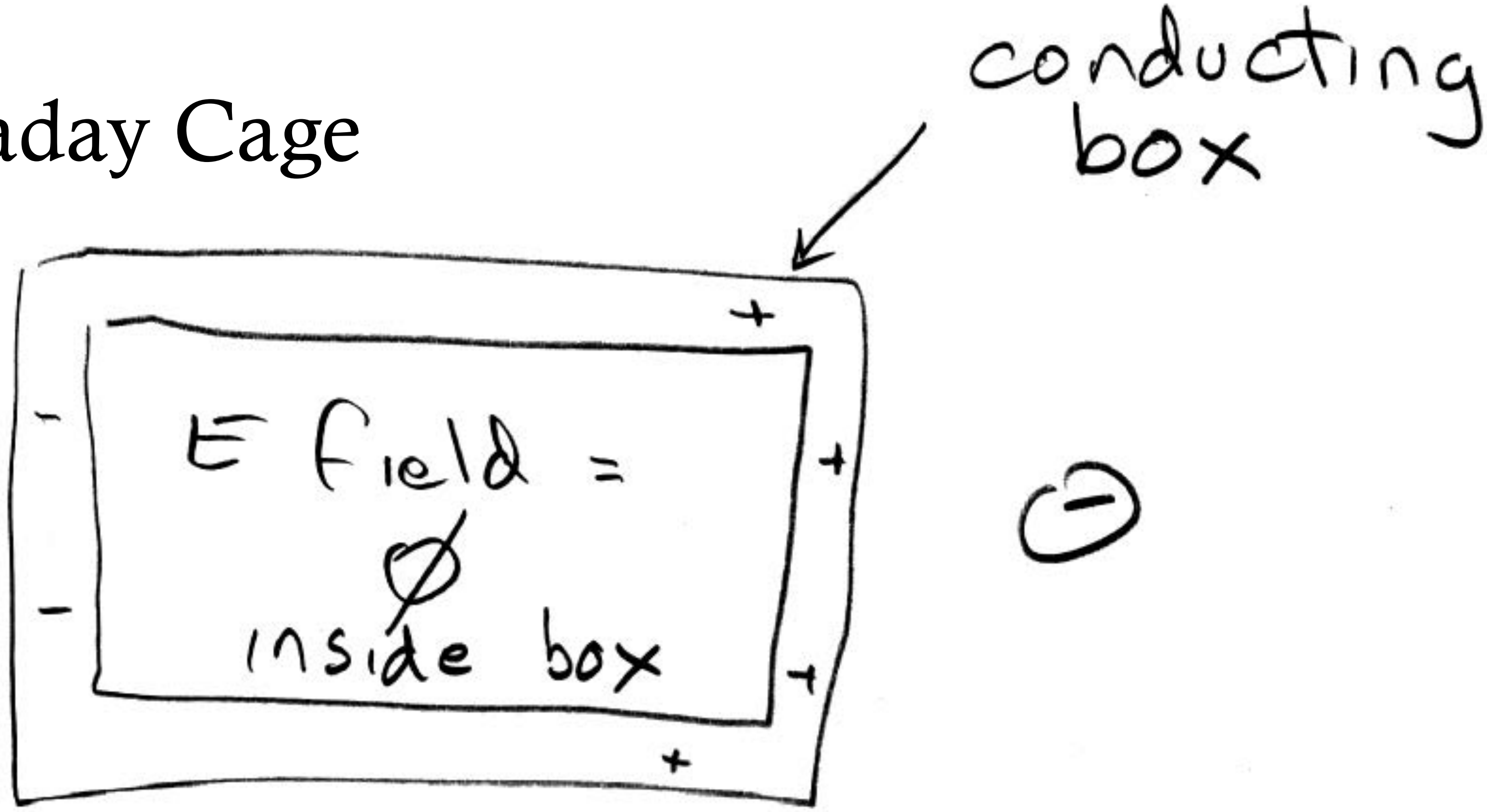
Shielding of Electric Fields

- Faraday Cage



- Bring external charge near the conducting box.
- Charges in wall of conducting box will shift to produce zero electric field within the box.

Shielding of Magnetic Fields

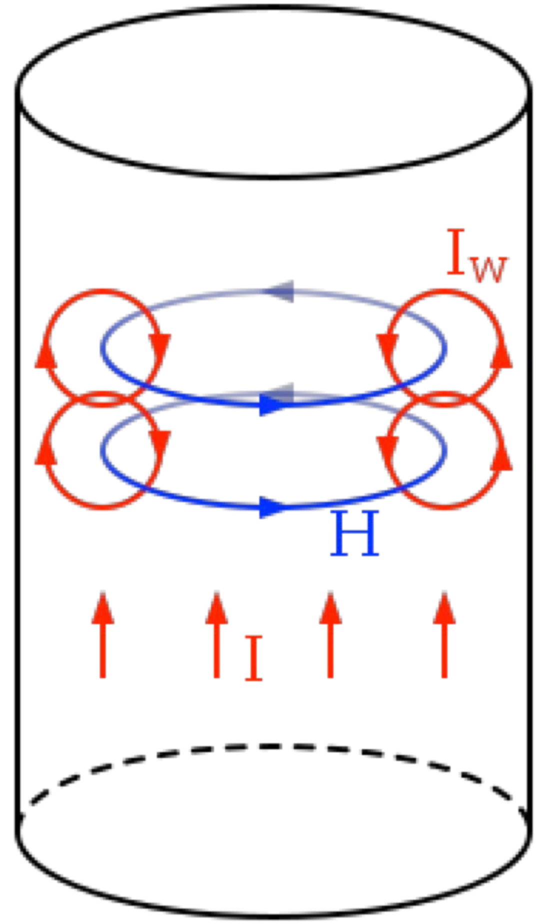
- Magnetic fields can penetrate conducting box, because there are no magnetic monopoles; north and south poles always come in pairs (unlike electrostatic charges).
- "Mu-Metal" has high permeability,
  - Consists of nickel and iron.
  - Used to shield transformers, disk drives, MRI scanners.
  - Cannot completely shield DC or low frequency magnetic fields
- In a superconductor, external magnetic fields *are* shielded by currents generated in the zero-ohm material (the Meissner effect).

High Frequencies

- At high frequencies (> 100 MHz), wave properties become important.
- Circuits can no longer be represented by just schematics with discrete nodes, and wires along which voltage is constant.
- When wavelength is similar in scale to the circuit, the EM field varies in time *and space*,
- Kirchhoff's laws do *not* apply.
- The physical shape of the circuit matters: the lengths and shape of components, conductors, and their relation to ground.

Skin Effect

- At high frequencies ($>10^6$ Hz) current concentrates at the surface of wire.
- Changing current causes changing magnetic fields, which generate opposing currents.
- Effective resistance goes up, except near the outer surface.
- You can counteract with multi-stranded wire, or use hollow pipes to save needless metal.



Eddy currents I_W due to changing magnetic field H cancels current I in center of wire.

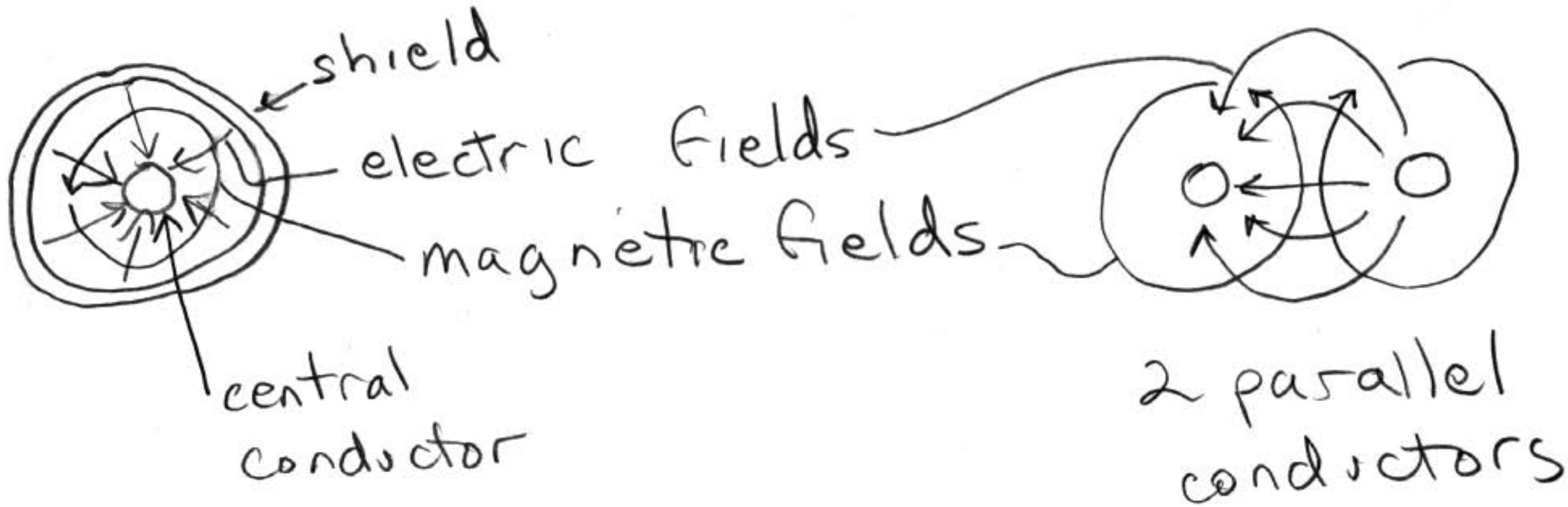
Wikipedia – Skin Effect

Cables – Transmission Lines

- Transporting high-frequency signals:

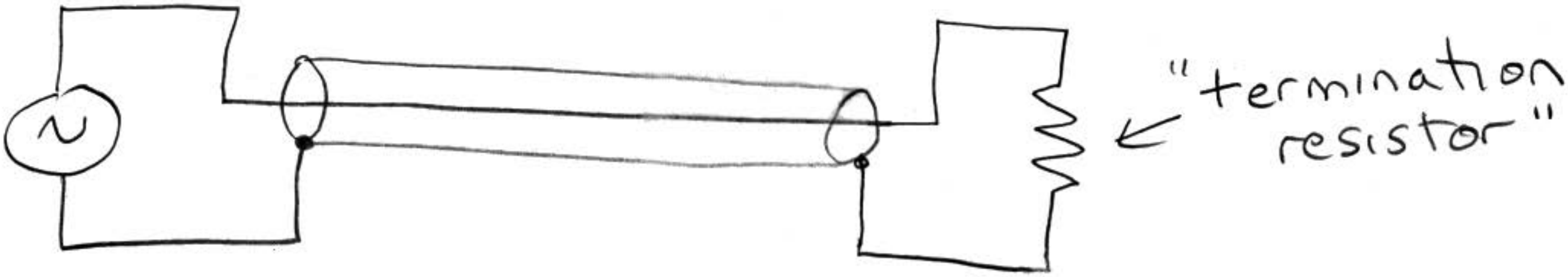
Coaxial Cable

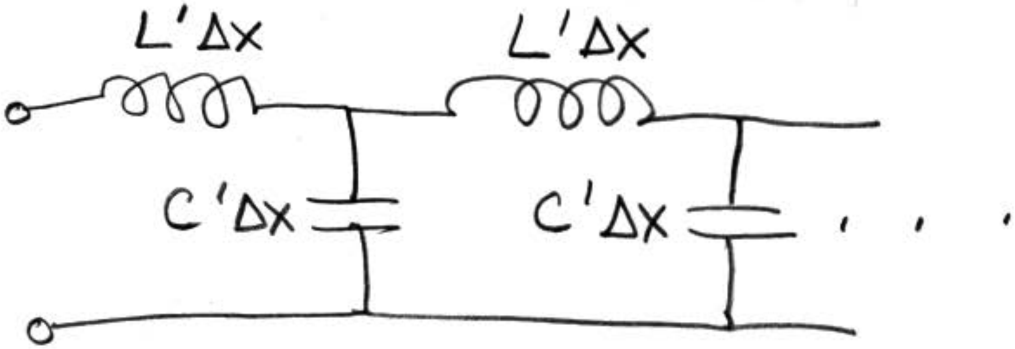
Paired Cable



Capacitance between conductors
Inductance along them

Characteristic Impedance of Transmission Line





capacitance/unit length

$C' = C/\ell$

inductance/unit length

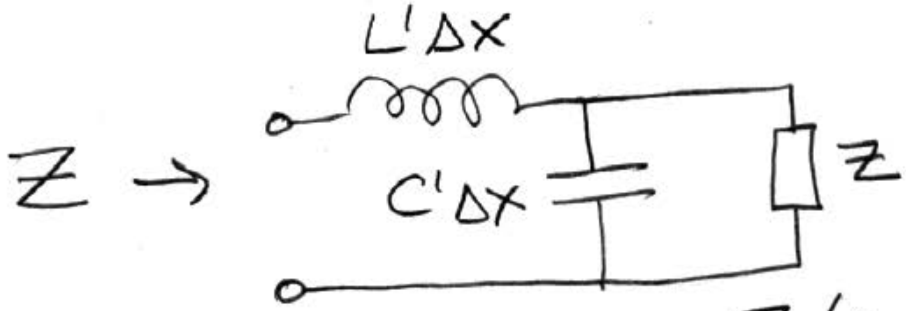
$L' = L/\ell$

acts like infinite series of coils and caps.

assume "characteristic impedance" Z.

adding one more rung does not change this.

…looking into infinite cable, impedance is real!



impedance remains *Z*

parallel is product over sum

$$Z = j\omega L'\Delta x + \frac{Z / j\omega C'\Delta x}{Z + 1/j\omega C'\Delta x}$$

$$Z = j\omega L'\Delta x + \frac{Z}{j\omega C'\Delta x Z + 1}$$

$$j\omega C'\Delta x Z^2 + Z = -\omega^2 L'C'\Delta x^2 Z + j\omega L'\Delta x + Z$$

as $\Delta x \to 0$

$$j\omega C'\Delta x Z^2 = j\omega L'\Delta x$$

$$Z^2 = \frac{j\omega L'\Delta x}{j\omega C'\Delta x} = \frac{L'}{C'} = \frac{L/\ell}{C/\ell} = \frac{L}{C}$$

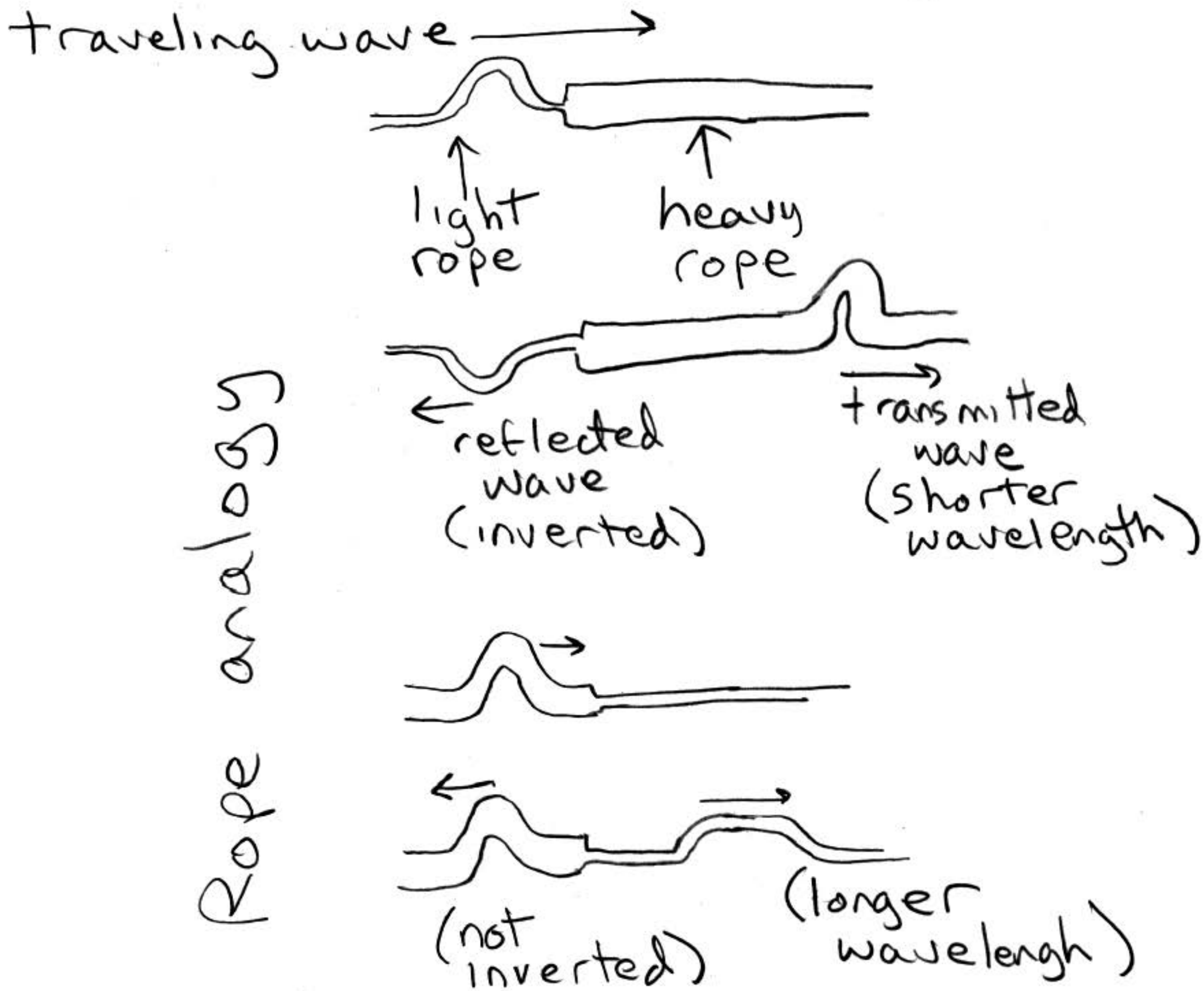
characteristic impedance ⟶ $Z = \sqrt{L/C}$ ⟵ a real number!

Impedance Matching

- Terminate high-frequency cables with a resistor at the characteristic impedance; avoids *standing waves*.
- Resistor looks like rest of cable going on to infinity.
- Various Common Cables
  - 75Ω (RG59) Coax: video.
  - 50Ω (RG58) Coax: oscilloscopes, meters, etc.
  - 100Ω (Cat 5) Paired Cable: local ethernet

Rope Analogy

As in light and sound, reflections occur at changes in impedance

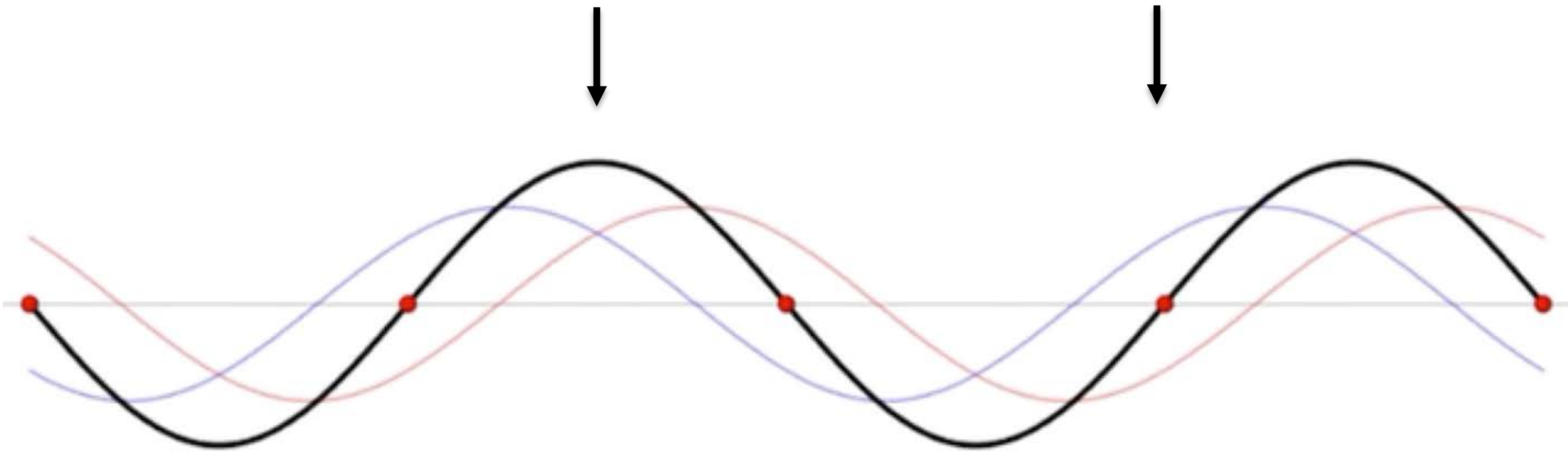


Constructive and Destructive Interference: results in <u>Standing Waves</u>

Constructive Interference

Destructive Interference

(null point)



- Animation of sum (black) of 2 sinusoids (red and blue) traveling in opposite directions.
- See https://oceanservice.noaa.gov/facts/seiche.html

Traveling Waves

- Already had ω, *temporal* frequency, radians per *second*.
- Now introduce k, *spatial* frequency, radians per *meter*.
- k also called *wave number*.

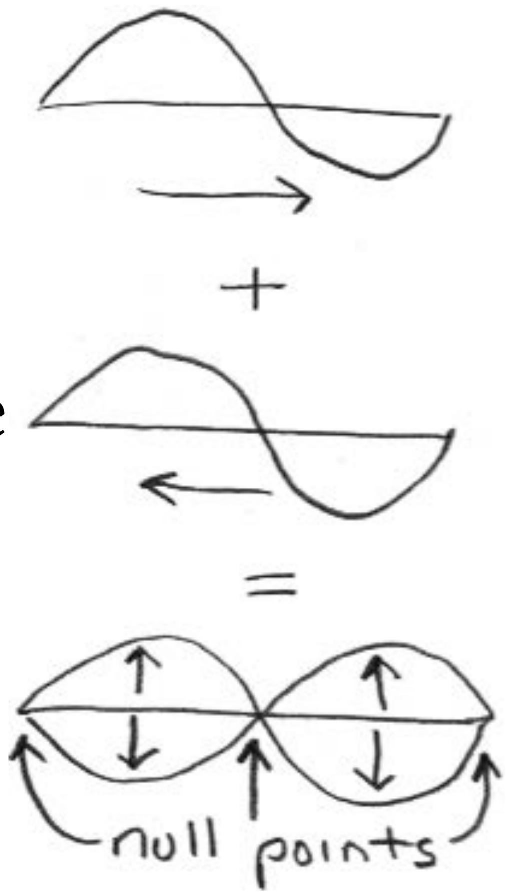
$$y = A\sin(kx - \omega t)$$

- Two independent variables, x and t.
- Can be viewed as changing in time at a given place, or as simply moving through space.

