gas lines everywhere
  - Lighting on demand whenever you wanted

Lighting

- Savoy Theatre in London first place to have in-house lighting for dramatic effect

- Iolanthe first dramatic experience to use "fairy lights"
  - Small lightbulbs sewn into fairy costumes
  - Powered by small batteries embedded in dresses
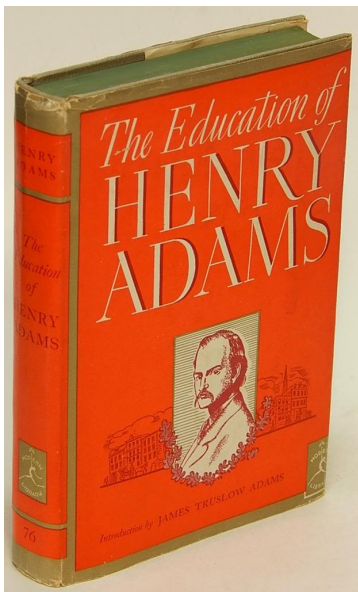   - Likely lead-acid cells or...
    - Some other liquid cell
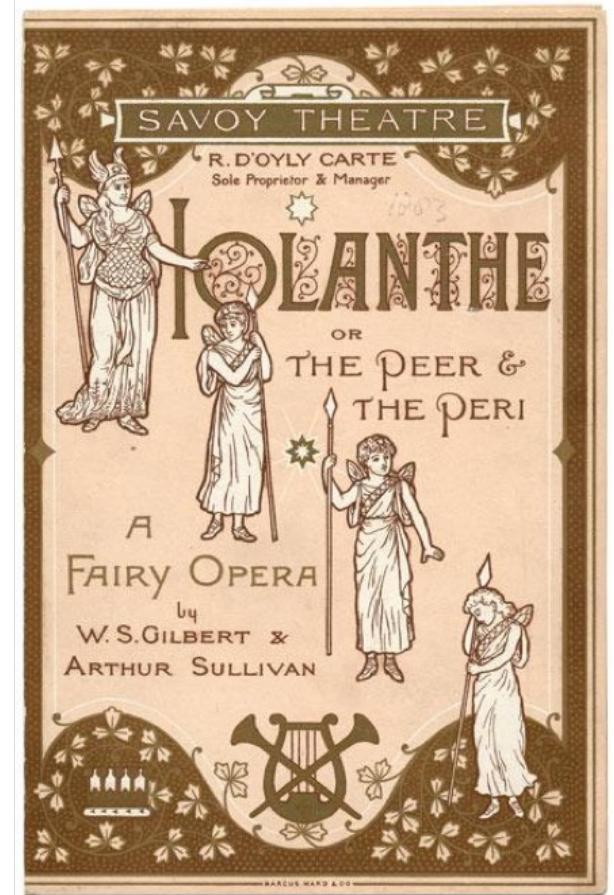
Original Iolanthe Program Cover 1882

Joseph Swan
English inventor of
practical lightbulb

Henry Adams

- Kind of Early Tech Journalist

- Wrote passages comparing Dynamos (type of generators) to the Virgin Mary

Charles River

BACK BAY

BOSTON COMMON

JOY ST BUILDINGS

Here's Henry writing About the Hall of Dynamos in 1905 about Columbian Exposition*

He wrapped himself in vibrations and rays which were new, and he would have hugged Marconi and Branly had he met them, as he hugged the dynamo; while he lost his arithmetic in trying to figure out the equation between the discoveries and the economies of force. The economies, like the discoveries, were absolute, supersensual, occult; incapable of expression in horse-power. What mathematical equivalent could he suggest as the value of a Branly coherer? Frozen air, or the electric furnace, had some scale of measurement, no doubt, if somebody could invent a thermometer adequate to the purpose; but X-rays had played no part whatever in man's consciousness, and the atom itself had figured only as a fiction of thought. In these seven years man had translated himself into a new universe which had no common scale of measurement with the old. He had entered a supersensual world, in which he could measure nothing except by chance collisions of movements imperceptible to his senses, perhaps even imperceptible to his instruments, but perceptible to each other, and so to some known ray at the end of the scale. Langley seemed prepared for anything, even for an indeterminable number of universes interfused,—physics stark mad in metaphysics.

Before this historical chasm, a mind like that of Adams felt itself helpless; he turned from the Virgin to the Dynamo as though he were a Branly coherer.

