Lecture 1

Tube Electronics, Early Transistors

Overview of Class

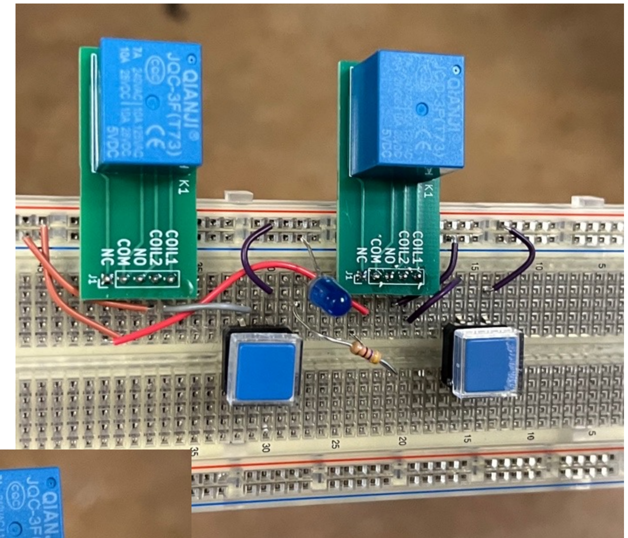
- **6.S917 Tube Electronics**
- *Level:* U
- *Units:* 1-0-5...PNR credit as far as I understand it
- *Prereqs:* 6.2000 (6.002)
- Class Website: **tubes.mit.edu/6S917/2025**
- *Instructor:* Joseph Steinmeyer (jodalyst@mit.edu) , Senior Lecturer, EECS
- *Schedule:* January 6 – January 31
  - Lecture: Tuesdays & Thursdays, 2:30-4, room 36-156
  - Open Lab hours: Lab open every weekday 9am-5pm
  - Office hours: See calendar on front page, room 38-601
  - *Description:* This class will study early electronics with a focus on vacuum tubes, early semiconductors, and other adjacent topics. While a largely technical class, we'll also look at some social aspects of these technologies. We will have lectures with accompanying readings, some technical and some more literary or in other disciplines. There will be lab exercises available to explore and build some circuits. Circuits will be kept below 36V for safety. Some familiarity with circuits and circuit theory(6.2000/6.002) is assumed, and if you're just starting out, I can try to help fill in some gaps, time-permitting. There are no homeworks/psets. There are no exams. The class is meant to be fun and low-pressure.

Schedule/ “Syllabus”

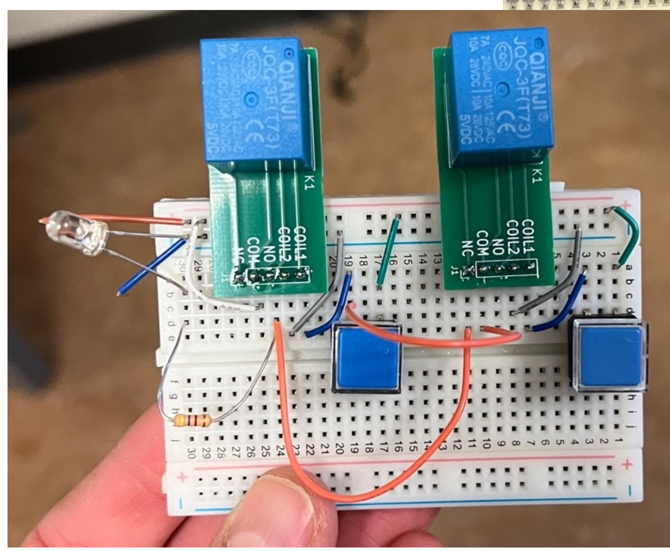
- Two lectures every week and a lab or two where you build something.
- Outline:
  - Week 1: Detectors, Diodes, Non-Linearity:
    - Lab 1A: Electromechanical Circuits
    - Lab 1B: Germanium Crystal FM radio receiver
  - Week 2: Vacuum Tubes
    - Lab 2A: Vacuum Fluorescent Displays
    - Lab 2B: Tube Audio Amplifier
  - Week 3: More Tubes:
    - Lab 3A: Tube Oscillator
    - Lab 3B: Tube Op Amp
  - Week 4: Early Transistors, Early Computers
    - Lab 4A: Germanium Transistor Audio Amplifier
    - Lab 4B: Iunno, maybe something, maybe nothing
- No Psets
- No Exams

Lab 1

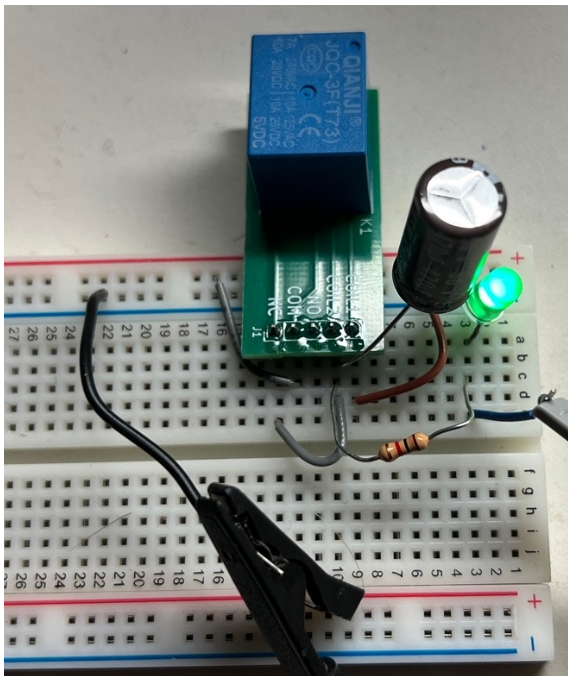
- Electromechanical Amplifiers



Relay-only NAND Gate



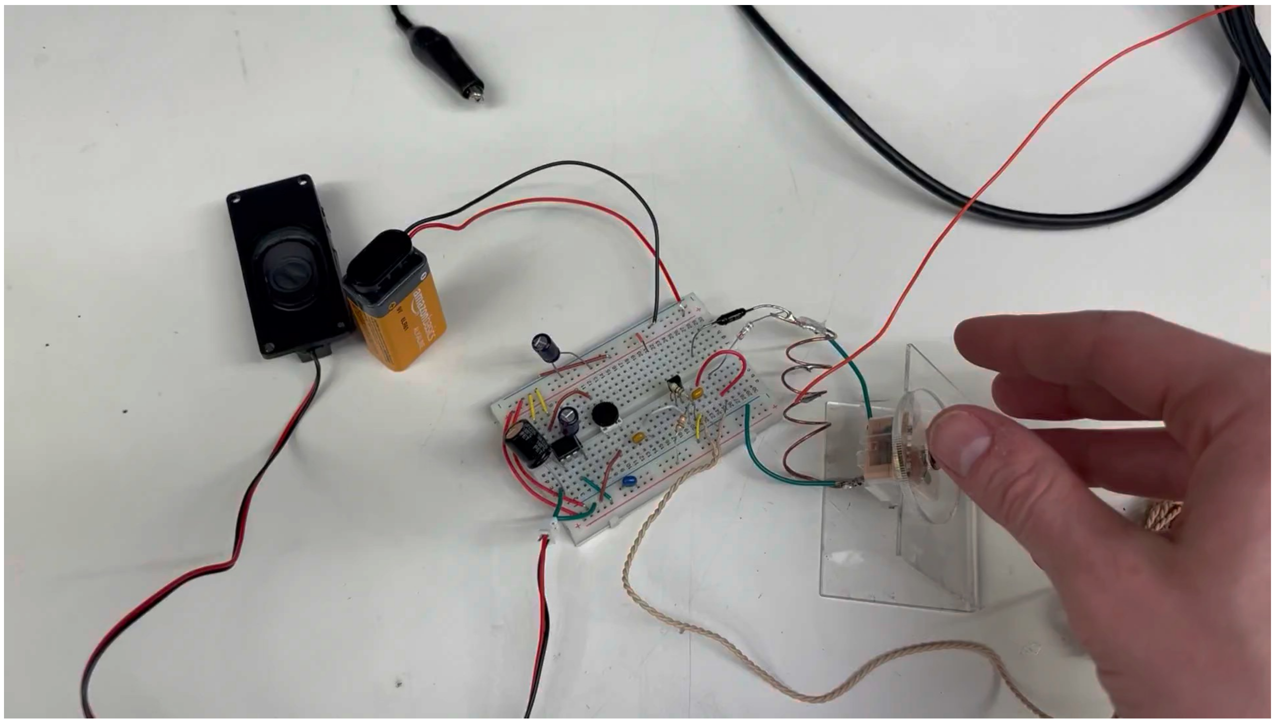
Relay-only SR Latch



Relay-only oscillator

Lab 2

- Build a Crystal Receiver



What were the Killer Apps in Electronics throughout recent history?

- A coarse set of categories:

- 1840s-1880s: Telegraphy
- 1880s-1920s: Lighting, Appliances, Things with motors
- 1880s-1940s: Radio/Telephony
- 1940s-1970s: TV
- 1970s-2000s: Gaming Systems, Computers
- 1990s-present: Internet
- 2000s-present: Smart Phones, ML/AI, who knows

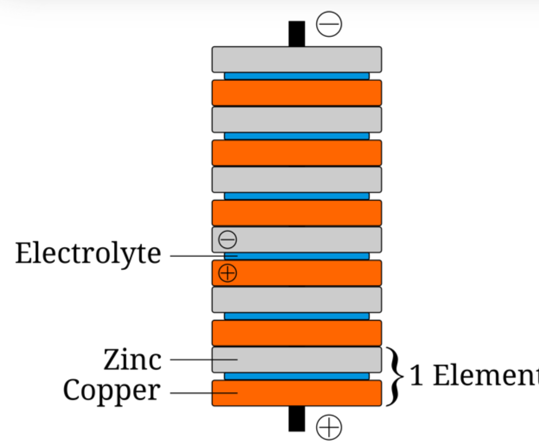
People and Electricity

- Prior to mid 1850s, there were no killer apps…electricity was to most people what dark matter is to us today

- Lightning, a random event
- Some forms of static electricity
- Leyden Jars, amber/graphite, random stuff
- Mostly novelties
- Some uses (electroplating)

Batteries/etc...

- Volta, Galvani, and many others figured out different types of metal with ionic juices between them could be used to make fixed voltages with constant currents

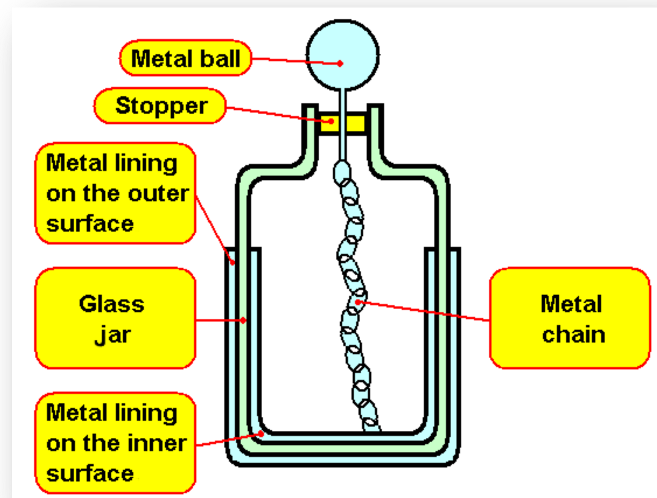


http://w1tp.com/imbatt.htm

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

Leyden Jars

- Early capacitors in the form of Leyden jars were extremely common and known to the general population
- Charge them up with static, a voltaic pile, sky static (in the case of Ben Franklin) then discharge them for entertainment or ”health” purposes



https://www.wired.com/2017/01/the-physics-of-leyden-jars/

https://www.edn.com/the-leyden-jar-a-colonial-era-capacitor/

Frankenstein et al

- Year 1818
- Take body parts
- Connect Body parts
- Apply electricity
- Make Life
- Profit

Mary Shelley

Aldini Reanimating an Ox Head

https://www.nypl.org/events/tours/audio-guides/treasures-audio-guide-frankenstein

https://www.insidescience.org/news/science-made-frankenstein

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

Salt/Soy Sauce Depolarizing muscles, causing them to fire

- Not that outlandish

What were the Killer Apps in Electronics throughout recent history?

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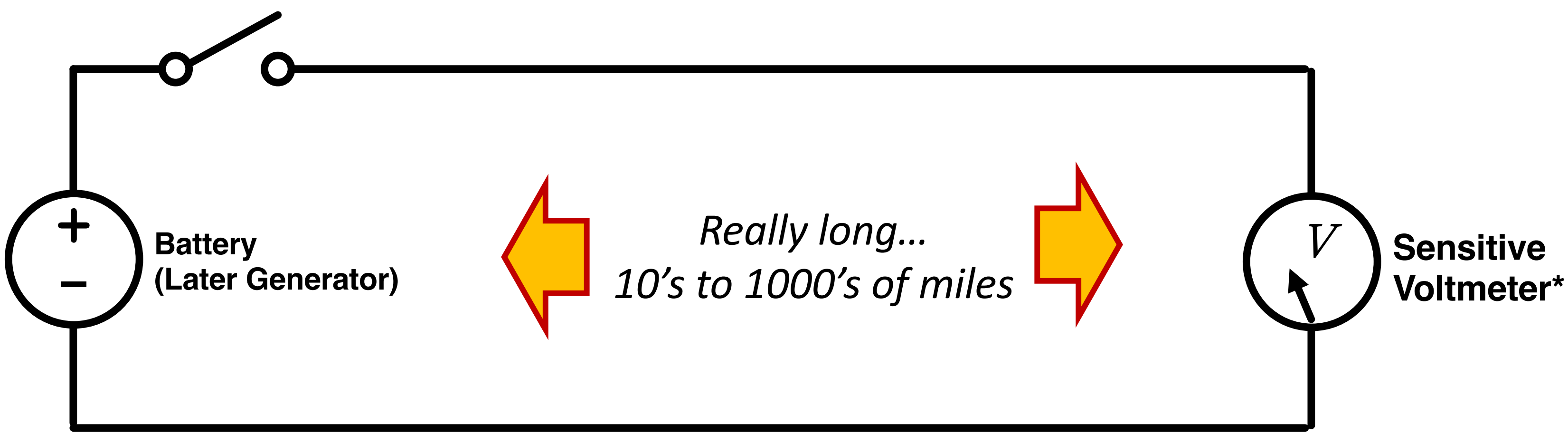
- 1990s-present: Internet
- 2000s-present: Smart Phones

Telegraphy/Morse Code (1830s)

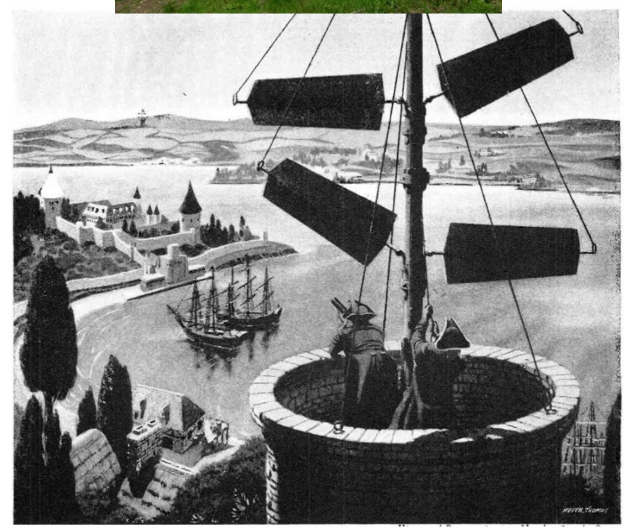
- Samuel Morse (also a ok-ish painter)
- Encode information using ON-OFF values of differing lengths
- Basic digital communication

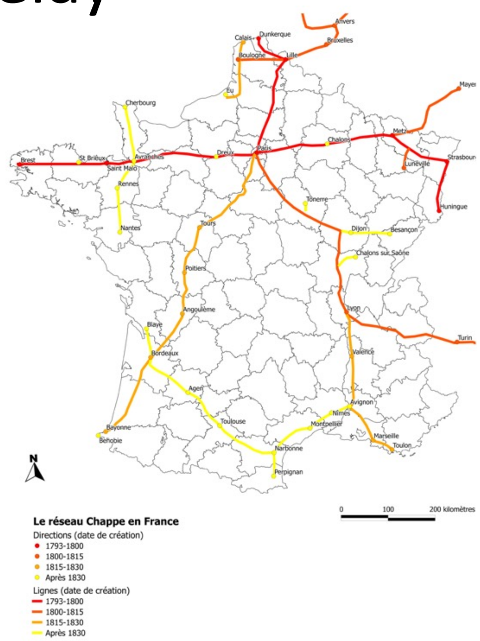


*actually what they used is closer to a current meter

Mechanical Telegraph (Semaphores)

- The original telegraph was made of chains of towers operated by people that would relay signals

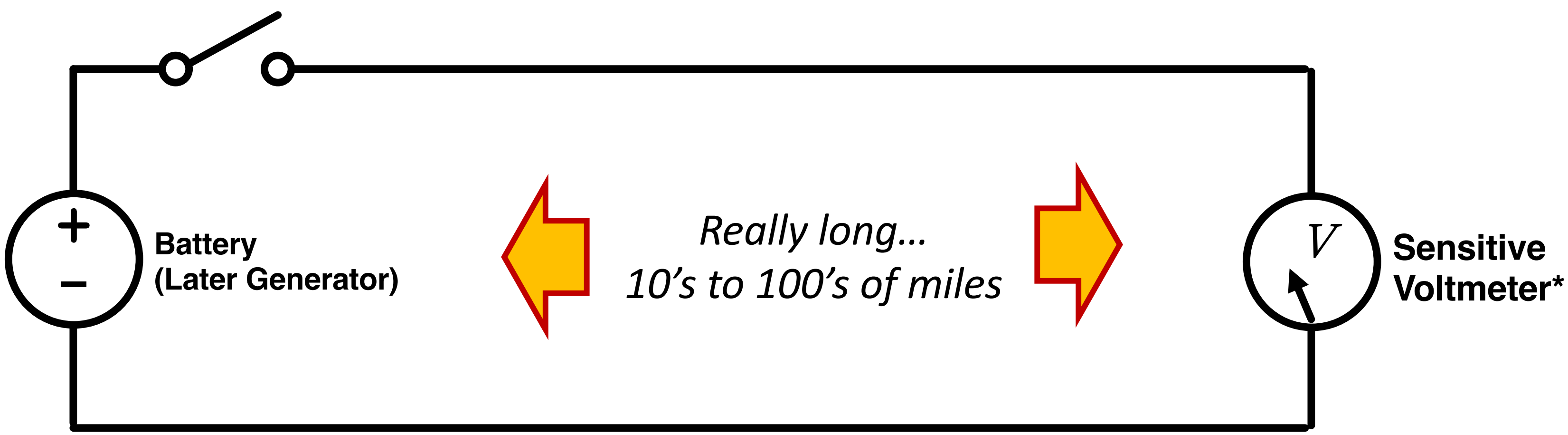




https://en.wikipedia.org/wiki/Optical_telegraph#/media/File:Signaling_by_Napoleonic_semaphore_line.jpg

Electric Telegraphy (1830s)

- Samuel Morse (also a decent painter) and many others developed electric telegraphy
- Encode information using voltage on/off pattern
- Basic digital communication



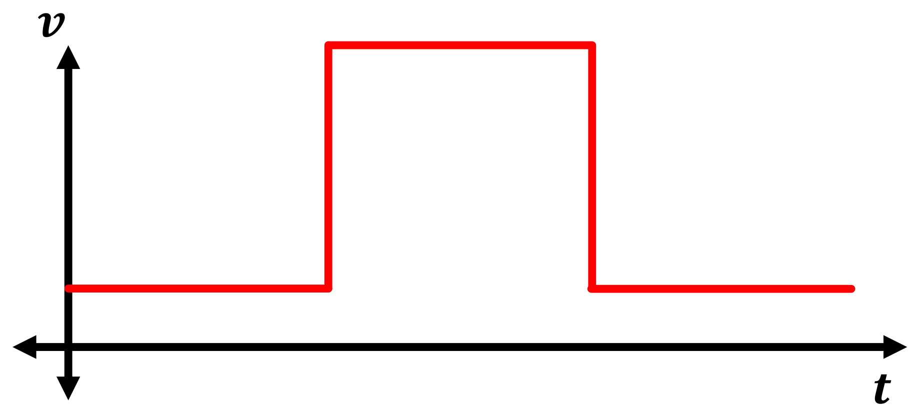
*actually what they used is closer to a current meter

How to Actually encode information?