Wikipedia – Standing Waves

Standing Waves

- Sum a wave and its reflection in 1D
- Constructive and destructive interference



Forward Wave $y = y_0 \sin\left(kx - \omega t\right)$

+ $\qquad$ +

Backward Wave $y = y_0 \sin\left(kx + \omega t\right)$

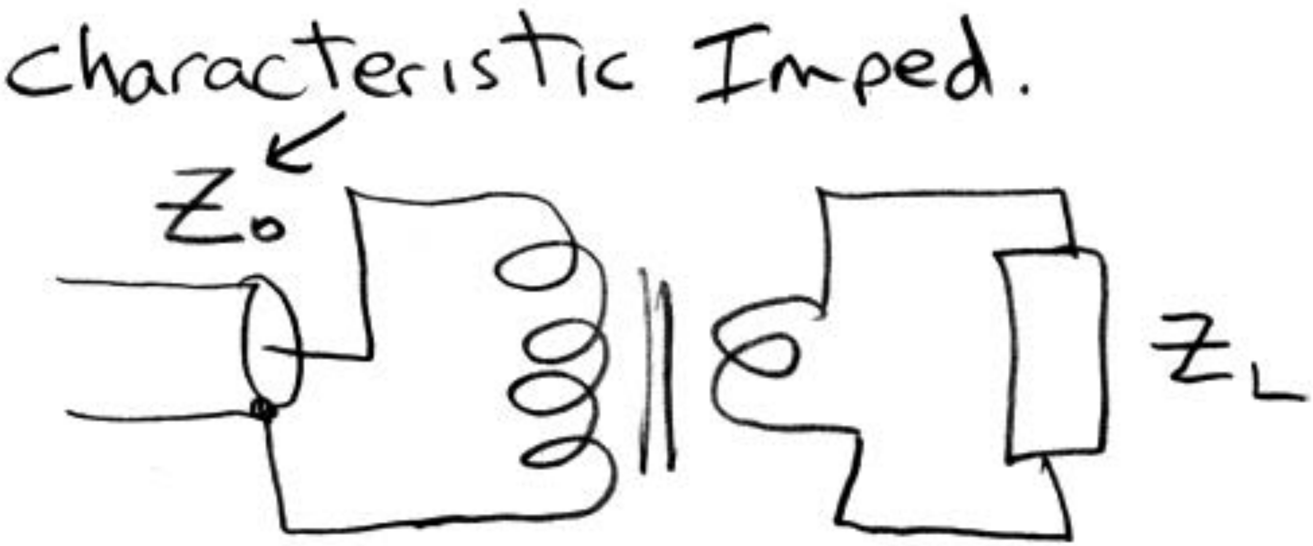
= $\qquad$ =

Standing Wave $y = 2y_0 \cos\left(\omega t\right)\sin\left(kx\right)$

trig identity: $\sin\left(\theta - \varphi\right) + \sin\left(\theta + \varphi\right) = 2\cos\left(\varphi\right)\sin\left(\theta\right)$

Impedance Matching

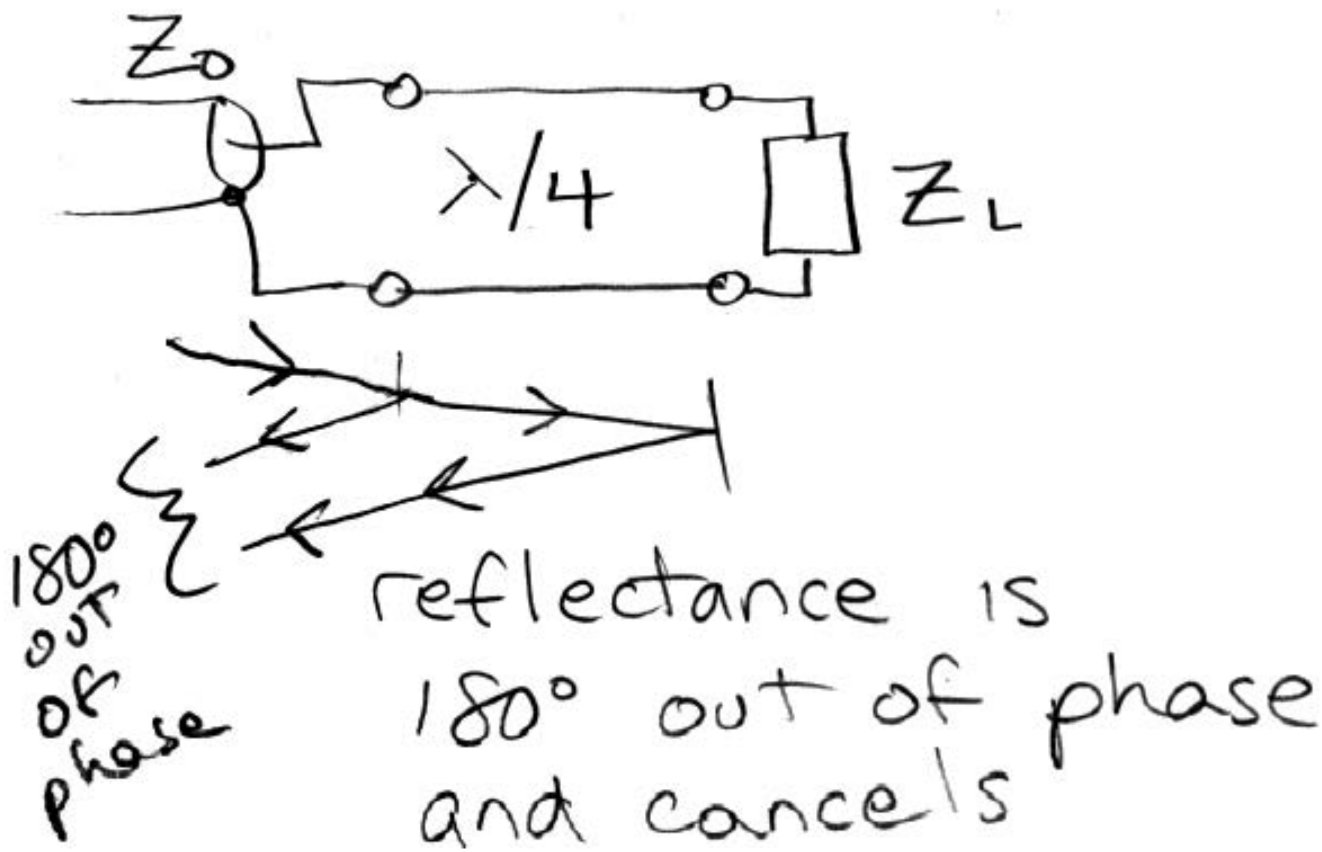
- To eliminate reflections and thus standing waves
- Use a transformer



- Analogous to the bones in the middle ear
  - Unequal lever trading force (voltage) against displacement (current) with power constant.

Impedance Matching

- Use a ¼ wave section of wire



- Also used in surface coating of cameral lenses

Velocity of Waves

- In cables, $$v = \frac{1}{\sqrt{LC}}$$ L tends to be constant. C varies with dielectric constant of insulation.
- In 3D, $$v = \frac{1}{\sqrt{\mu\varepsilon}}$$ μ= permeability
ε= permittivity

Medium	C (pF/m)	L (nH/m)	v (m/μs)	Z (Ω)	R for $f \leq$ 1kHz (mΩ/m)
RG58/U Coaxial Cable	93.5	273	198	54	53
RG58C/U Coaxial Cable	101	252	198	50	50
RG59B/U Coaxial Cable	72.0	405	185	75	45
CAT-5 Twisted Pair (Solid)	49.2	495	203	100	180
Vacuum	8.85	1260	299	377	0
Water	708	1260	34	42	0

Wave velocity in cable generally due to dielectric constant *k* of insulation, because permittivity varies but permeability does not.

$$V = \frac{c}{\sqrt{k}}$$

c ← speed of light

$\sqrt{k}$ ← dielectric constant of cable insulation

recall that $c_0 = \dfrac{1}{\sqrt{\mu_0 \epsilon_0}}$

c_0: speed of light in vacuum

μ_0: permability in a vacuum

ϵ_0: permitivity in a vacuum

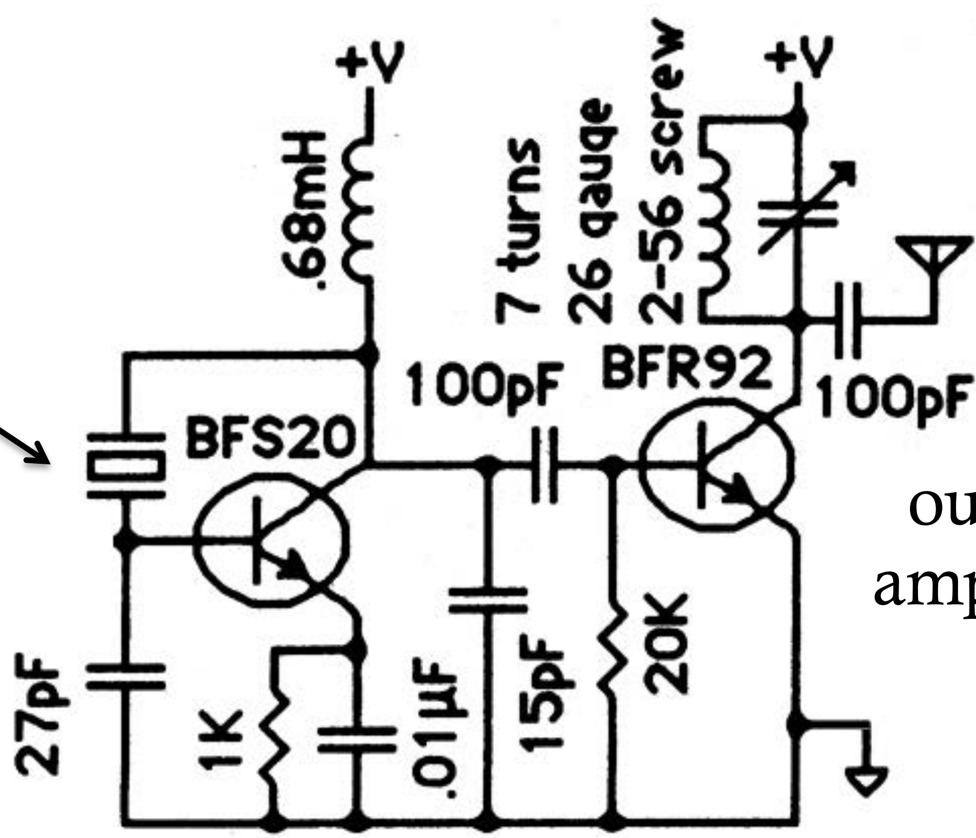
permitivity of capacitor

$$\epsilon = k\epsilon_0$$

High Frequency (>100 MHz) Oscillators

- Need discrete transistors rather than op amps, e.g. from my telemetry system for birds' eggs.

crystal resonates like a tuning fork



output amplifier

- Resonance (crystal)+ Gain (transitor) = Oscillation.

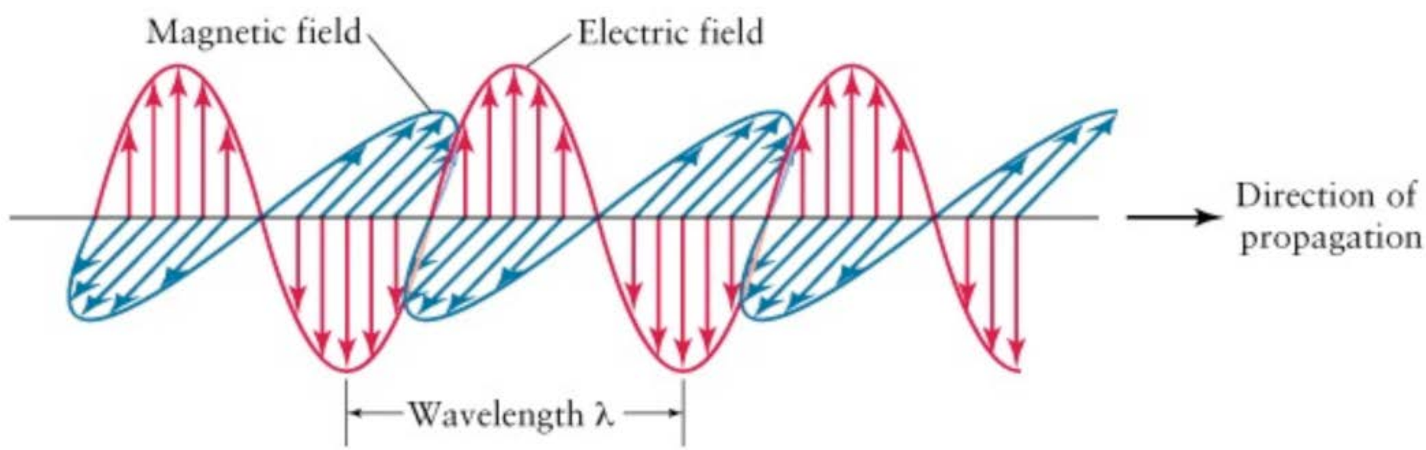
Microwave (1- 40 GHz)

- Waveguides (pipes) instead of wires.
  - Hollow to use skin effect
  - Bends and junctions specific shapes

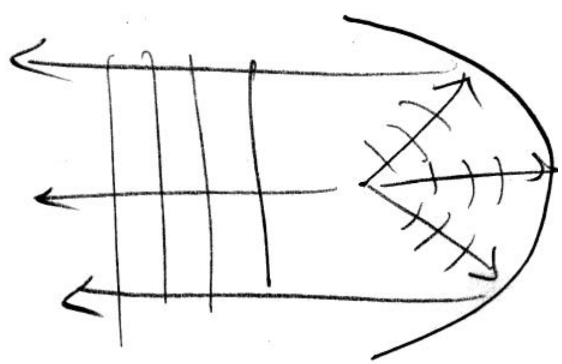
- Klystron tubes instead of oscillator circuits.
  - Resonating chamber: basically a flute for electrons

Radio Waves through Space

- Clark Maxwell predicted radio in 1866 from his theory of light
  - "Displacement Current" through capacitor



- Hertz used 1.2 meter parabolic dish in 1888 to demonstrate first radio (450 MHz)



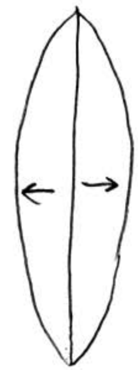
Radio Wavelength

- c = 300,000 kilometers/second

- Thus

  – 30 MHz ➔ $\lambda = 10$ meter (radio)
  – 300 MHz ➔ $\lambda = 1$ meter (hi freq radio)
  – 3 GHz ➔ $\lambda = 10$ cm (microwave ovens)
  – 30 GHz ➔ $\lambda = 1$ cm (radar)

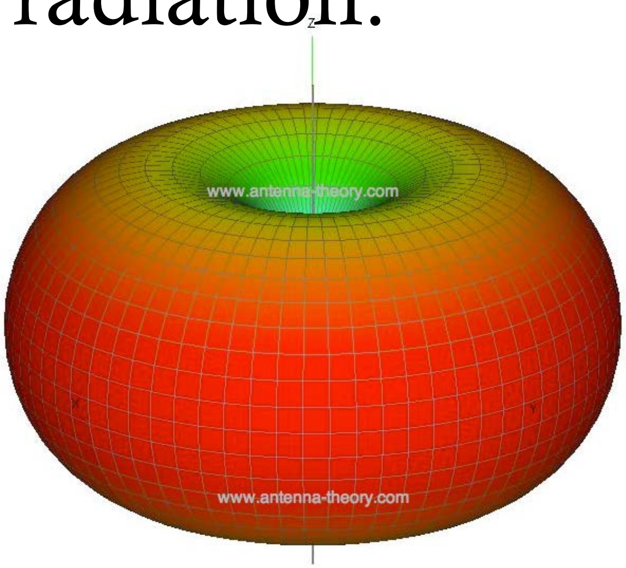
- Simple monopole (whip) antenna



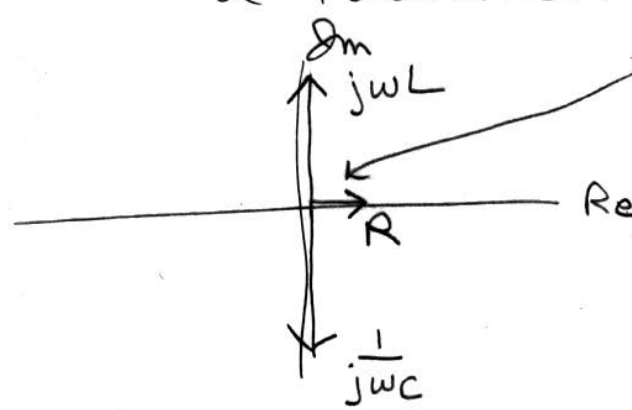
half-wave antenna, like a guitar string

would be a perfect LC circuit but for the speed of light.

- Field pattern for transmitted and received radiation.

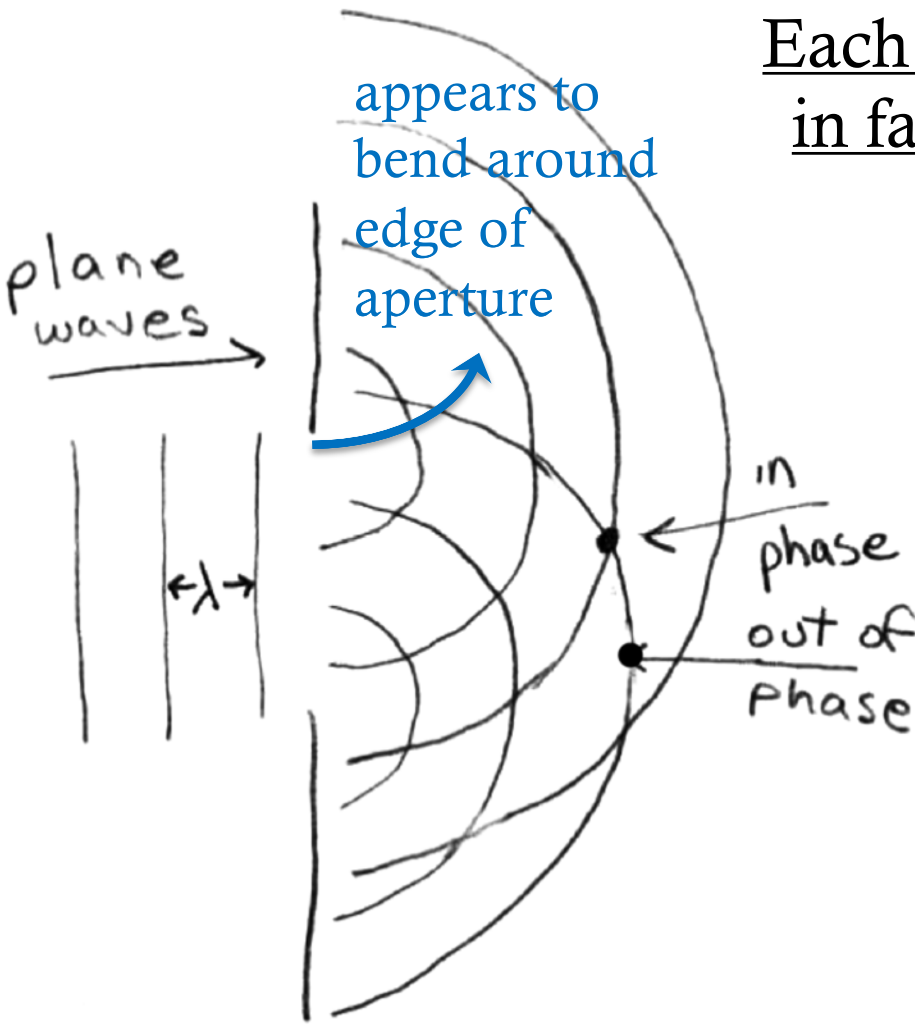


this introduces a slight phase shift, causing a radiation "resistance"

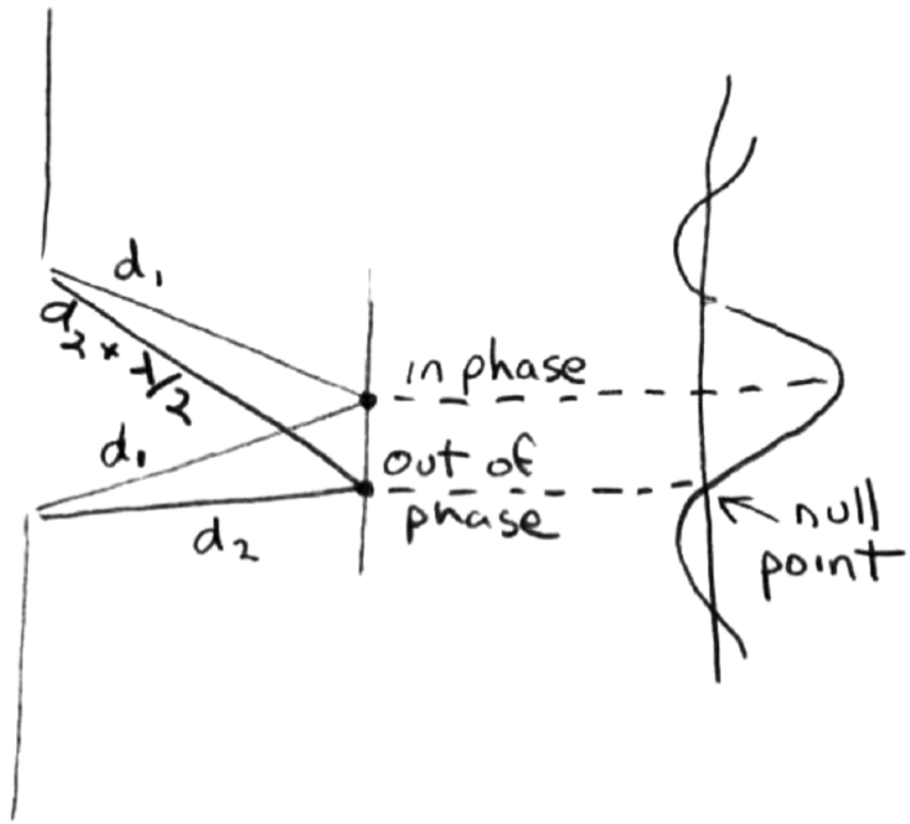


Huygens' Principle

Particle-Wave Duality: Newton said *particle*, Huygen said *wave*.

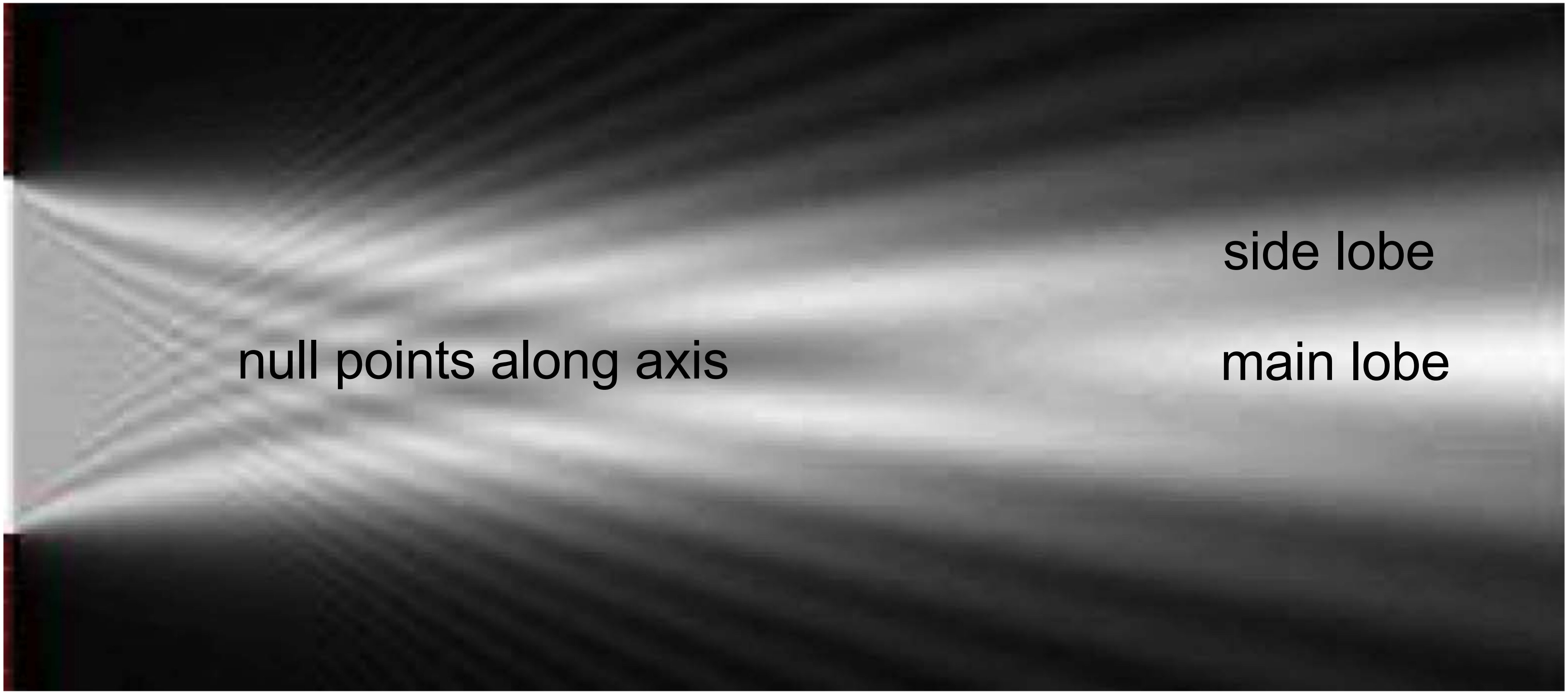


Each point of an advancing wave front is in fact the center of a fresh disturbance



Results in constructive and destructive interference (null points) from integration over an aperture.

Field Pattern of a flat transducer, antenna, or aperture.