*Adams narrates himself in third person. Kinda cringe ngl

Edison, etc FanFic

- Huge amounts of cheap literature written at time of fictional and real engineers

- *The Future Eve* (I'Isle-Adam, 1886) has fictional Thomas Edison inventing lady robots (term Android first appears)

- *Edison's Conquest of Mars* (Serviss, 1898) was an unofficial follow-up to *War of the Worlds* where Thomas Edison captures and reverse engineers Martian technology

Thankfully we've advanced as a society....

the social network

PIRATES of SILICON VALLEY

r/teslamotors
reddit
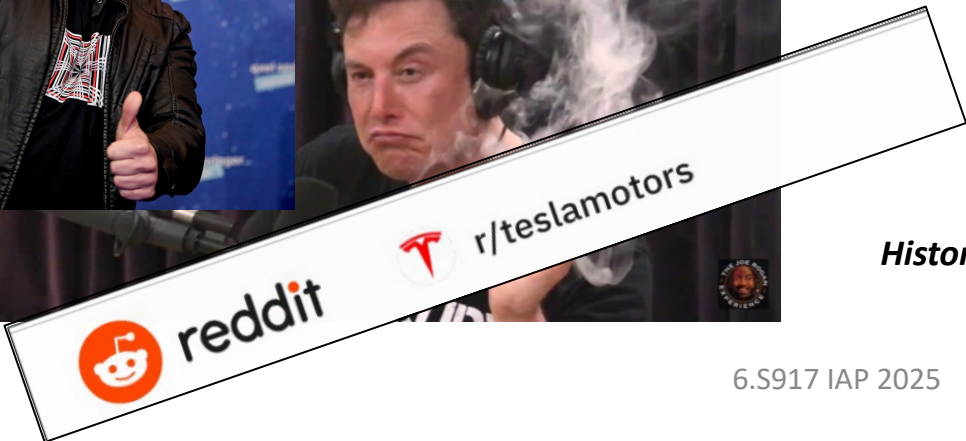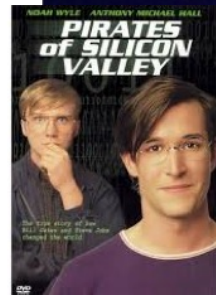
History never repeats itself, but it does often rhyme.
-Mark Twain

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
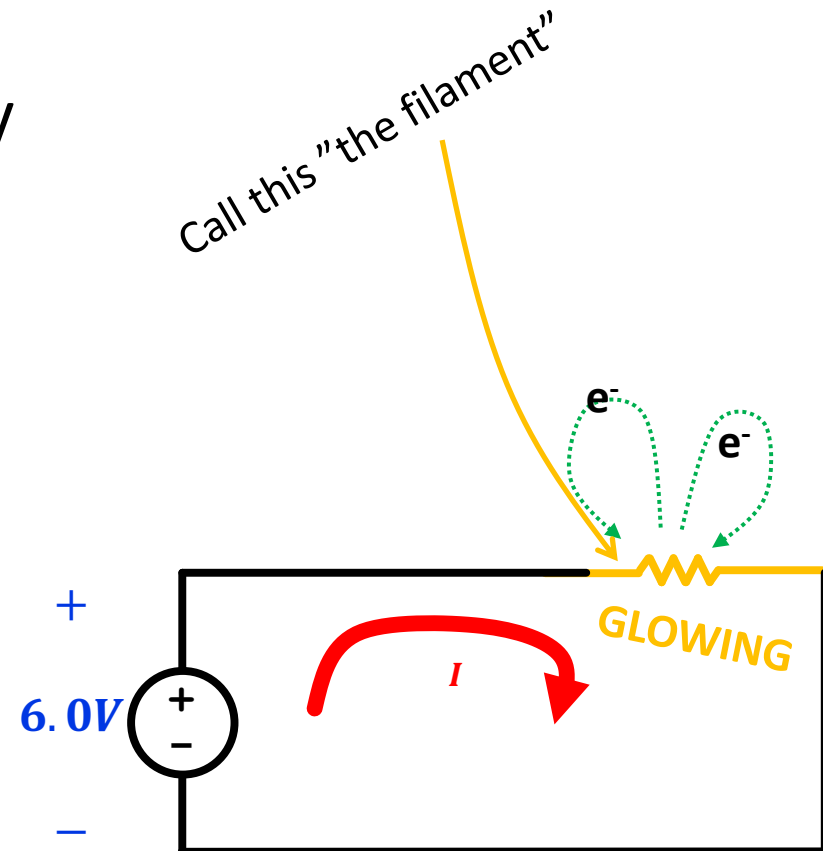
Beginnings of Vacuum Tubes