- Same problem we deal with today when we send information.
- Rarely is signal encoded as:
  - Signal = 1
  - No signal = 0
- You run into lots of synchronization issues

Sync Issues...

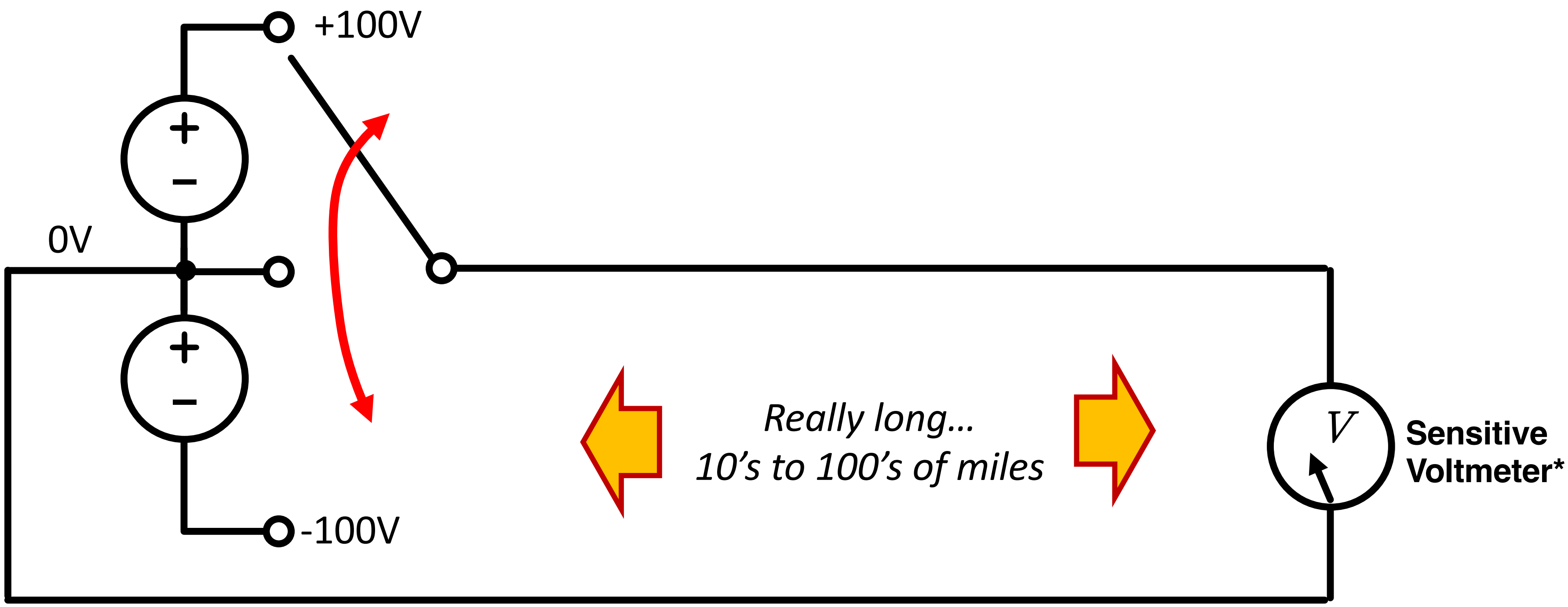
- Consider this signal...



- Is this a 010? Is this a 001100? Is it a 000111000?
- Or is it no signal...followed by a 1 followed by a 0?
- Very confusing...
- In transmitting binary data...you usually need to be able to express ***three*** things...
  - 1
  - 0
  - no signal

Early Variants of Telegraphy

- A lot of European systems actually encoded three levels (large positive, large negative, and 0V)



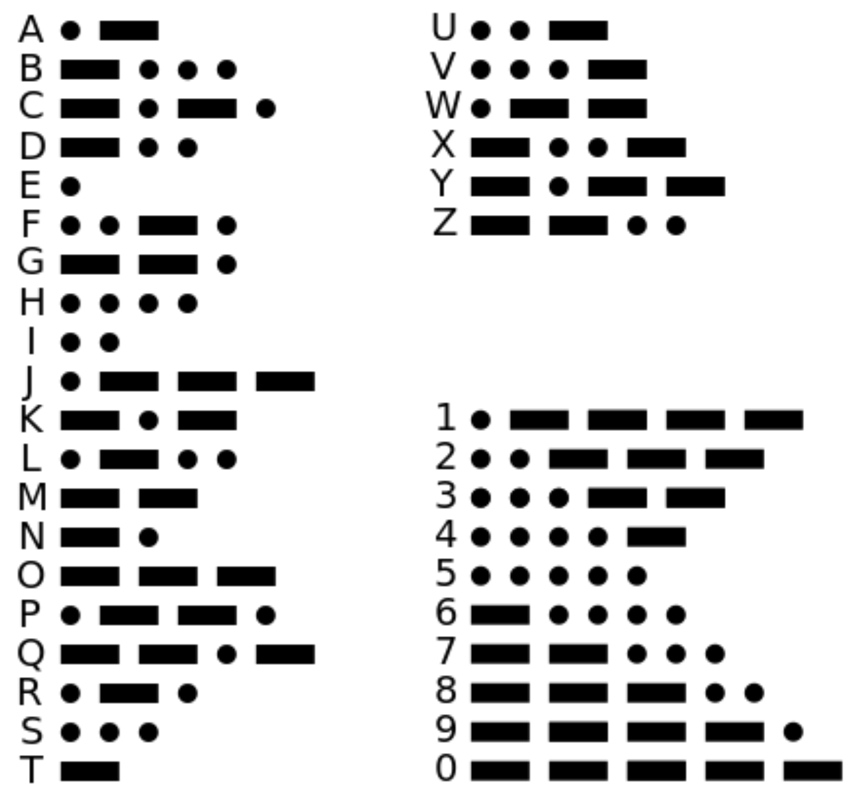
- This actually required significantly more complicated detection equipment than just on/off signals

Morse Code

- What Samuel Morse (And Joseph ***Henry***) and Alfred Vail did was develop an encoding scheme that just involved on-off values
- They then used duration as an additional axis to get more expression
  - Short on pulse is a “1”
  - Long on pulse is a “0”
  - No signal is a no signal

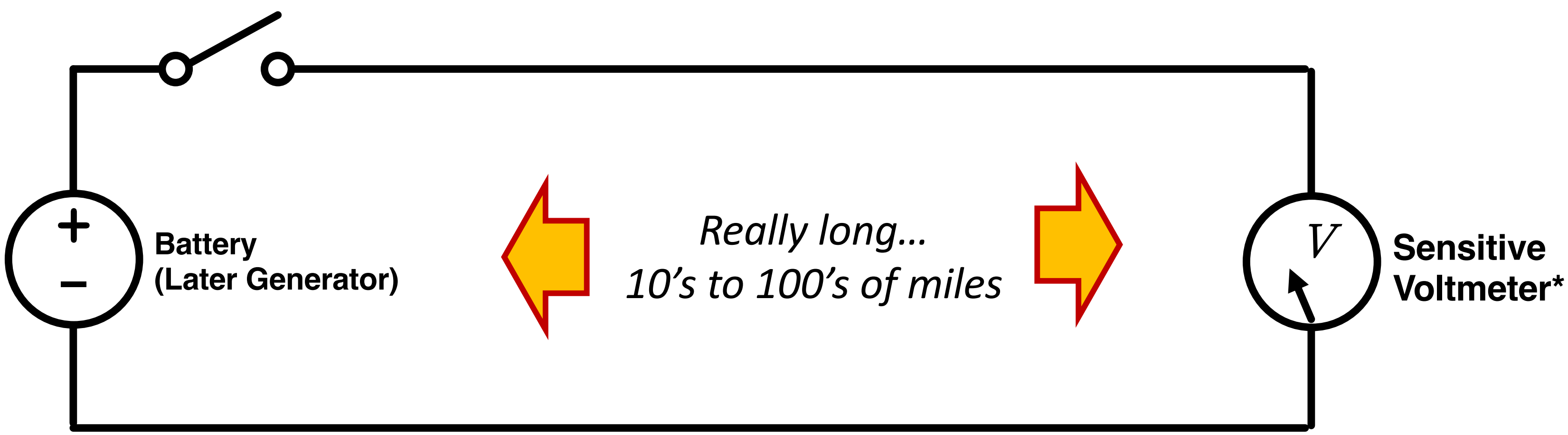
Morse Alphabet (one version anyways)

- This allowed significantly simpler equipment and infrastructure and was actually easier to record, interpret
- It was also easy to sync data rates since silence meant “no signal”
- Proved easy to port to wireless 50 years later



Why digital? Why not analog?

- Well, first we had no meaningful signals in analog format anyways
- Also losses were so great (and poorly understood) that having anything other than the harsh 1/0 interpretation of signal proved problematic



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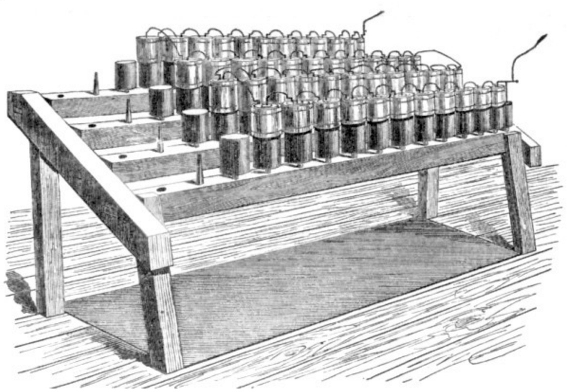
Powering Telegraphy

- How did they do it?
- Generators weren't a thing until 1870s so used giant cell stacks in parallel/series combos (electrical batteries)



Grove Battery

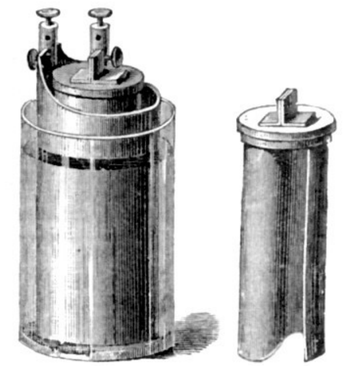


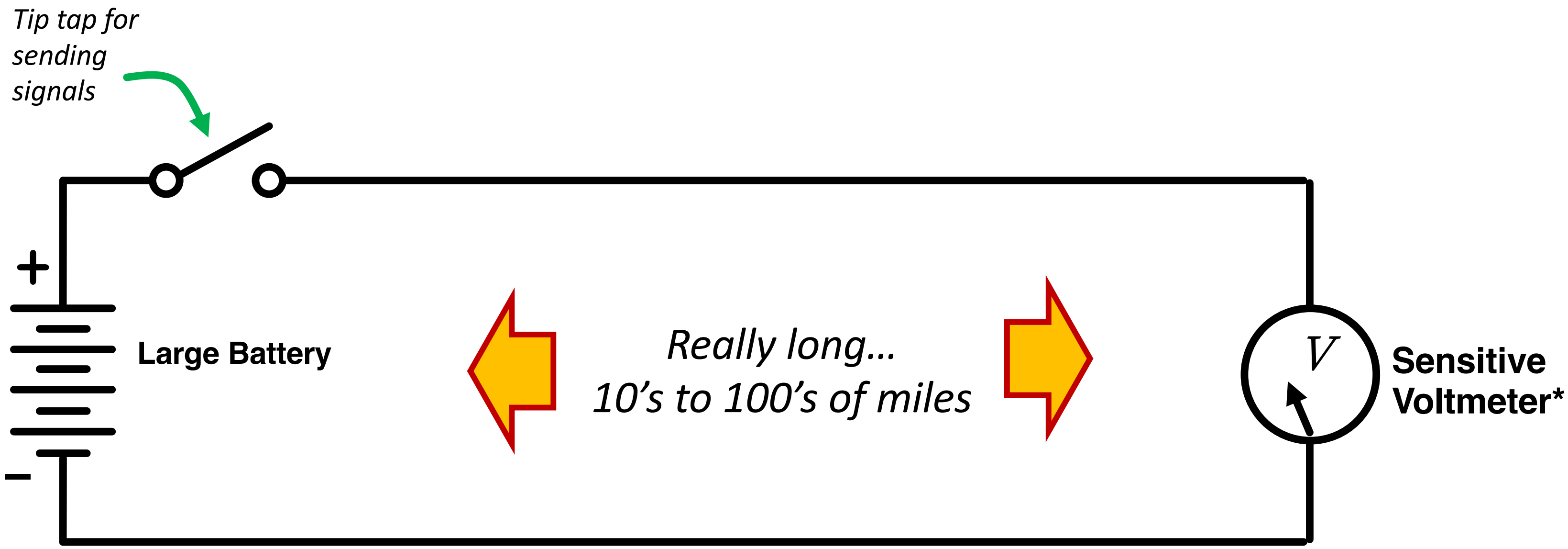
Fig. 141.—A Grove's Cell. Fig. 142.—The Platinum.

Grove Cell
Zinc, Platinum/Carbon, Sulfuric Acid battery

- I've read about 2V per 10-to-20 miles of telegraph would work

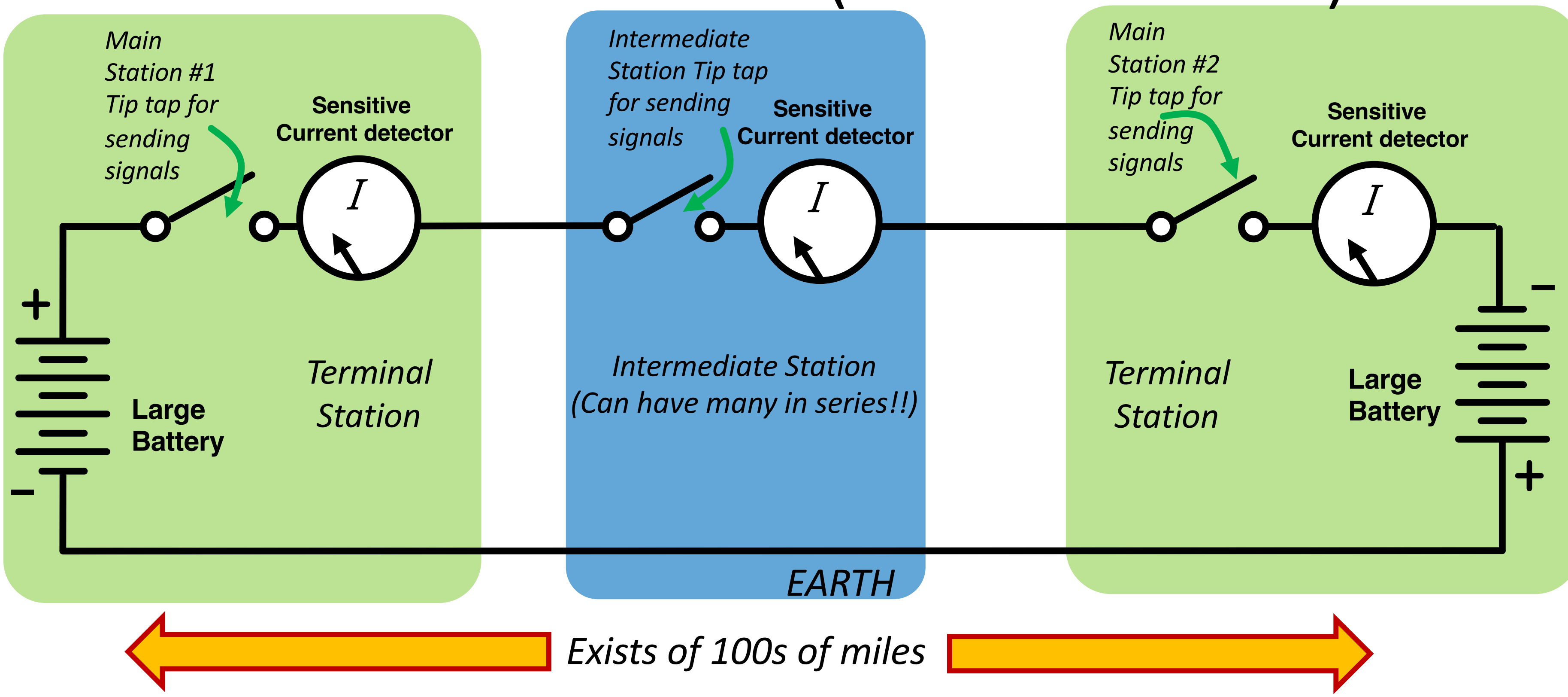
http://members.kos.net/sdgagnon/te4.html

How Would it Work?



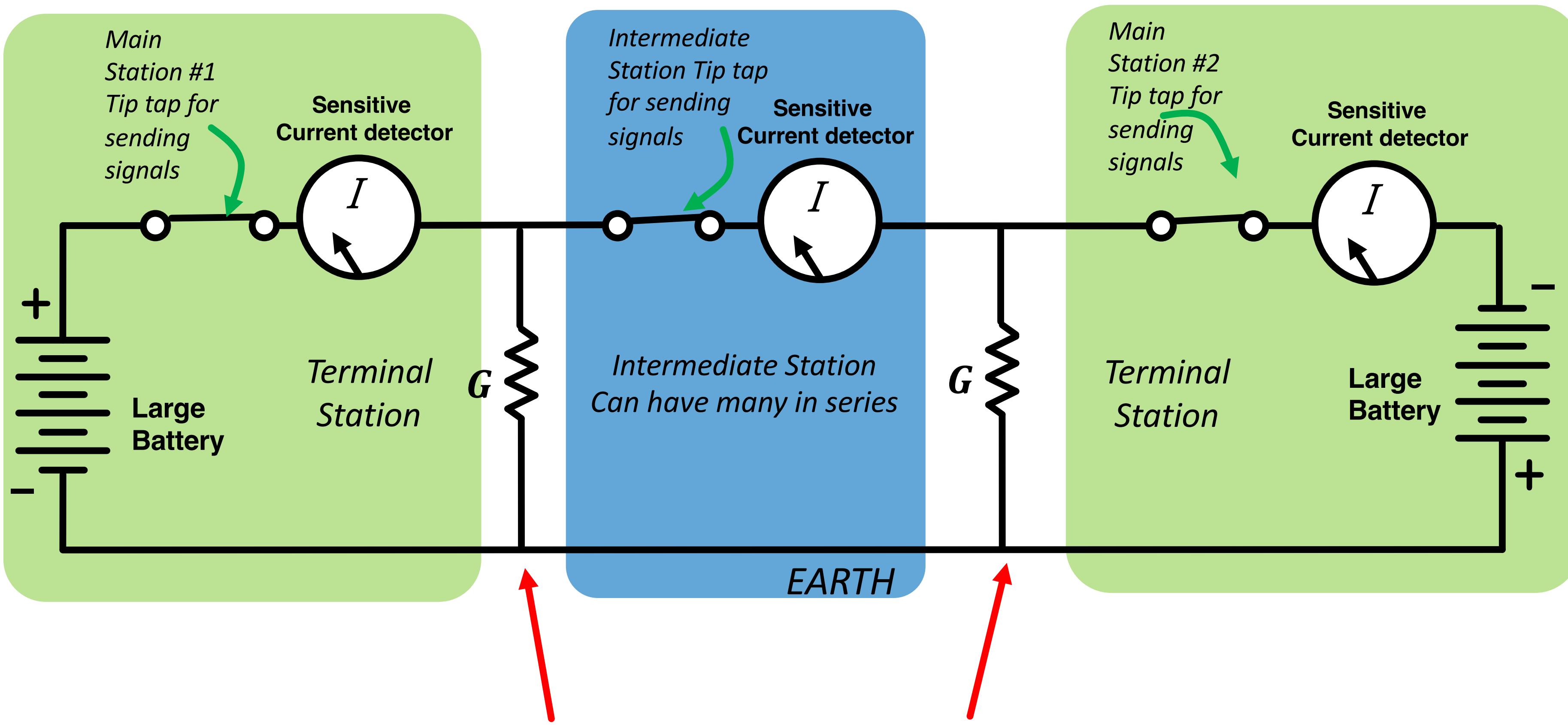
- More Complicated than this…and a bit different…

How Would it Work (More Detail)



- Note opposite battery orientations…why?
- In reality the "return path" was usually Earth…why?
- How Did they make sensitive Current Meters?