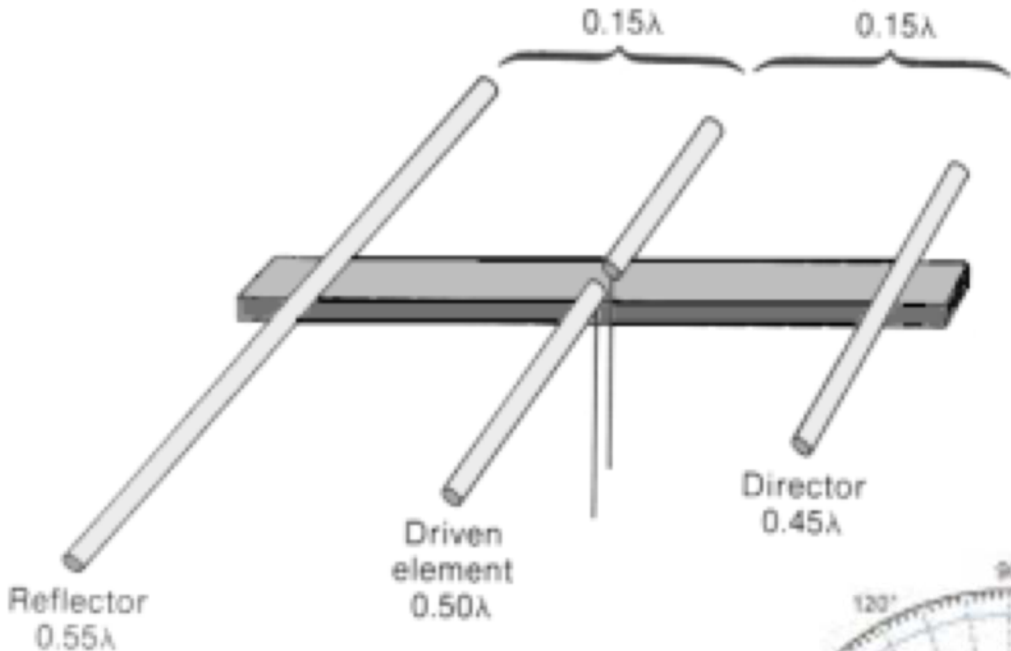


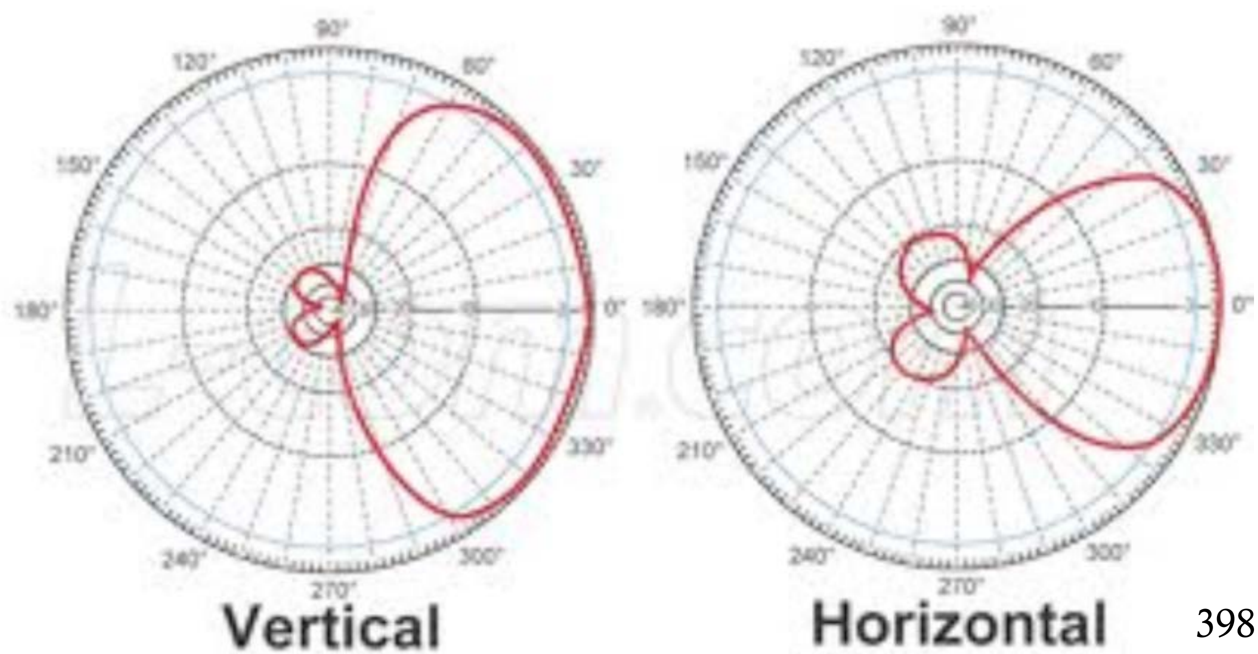
standing waves

"Fourier Optics" of radio waves, light, x-ray, sound, etc.

Directional Antennas

- For example, “Yagi” antenna

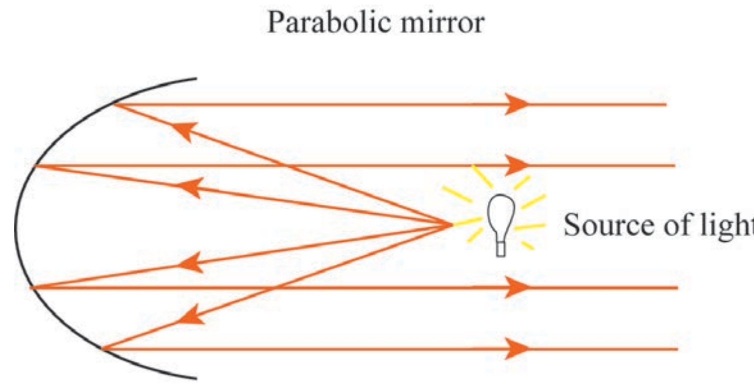




http://tymkrs.tumblr.com
http://www.l-com.com

Reflection can focus EM radiation

Small parabolic mirror
for tiny-wavelength
visible light

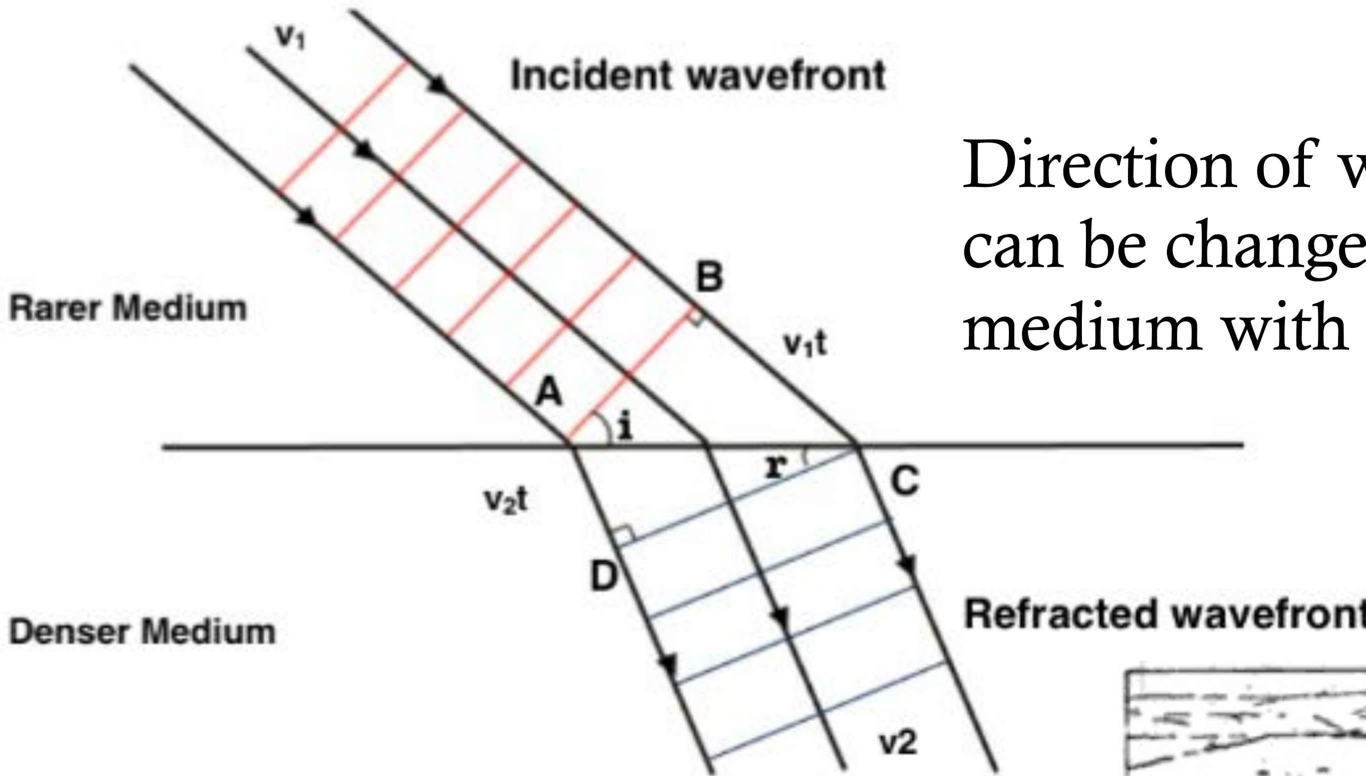


Geometric Optics views directions of wave fronts as rays, but actually governed by Huygen's principle.

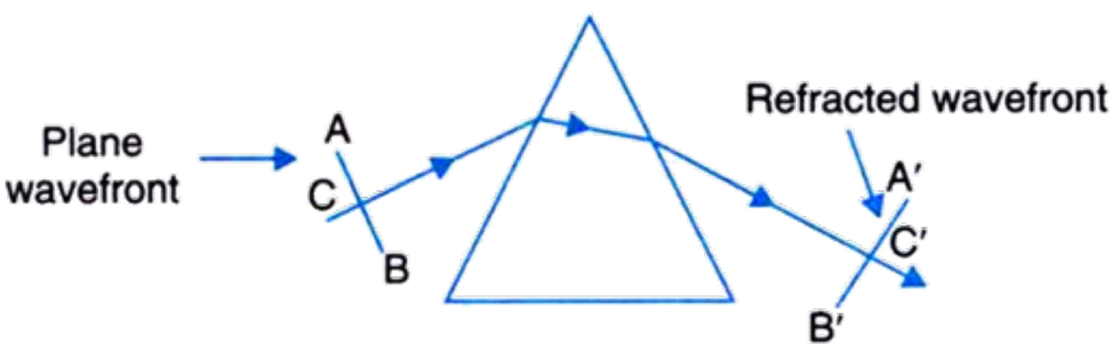
World's largest parabolic antenna in Puerto Rico
for long-wavelength radio waves

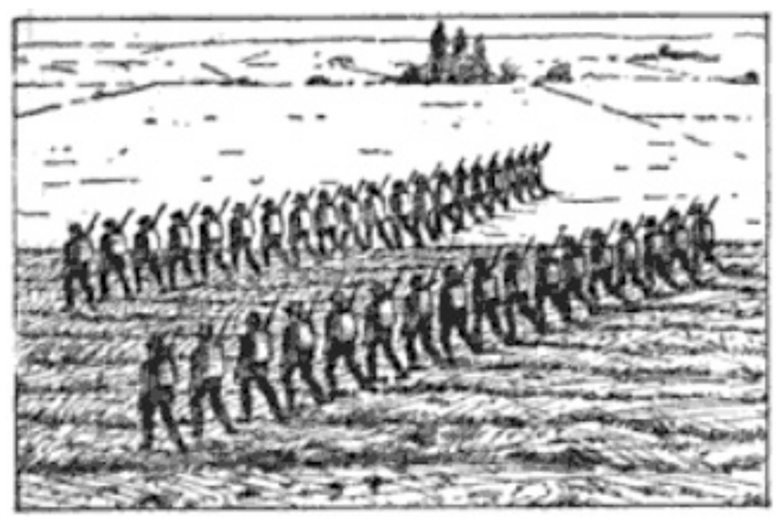
3-foot dish for short wavelength
microwave

Refraction - Prism



Direction of wave front (ray) can be changed by entering a medium with different velocity.

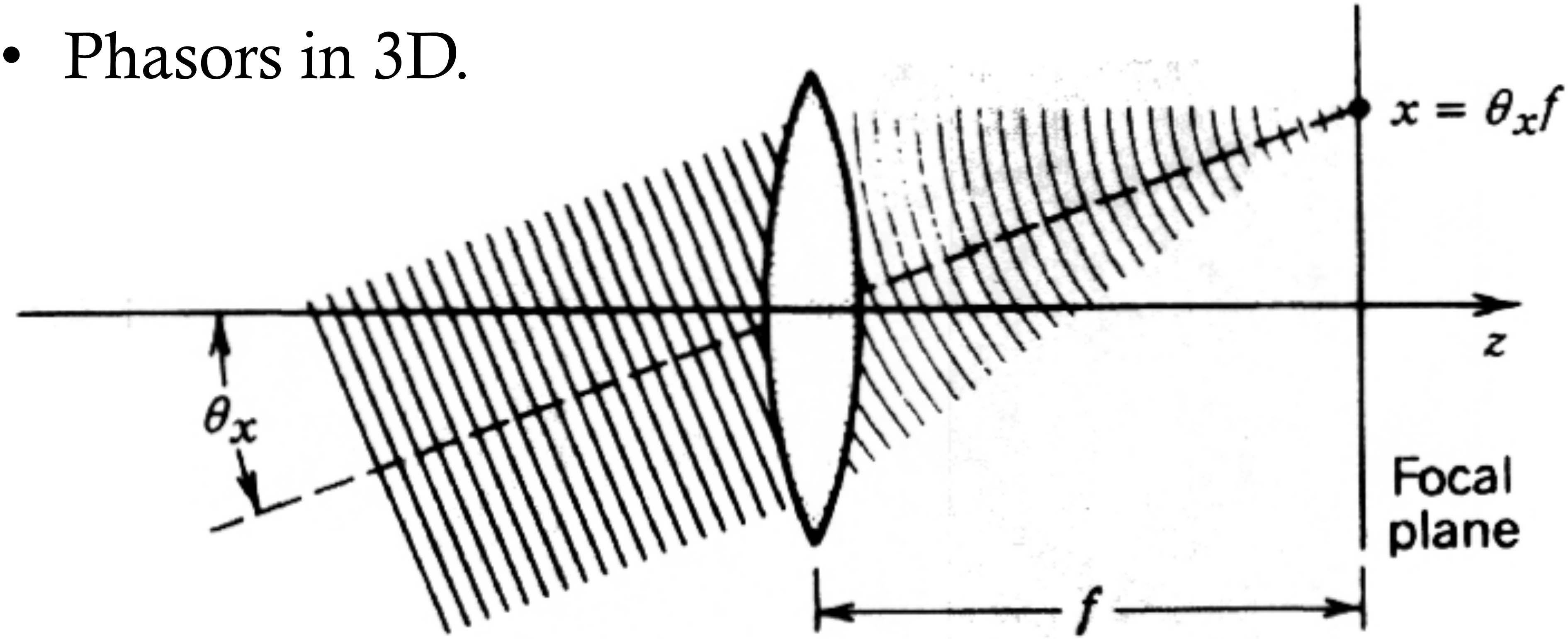




Lines of soldiers leaving a cornfield will change the angle of their wave front.

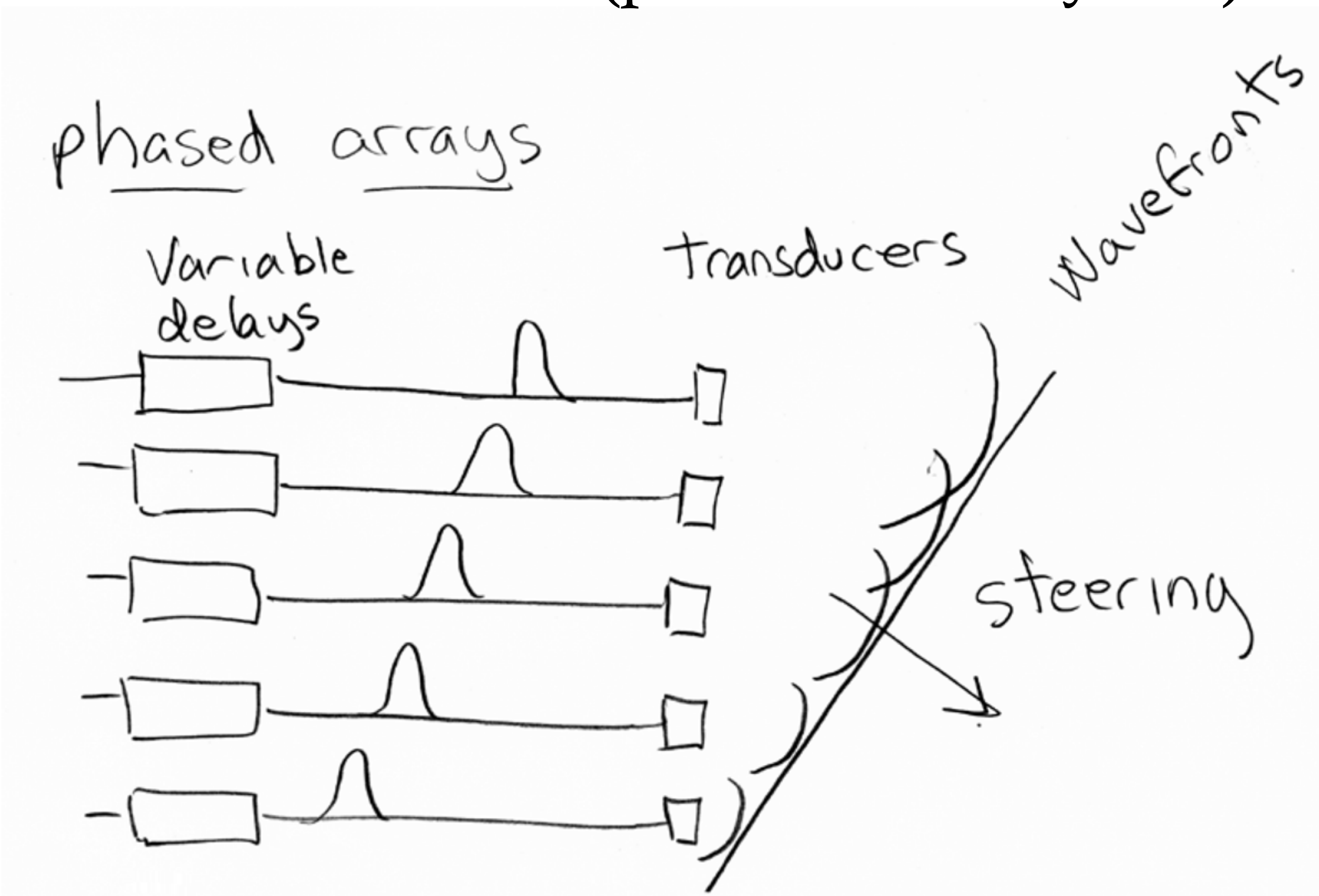
Lens – Glass slows down light

- Glass in lens slows down light.
- Wave front falls further behind at thick center of lens.
- *Fourier Optics*, not *Geometric Optics* is what's actually happening.
- Phasors in 3D.

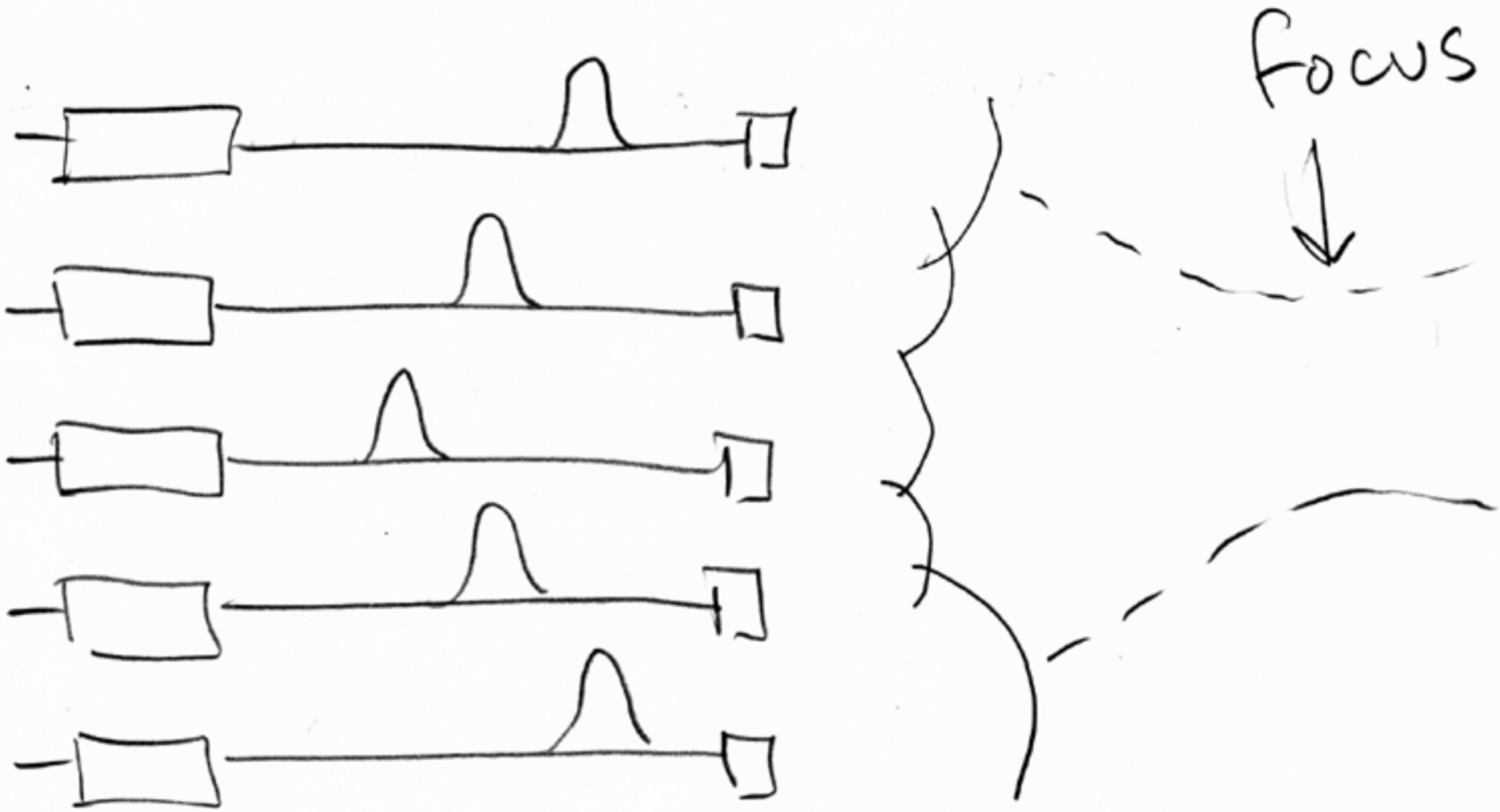


Phased Arrays

- Can act as a controllable prism (delays, like glass).
- e.g., steering ultrasound with a phased array of ultrasound transducers (piezoelectric crystals).