- 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

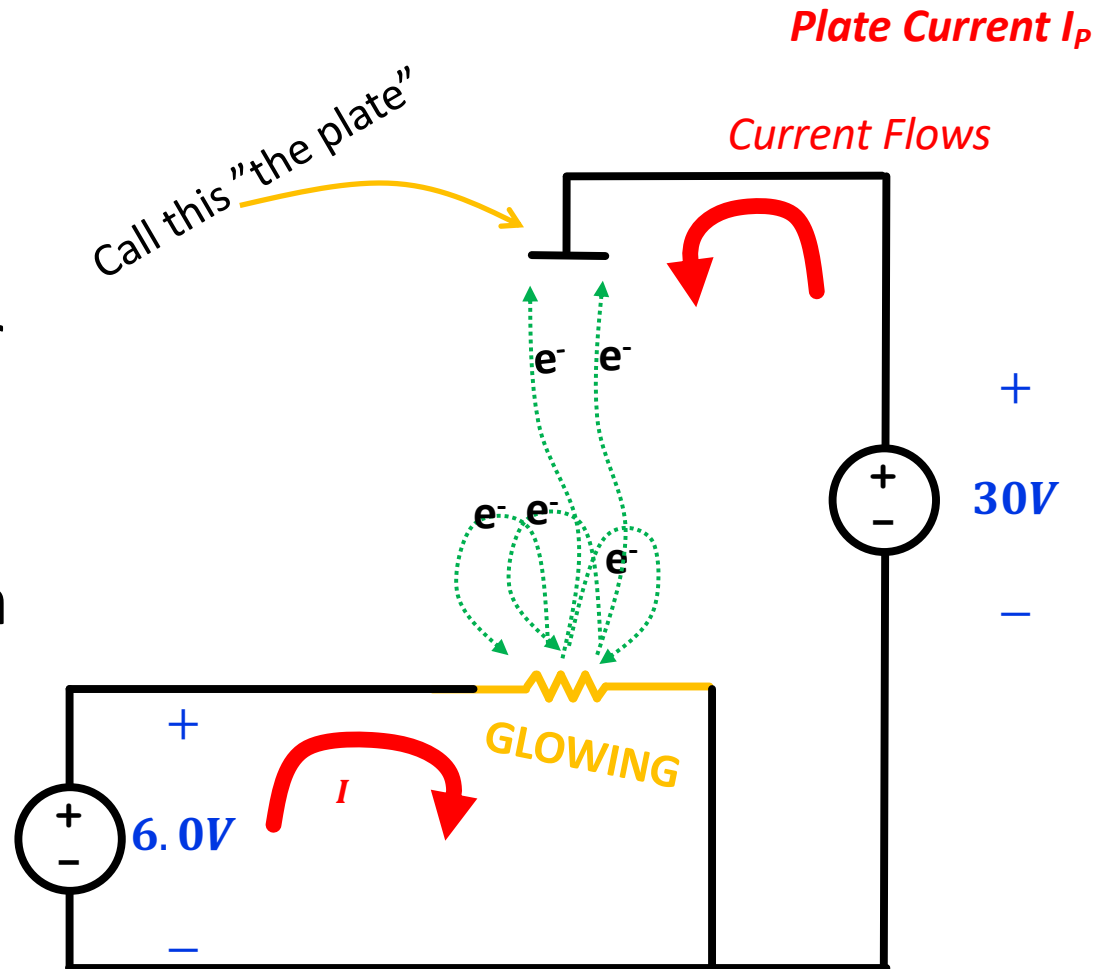- Do this enough and material will glow....that's the idea behind a lightbulb