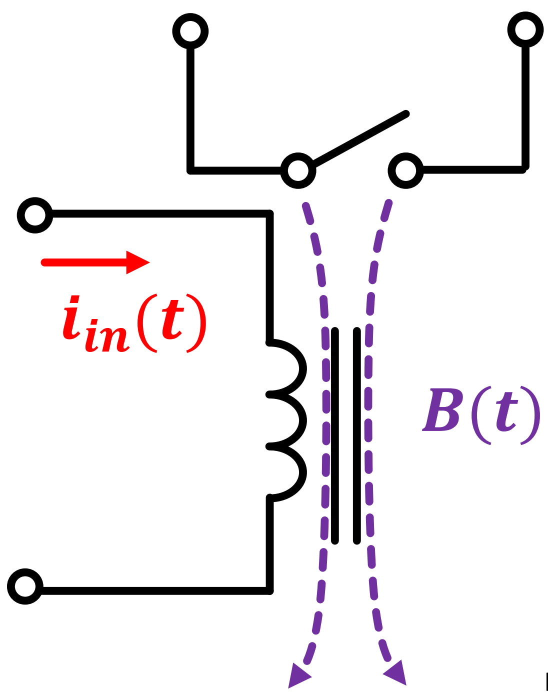
Leakage! Too



Parasitic Leakage all along the line

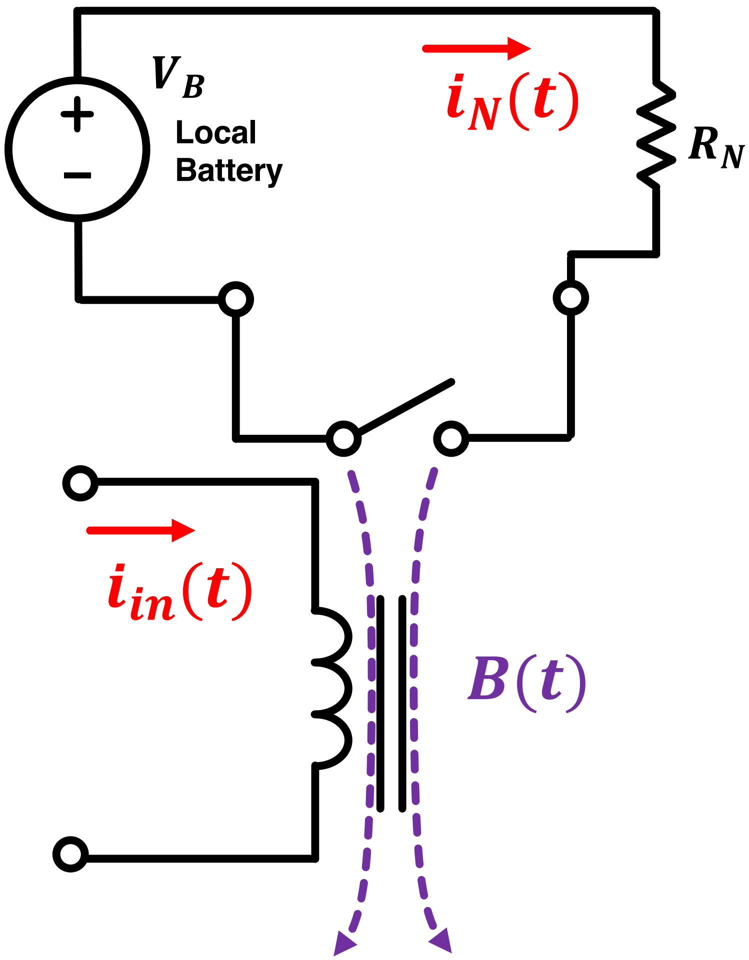
Sense Current Using a Relay...what is a relay?

- An input set of terminals connected to a coil
- Coil can induce magnetic field
- Magnetic Field can influence position of nearby switch
- Incorporate that Switch Into a Local Circuit

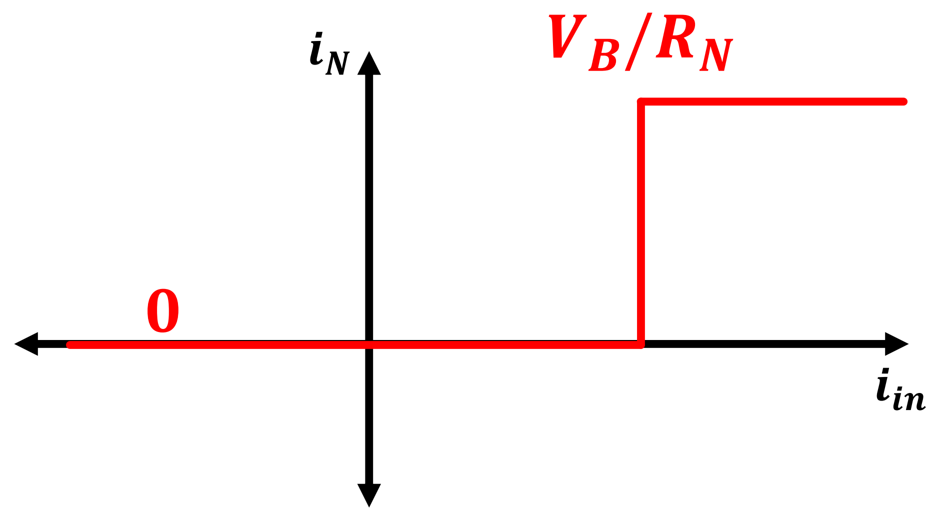


https://www.digikey.com/en/products/detail/omron-electronics-inc-emc-div/G2R-1-E-AC120/368674

Incorporate the Relay into a Circuit

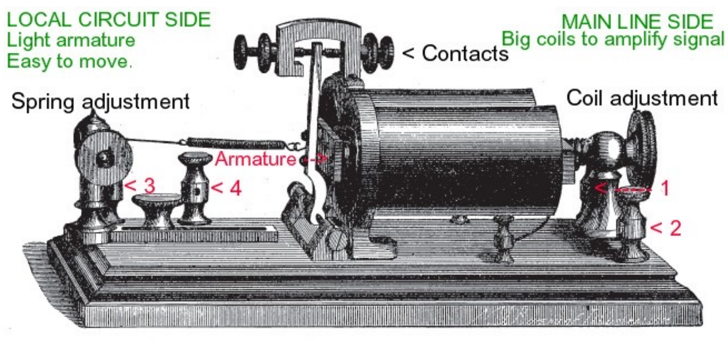


- How will this circuit operate?
- What will its In/Out relationship look like?



- No current in secondary circuit will flow until current in coil passes some threshold

This I/O curve can be engineered

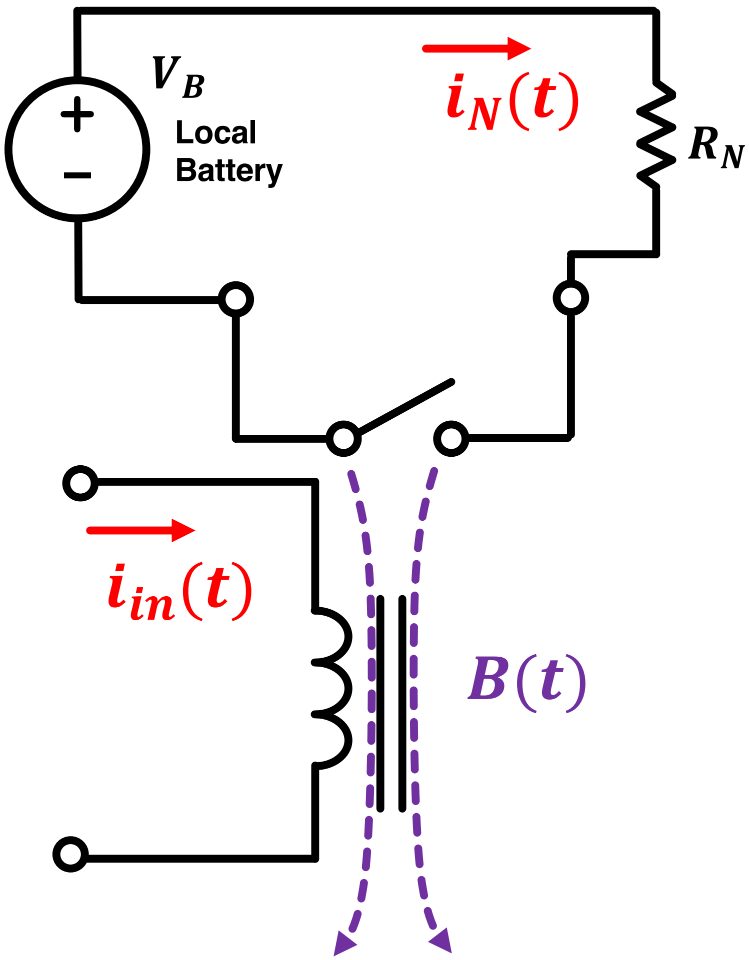


N

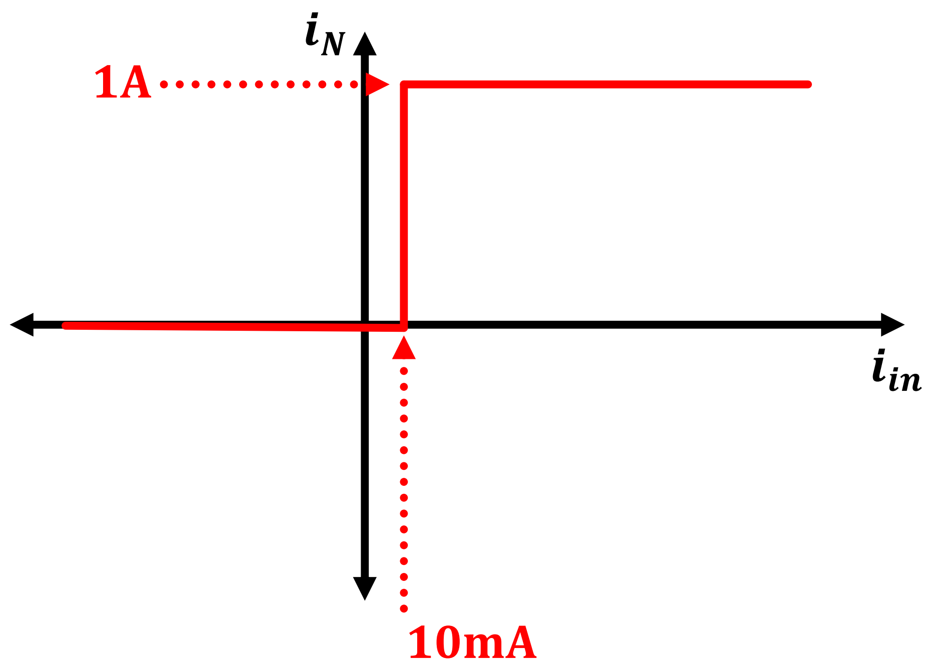
- A ton of effort went into designing these relays to be very sensitive
- More windings of coil (increase induced field)
- Design a really nice switch
- Make sure it doesn't bounce…
- List goes on

http://members.kos.net/sdgagnon/te5.html

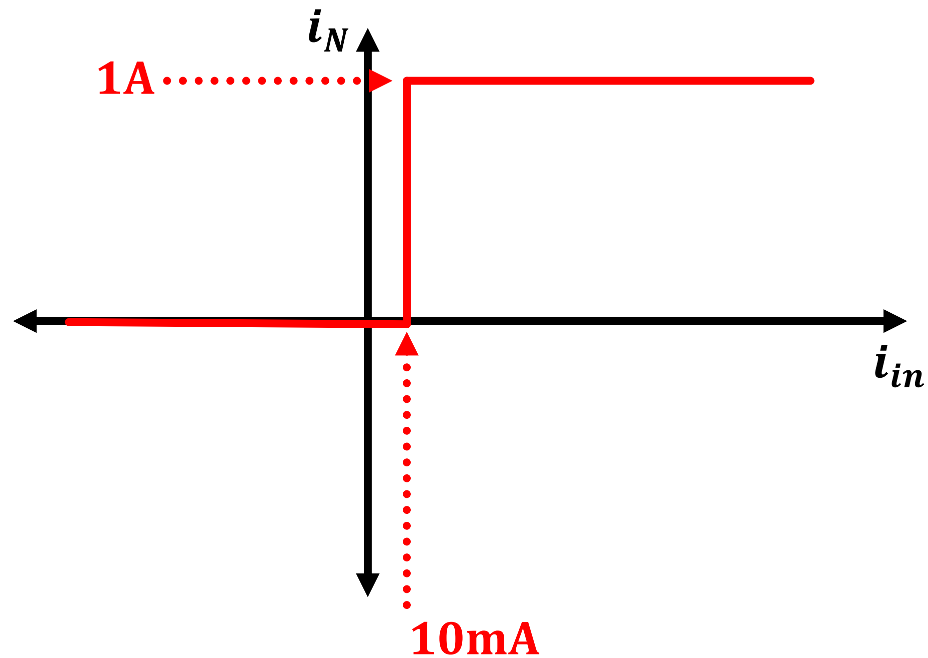
This I/O curve can be engineered



- Careful tuning could result in a relay circuit that looked like this (for example):



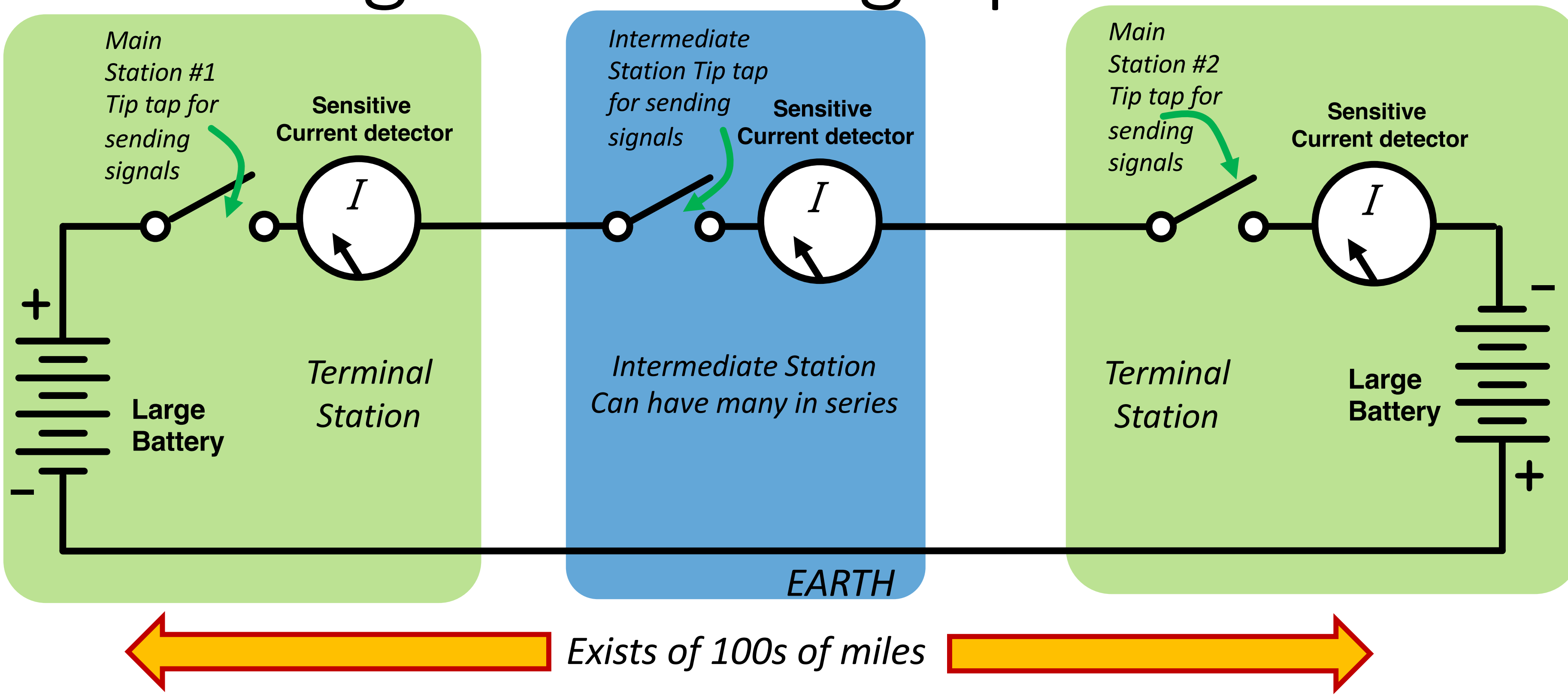
What are some Characteristics of this Curve?



- Reliably and Reproducibly Nonlinear!
- Amplifies!

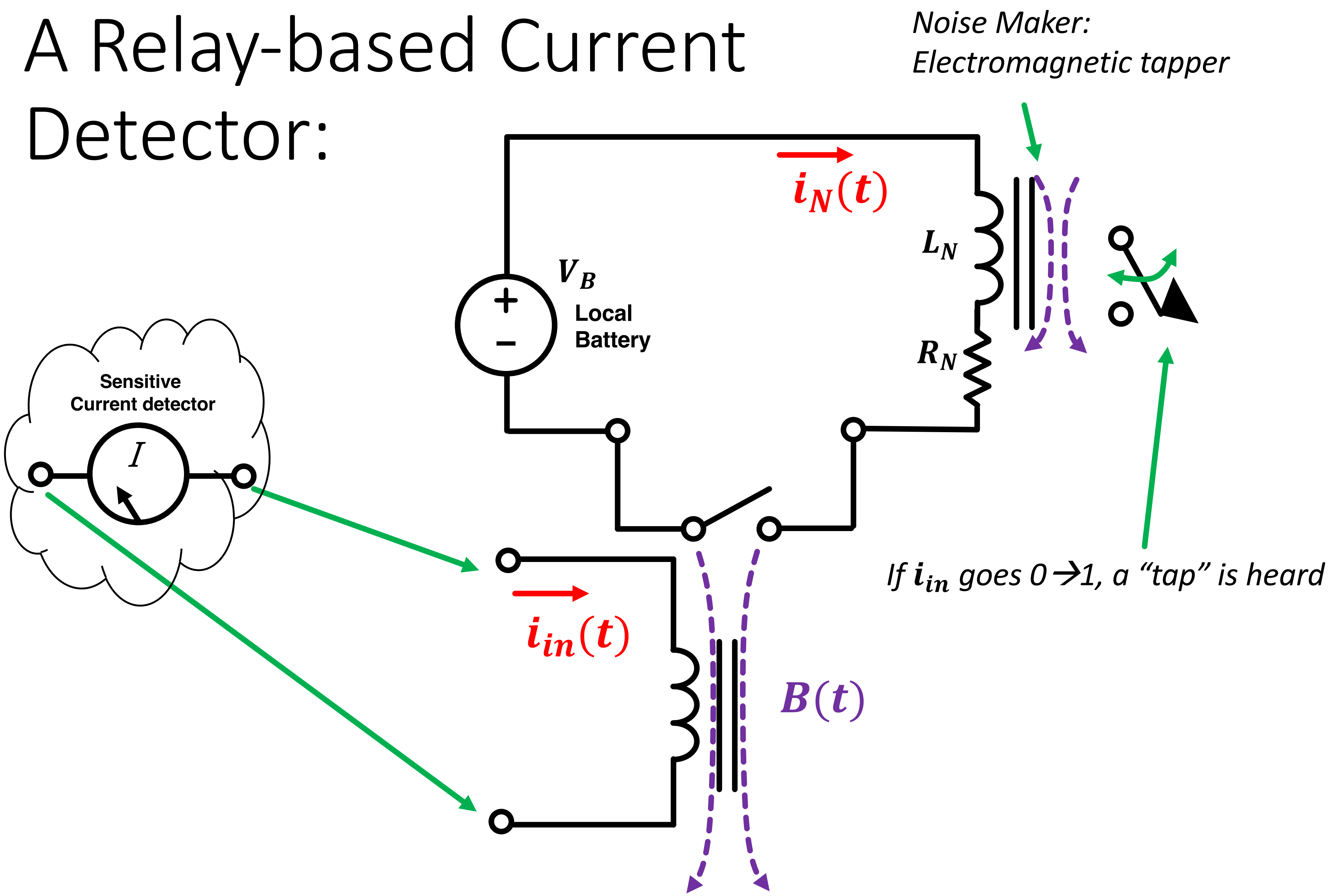
These two characteristics are critical for appreciating what subsequent technologies provided!