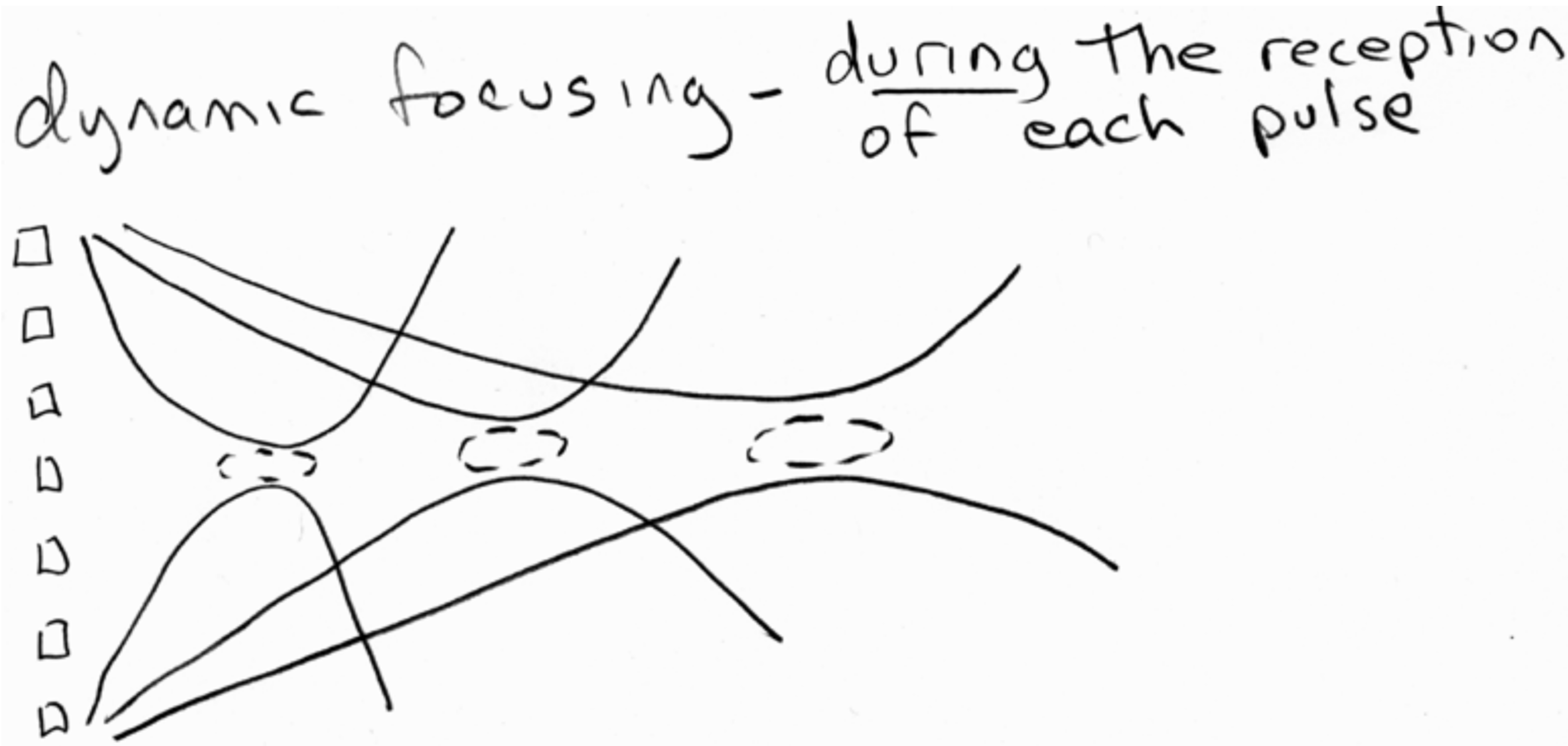
• Can also act as controllable lens



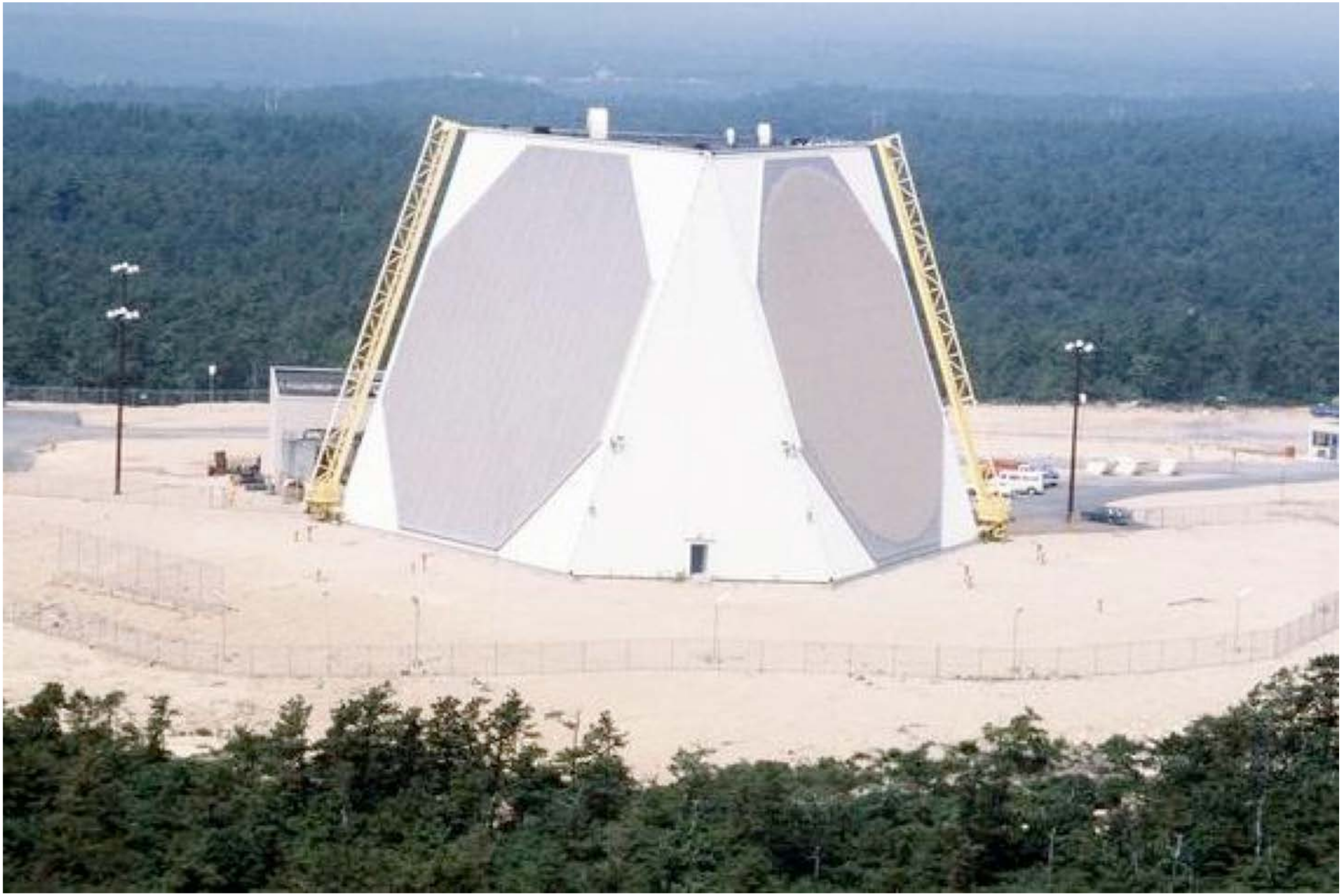
transmit same as receive

"listening" arrays on submarines

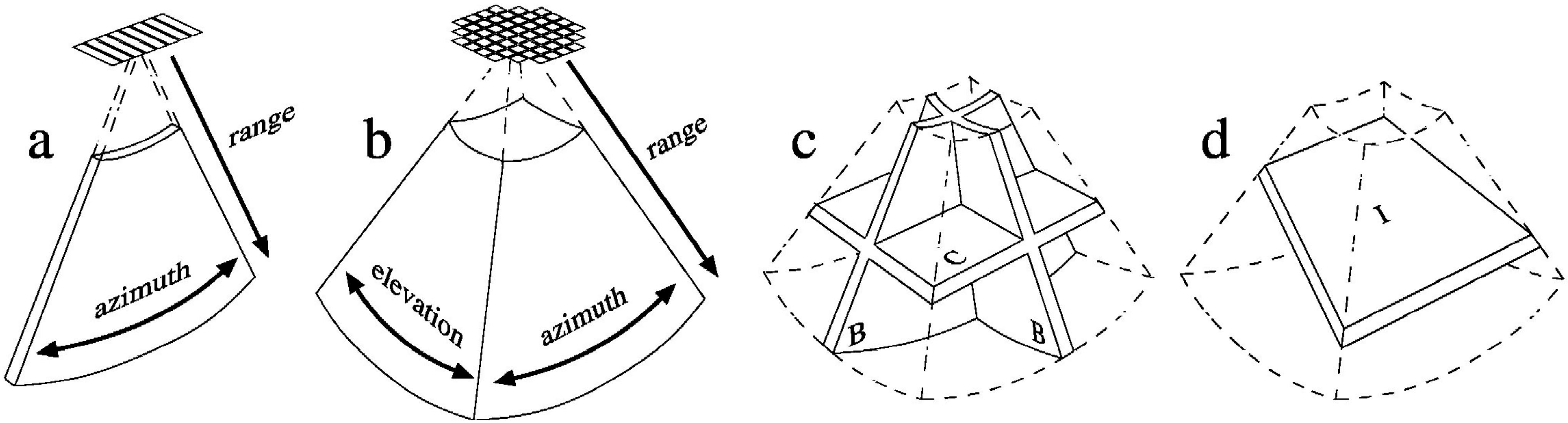
- When receiving echoes from pulses, it can refocus at greater distances as time progresses

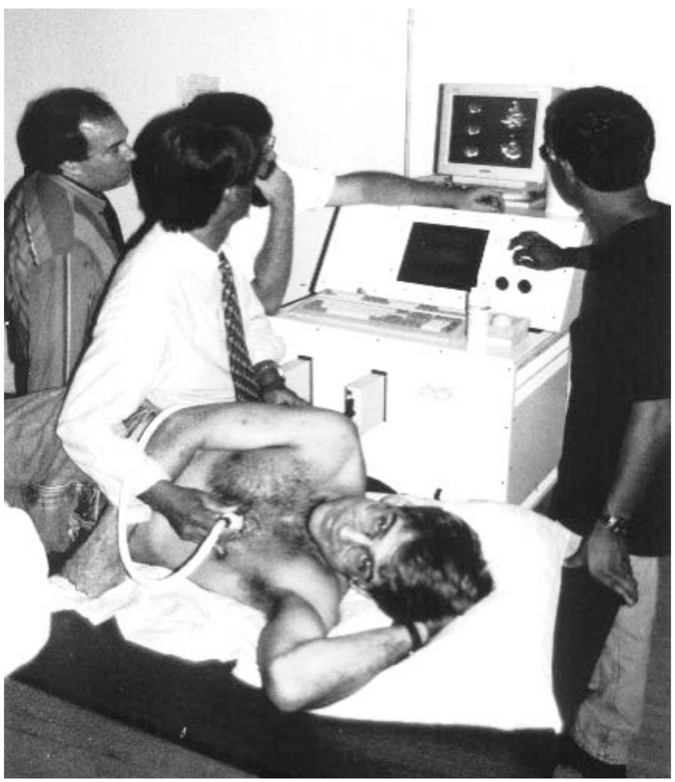


Phased Array Radar



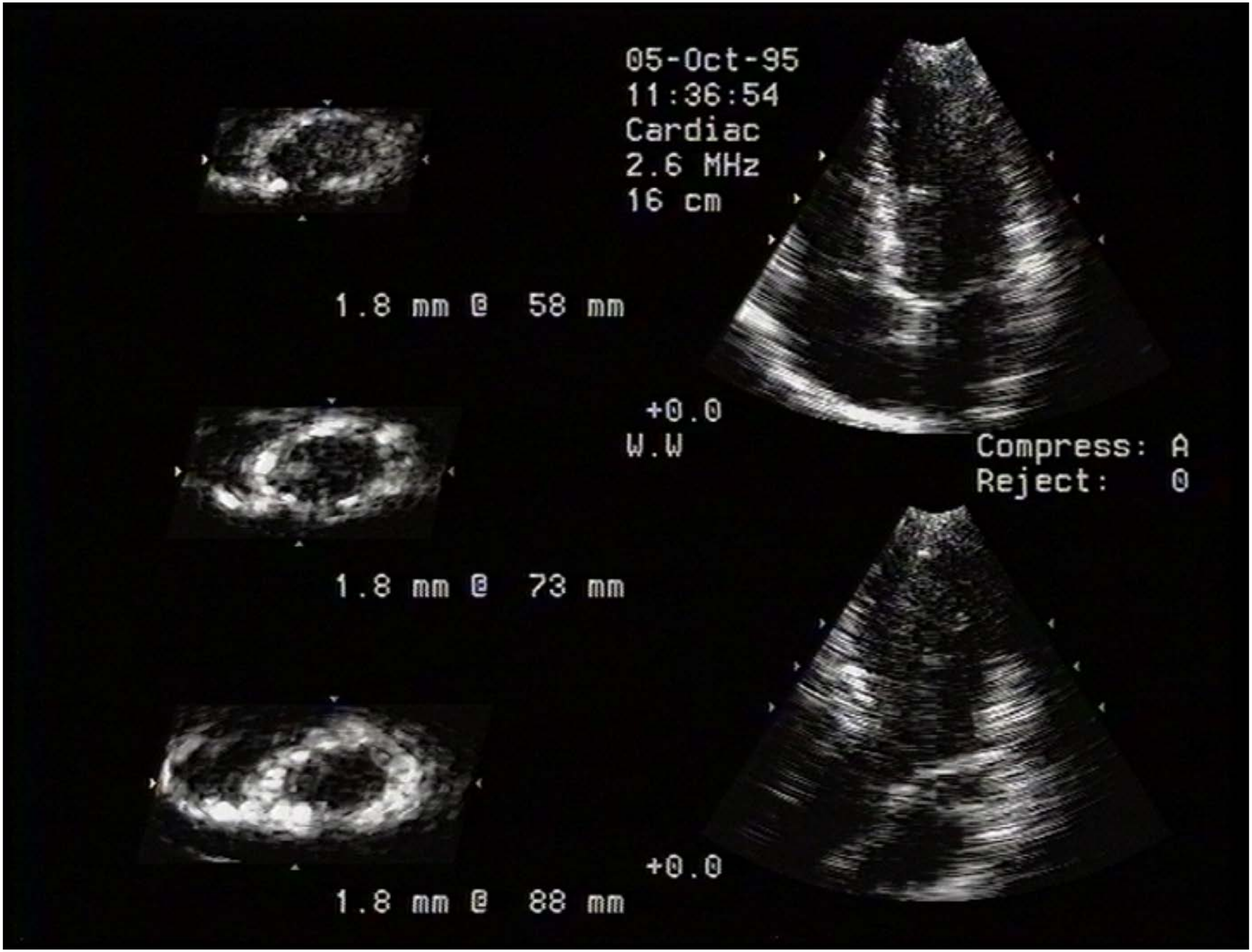
RT3D ultrasound, von Ramm, Duke, 1990s

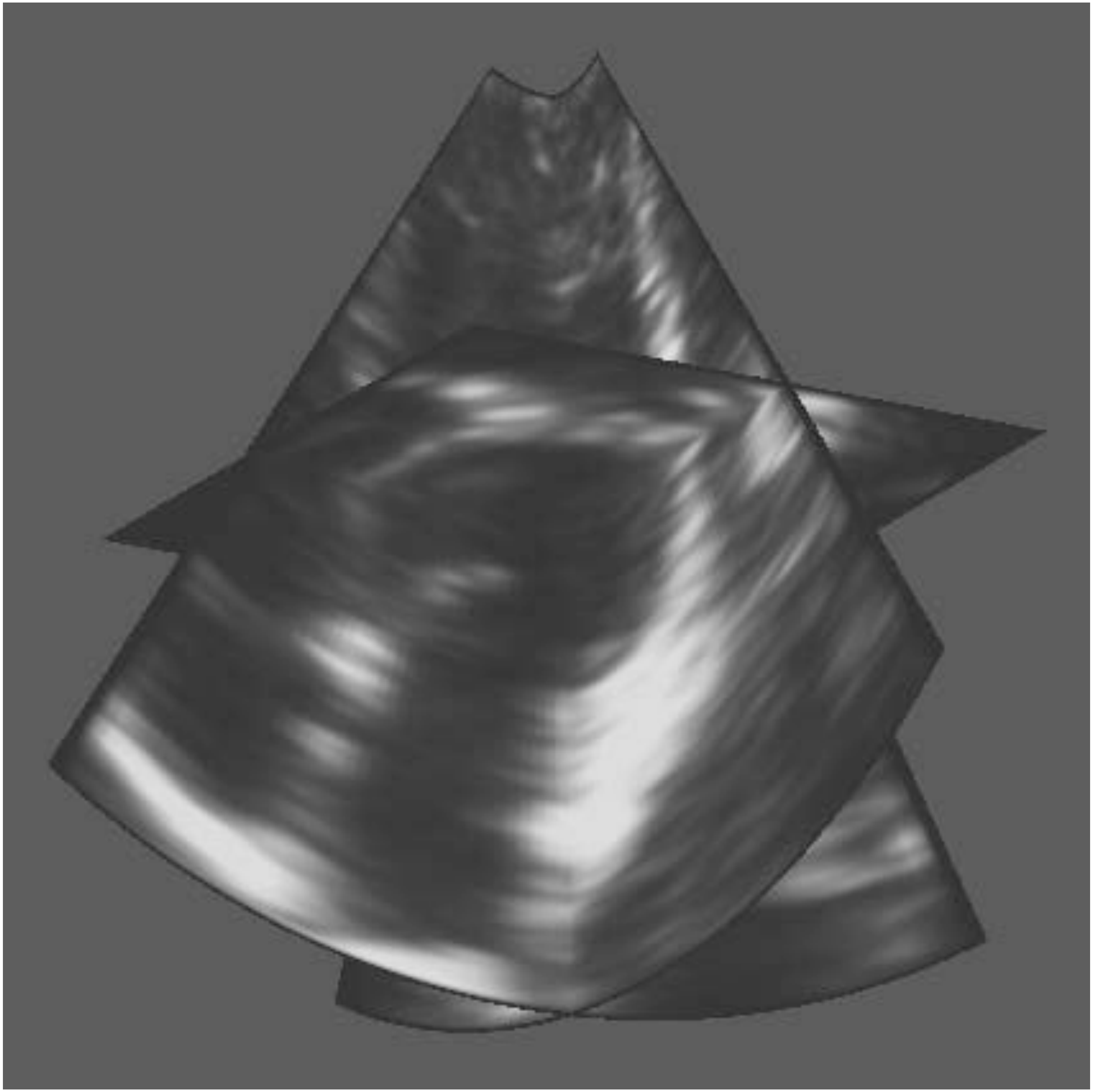


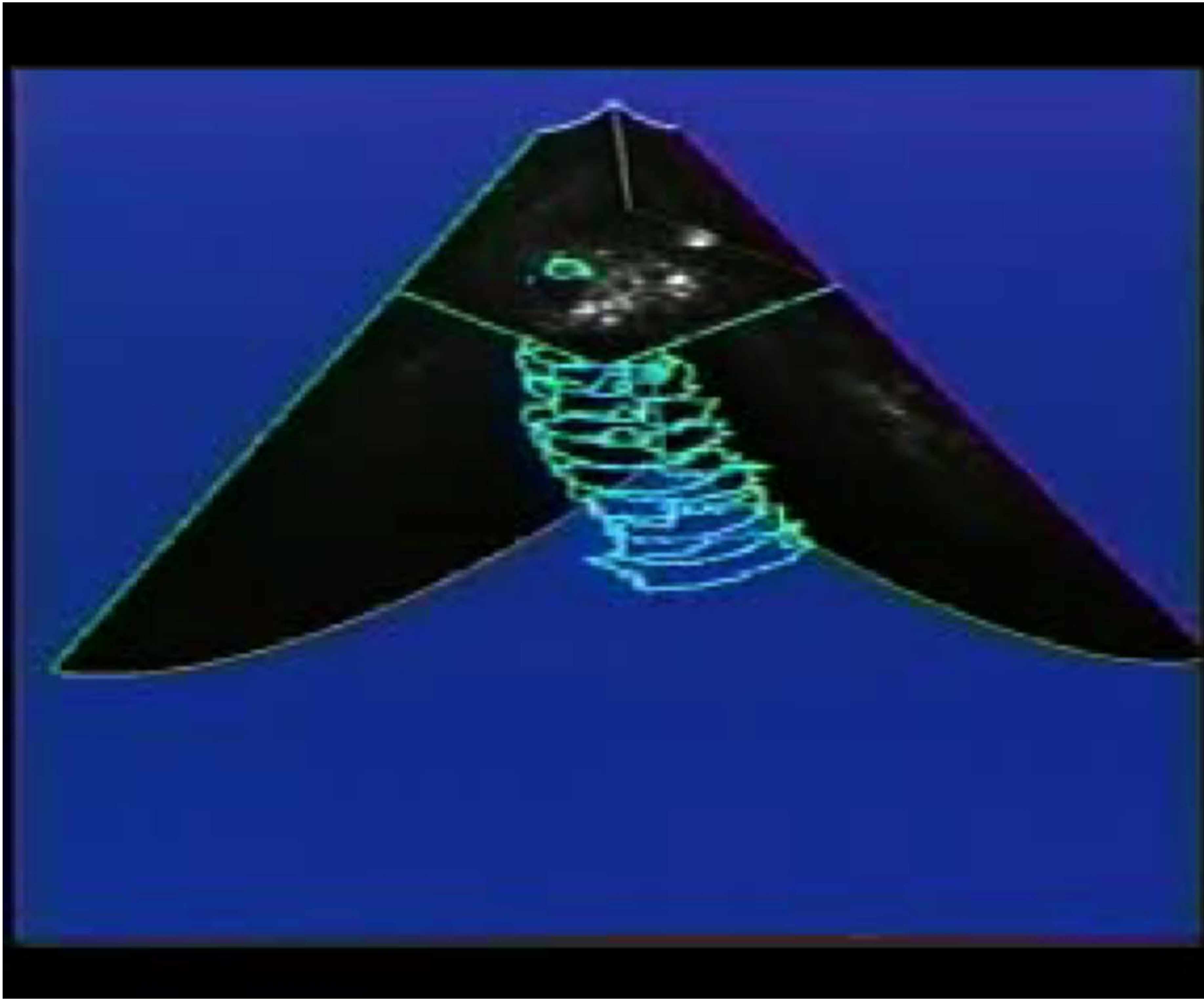


Multiple receive circuits do 16:1 parallel processing beamforming in 16 directions at once from a single broad transmit transmit pulse.

Fast enough to capture 3D heart without gating to ECG

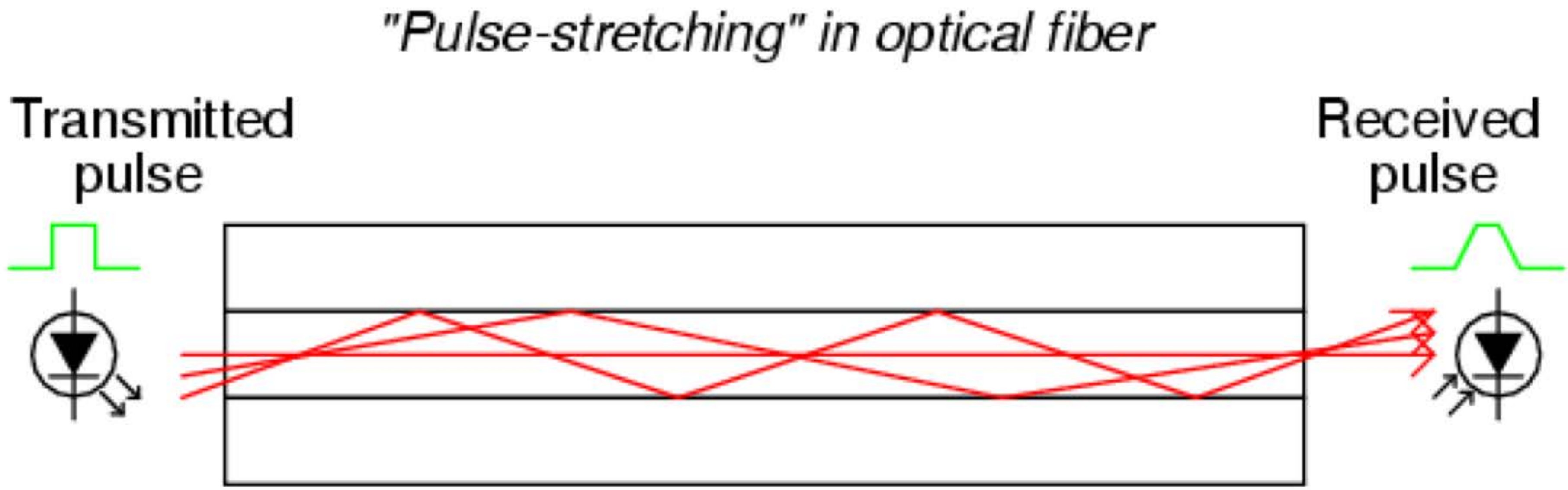

05-Oct-95
11:36:54
Cardiac
2.6 MHz
16 cm
1.8 mm @ 58 mm
+0.0
W.W
Compress: A
Reject: 0
1.8 mm @ 73 mm
+0.0
1.8 mm @ 88 mm





Pulse Stretching in Optical Fiber

- Temporal combination of waves traveling different distances in an optical fiber. Stretches a square pulse into a trapezoid.



LED

monochromatic but not *coherent*

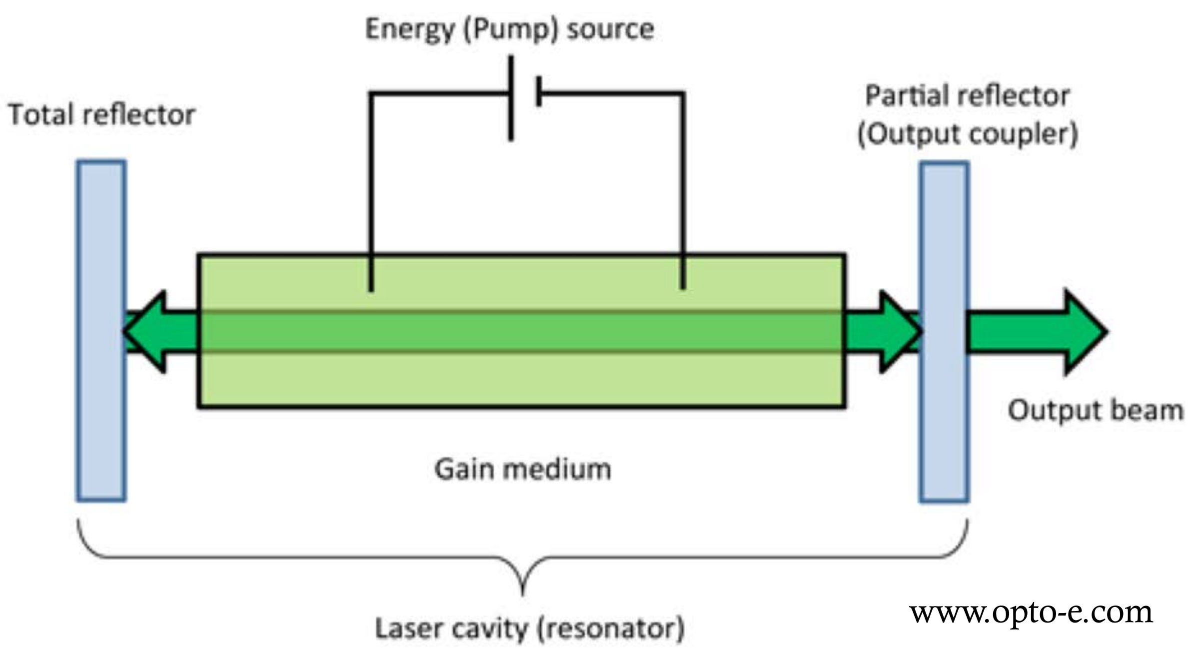
http://www.allaboutcircuits.com/textbook/digital/chpt-14/optical-data-communication/

Laser – Monochromatic Coherent

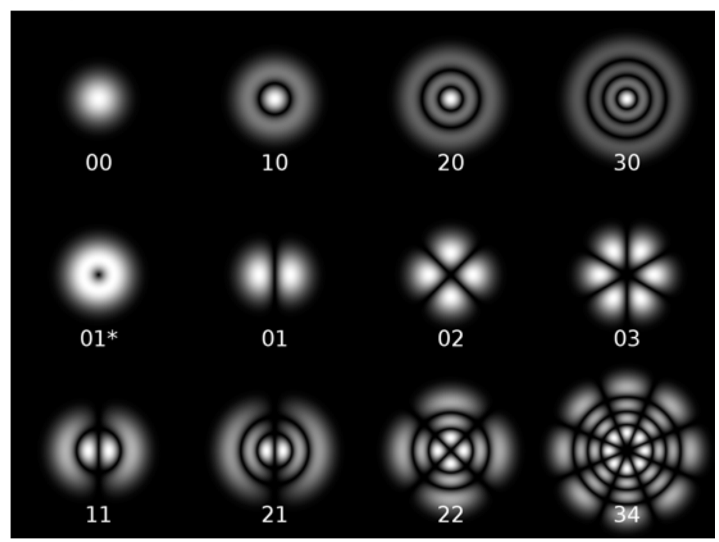
- Light Amplification by Stimulated Emission of Radiation
- Atoms *pumped* into their excited states.
- Once excited, atoms convert this stored energy into light by *stimulated emission.*
- Resonant cavity determines *longitudinal modes* of the constructive/destructive interference patterns between reflectors.
- TEM_{00} is the central of the *transverse modes* of the main beam.