HEAT And LIGHT

$+$

$6.0V$ $\overset{+}{\underset{-}{}}$

I

$P = VI$
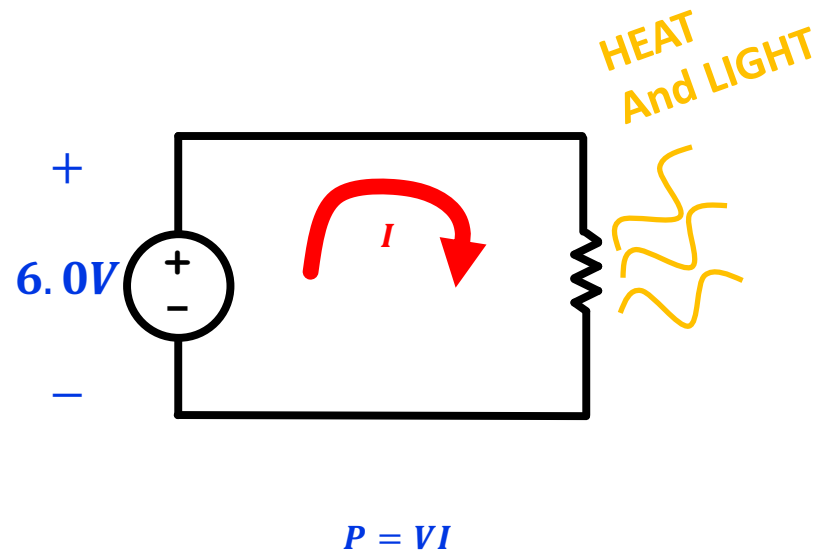
Beginnings of Vacuum Tubes

- 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

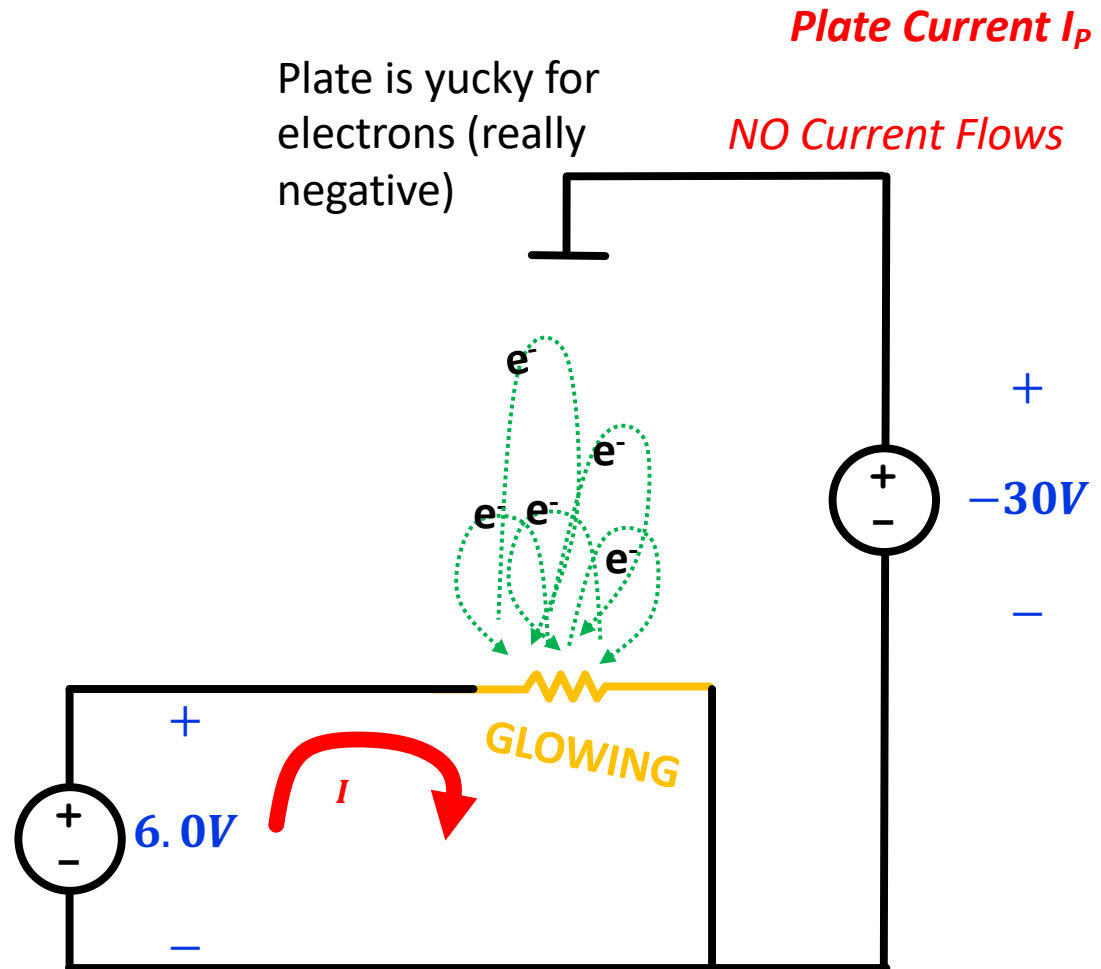- Normally they'll fly off and then fly back down

Call this "the filament"

e⁻ e⁻

GLOWING

$6.0V$ +   I

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!