Returning to our Telegraph Circuit



- Each station would have a local sensitive current meter built around a relay and a sounder!

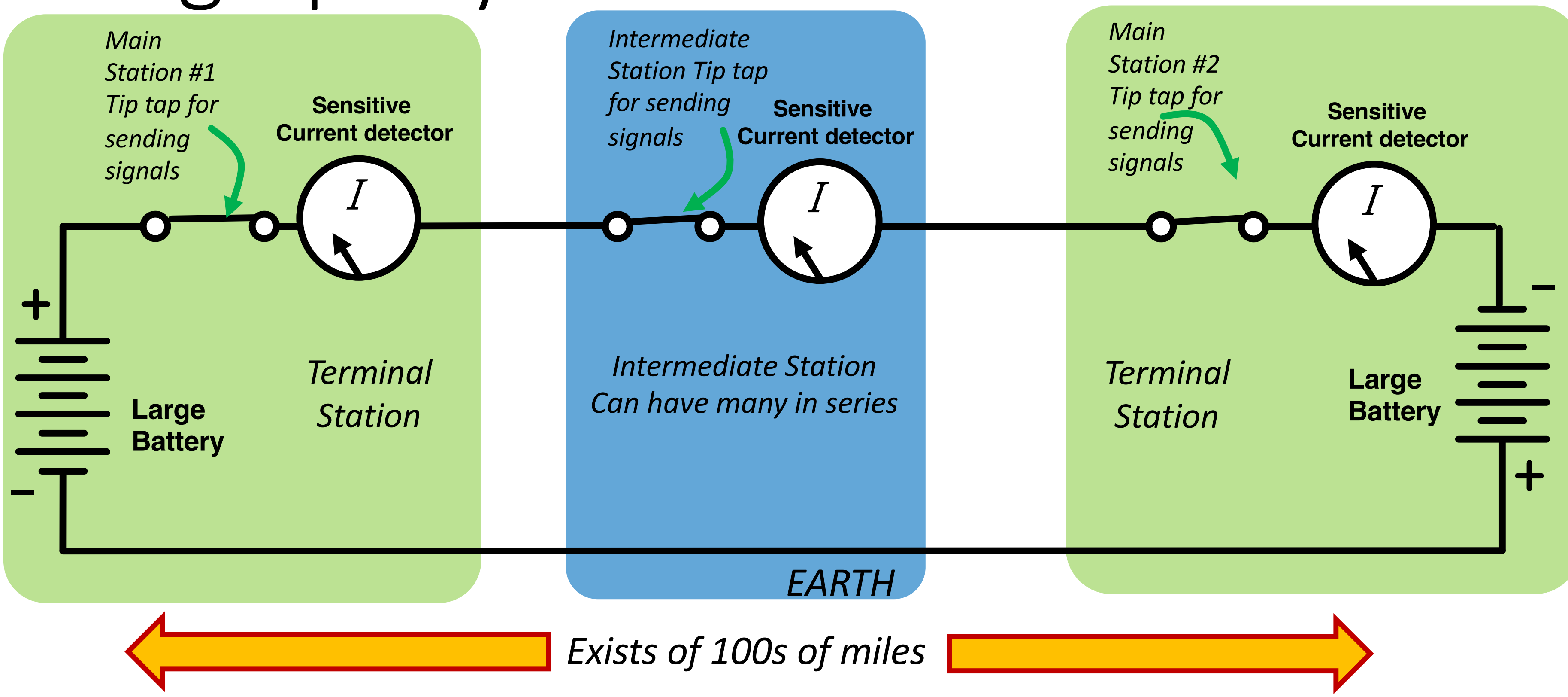
A Relay-based Current Detector:



Amplification

- Many miles from the terminal station $\boldsymbol{i_{in}}$ (and $\boldsymbol{v_{in}}$) will be small due to parasitic losses in the line. They would lack the ability to make much signal for a local listener
- A well-designed relay acted as an **amplifying device** for the signal so that the operator could easily hear the message!
- Not a strictly electrical amplifier. (electromechanical)

Telegraph system



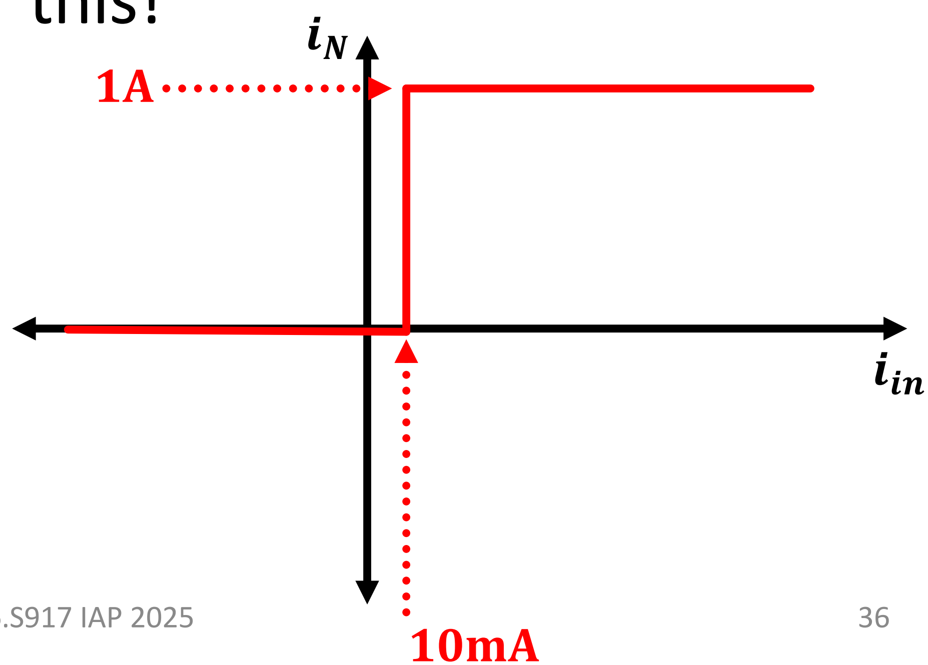
- At rest all stations would have their keys closed in a listen/propagate mode

Telegraph Operation

- Each run of telegraph was a “party line”, meaning all stations on that run could listen in
- At “rest” all stations kept their keying switches closed!
  - Current therefore almost always flowed through the entire system!
  - Wasted power, but actually was good for early batteries
- If a station needed to broadcast, that station would open up their key, breaking entire circuit!
- *All* stations on line would detect this break in current and know to wait for start of message
- Transmitter would then send message

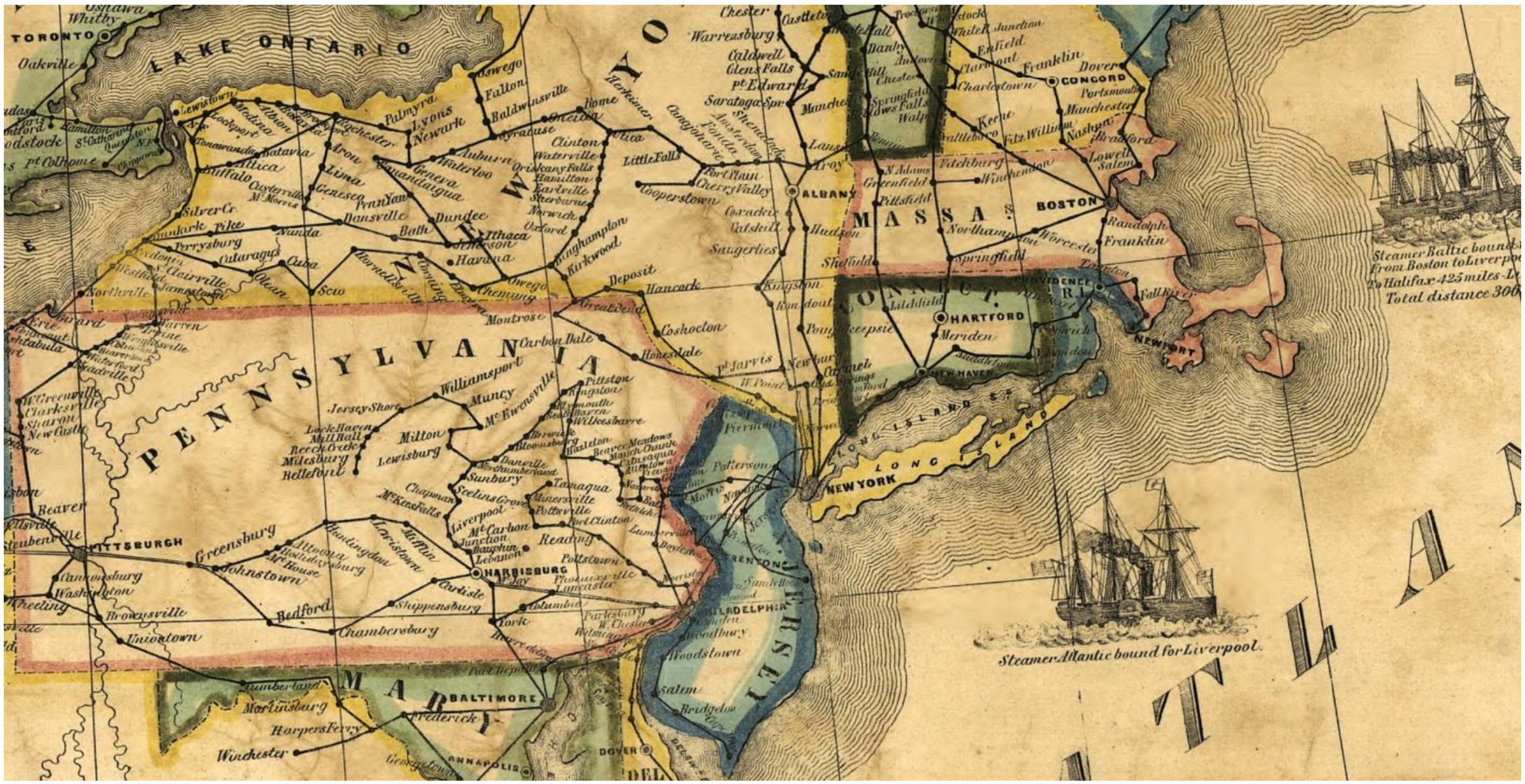
Noise

- Noise in these systems was disgusting!
  - Parasitic leakage
  - Earth Ground
  - Leakage from nearby circuits
- A digital communication scheme was used (on-off signaling) because of all this. Electromechanical relays were perfect for this!



Build Up Network of these Circuits

- North East US telegraph network, 1853

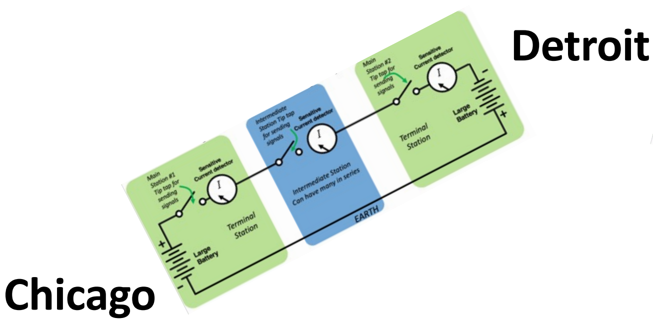


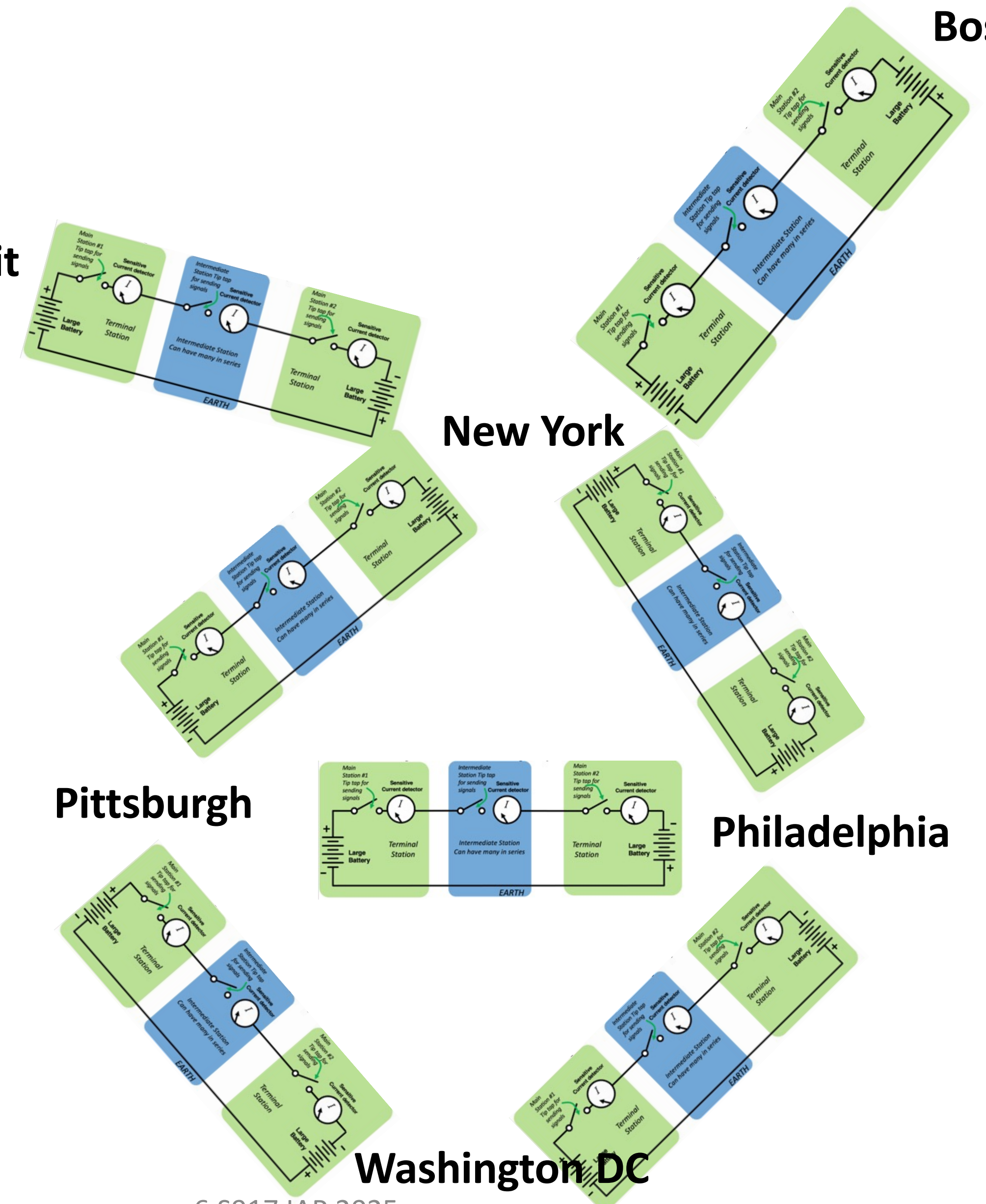
https://www.loc.gov/resource/g3701p.ct000084/?r=0.577,0.18,0.283,0.154,0

Telegraph Network Europe 1856

http://members.kos.net/sdgagnon/te3.html

Build Up Network of these Circuits

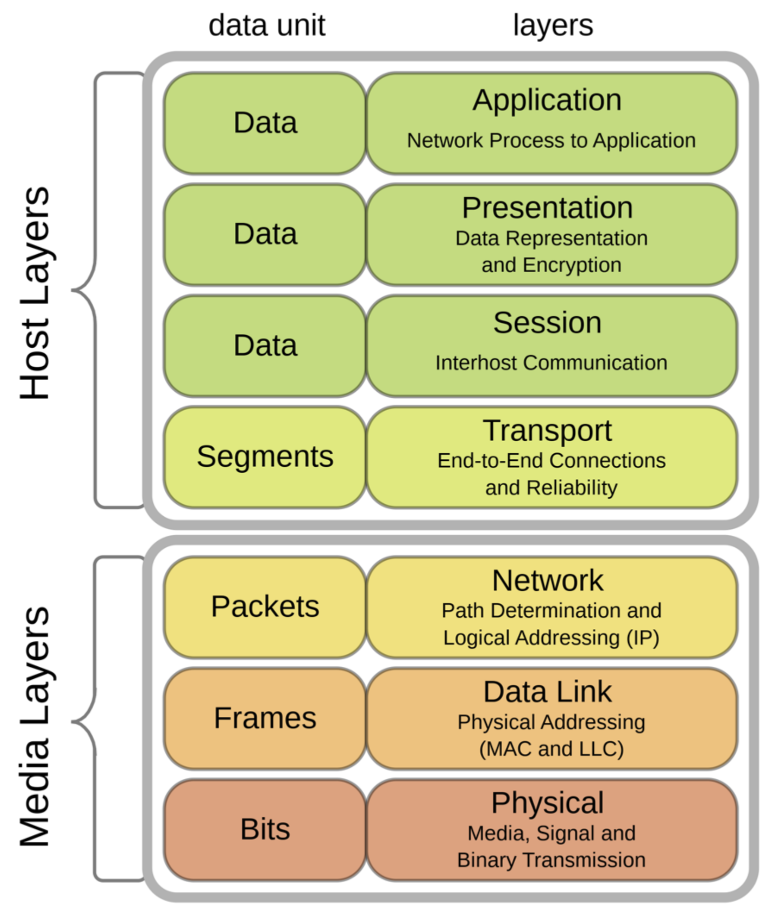




- Pass messages between circuits
- Automate with relays

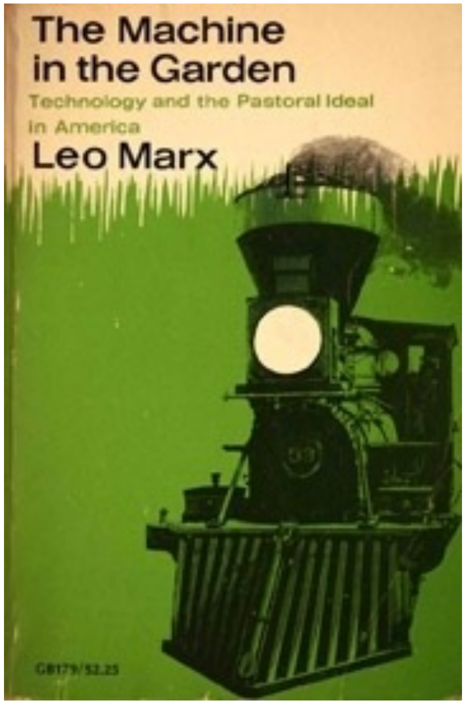
Telegraph Operation

- Had to develop an entire communication protocol!
- Morse was your alphabet (in US), but then you had to have addressing, message-begin/end/qualifiers, forwarding, etc…
- Much of our modern "protocol stack" can be reverse-applied to what they came up with!