Delayed by wavelength $\lambda \times n$

$\lambda \times 1$ $\lambda \times 2$ $\lambda \times 3$ …



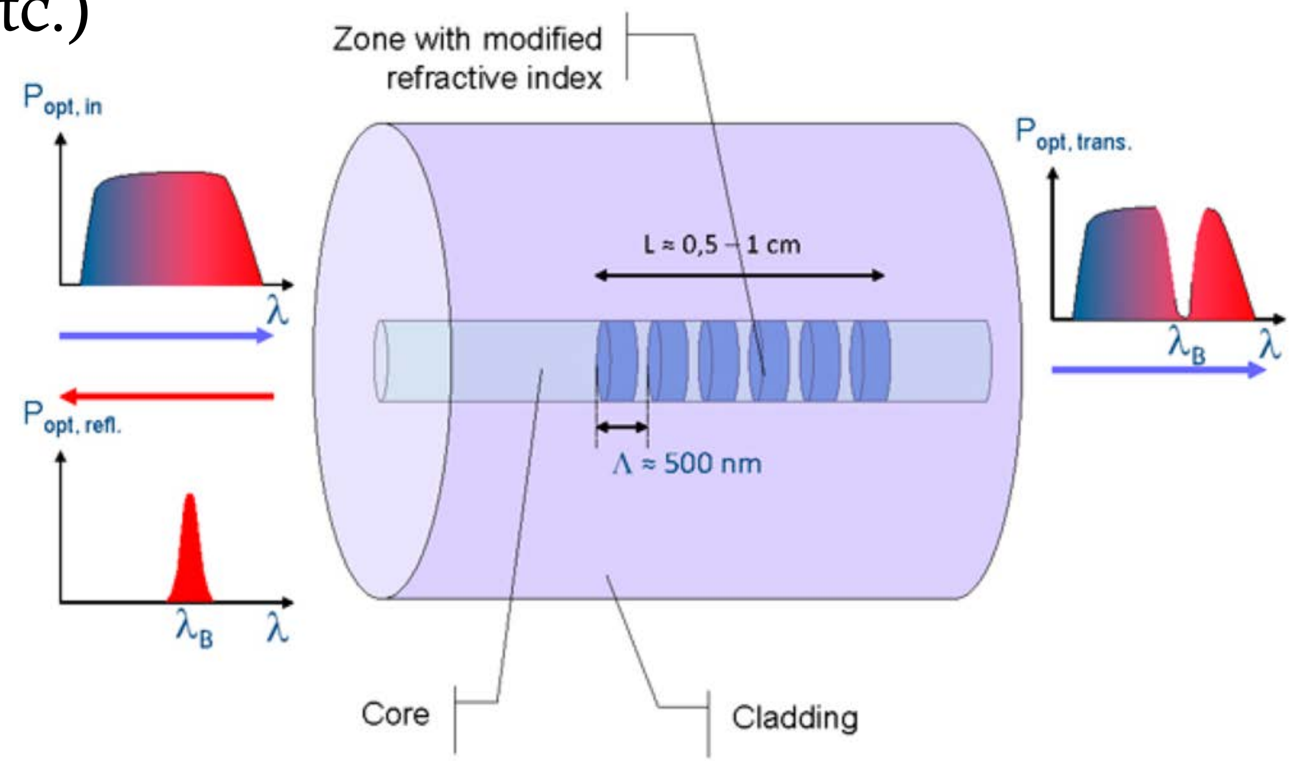
www.opto-e.com



wikipedia.org

Fiber Optic Grating (Bragg) Sensor

- Small region in optical fiber with multiple evenly spaced grating.
- Specific frequency of light enhanced in reflection (or removed from transmission) depends on spacing of grating.
- Great noise immunity (isolated light signal).
- Can sense anything that changes length of fiber (temperature, force, sound, etc.)

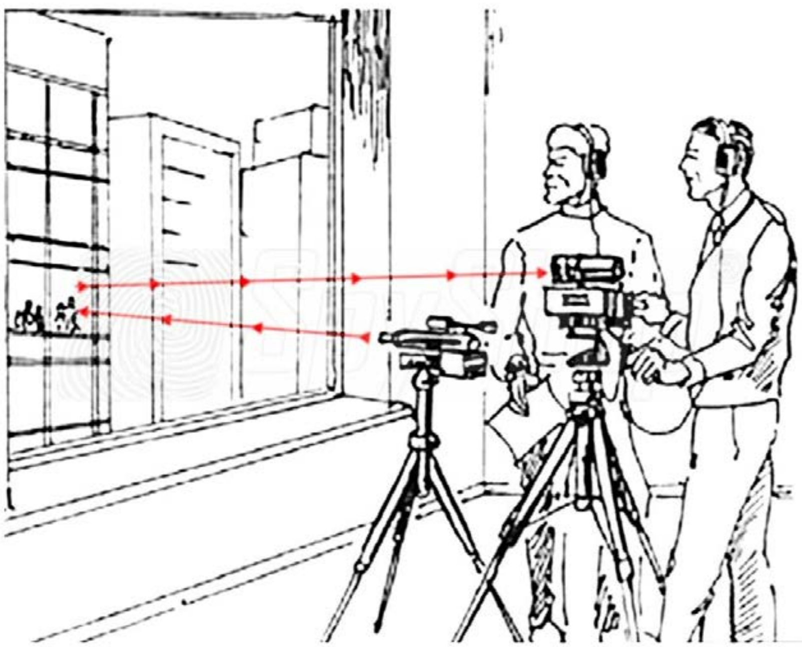


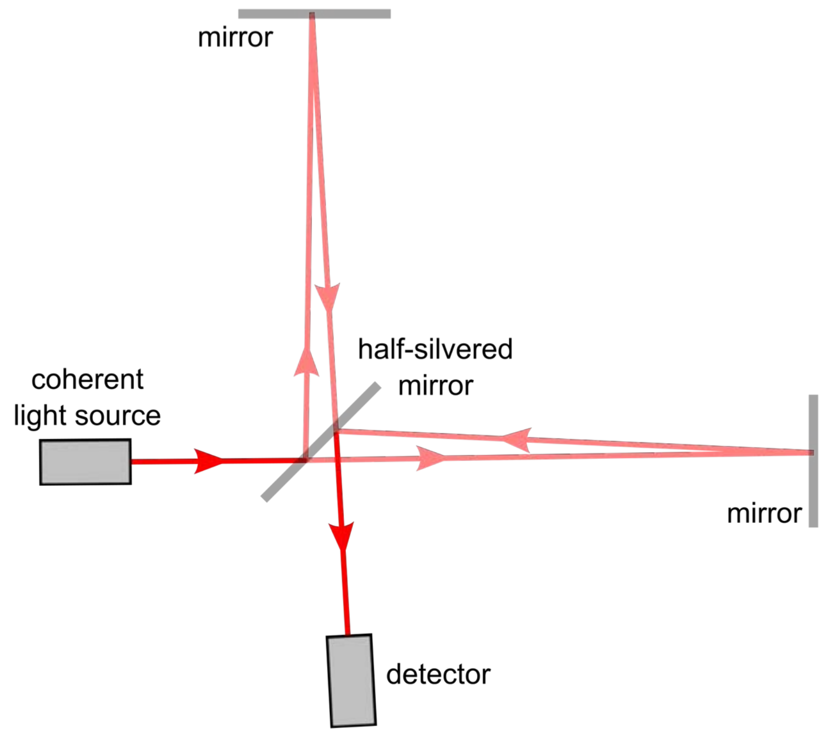
Laser-Based Microphonics

Can read sound at a distance.

Russians bugged US embassy in Moscow bouncing off windows.

Uses *interferometry* to measure within 1 wavelength.

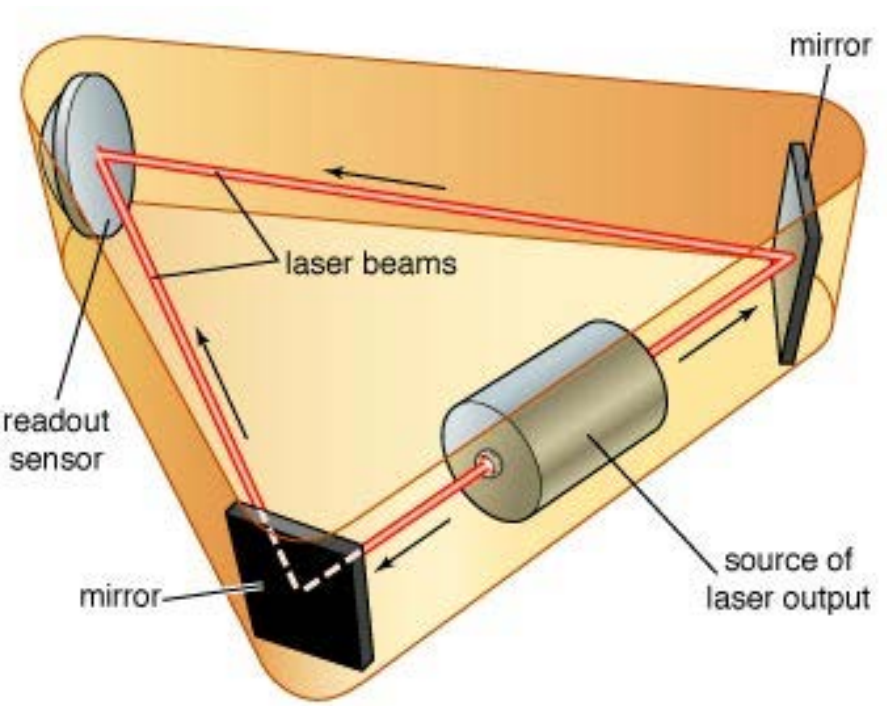


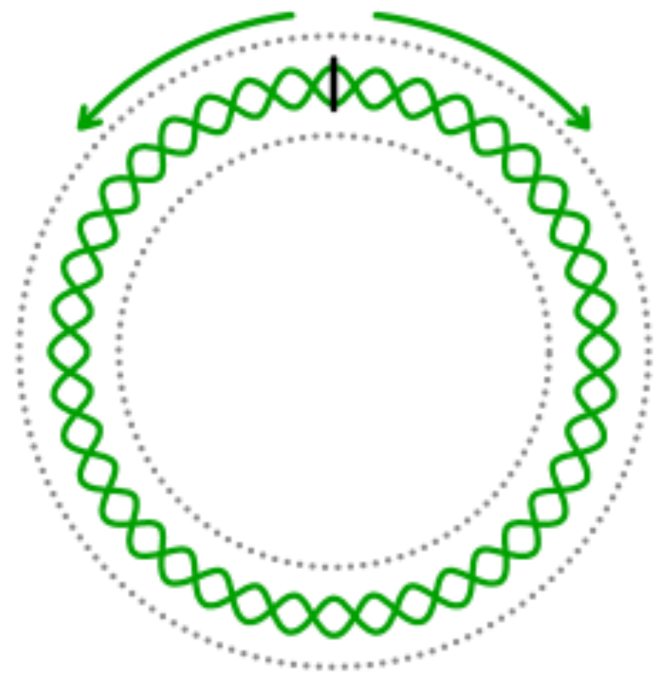


Ring Laser Gyroscope

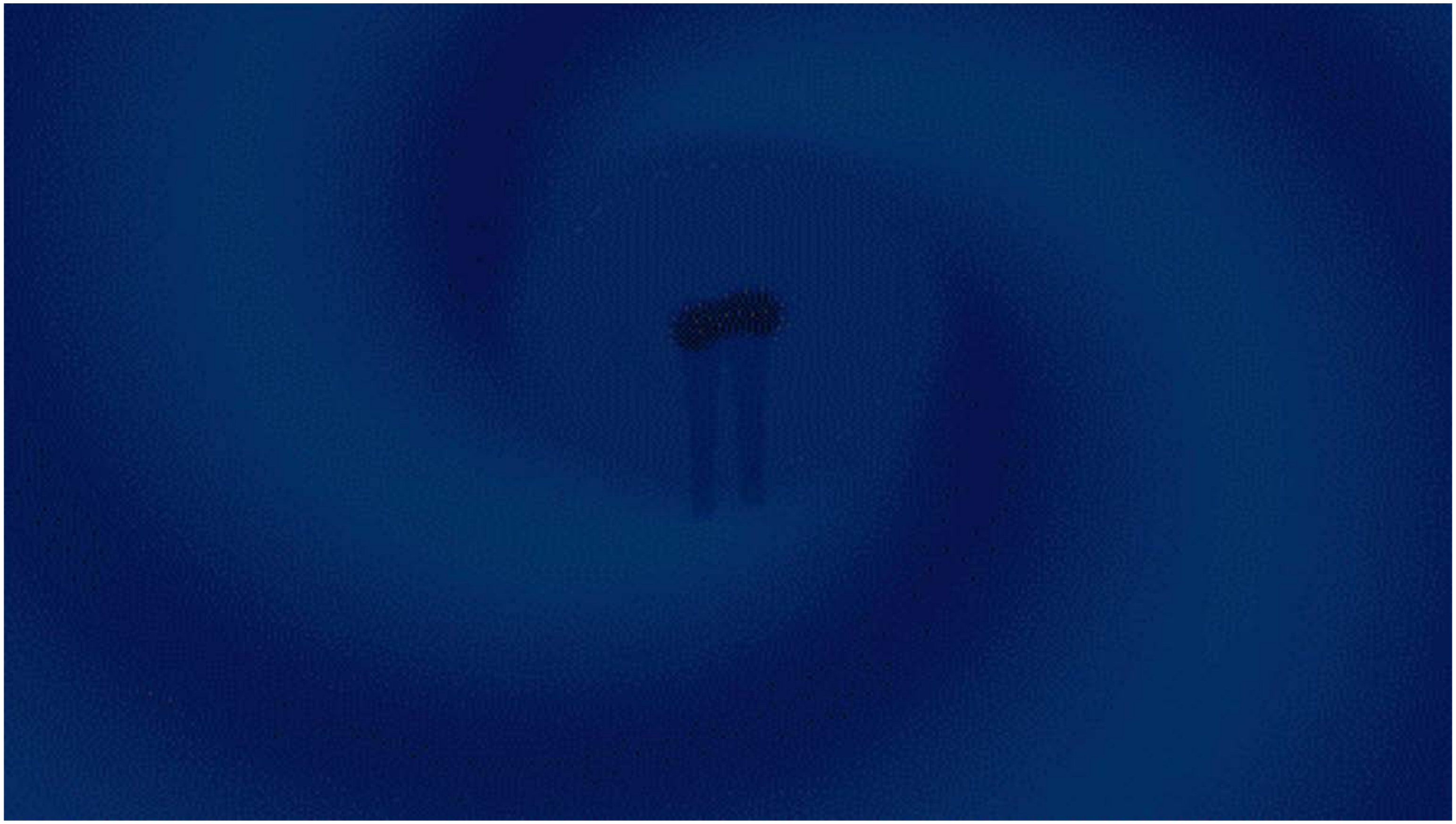
Laser transmitting both direction around a “ring” (actually a triangle or square).

Standing waves form (like on the guitar string) which are stationary when “ring” is rotated, so beats can be counted as they pass by sensor.





Gravity Waves



- Laser Interferometer Gravitational-Wave Observatory (LIGO).
- Detects gravity waves from black holes spiraling to merge, 3 billion light years away.
- At that moment, more power than all stars in the observable universe.

https://www.nytimes.com/2016/06/16/science/ligo-gravitational-waves-einstein.html

https://www.ligo.org/detections/ringtones/gw150914.m4r

Batteries

Engineering is always a TRADE-OFF

cost

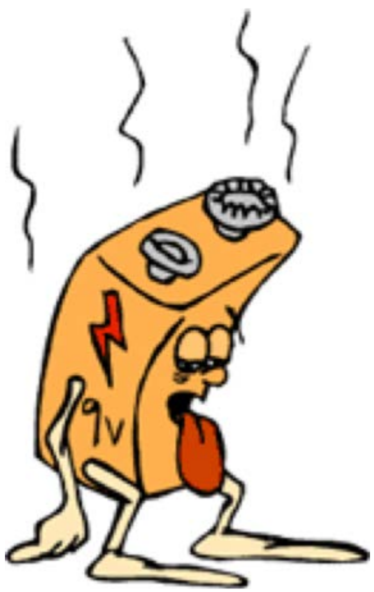
size

weight

energy density

fire-explosion hazard

toxicity upon disposal



Energy in a Battery

- Power = Current × Voltage
  - (how bright is bulb)
- Energy = Power × Time
  - (how much gas is in generator tank)
  - for a given battery, described as *ampere hours*
    actually current × voltage × time (voltage is a given)
- Energy Density
  - how much energy per volume or weight.
- Batteries can get hot if short-circuited
  - all energies released at once
  - some may catch fire or explode

Electrochemical Reaction

– *Electron affinity* determines *reduction potentials*.

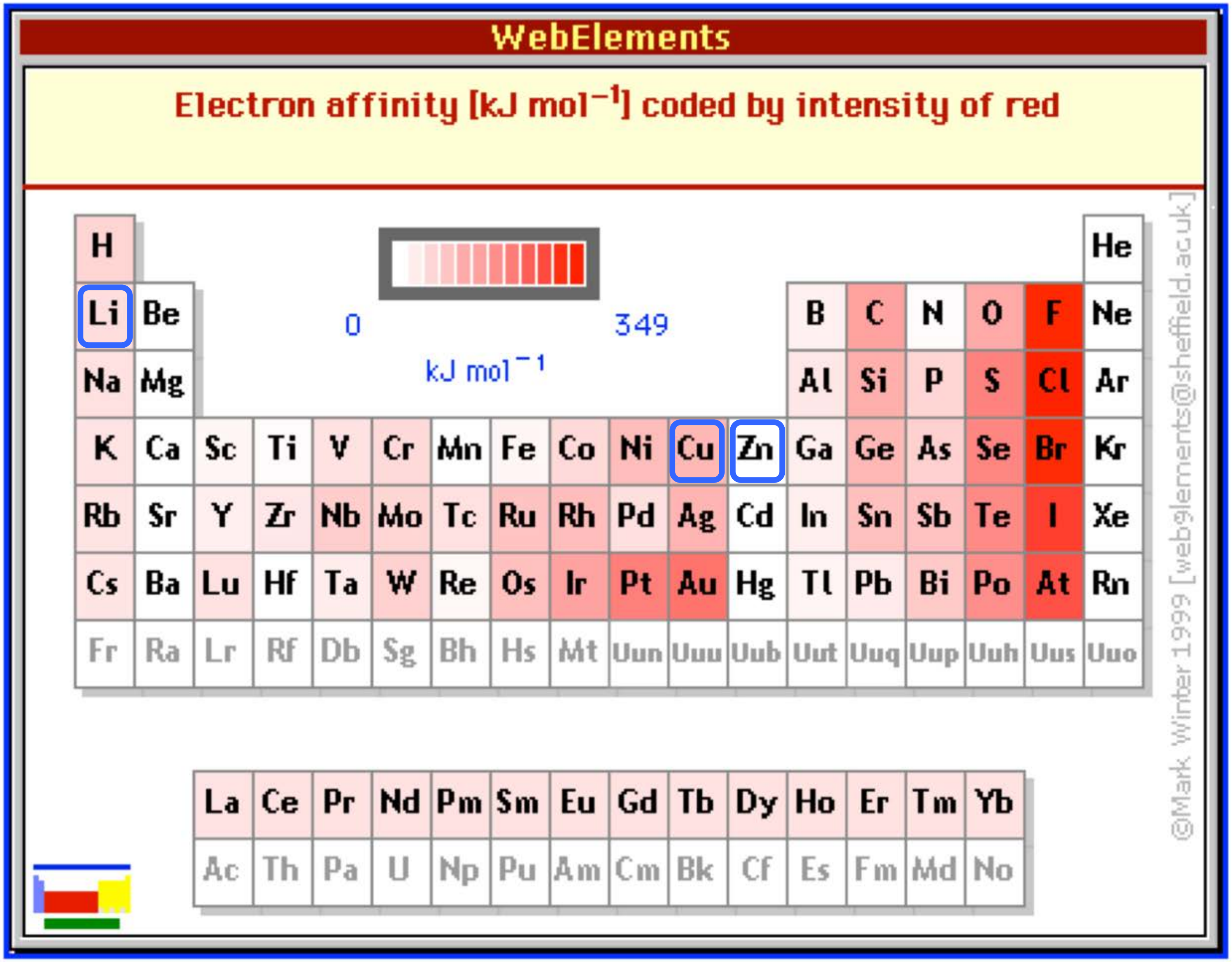


Table of Standard reduction potentials

www.vaxasoftware.com

Half reaction	ε° (V)
$Li^+ + e^- \rightarrow Li_{(s)}$	–3.040
$K^+ + e^- \rightarrow K_{(s)}$	–2.924
$Ca^{2+} + 2e^- \rightarrow Ca_{(s)}$	–2.869
$Na^+ + e^- \rightarrow Na_{(s)}$	–2.7144
$Mg^{2+} + 2e^- \rightarrow Mg_{(s)}$	–2.3568
$Al^{3+} + 3e^- \rightarrow Al_{(s)}$	–1.676
$Mn^{2+} + 2e^- \rightarrow Mn_{(s)}$	–1.182
$2H_2O + 2e^- \rightarrow H_{2(g)} + 2OH^-$	–0.828
$Zn^{2+} + 2e^- \rightarrow Zn_{(s)}$	–0.7621
$Cr^{3+} + 3e^- \rightarrow Cr_{(s)}$	–0.74
$Fe^{2+} + 2e^- \rightarrow Fe_{(s)}$	–0.440
$Cr^{3+} + e^- \rightarrow Cr^{2+}{}_{(s)}$	–0.41
$Cd^{2+} + 2e^- \rightarrow Cd_{(s)}$	–0.40
$Ni^{2+} + 2e^- \rightarrow Ni_{(s)}$	–0.236
$Sn^{2+} + 2e^- \rightarrow Sn_{(s)}$	–0.14
$Pb^{2+} + 2e^- \rightarrow Pb_{(s)}$	–0.1266
$\mathbf{2H^+ + 2e^- \rightarrow H_{2(g)}}$	**0.0000**
$Cu^{2+} + e^- \rightarrow Cu^+{}_{(s)}$	+0.160
$SO_4^{2-} + 4H^+ + 2e^- \rightarrow SO_{2(g)} + 2H_2O$	+0.17
$Cu^{2+} + 2e^- \rightarrow Cu_{(s)}$	+0.3394

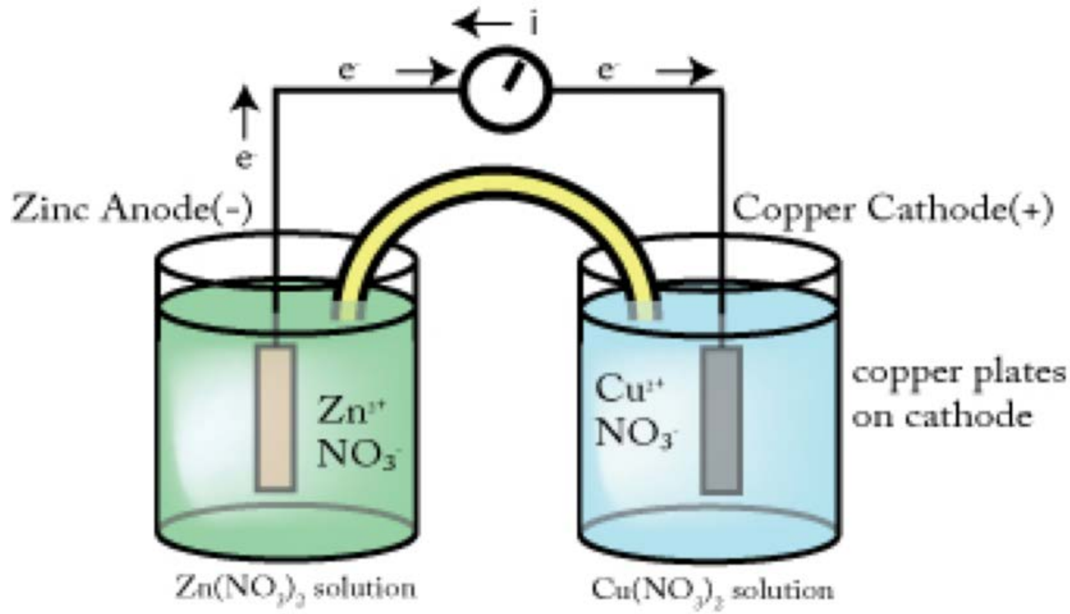
wants to *give* electron

+REDUCING

$Cu^{+} + e^{-} \rightarrow Cu_{(s)}$	+0.5180
$I_{2(s)} + 2e^{-} \rightarrow 2I^{-}$	+0.535
$MnO_4^{-} + 2H_2O + 3e^{-} \rightarrow MnO_{2(s)} + 4OH^{-}$	+0.597
$Fe^{3+} + e^{-} \rightarrow Fe^{2+}$	+0.769
$Ag^{+} + e^{-} \rightarrow Ag_{(s)}$	+0.7991
$NO_3^{-} + 4H^{+} + 3e^{-} \rightarrow NO_{(g)} + 2H_2O$	+0.96
$Br_{2(l)} + 2e^{-} \rightarrow 2Br^{-}$	+1.0775
$2IO_3^{-} + 12H^{+} + 10e^{-} \rightarrow I_{2(s)} + 6H_2O$	+1.2093
$O_{2(g)} + 4H^{+} + 4e^{-} \rightarrow 2H_2O$	+1.2288
$Cr_2O_7^{2-} + 14H^{+} + 6e^{-} \rightarrow 2Cr^{3+} + 7H_2O$	+1.33
$Cl_{2(g)} + 2e^{-} \rightarrow 2Cl^{-}$	+1.3601
$Au^{3+} + 3e^{-} \rightarrow Au_{(s)}$	+1.42
$PbO_{2(s)} + 4H^{+} + 2e^{-} \rightarrow Pb^{2+} + 2H_2O$	+1.458
$ClO^{-} + 2H^{+} + 2e^{-} \rightarrow Cl^{-} + H_2O$	+1.46
$MnO_4^{-} + 8H^{+} + 5e^{-} \rightarrow Mn^{2+} + 4H_2O$	+1.5119
$Au^{+} + e^{-} \rightarrow Au_{(s)}$	+1.68
$H_2O_{2(l)} + 2H^{+} + 2e^{-} \rightarrow 2H_2O$	+1.77
$F_{2(g)} + 2e^{-} \rightarrow 2F^{-}$	+2.890

+OXIDIZING

wants to *take* electron



Galvanic Cell

$E_{emf} > 0$

The cell reaction is

$$Zn(s) + Cu^{2+}(aq) \longrightarrow Zn^{2+}(aq) + Cu(s)$$

which can be divided into the half-reactions

equation flipped so we use *oxidation* potential (opposite sign)

Anode: $\boxed{Zn \longrightarrow Zn^{2+} + 2e^-}$ 0.76

Cathode: $Cu^{2+} + 2e^- \longrightarrow Cu$ 0.34

reduction potential

1.10 battery voltage

Then

$$\mathscr{E}^\circ_{cell} = \mathscr{E}^\circ_{Zn \to Zn^{2+}} + \mathscr{E}^\circ_{Cu^{2+} \to Cu}$$

- Battery voltage is sum of a reduction and oxidation potential.