Plate Current I_P

Current Flows

Call this "the plate"

e⁻ e⁻

e⁻ e⁻

e⁻

+

30V

−

+

GLOWING

+

6. 0V

−

I

Beginnings of Vacuum Tubes

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

- Weird behavior

Plate Current I_P

Plate is yucky for electrons (really negative)

NO Current Flows

e⁻ e⁻ e⁻ e⁻ e⁻ e⁻

GLOWING

I

$6.0V$

$-30V$

Plot it Out!

- What does this look like?

- …

- NON-LINEAR

- A diode!

- One way electrical valve

I_{plate}

V_{plate}
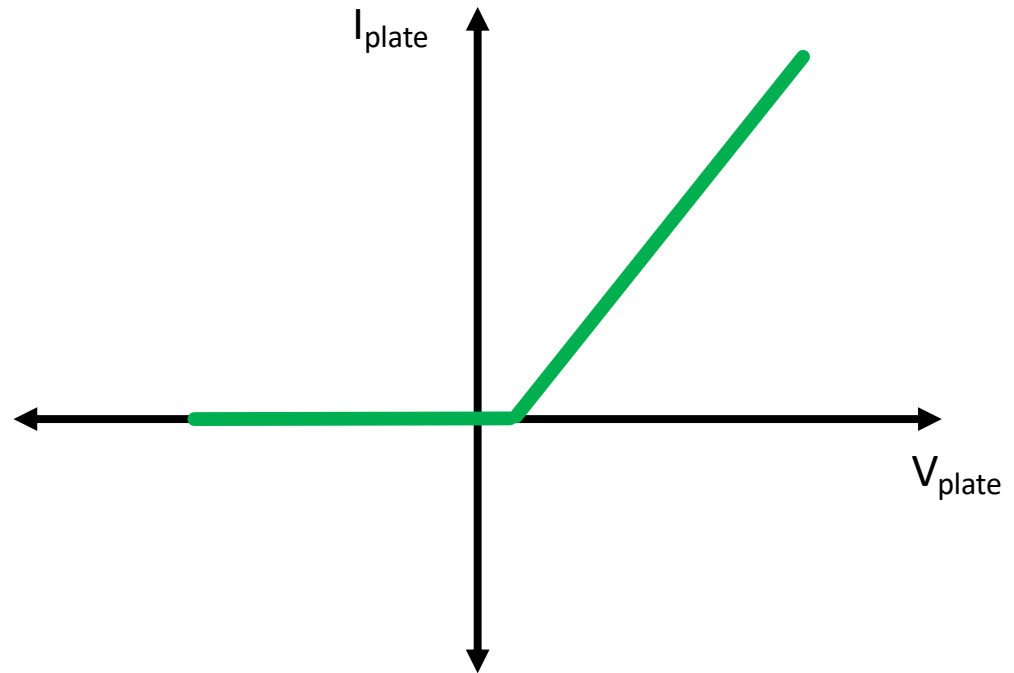
More realistically it might look like:

Current (mA): 10, 8, 6, 4, 2, 0

Volt (V): 0.2, 0.4, 0.4, 0.8, 1.0, 1.2
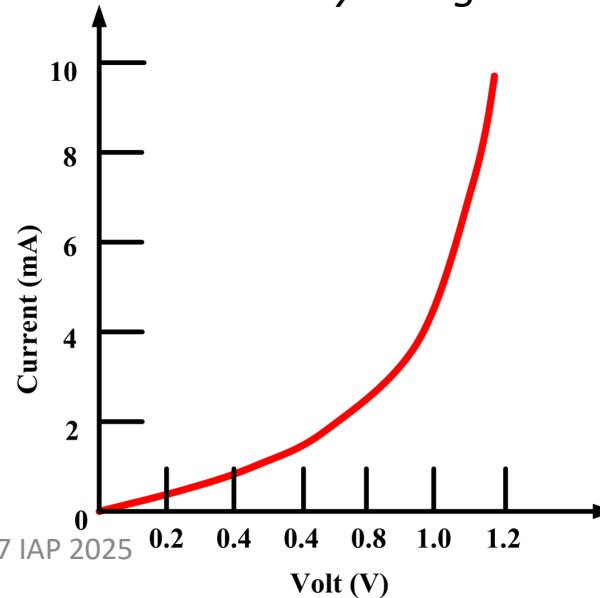
Diode