End of an Era (No More Pastoral)

- The Laying of Telegraph lines was the first exposure of the masses to anything really electrically designed
- Usually followed train lines, so it was a dual punch of “progress”, often turned into a metaphor in literature and analyzed as such more literary studies



The Machine in the Garden
Prof Leo Marx, @MIT one of the real founders of Technology/Society Studies

Beginnings of Cultural Shift

It is an extraordinary era in which we live. It is altogether new. The world has seen nothing like it before. I will not pretend, no one can pretend, to discern the end; but everybody knows that the age is remarkable for scientific research into the heavens, the earth, and what is beneath the earth; and perhaps more remarkable still for the application of this scientific research to the pursuits of life. The ancients saw nothing like it. The moderns have seen nothing like it till the present generation… We see the ocean navigated and the solid land traversed by steam power, and intelligence communicated by electricity. Truly this is almost a miraculous era. What is us no one can say, what is upon us no one can hardly realize. The progress of the age has almost outstripped human belief; the future is known only to Omniscience.

-Senator Daniel Webster
1847

- Optional Reading "Technology:The Emergence of a Hazardous Concept" by Leo Marx 2010

People were intimately exposed to the telegraph (and follow-on telephone)

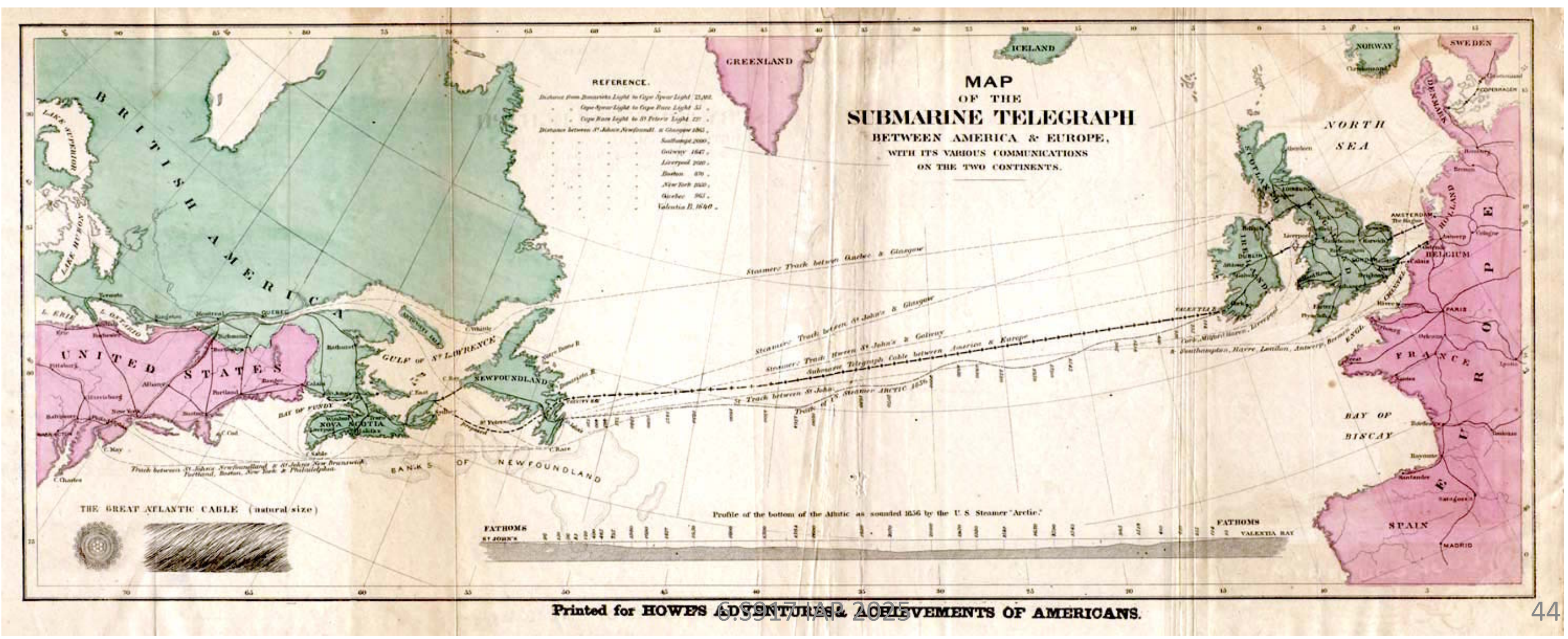
Stockholm Central
Telephone/Telegraph Tower

New York 1887

https://io9.gizmodo.com/photos-from-the-days-when-thousands-of-cables-crowded-t-1629961917

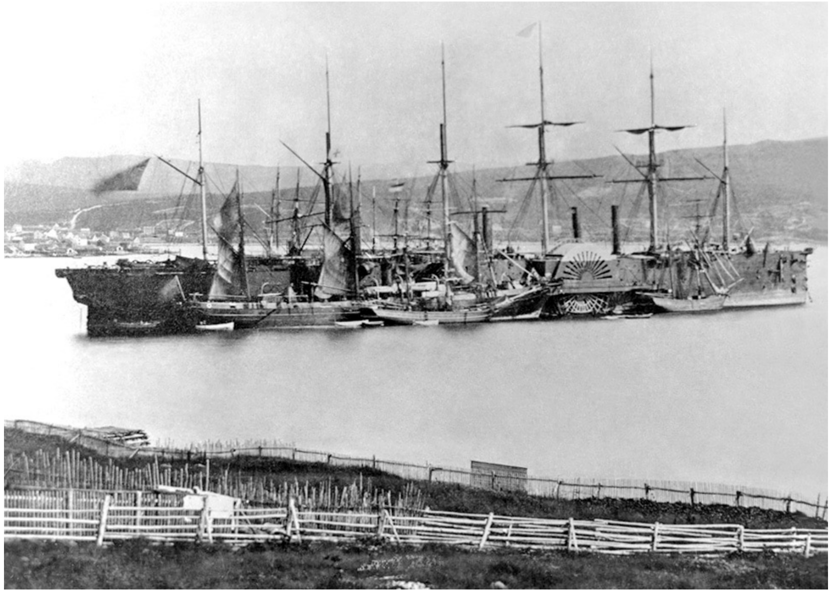
Telegraph to the Extreme: Transatlantic Cable

- Mid-19th Century, London to Paris could chat in a minute with telegraph, but London to New York needed six weeks for each exchange.
- That changed starting in 1858:

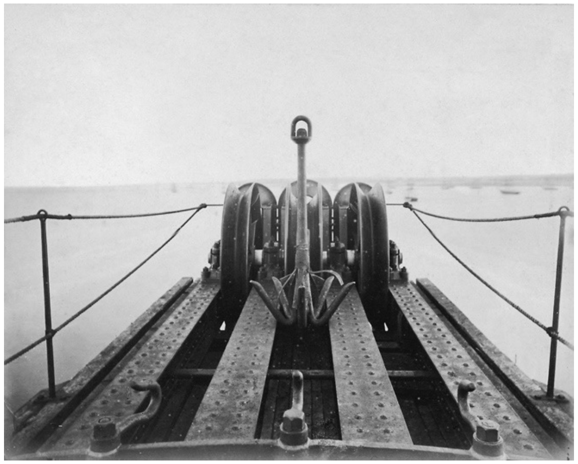


Transatlantic Cable

- Sail the ship
- Drop the cable
- Start in Ireland
- End in Newfoundland (Canada)



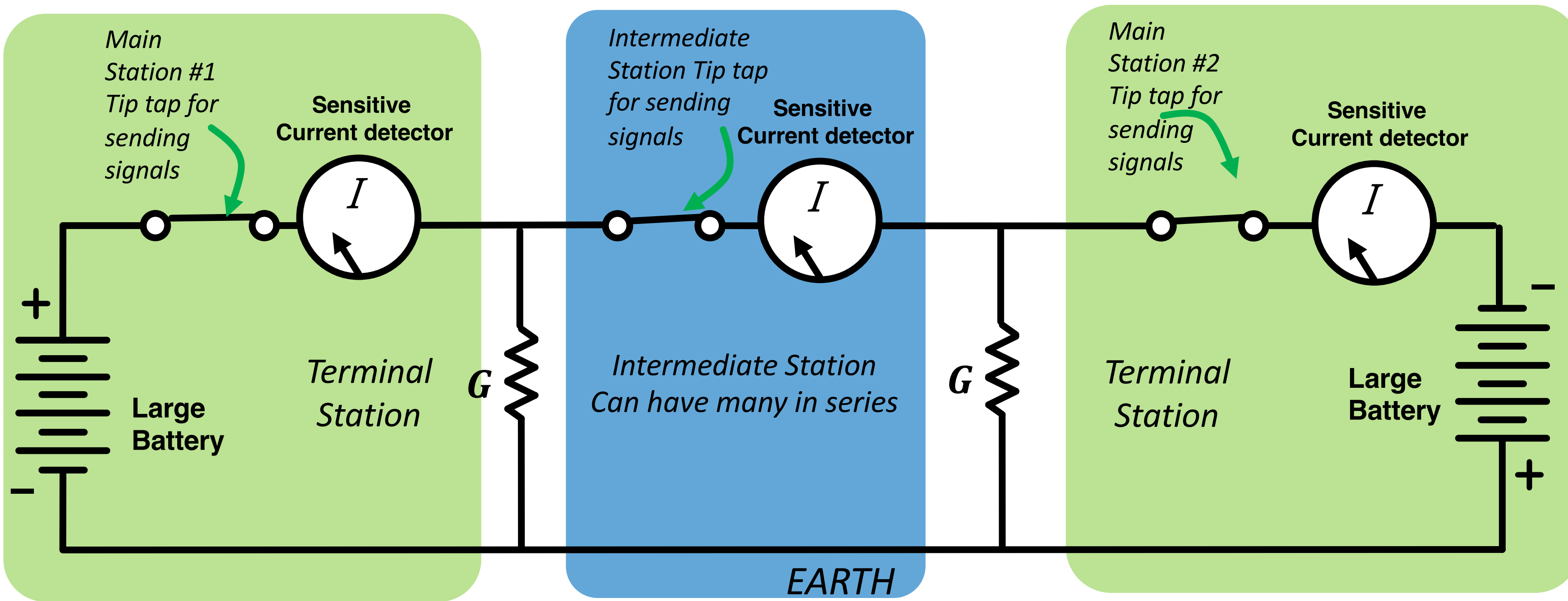
Ship they used



Recovery Hook

- Scale of cable was unheard of (2900 miles)
- Most land-based telegraphs were ~100 miles or so
- Also a undersea cable was *very* different than air cable

Land-Telegraph system

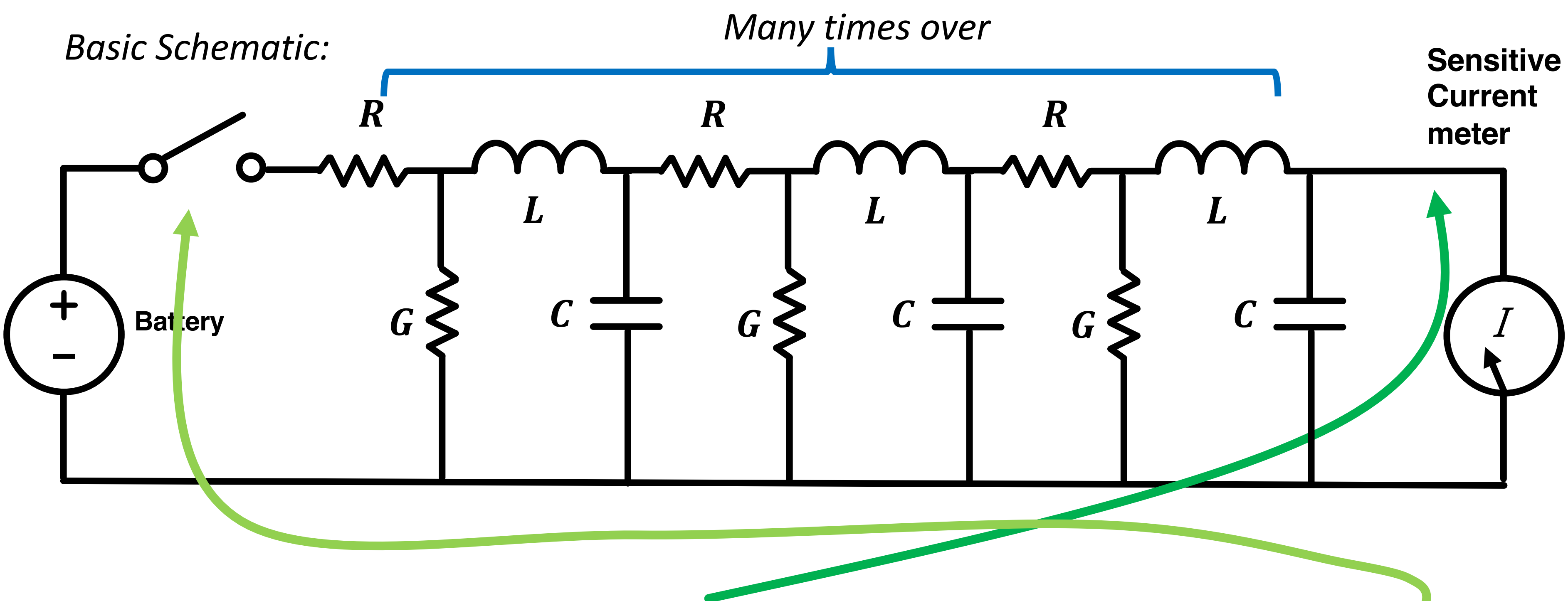


- Parasitic Leakage all along the line

Telegraphy/Morse Code Transatlantic Cable

- A wired telegraph system is anything but just a wire, with lots and lots and lots of:
  - Parasitic resistance, capacitance, and inductance

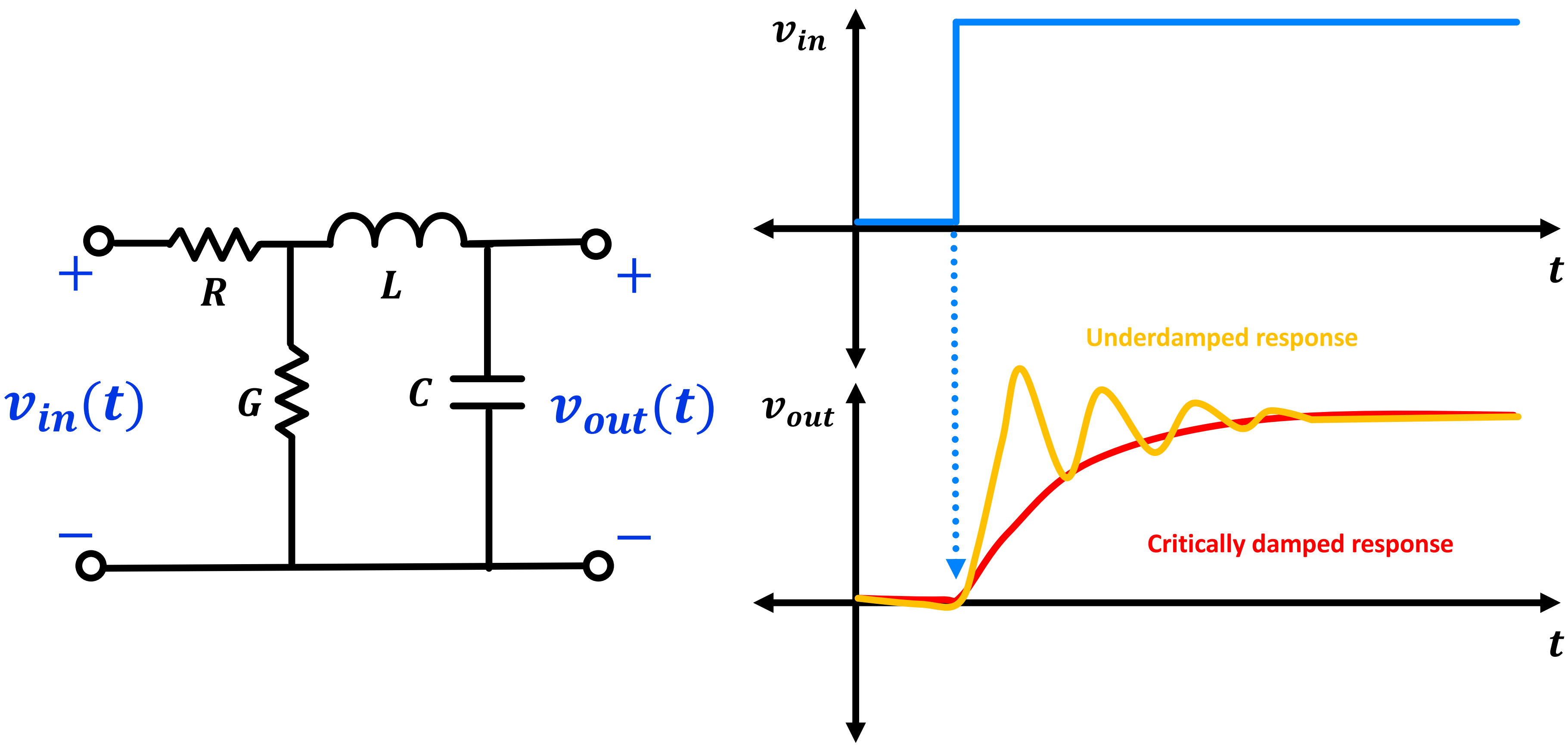
Basic Schematic:



*Note there is no amplifier in this…signal **here** will always be lower/worse than signal **here***

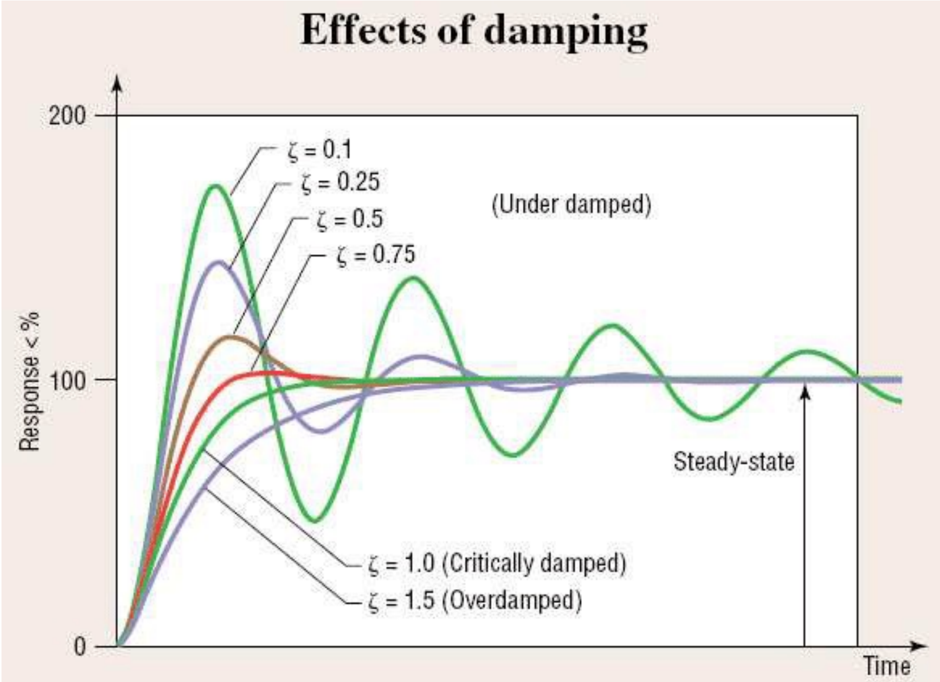
What's the problem?