Cathodes and Anodes

- A cathode is an electrode through which electrons enter a polarized electrical device.
- Thus in a…
  - Cathode Ray Tube (CRT), it is the terminal through which electrons enter the evacuated tube.
  - Diode, it is the electron-doped (N material) side of the device, through which electrons enter the device when forward biased.
  - Battery, it is the positive terminal, through which electrons enter the battery when it is discharging.
- The anode is the other terminal

Different Types of Batteries

- Non-Rechargeable
  - Alkaline and Lithium (different from Lithium Ion)
    - common AA's, AAA's, C's, D's, and 9V
  - Mercury, Silver, Zinc
    - tiny, in watches, hearing aids, car key remotes.
- Rechargeable
  - Nickle-Cadmium (NiCad), Lead-Acid, Lithium-Ion

http://www.ehso.com/ehshome/batteries.php

Which types are bad in the landfill?

- Really bad
  - lead, cadmium, and mercury (mad as a hatter), lithium-ion
- Somewhat bad
  - silver, zinc, and nickel, lithium
- OK to dump in trash
  - Alkaline (since 1997, used to have mercury before)

http://www.grinningplanet.com/2004/12-21/battery-recycling-article.htm

Non-Rechargeable Batteries

- Alkaline
  - cheaper, not as long-lasting

- Lithium (different from Lithium-ion)
  - come in same sizes
  - more expensive longer-lasting
  - works better in cold

Rechargeable Batteries

- generally have greater internal leakage, shorter "shelf-life"

- Nickel-Cadmium (Ni-Cads) and Nickel-Hydride
  - bad because heavy metals
  - limited # recharges
  - "memory" - deep discharge is best
  - being phased out

- Lithium-ion
  - greater # recharges, very high energy density
  - fire-explosion hazard, but getting better
  - favorite for phones and computers
  - no memory, in fact, better to "top off"

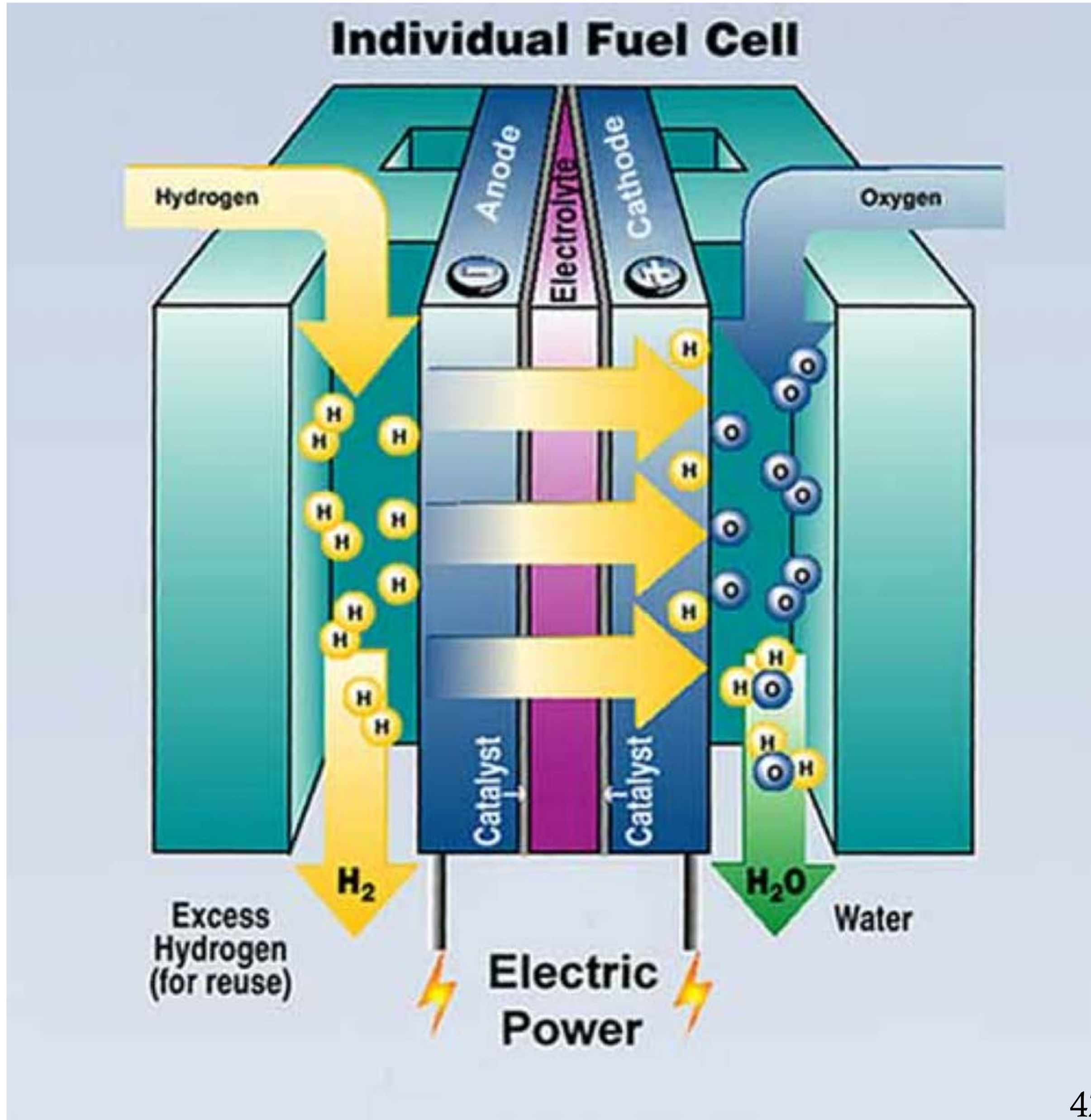


- Lead Acid
  - Very large currents
    - can turn the engine over in a car
  - Rechargeable many times
  - Large amount of lead! Very toxic!
  - Sulfuric acid - very dangerous.
  - Can explode (safer now that they are sealed)
  - We have figured out how to recycle
    - since expensive, large, and heavy

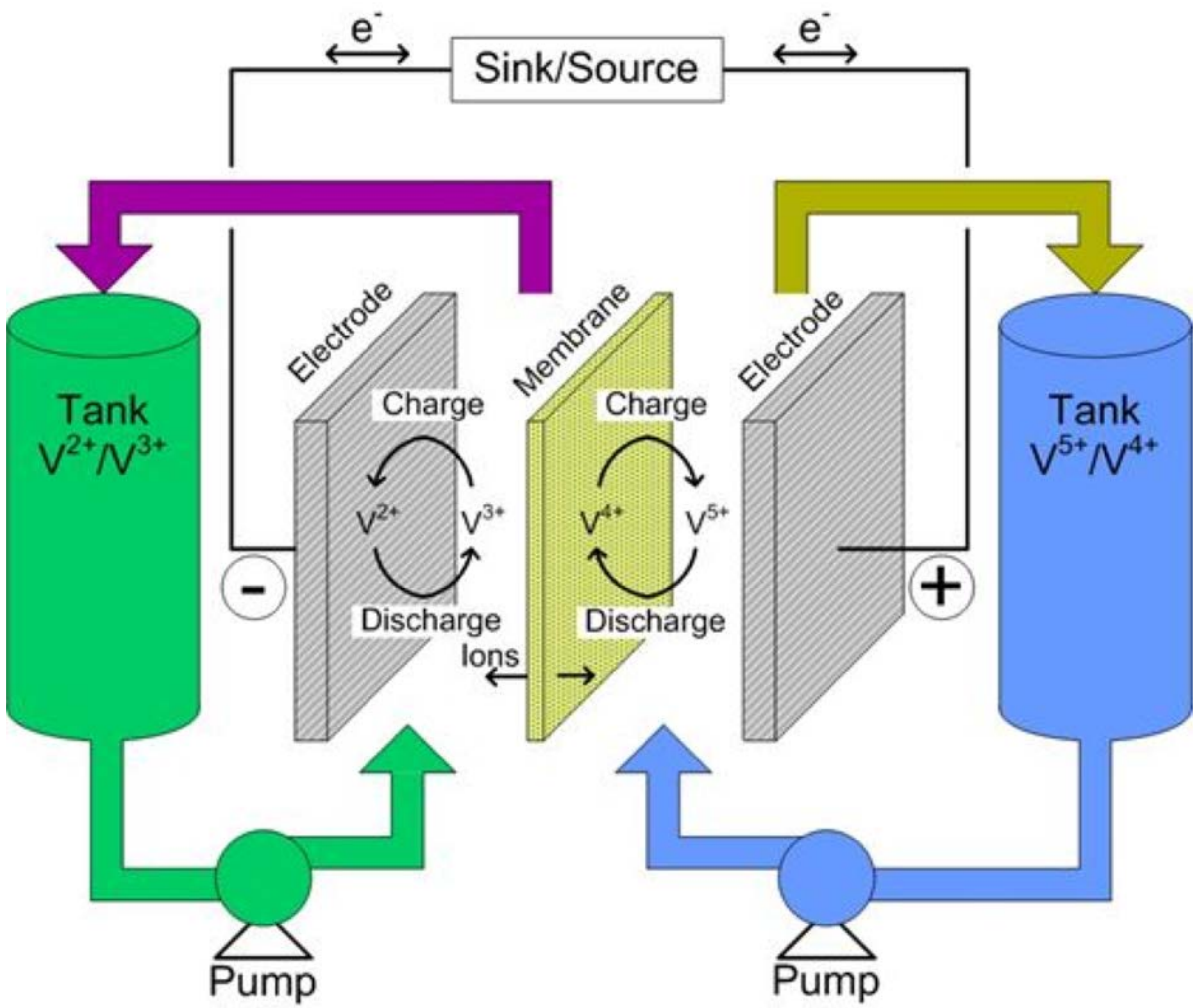
Alternate to battery is Fuel Cell

- Uses fuel continuously to produce electricity.

- Similar to how mitochondria proton pumps produce membrane potential in oxidative phosphorylation.



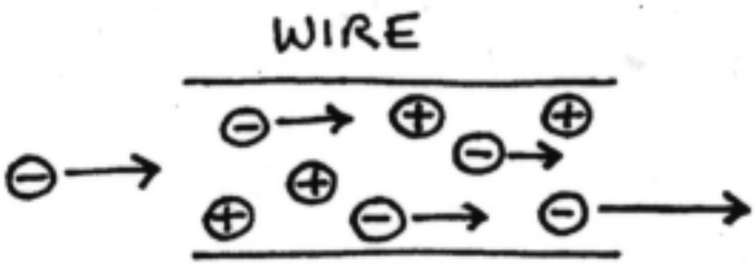
- Flow Batteries:
  - Hybrid between traditional batteries and fuel cells
  - Liquid electrolytes, cheap materials such as iron
  - Store huge amounts of energy as chemicals in tanks.
  - Rapid recharge by replacing the electrolyte liquid

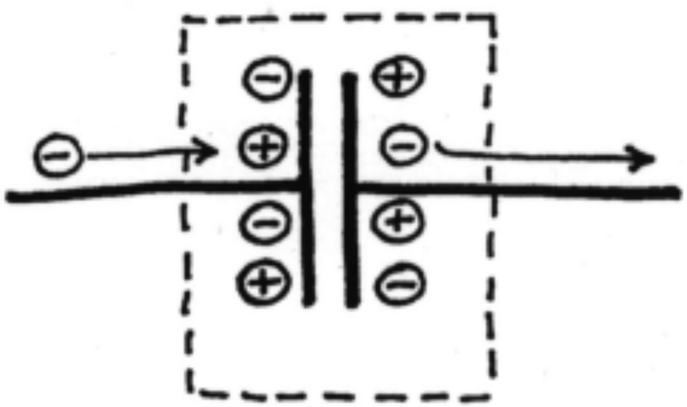


Possible solution to the problem of storing solar or wind energy

http://www.messib.eu

Ultimate "battery" may be Super-Capacitor

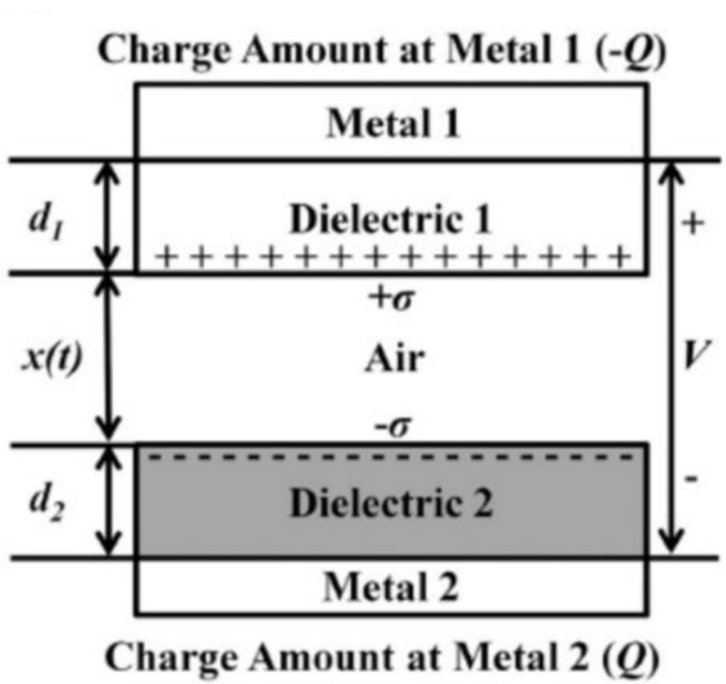




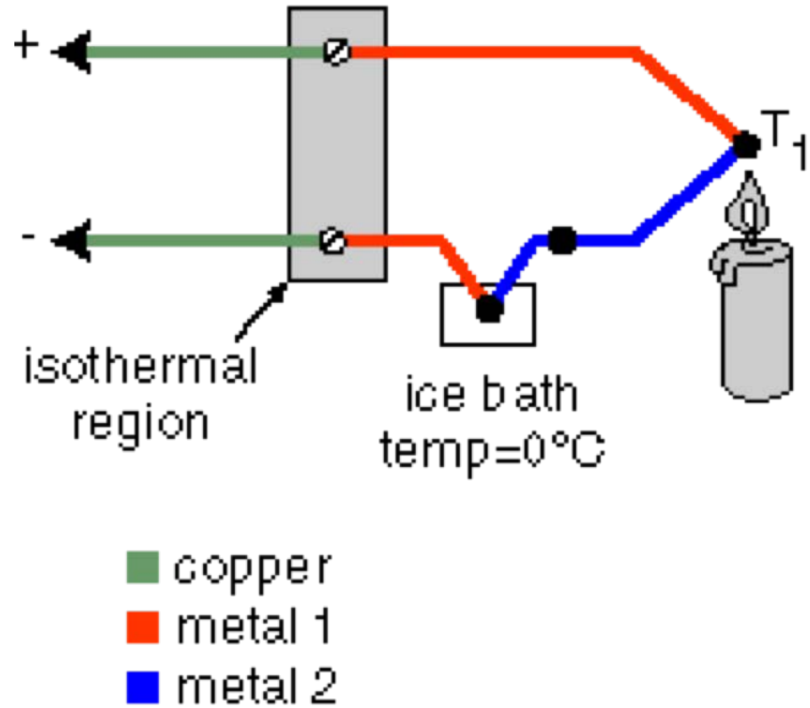
- Not electro-chemical
- Faster charge rate
- Higher energy density
- Just store electrons
- Infinite # recharges
- Non toxic materials
- Electric cars

Triboelectric Effect

- Accounts for static electricity.
- One material becomes electrically charged after being in contact with a different material (with or without friction).
- Exchange of electrons based on affinity for electron in triboelectric series.
- Unlike batteries, these materials must be insulators to maintain charge).



Seebeck Effect - Thermocouples



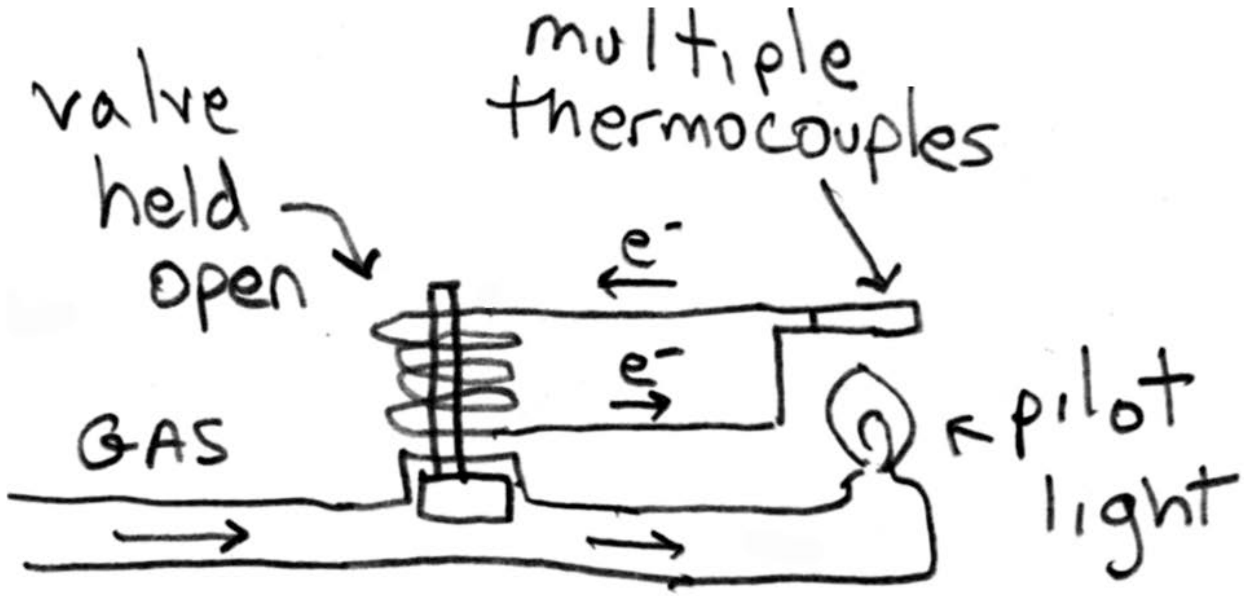
- Electron Affinity varies with temperature

- A *thermo-electric* (*Seebeck*) voltage is produced due to differences in electron affinities as a function of temperature.

2 thermocouples (1 as reference) used back-to-back.

Seebeck Effect - Thermocouples

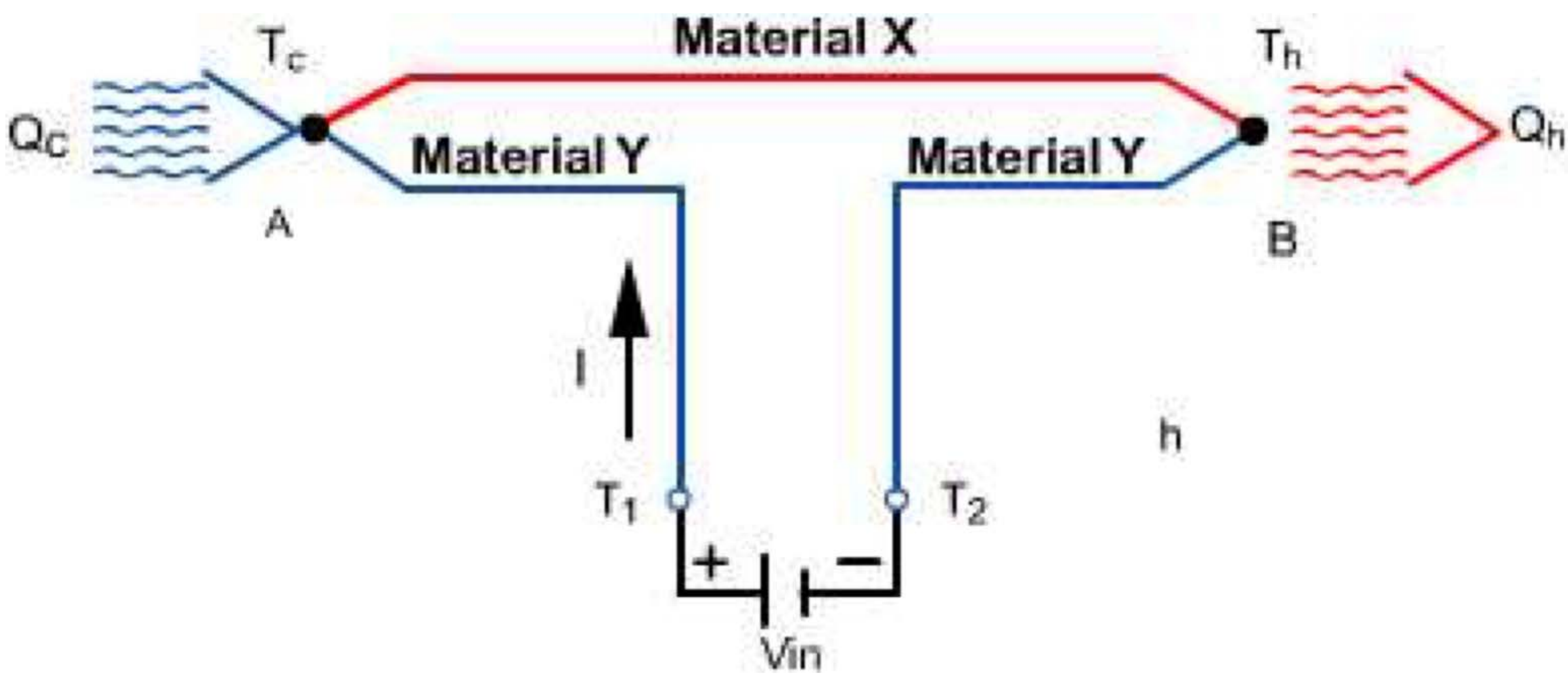
- Multiple thermocouples in series (a *thermopile*) can produce useful power, such as in water heater, to keep gas valve open only if pilot light remains lit.
- Example of a Latch (positive feedback).



If pilot light blows out, current stops and gas valve closes.