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

Anode (plate)

Tube enclosure

Vacuum inside tube

Cathode

e⁻ e⁻ e⁻

+

−

Directly heated

Anode

Fillament

Indirectly heated

Anode

Heater

Cathode

SM0VPO

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

I-V Relationship for 879 Tube
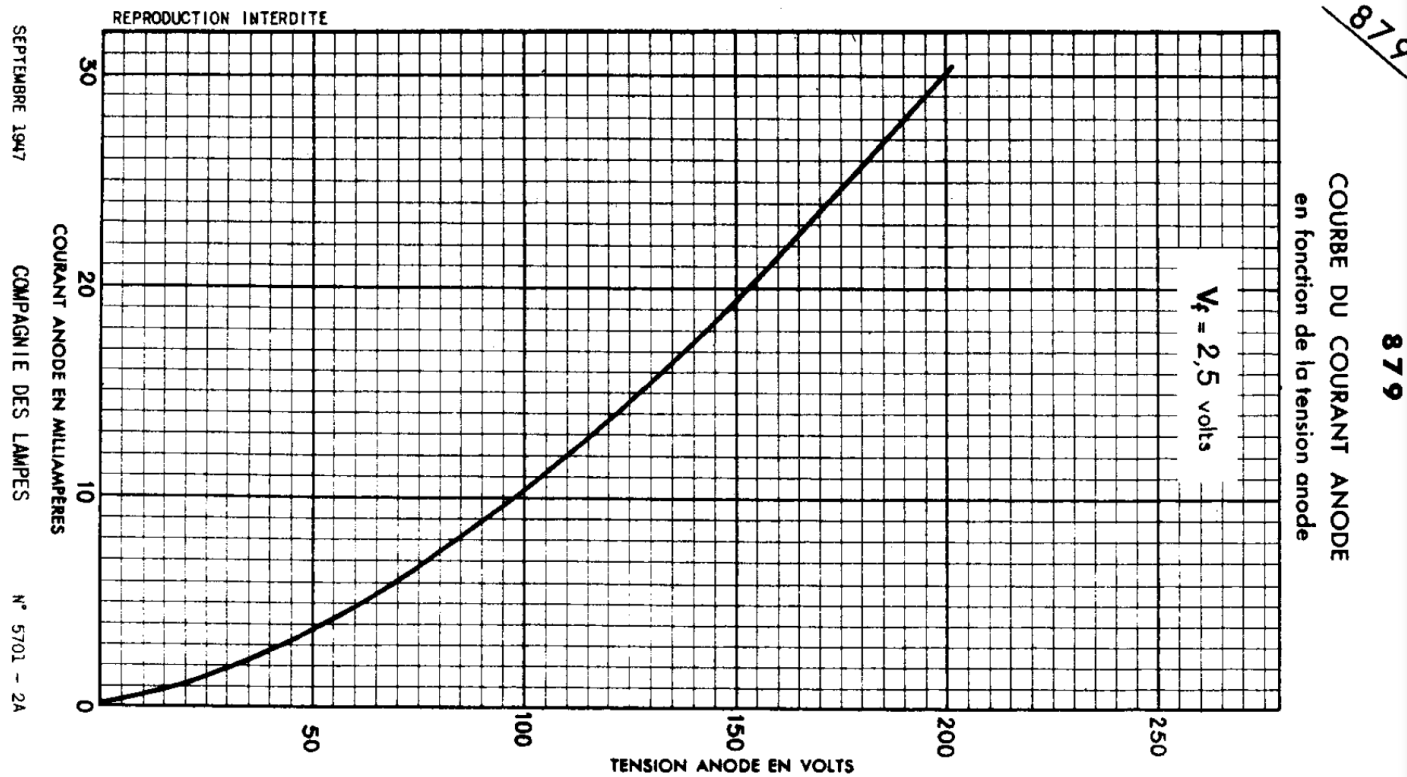
In French because that's the only datasheet I could find for it with curves

Discovered Several Times

- Fesseden 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")

- 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)

*and since they were older tech, they were much cheaper

Next Week

- What if we stick another wire into the thermionic diode (~1906)?...perhaps make a three-electrode device...three-electrode

- ...three-ode...
- treeode...
- triode