- The series Rs, series Ls, parallel Gs and parallel Cs all work together.
- Form a *very* disgusting differential equation



Any Higher Order Circuit:

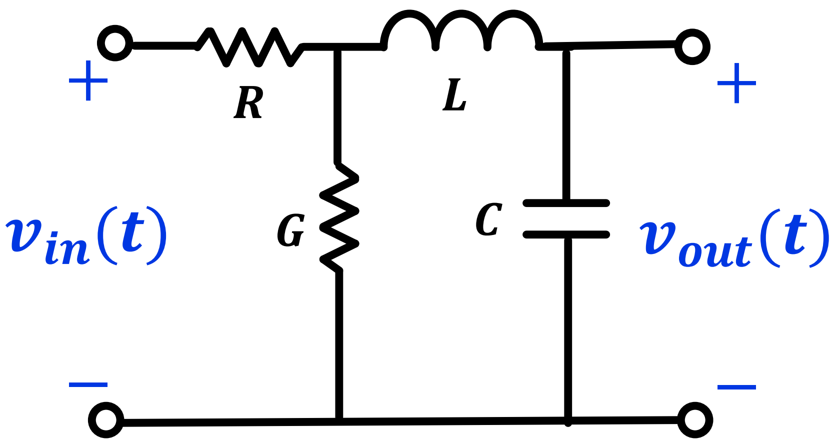
- Once R's, L's, and C's are in the mix and can't be ignored, you will have delayed response
- And with leakage, the final steady-state value will be smaller

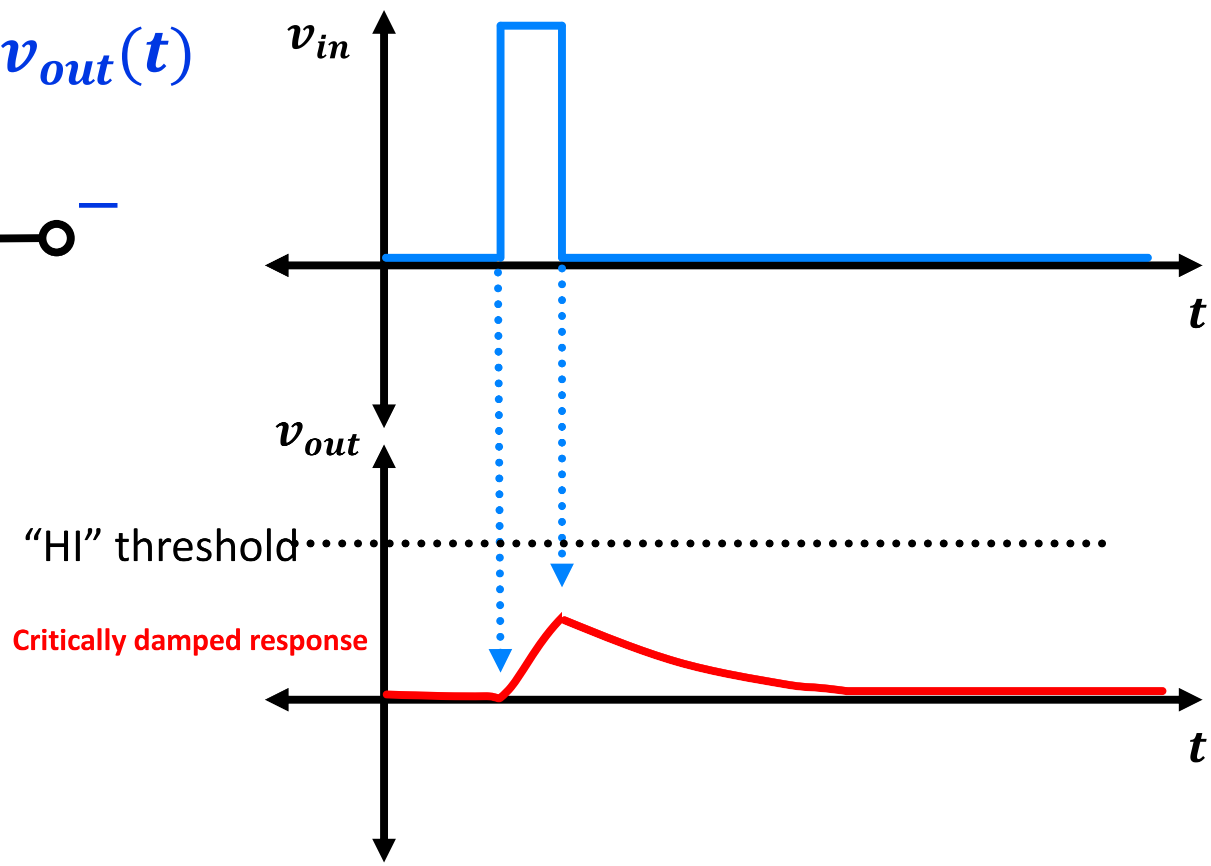


https://www.researchgate.net/figure/Step-response-of-an-RLC-circuit-for-different-values-of-the-damping-factor-z_fig13_263713877

What's the problem?

- So if you want to send a "dot" (short on signal)…





Can't do it!
Have to slow down!

Transatlantic Cables

"Directors of Atlantic Telegraph Company, Great Britain, to Directors in America:—Europe and America are united by telegraph. Glory to God in the highest; on earth peace, good will towards men."

-Queen Victoria to Pres James Buchanan,

August 16, 1858

- 98 words, took 16 hours to send
- ~0.2 characters/min…
- ~ 0.026 bps (bits per second of information)

https://newatlas.com/last-telegraph-message/28314/
https://www.reddit.com/r/HistoryPorn/comments/69cpuu/a_cross_section_of_one_of_the_first_transatlantic/

Sending Ten Words in 1860

- New York -> New Orleans: $2.70 ($65 today)
- New York -> San Francisco: $7.40 ($210 today)
- Over Transatlantic was $100 dollars ($2600 today)

- Prices did drop with time
- Telegraph messages peaked in 1929 (>200 million in US alone)

https://newatlas.com/last-telegraph-message/28314/

Problems with Telegraph

- Had to lay down lines and maintain them
- Data rates were slow…could be improved with repeaters, shorter runs, but couldn’t do that in ocean
- Limited to only binary data. Couldn’t send voice!

What were the Killer Apps in Electronics throughout recent history?

- A coarse set of categories:

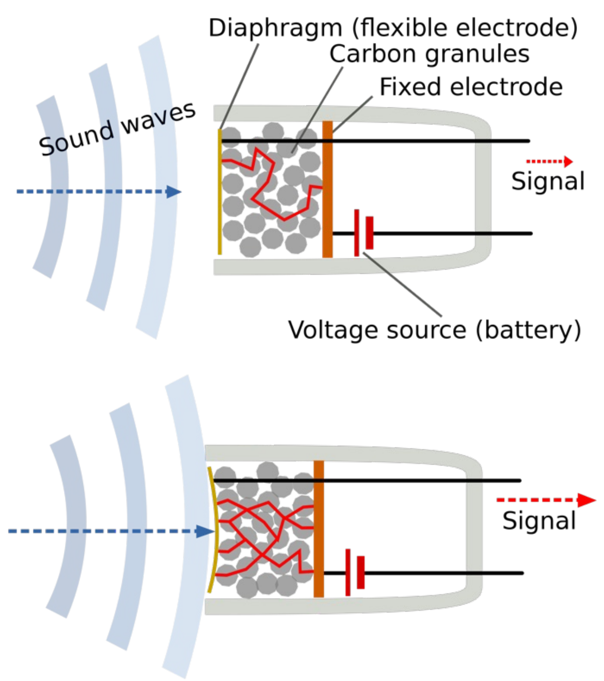
- 1840s-1880s: Telegraphy
- 1880s-1920s: Lighting, Appliances, Things with motors, Telephone
- **1880s-1940s: Radio/Telephony**
- 1940s-1970s: TV
- 1970s-2000s: Gaming Systems, Computers
- 1990s-present: Internet
- 2000s-present: Smart Phones

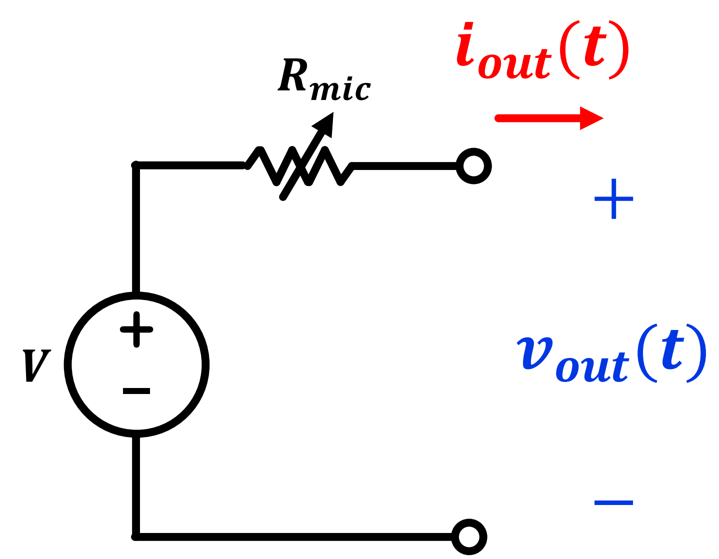
Radio? Telephony?

- The two technologies developed in parallel
- Telephones built on telegraph infrastructure (cabled) except they transmitted analog information
- Radio built its own infrastructure (no cables), but originally started out only doing telegraph (digital comms)…wasn't until quite a few years into the 1900s that audio could start being broadcast on radio waves.

Early Telephone

- By 1870s and 1880s they had ok-ish microphones and speakers.
- Early microphones used carbon/metal contacts that would get wiggled by air. The wiggling would affect the resistance of the carbon-metal junction

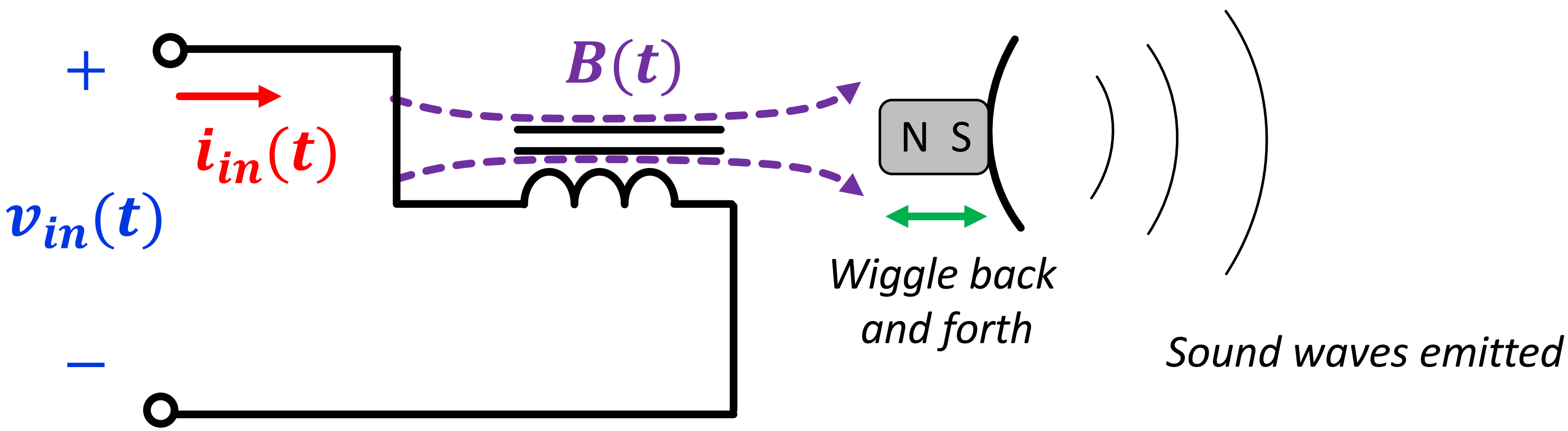




https://en.wikipedia.org/wiki/Carbon_microphone

Early Telephone

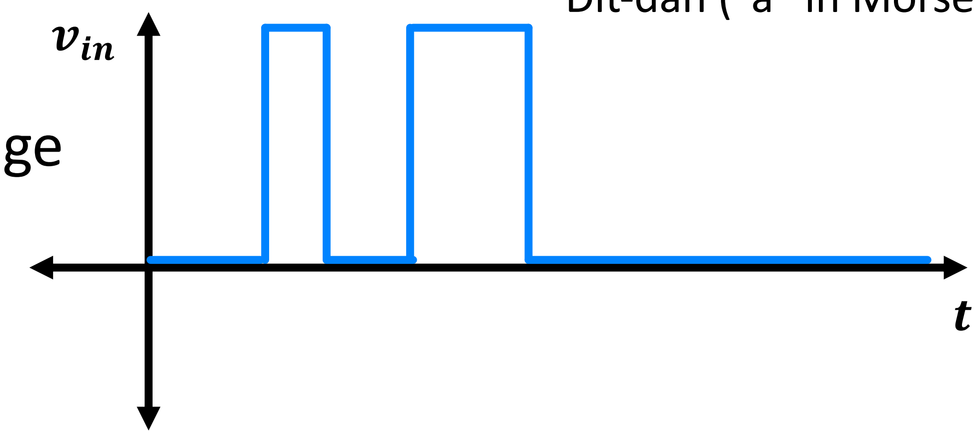
- By 1870s and 1880s they had ok-ish microphones and speakers.
- Early speakers used piezoelectric effect or electromagnetic coils to responding to incoming current to wiggle a membrane and cause air to move



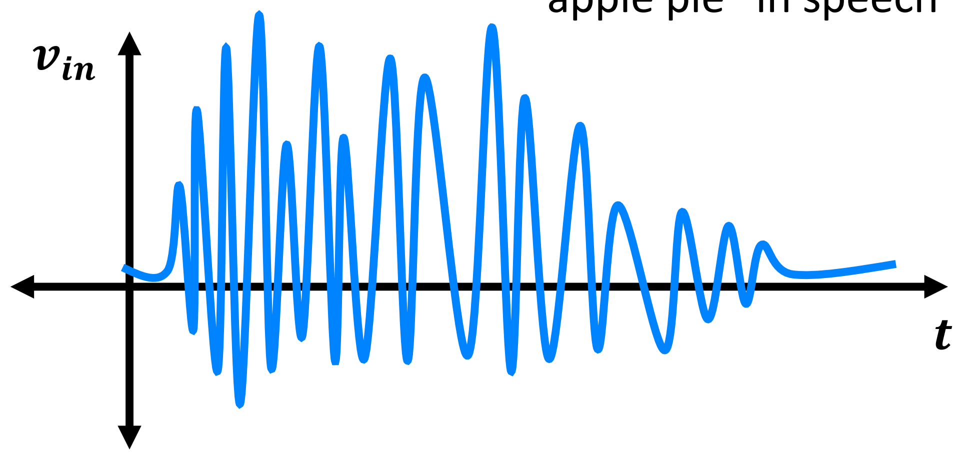
Big Difference Between Telegraphy and Telephony

- Telegraph was **Digital!**
  - Really just cared about range of voltage/current…not its exact value
  - More robust to noise!
  - Slower to transmit data
- Telephone was **Analog!**
  - The exact value matters!
  - Less robust to noise!
  - Transmit Data Faster (potentially)

Dit-dah (“a” in Morse)

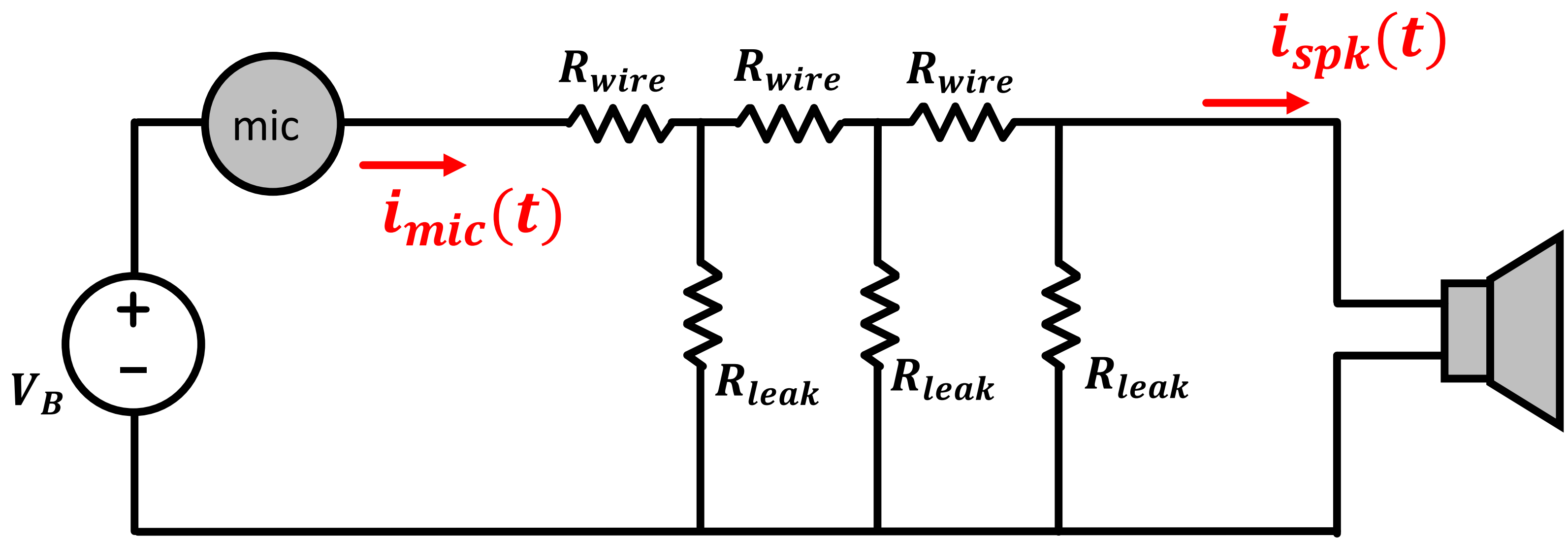


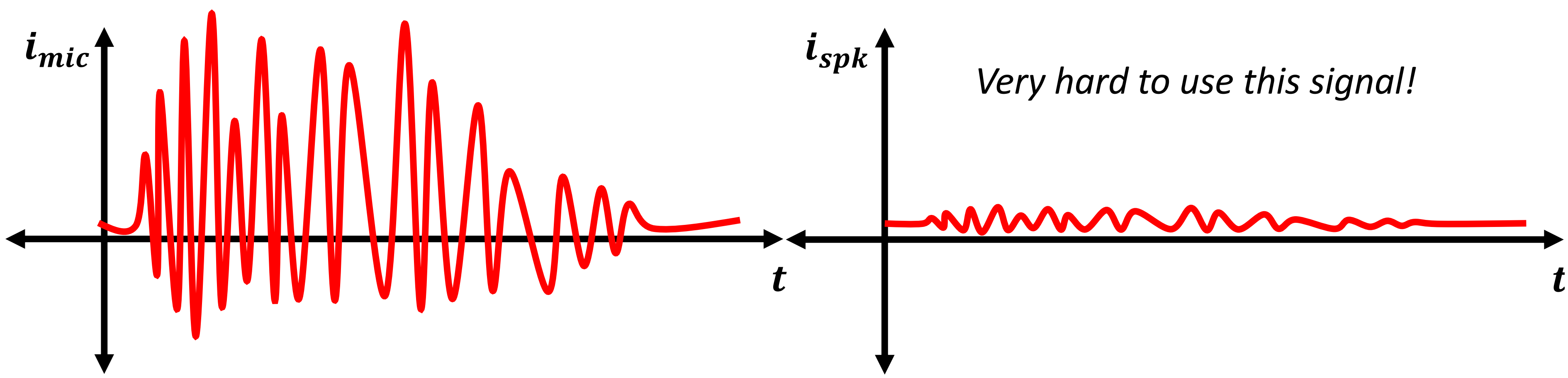
“apple pie” in speech*



*just a representative sketch not real

Effective Telephone Circuit





Crystal Earpiece

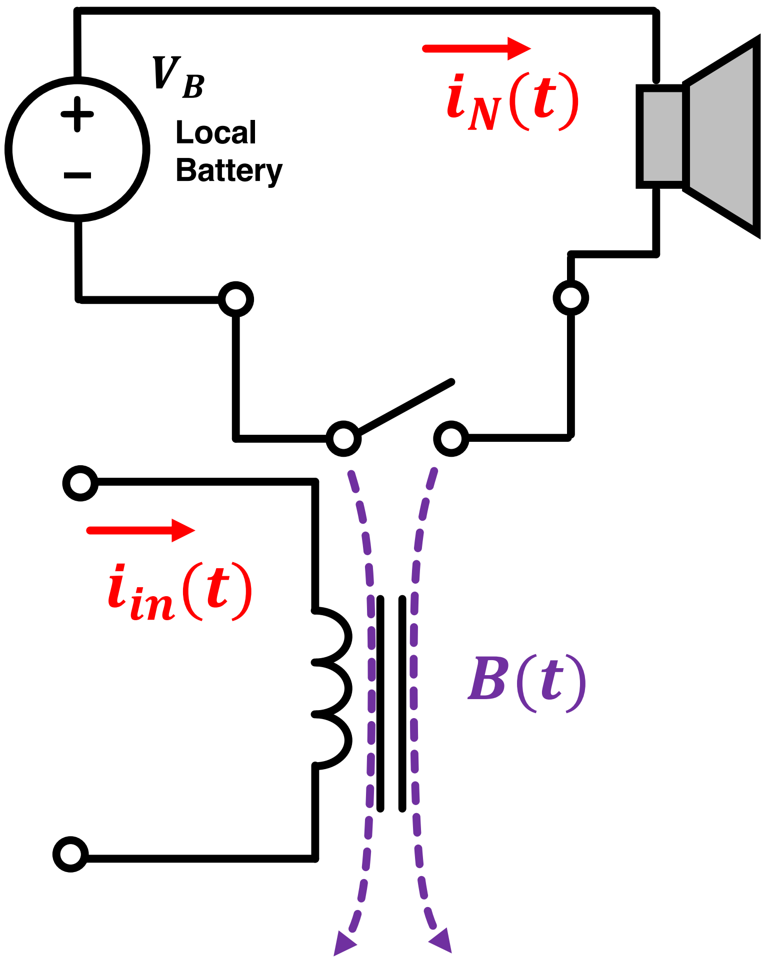
- A piezoelectric crystal earpiece is sometimes capable of producing tiny amounts of audio from a tiny signal.
- You have to really jam it into your ear and not be near anything
- Audio quality is very poor though (no bass…usually very “tinny”)