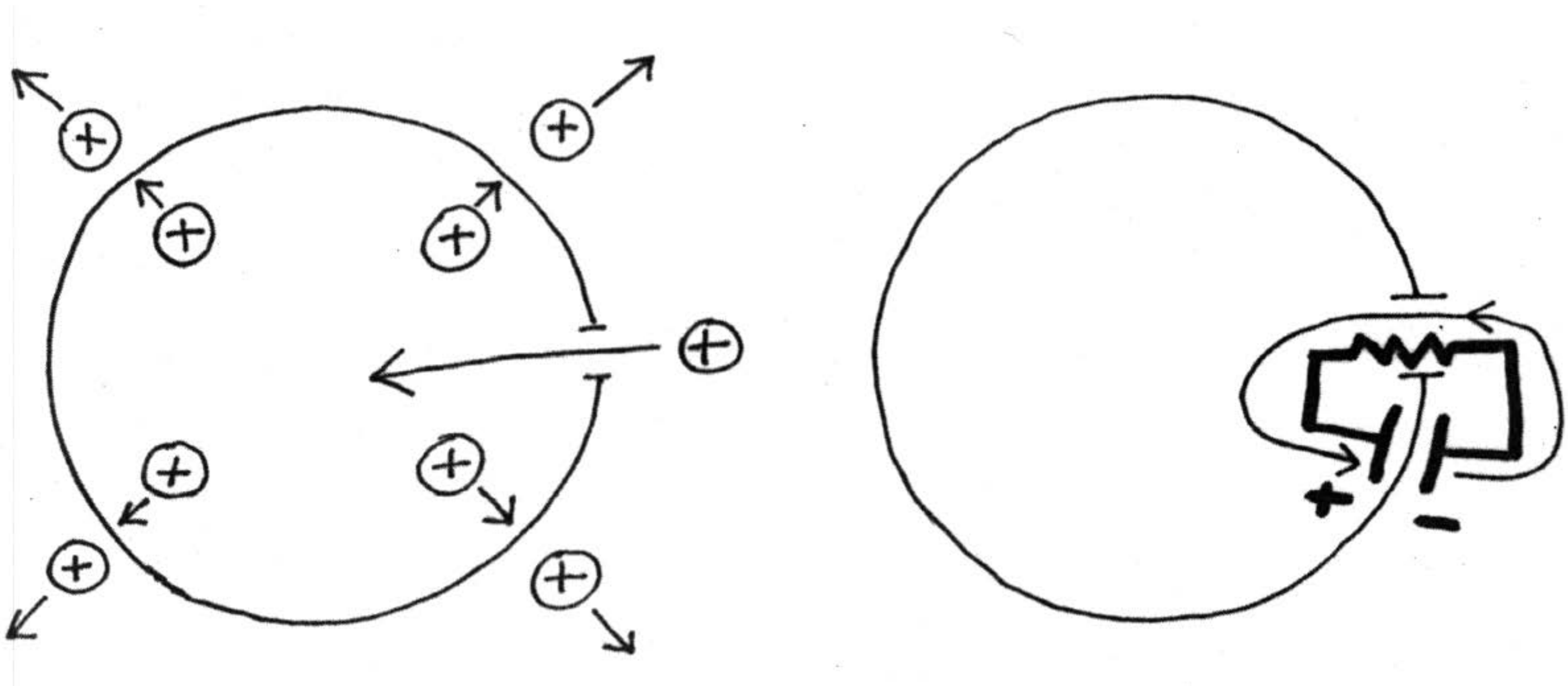
Peltier Effect – Thermocouples in reverse

- Pass a current through a pair of thermocouples.
- Energy in transferred from one to the other.
- Produces heating Q_h and cooling Q_c (in Watts)



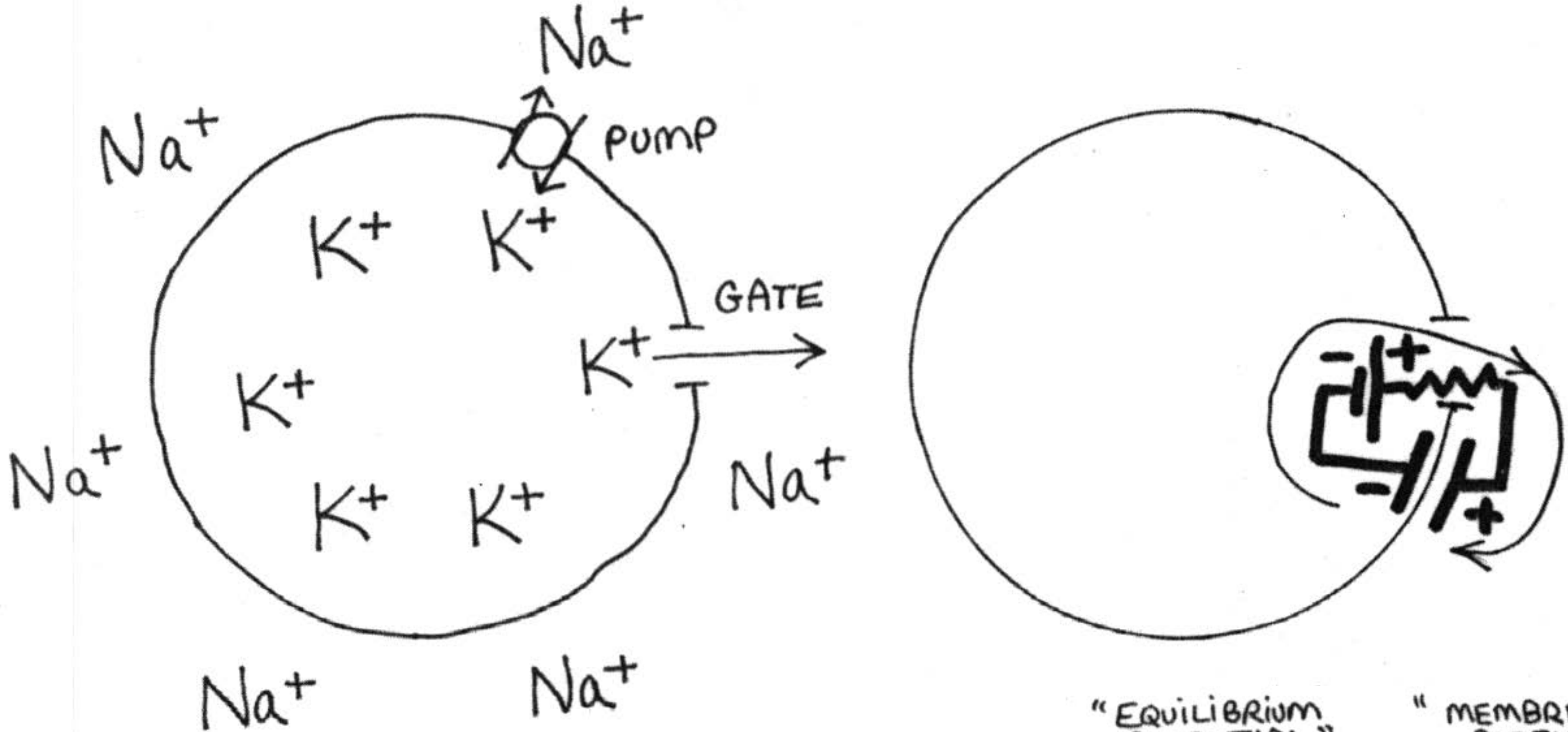
Capacitance and Resistance of Cells

- Cell membrane is a capacitor: nonconductive lipid bilayer between conductive extracellular and intracellular regions.
- Gates are channels with a different ion conductivity g_{ion} for specific ions (Na^+, K^+, etc.).



Entropy provides this "battery"

- Electro-chemical gradient (driving potential)



"EQUILIBRIUM POTENTIAL"

"MEMBRANE POTENTIAL"

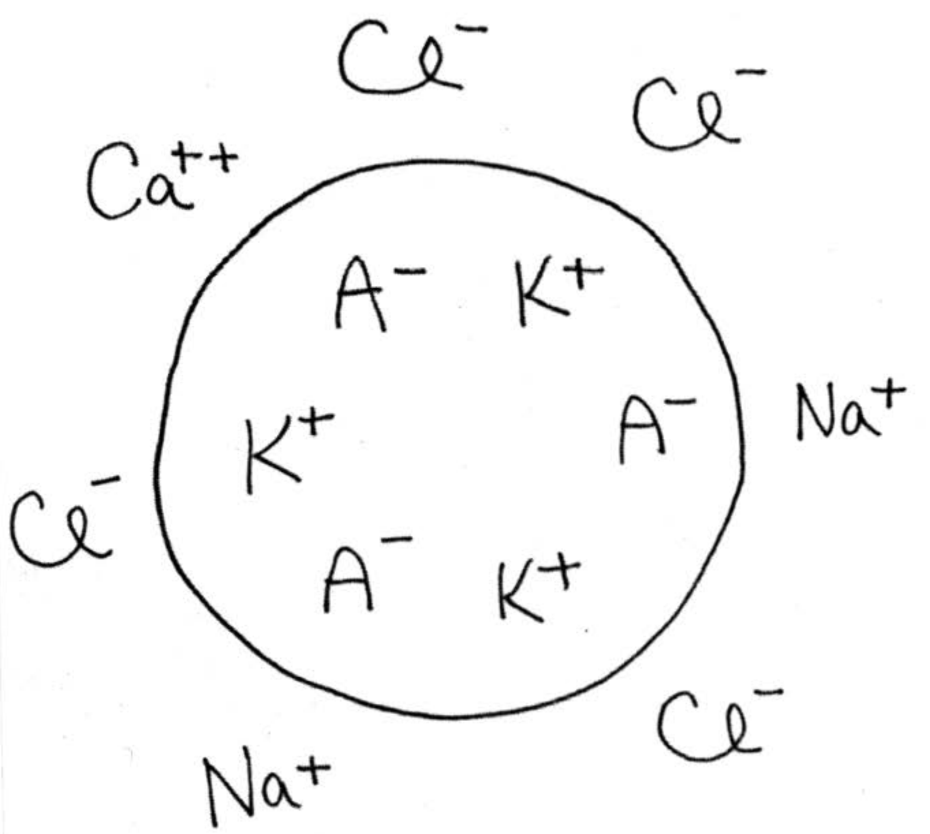
$$I_{ion} = g_{ion}\left[\underbrace{\mathcal{E}_{ion} - E_m}_{\text{"DRIVING POTENTIAL"}}\right]$$

A negative r*esting Potential* is due to K^+, which is kept high inside the cell and low outside, by the Na^+/K^+ pump.

Nernst Equation

$$\mathcal{E}_{ion} = \pm 60_{mV} \log_{10} \frac{[ion]_{in}}{[ion]_{out}}$$

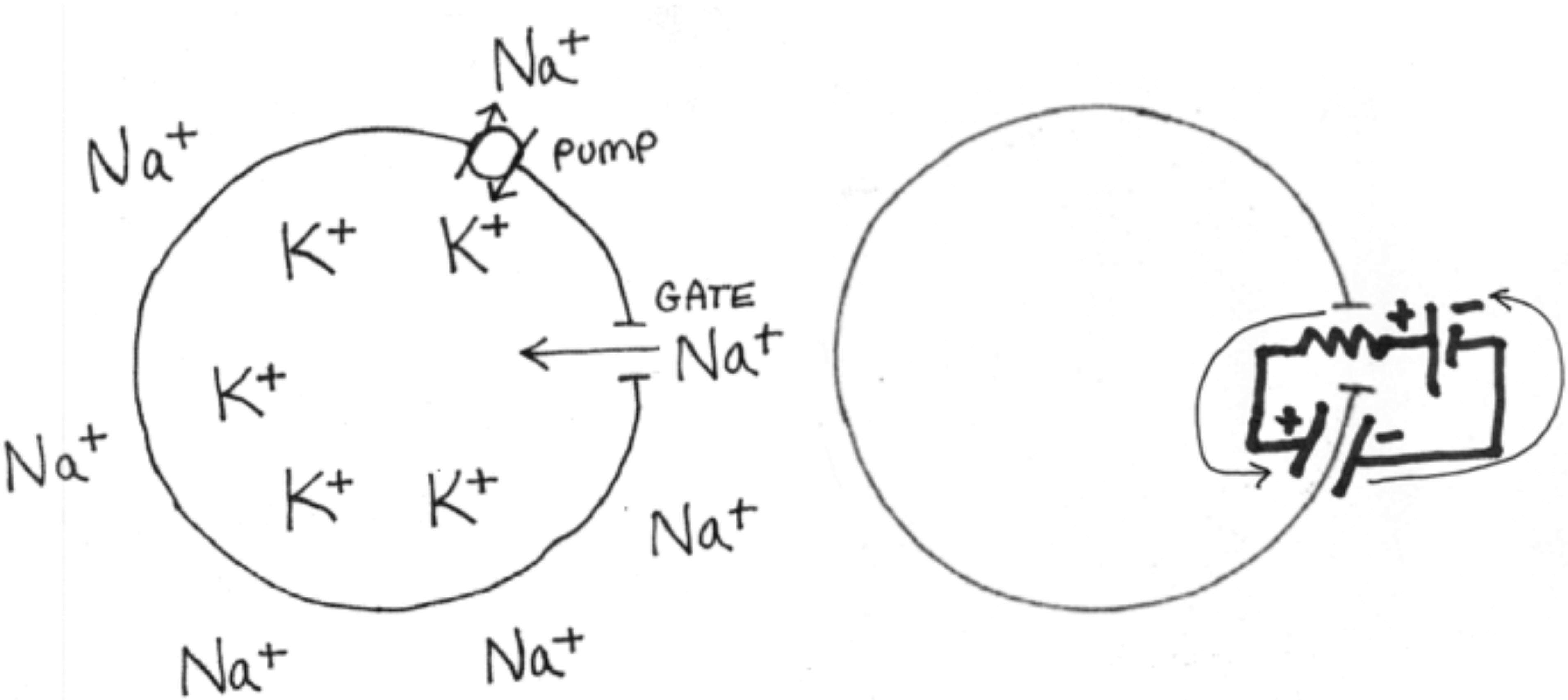
The equation is (-) for cations, and (+) for anions, but the best way to know is to deduce it from the fundamentals.
(for divalent ions, such as Ca++, use 30 mV. instead of 60 mV.)



	$\mathcal{E}$
K^+	$-90mV$
Na^+	$+40mV$
Ca^{++}	$+140mV$
Cl^-	$-90mV$

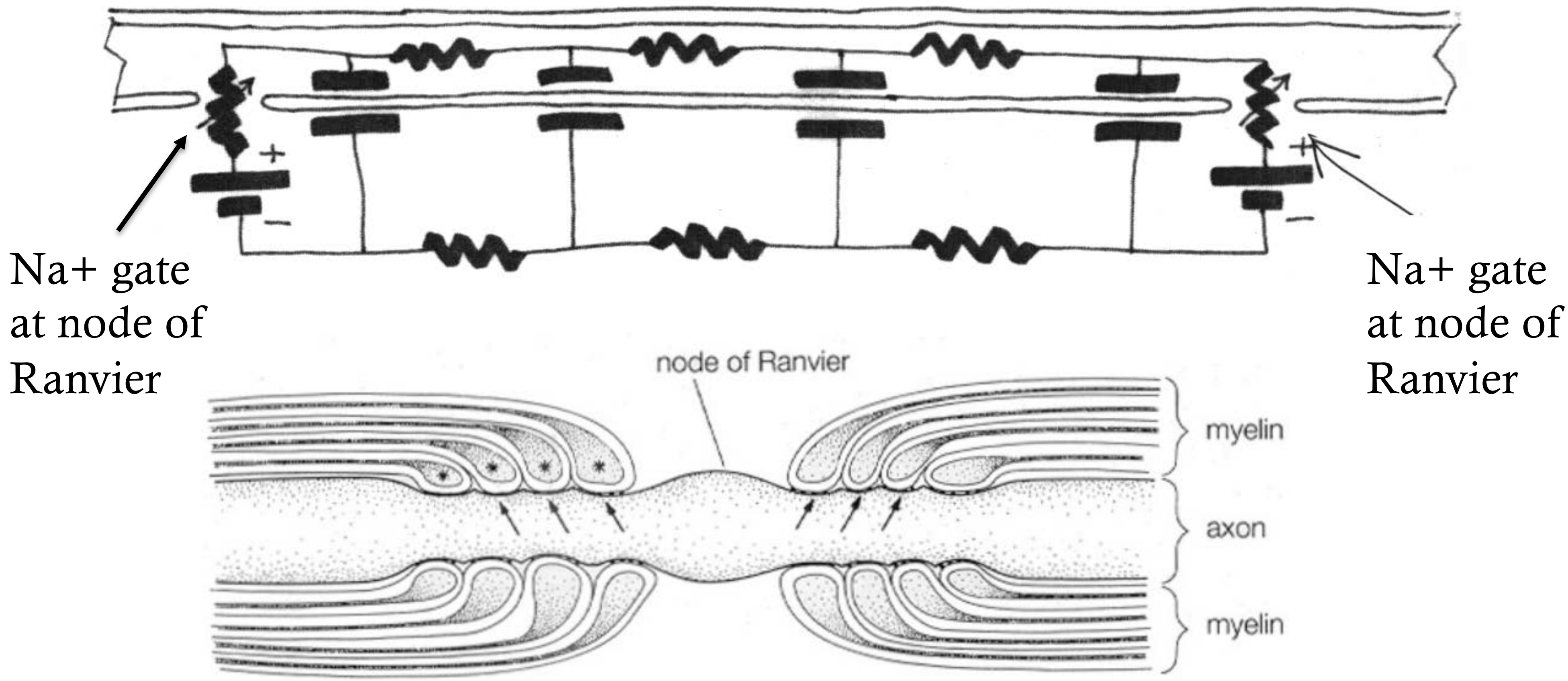
Action Potential

- Caused by the opening of Na^+ gates.



Na^+ gate opens and lets Na^+ ions come rushing in down their electro-chemical gradient, making the inside of the cell go positive

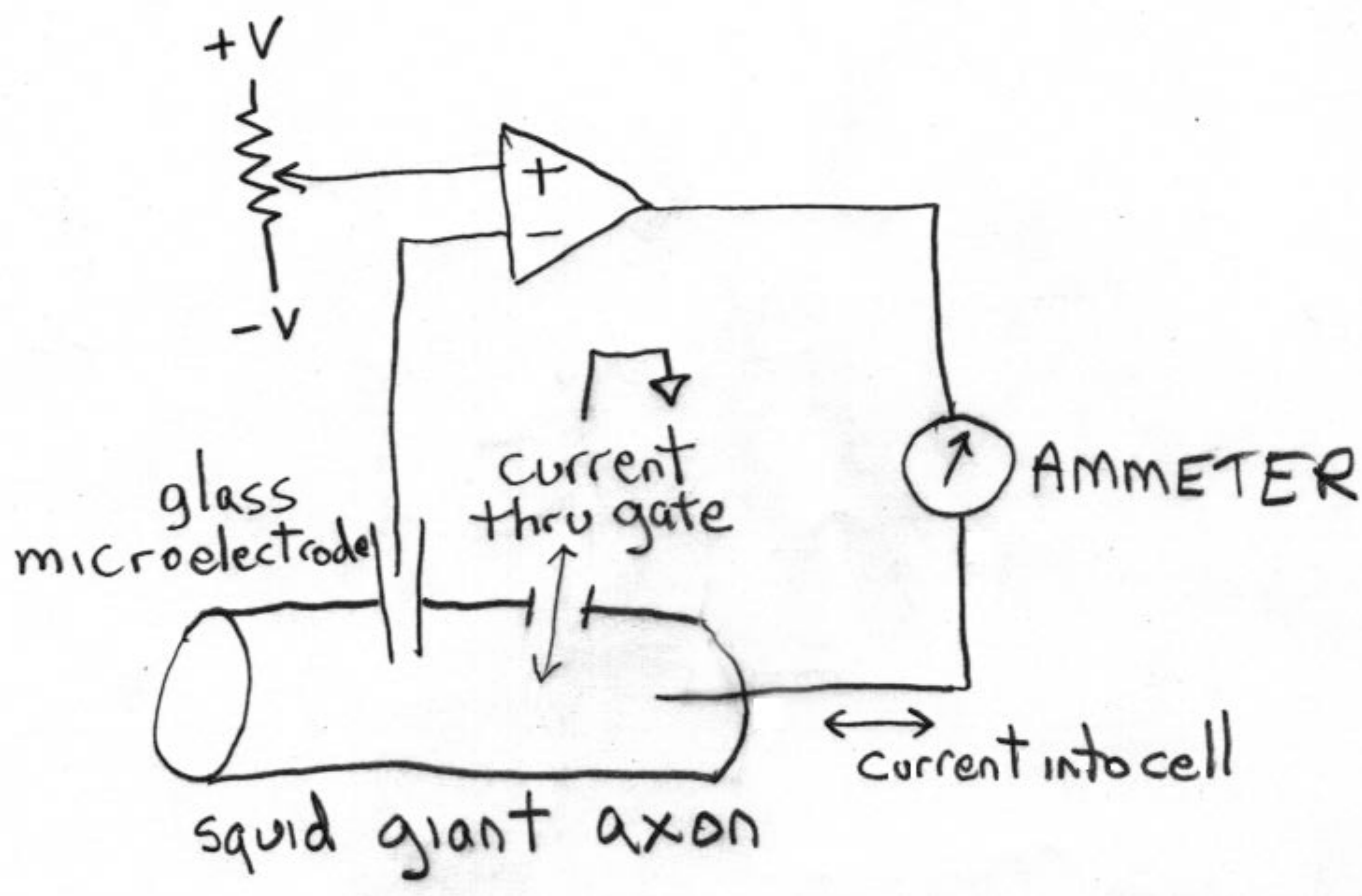
Conduction along Axon



- Each voltage-sensitive Na+ gate opens as inside goes positive.
- Results in Self Propagating Wave of Depolarization
- Myelin (white matter) decreases capacitance increases speed.
- Invertebrates don't have myelin, thus squid's "giant axon".

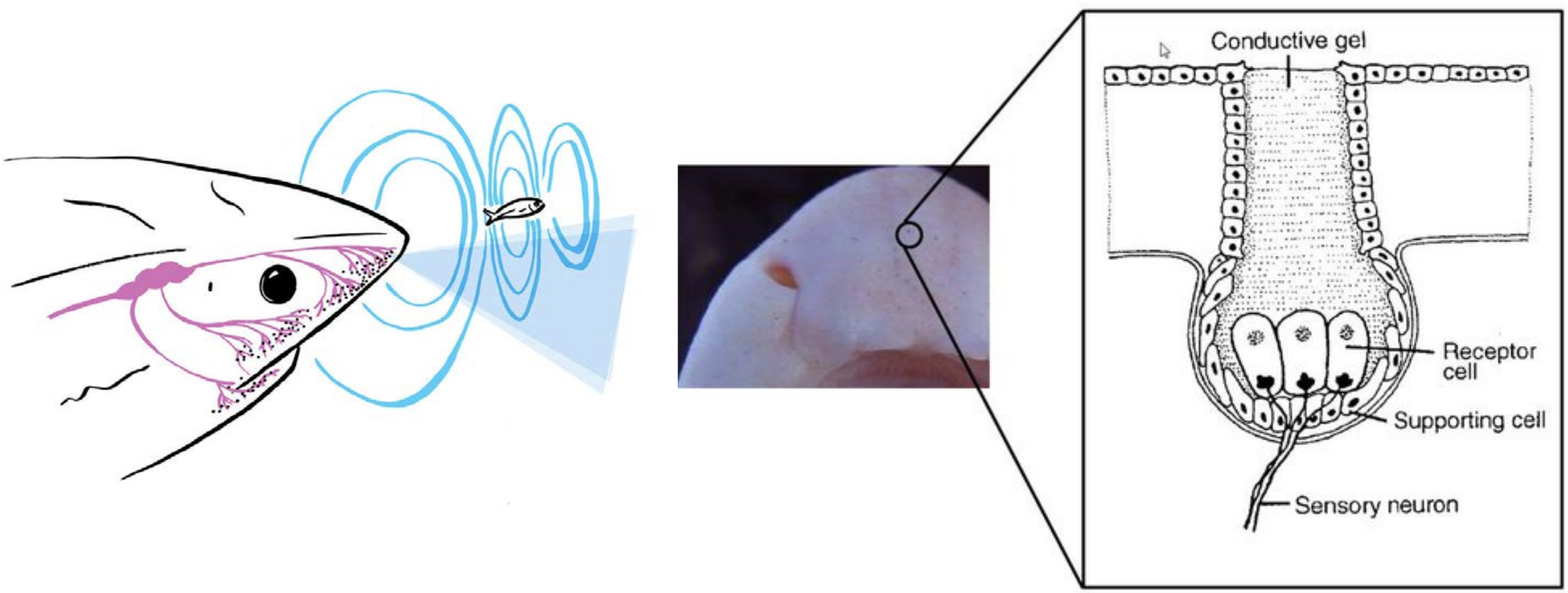
Voltage Clamp

- Used to measure currents through Na^+ and K^+ gates as a function of voltage across axon membrane.
- Squid giant axon (1.5 mm diameter axons in normal sized squid).
- Pulled glass microelectrodes (1 μm hollow tip).