Need to Amplify

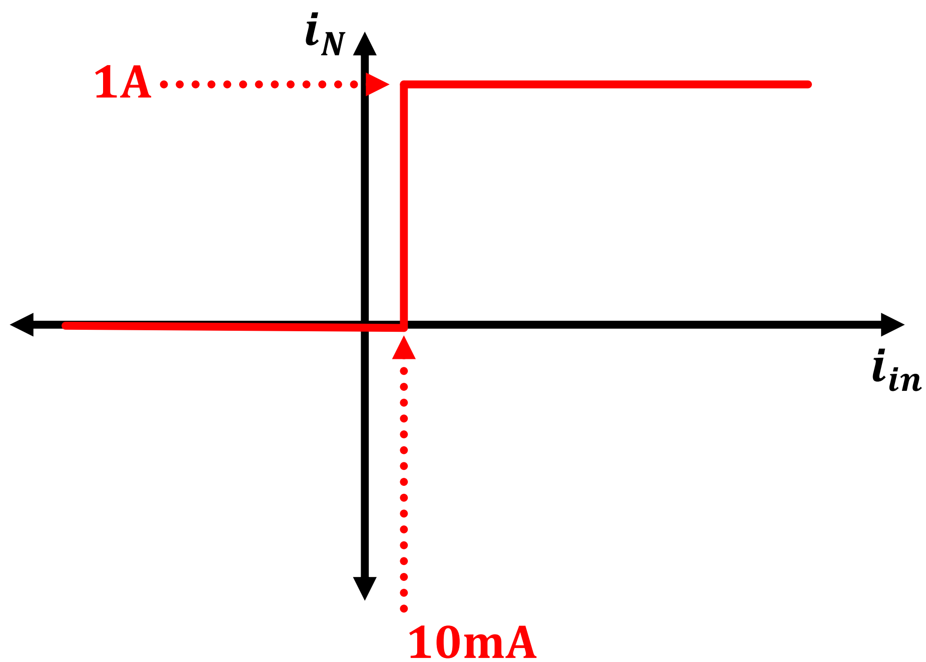
- We really need to make the signal ”big” again
- And this needs amplification!
- The relay solved this problem for Telegraphy
- Induce larger current based on the tiny recovered current at distant stations
- Could we use it here again? Take tiny recovered current and induce a larger current?

KINDA

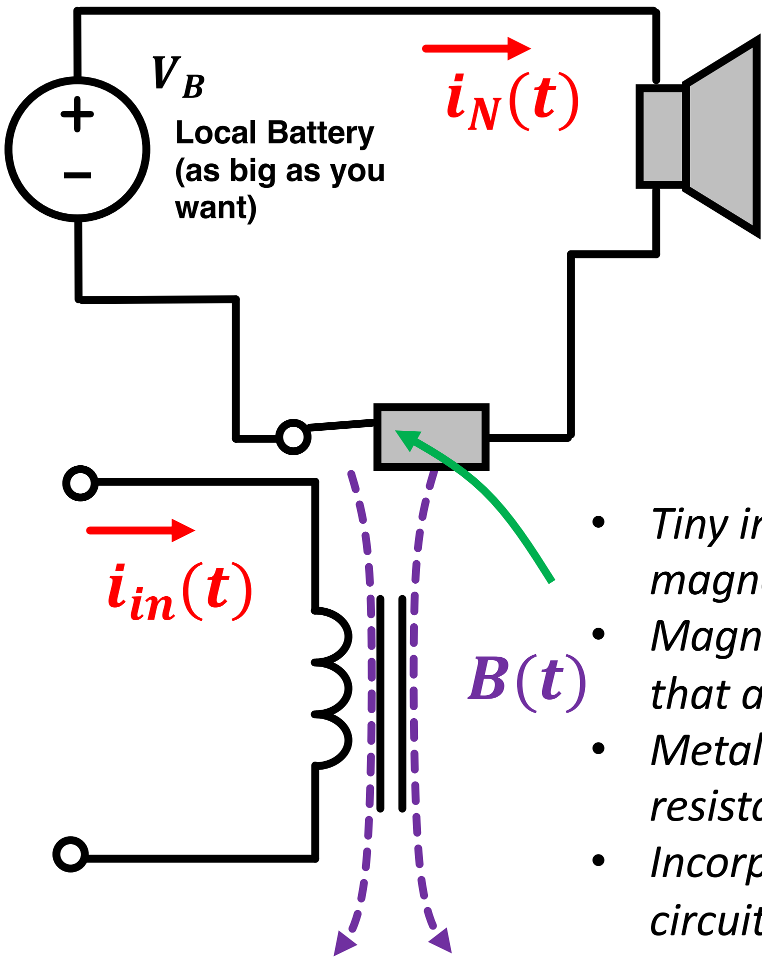
Why Can’t we use the Relay?



- Relay was a Yes/No system
- We don’t want thresholding



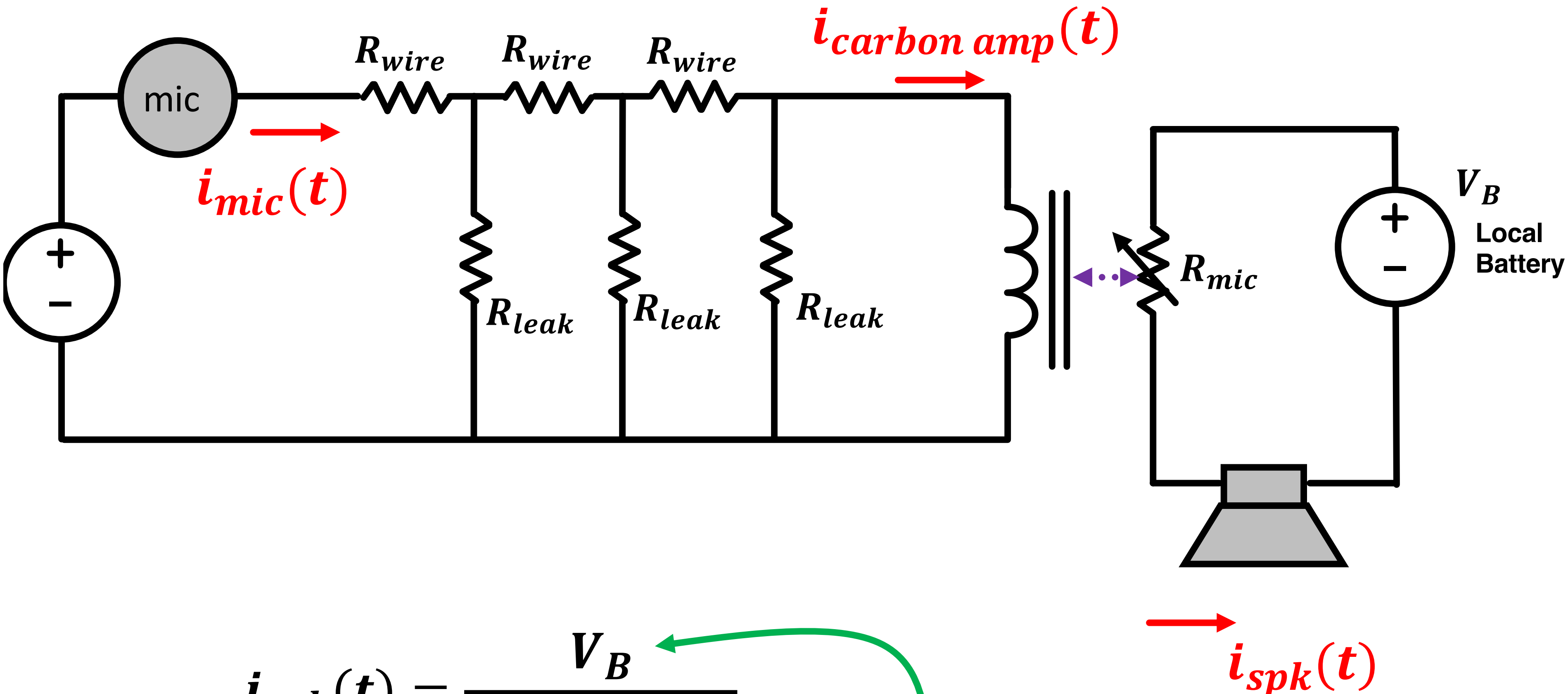
Let’s take same idea and modify it



- Make a variable resistor based on incoming current

- *Tiny incoming current of audio induces magnetic field in coil*
- *Magnetic field wiggles tiny group of wires that are making contact with carbon*
- *Metal-carbon interface has variable resistance depending on position of wires*
- *Incorporate metal carbon into more powerful circuit!*

Effective Circuit



$$i_{spk}(t) = \frac{V_B}{R_{mic} + R_{spk}}$$

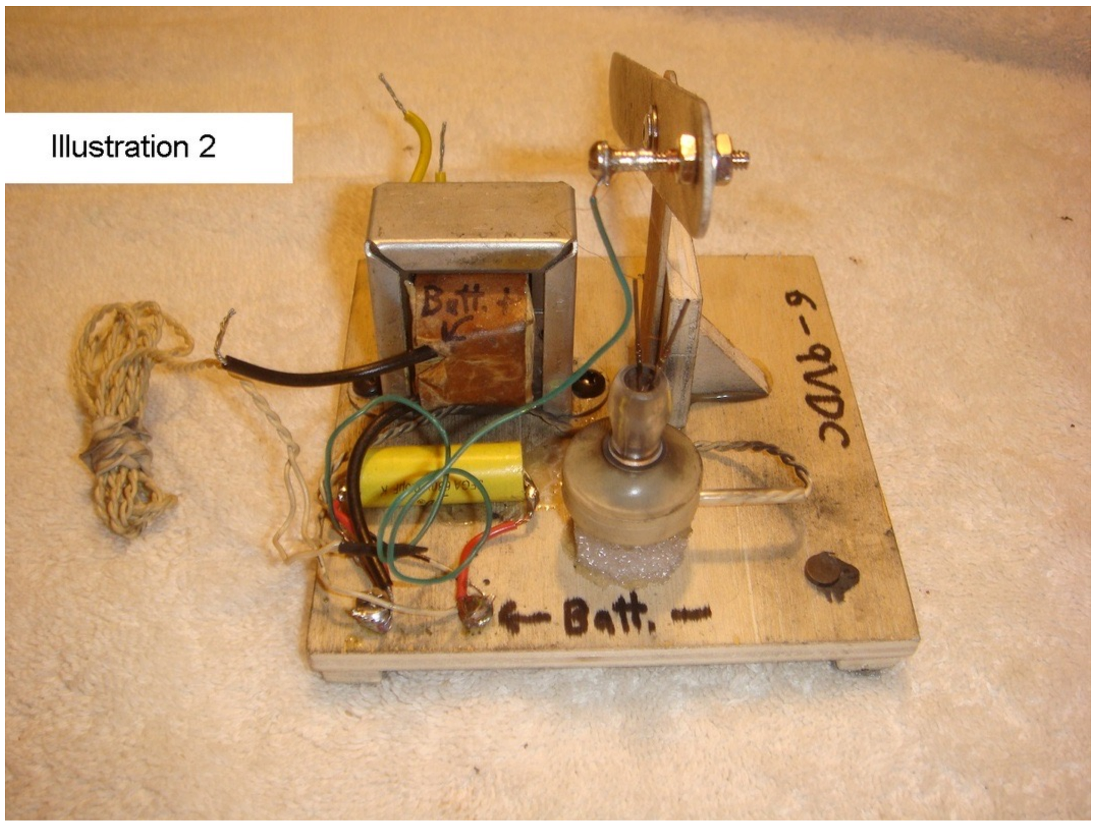
Can increase to crank volume

Fixed

Function of incoming audio signal
Futz with coil, wire, carbon to get
different amounts of influence

Cool Site

- This person built a carbon amp using junk components: https://www.robsradioactive.com/carbon-audio-amp



Carbon Amplifiers

- In reality, carbon amplifiers sucked. Very non-linear, temperamental, delicate, unreliable.
- We needed something better, but for a couple decades these helped.
- A lot of early telephone networks used these things for periodic amplification along the lines, up 1910 or so.

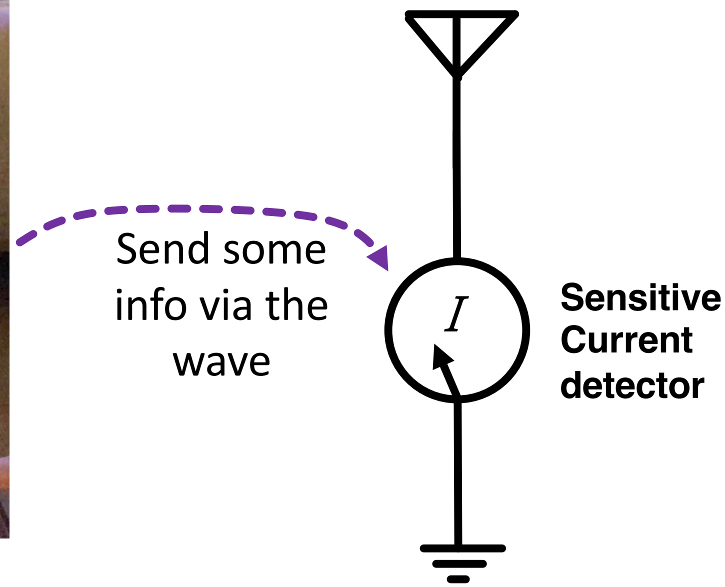
What about Radio?

- In the last few decades of the 19th century a lot of action-at-a-distance phenomena were being investigated
- Making a spark on a coil **here**, could cause an electromagnetic phenomenon **here**
- And there were no wires connecting the two!

“Wireless"

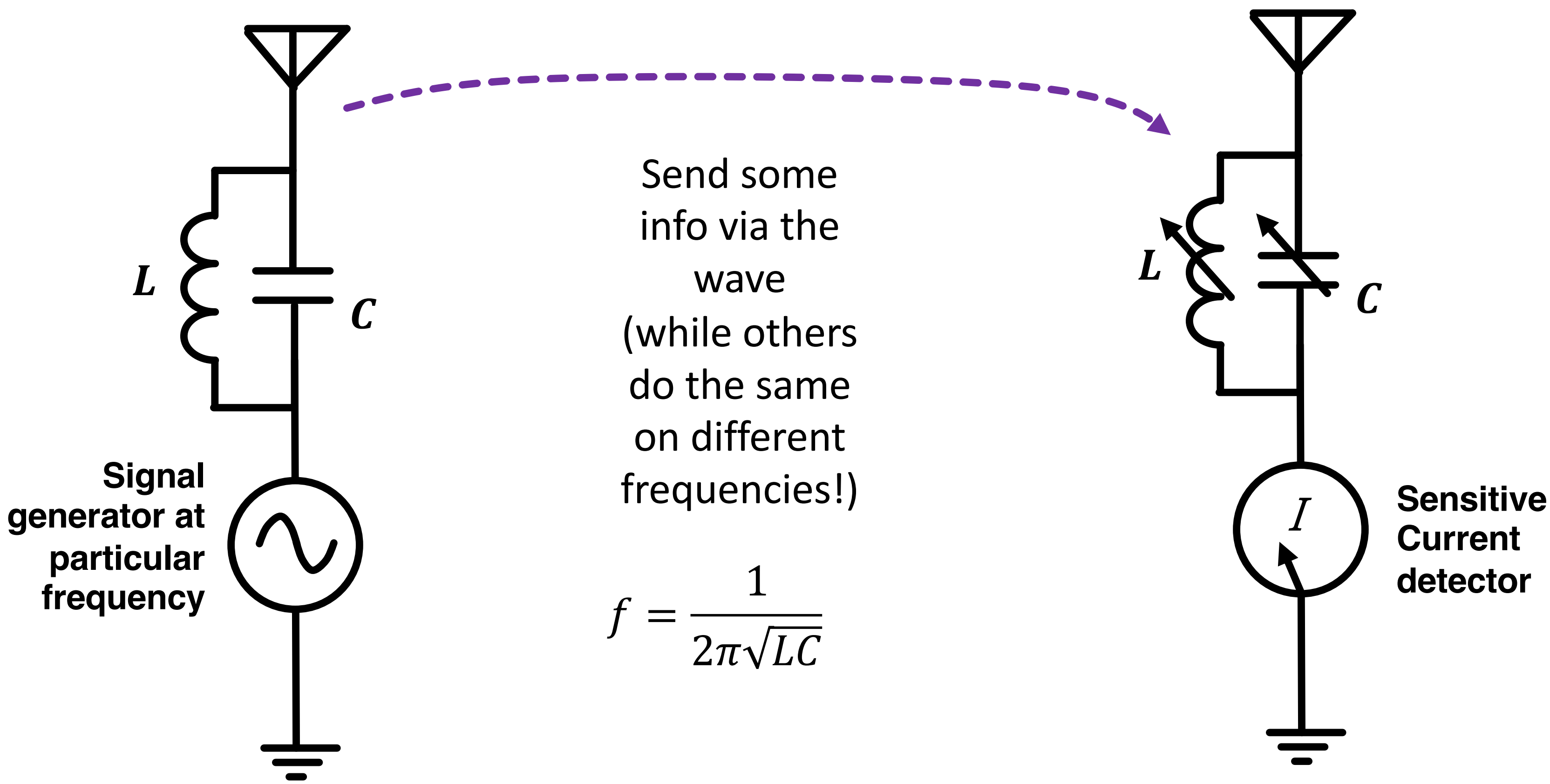
- Most early transmitters worked by just blasting noise on and off

Spark Gap Transmitter



Soon enough…

- Add in resonant circuits to restrict how many different frequencies were sent out and be able to only listen on certain frequencies!



Send some info via the wave (while others do the same on different frequencies!)

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

What was Different?

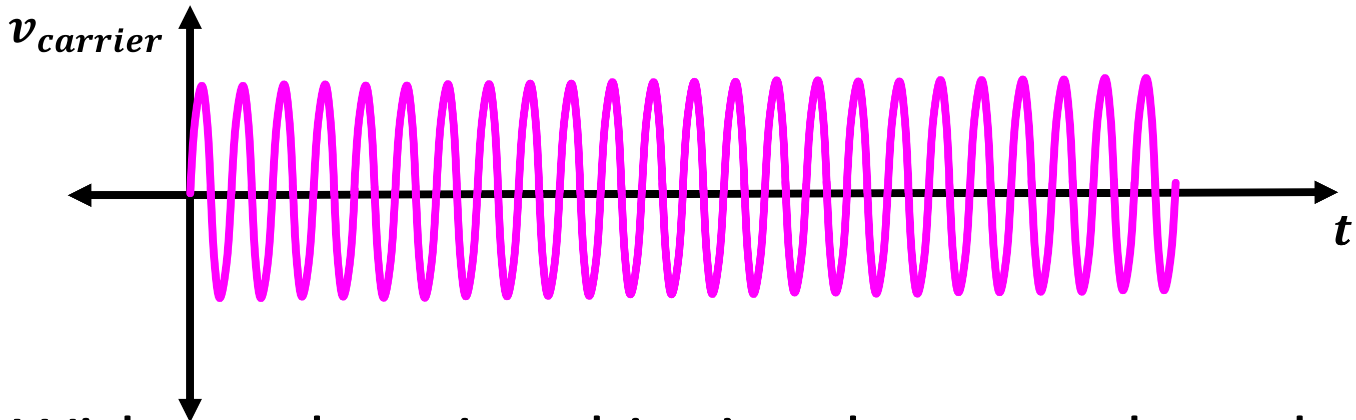
- In Telegraphy and Telephony, the information was related to the value being applied to the line.
- In both cases the variations of your voltage and current over time directly correlated the information you were sending!
- No other interpretation needed to be carried out

Radio was different

- It turned out that in order to make "Hertzian waves" that traveled any distance, you needed to make oscillating signals that were very high in frequency
  - 10's or 100's of kHz
- You couldn't just send 1's and 0's of Morse code or audio signals.
- You instead needed to have them be "carried" by a sine wave of the appropriate frequency

What does that mean…to carry?

- Find a sine wave of a particular frequency that works for you in the sense that you know you can generate it and detect it wirelessly We'll call it our carrier:



- Without changing this signal too much so that it still stays a radio wave, we need to encode the information we care about into it *<u>and then recover and decode it!</u>*

Particularly challenging

How to do that?

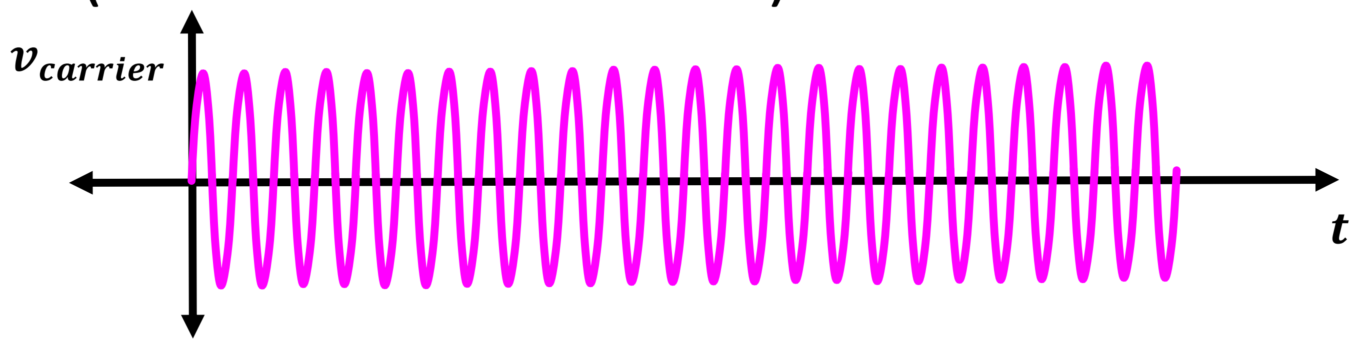
- A sine wave only has a few characteristics about it that we could vary to encode information:
  - Frequency f
  - Phase ϕ
  - Amplitude A

$$v_s(t) = A\sin(2\pi f t + \phi)$$

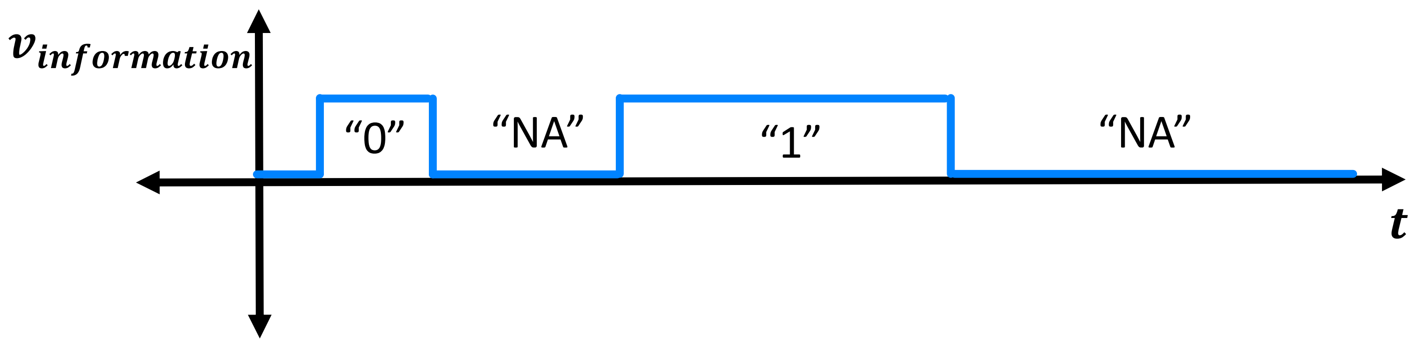
- Most modern communications almost invariably use the first two, but these are harder to understand/visualize and harder to implement
- Historically, the easiest first step was to encode information in the amplitude A

Let's Encode Info in the Amplitude of our Carrier Wave (aka "modulate")

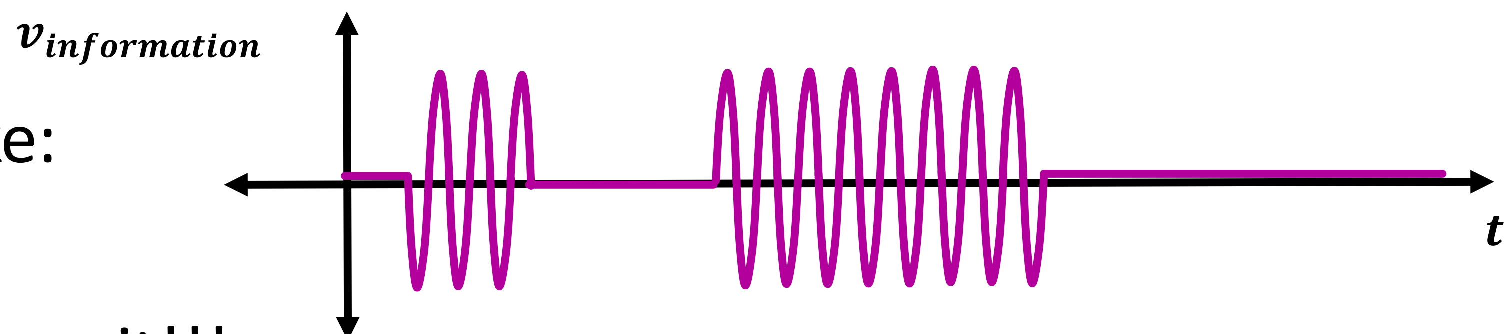
- Start with:



- And with:



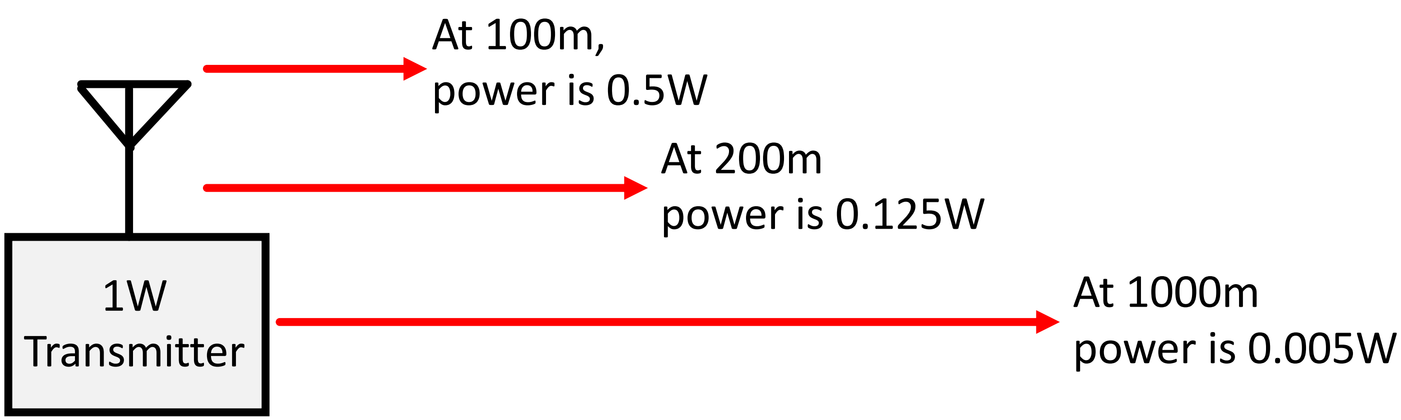
- And make:



- Then transmit!!!

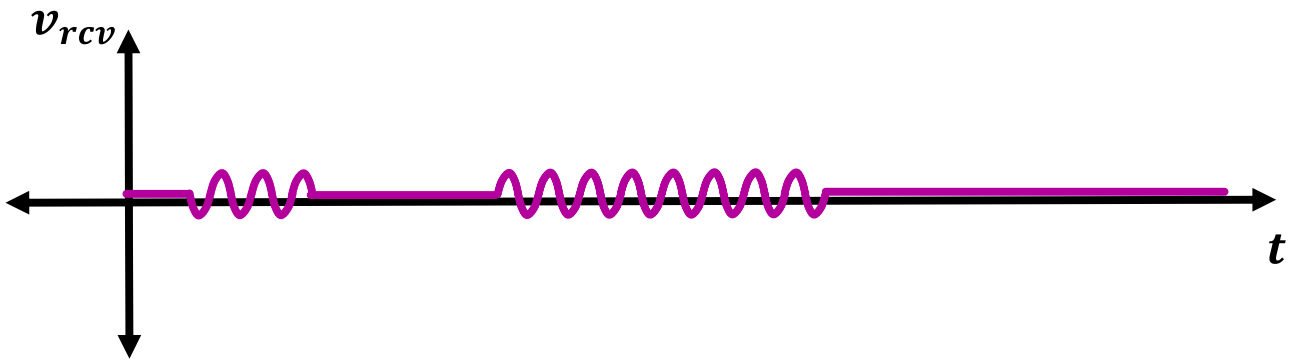
Send the Radio Wave Out

- Amplitude goes way down, following inverse square law ($\propto {}^{1}/_{d^2}$)…in other words signals get small very quickly!
- Either operate close by or use a lot of power!

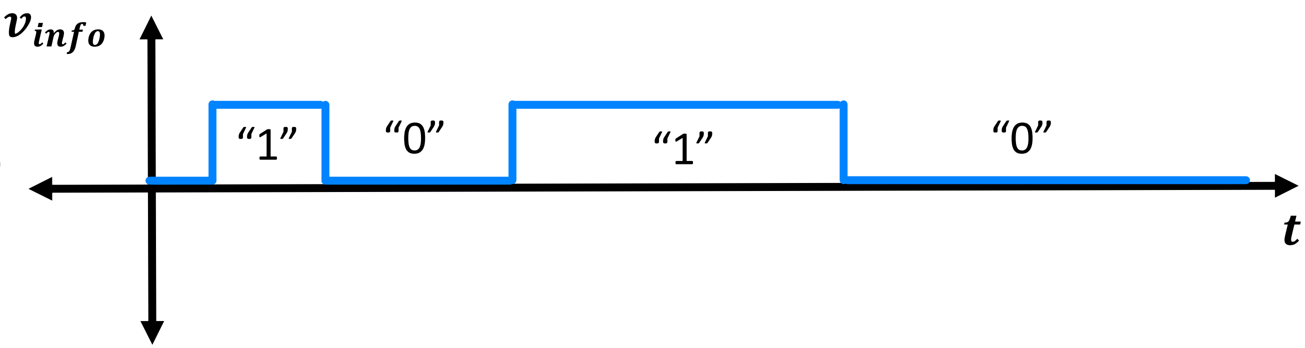


The situation on the receiver side

- You receive this:



- How do you turn it back into this?:



- This problem is harder than it looks

How to extract amplitude?

- Information is encoded in amplitude, given a sine wave, how do you determine its amplitude or something related to it?
- You could:
  - Calculate the RMS of the signal

What if signal is too weak?

- What if your signal is too weak to even be subjected to the math operations?
- Received radio signals can be tiny (inverse square law)…much harder problem than telegraphy with wires.
- We need to amplify, but amplifying at radio frequencies is not as easy

Where do we find ourselves around 1890?

- We need the ability to perform ***nonlinear operations*** on incoming radio waves
  - Electromagnetic (relays) thresholders are too slow and insensitive
- We need the ability to reliably ***amplify signals***
  - Electromagnetic devices (carbon amps or relays) are too slow, non-linear, unreliable. Need more options.

Next Lecture

- Look at Early "detectors" (non-linear devices)
- See how side results from the development of incandescent lighting hinted at a better future

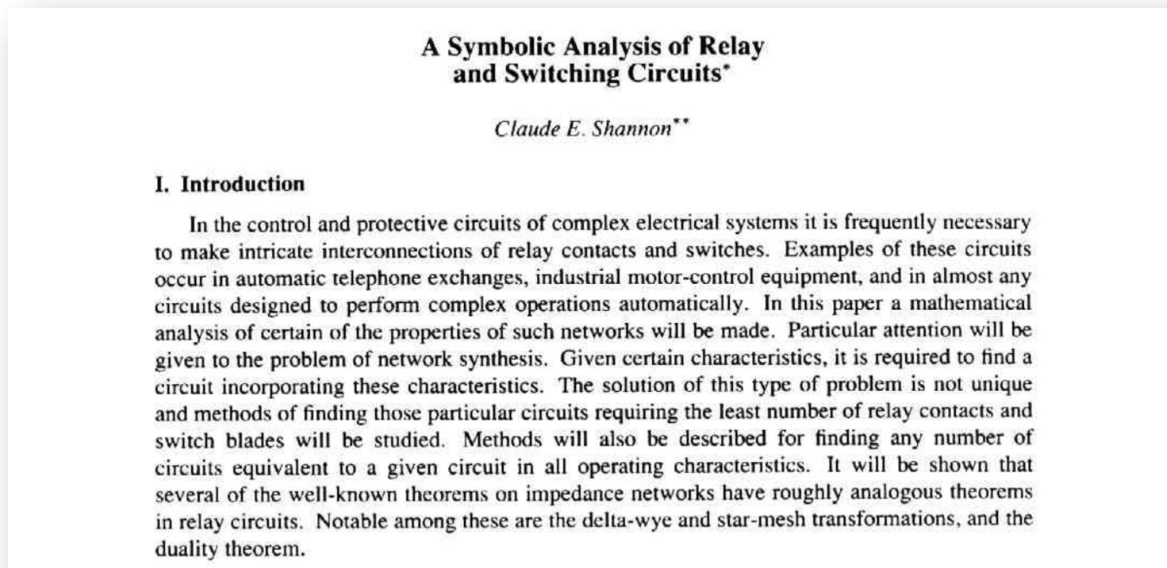
1893 Columbian Exposition ("Great White City")

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

Extra: Lab 1: Relays

- Relays did not disappear.
- The fact that they are inherently digital in operation and the fact that they could be made very robustly meant they got used widely in early computer development up to the 1950s

- Claude Shannon's 1938 thesis which first proposed digital circuits as a field focused on relays



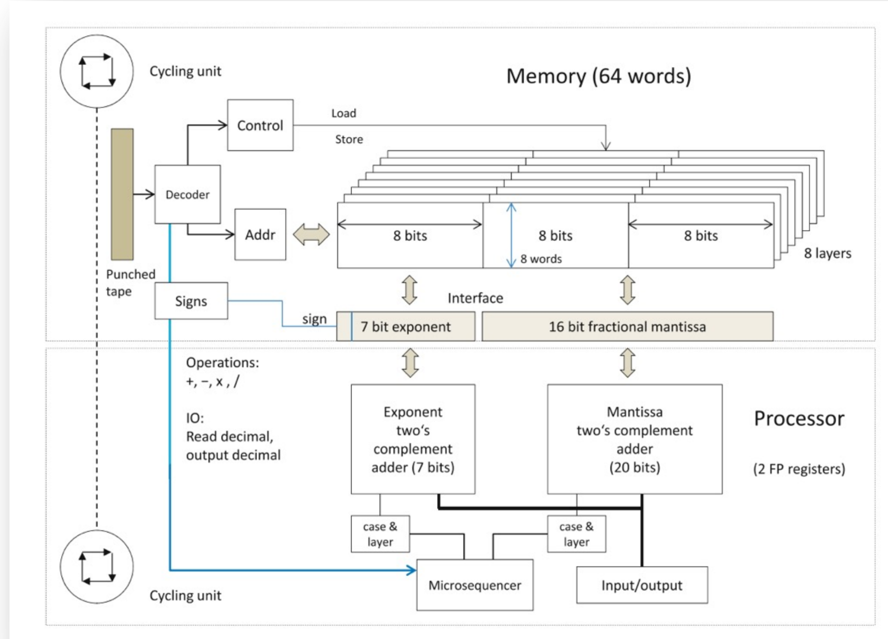
A Symbolic Analysis of Relay and Switching Circuits*

*Claude E. Shannon***

I. Introduction

In the control and protective circuits of complex electrical systems it is frequently necessary to make intricate interconnections of relay contacts and switches. Examples of these circuits occur in automatic telephone exchanges, industrial motor-control equipment, and in almost any circuits designed to perform complex operations automatically. In this paper a mathematical analysis of certain of the properties of such networks will be made. Particular attention will be given to the problem of network synthesis. Given certain characteristics, it is required to find a circuit incorporating these characteristics. The solution of this type of problem is not unique and methods of finding those particular circuits requiring the least number of relay contacts and switch blades will be studied. Methods will also be described for finding any number of circuits equivalent to a given circuit in all operating characteristics. It will be shown that several of the well-known theorems on impedance networks have roughly analogous theorems in relay circuits. Notable among these are the delta-wye and star-mesh transformations, and the duality theorem.

Relays to the Extreme



- Most computers until about 1945 were wholly or largely relay based.
- Konrad Zuse in Germany created full arguably Turing-complete relay only computers with many elements of modern processors
  - Slow though...clock speed of a couple Hz