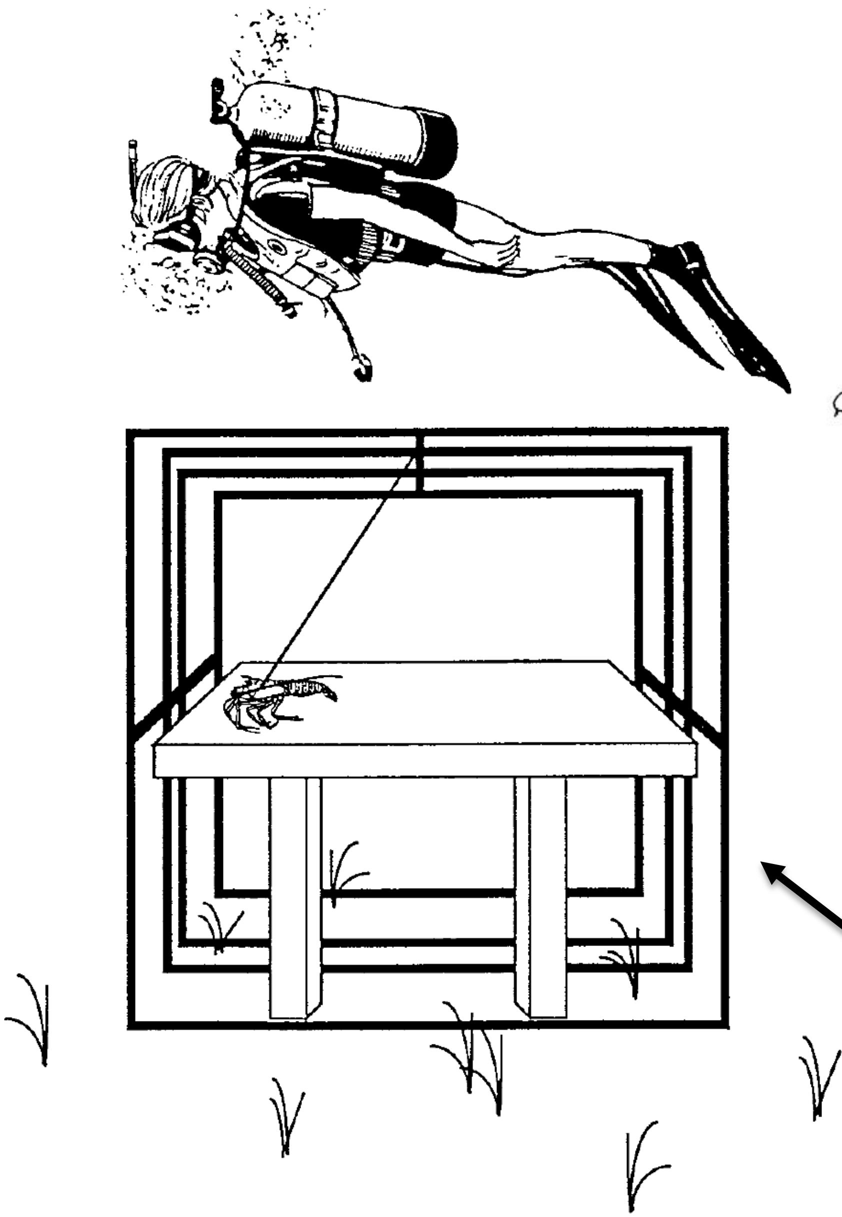


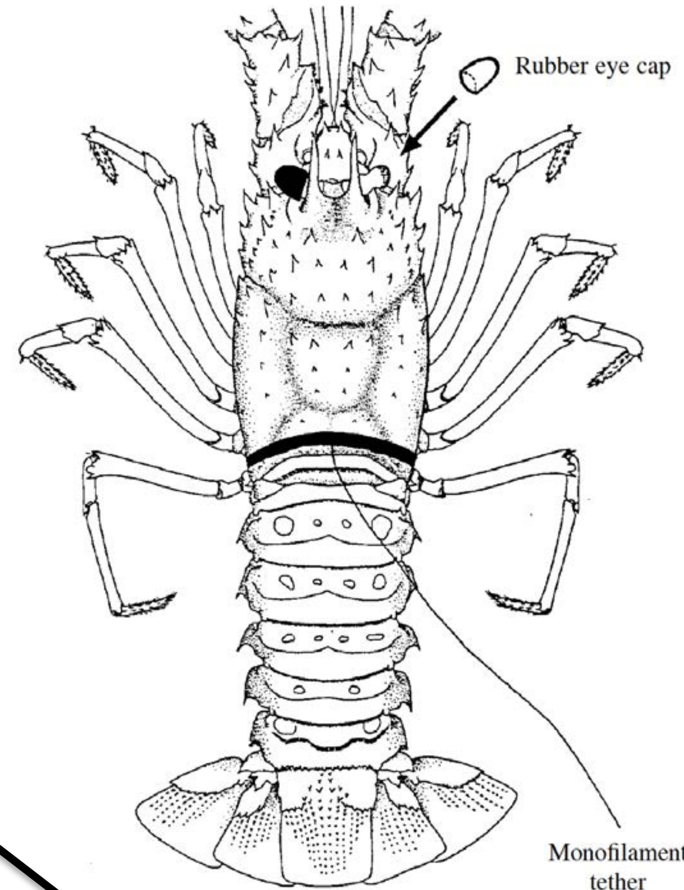
Biological Electroreception

- Sharks can track electric fields caused by muscular activity in prey.
- Sensor organ: tube of conductive gel opening to the outside with voltage-sensitive receptor cells.



Biological sensing of Earths magnetic field



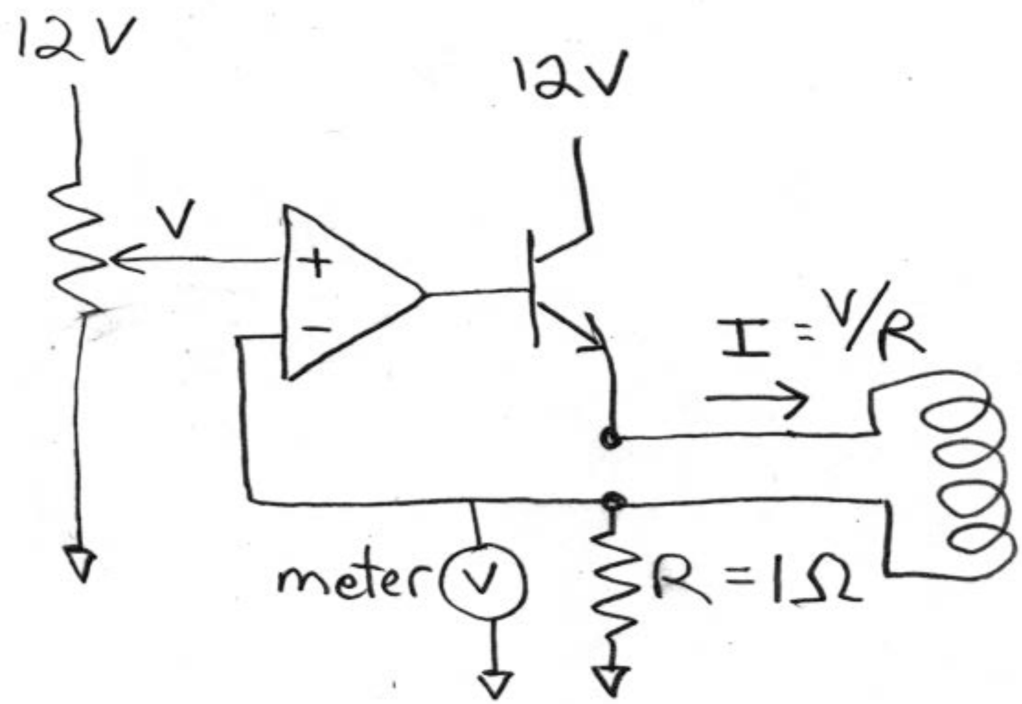


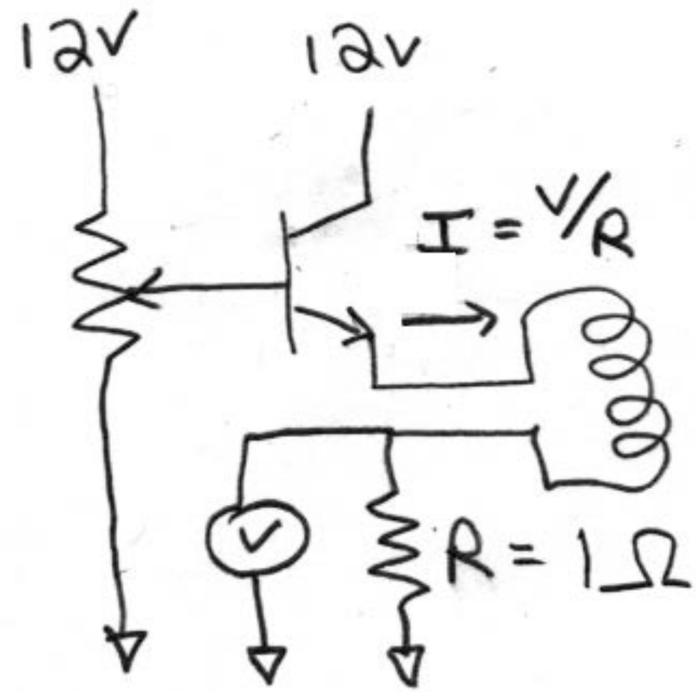
Birds, turtles, lobsters, etc., can sense the earth's magnetic field.

Large coil to produce magnetic fields effected lobsters direction of motion.

Pentcheff, Nevitt, Stetten, et al, Journal of Experimental Biology 198, 2041–2048 (1995).

Circuit to drive large currents (5A) through coil for Lobster experiment. Example of instability.





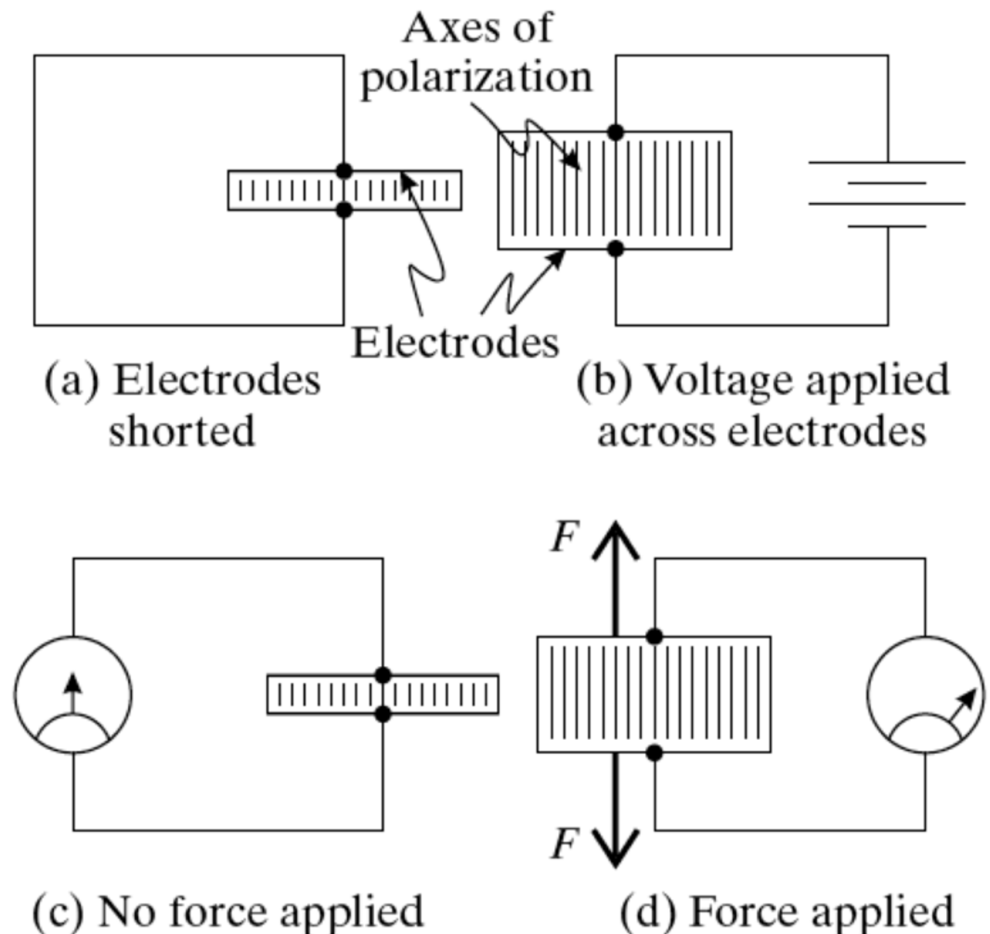
Use of feedback proved unstable because of high gain and inductance…
oscillated at >100 Volts!

Without feedback, it was stable, but needed continual manual adjustment.

Piezoelectric Effect

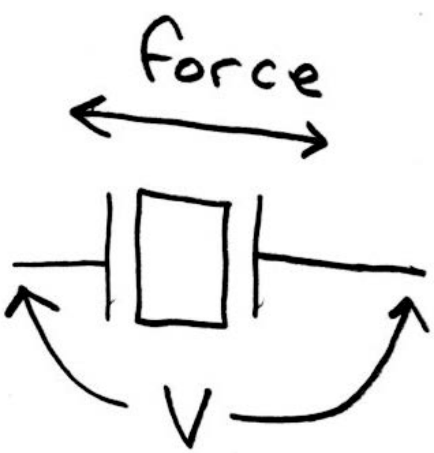
Discovered by Pierre Curie, husband of Marie Curie who discovered radioactivity.

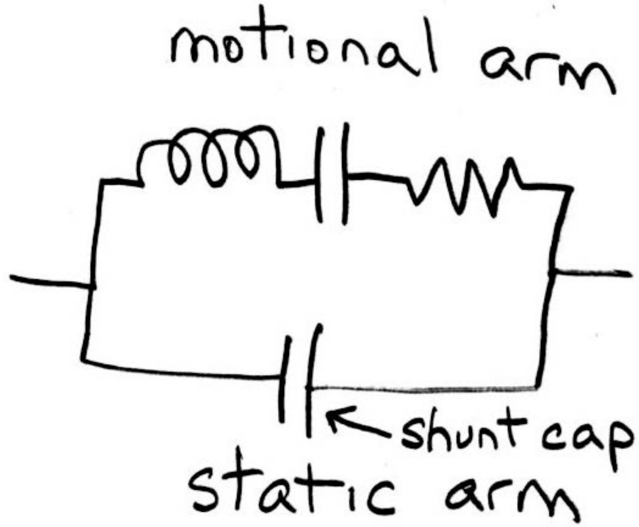
- Used in ultrasound transducers.
- An induced electric field produces *strain* (mechanical displacement), which causes an acoustic wave.
- An incoming acoustic wave (*stress*) creates *strain*, which creates an electrical potential.
- Very high mechanical impedance (very stiff).
- Very high electrical impedance, so not good for detecting constant force (small charge dissipates).



Piezoelectric Transducers

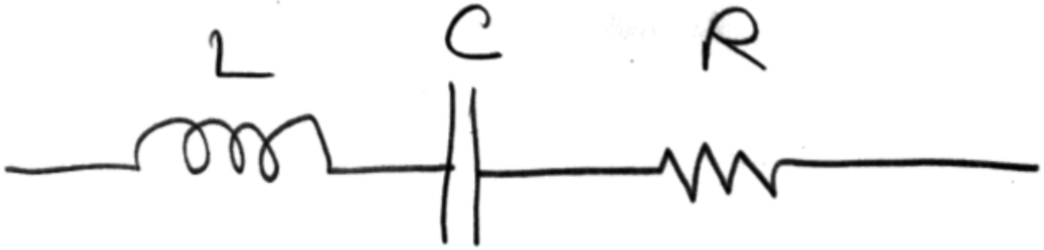
- Converts displacement (from a force) into voltage.
- Converts voltage into displacement (through a force)
- Electromechanical tuning fork.
- Accurate frequency of resonance, with small temperature coefficient for temperature (can be used to measure temperature)



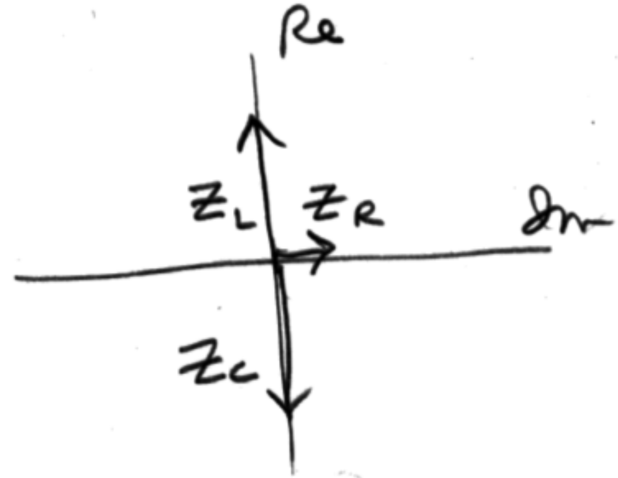


passive circuit: <u>cannot oscillate on its own without gain</u>.

Resonance and damping: Recall the LCR circuit…



Damping caused by *R*



$$Z = j\omega L + \frac{1}{j\omega C} + R =$$

$$\frac{1-\omega^2 LC}{j\omega C} + R =$$

$$\underbrace{j\left(\frac{\omega^2 LC - 1}{\omega C}\right)}_{\text{pure imaginary}} + \underbrace{R}_{\text{pure Real}}$$

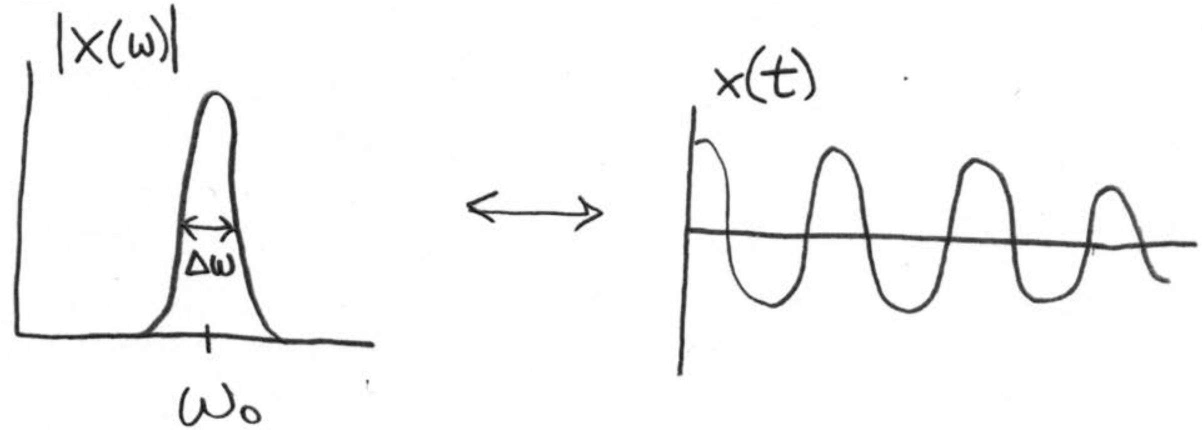
can never equal zero

passive circuit:
<u>cannot oscillate</u>.

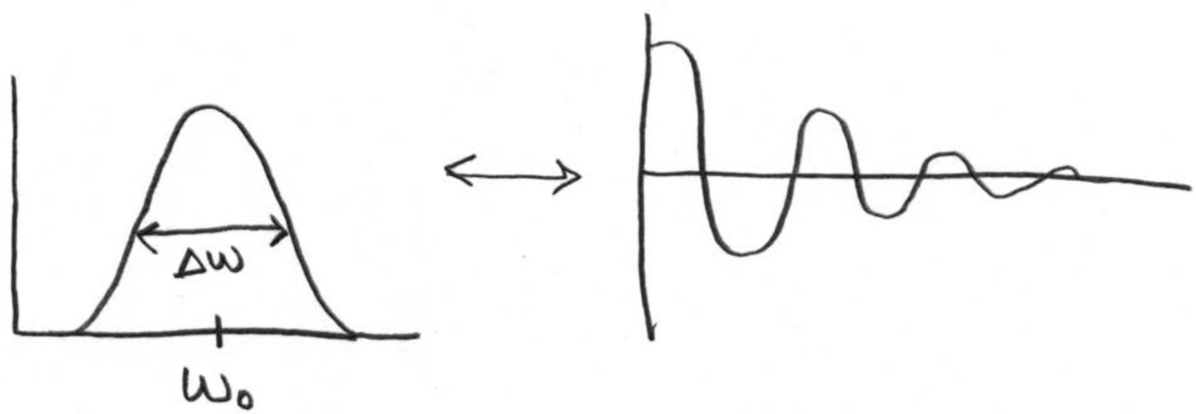
Q-Factor and Resonance

- The bandwidth, $\Delta\omega$, of two damped resonators shown below.
- The Q factor is $\omega_0 / \Delta\omega$.

Hi Q factor
Narrow spectrum
Long resonance



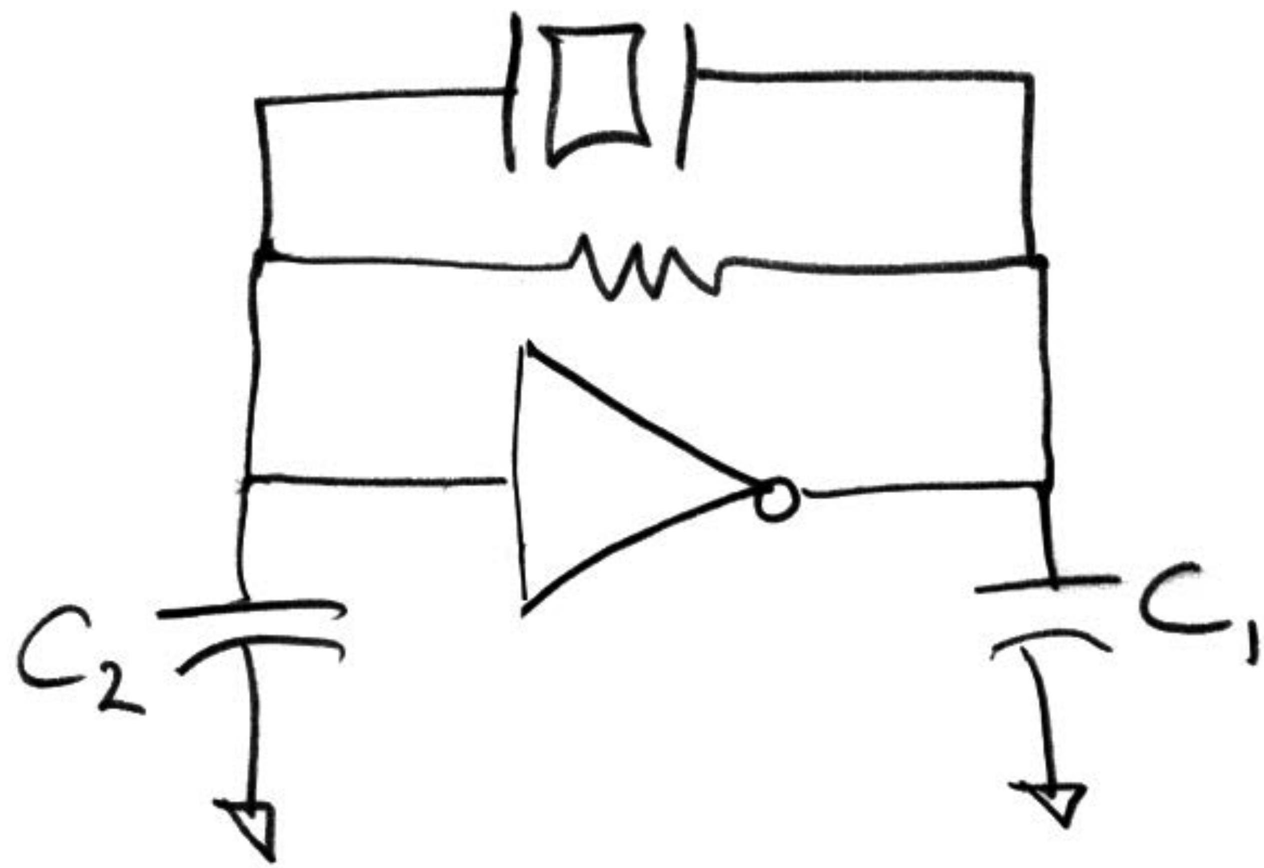
Low Q factor
Broad spectrum
Short resonance



- Perfect resonator ($R = 0$ in the LCR circuit) has $Q = \infty$.

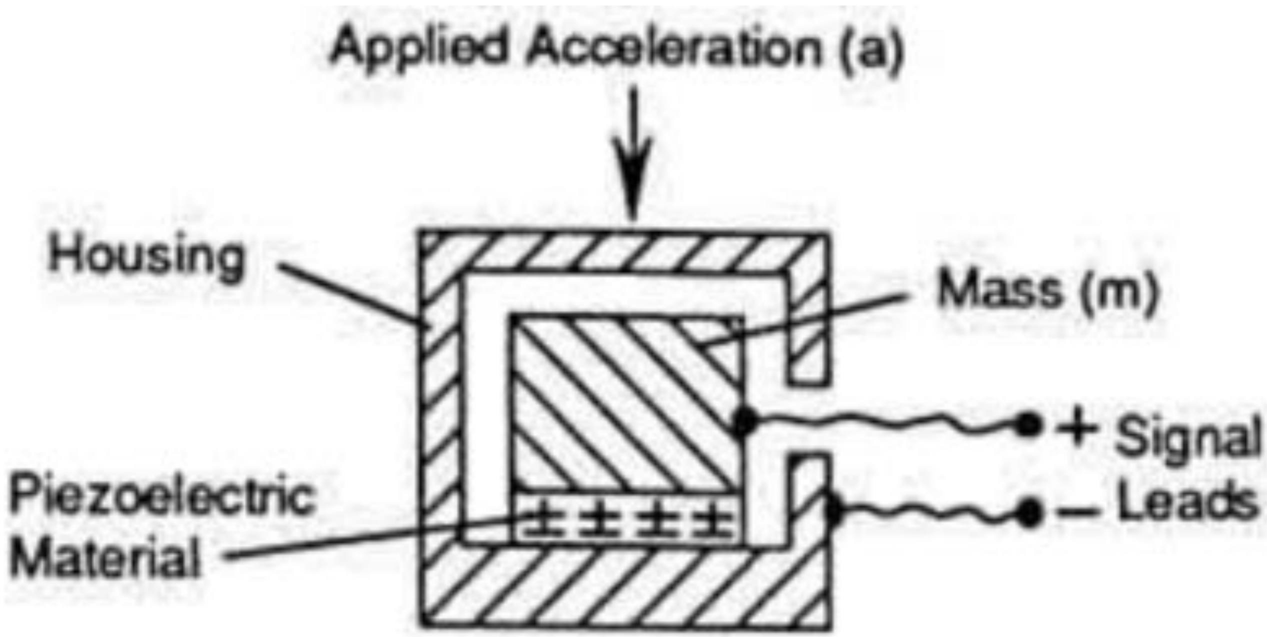
Pierce Oscillator

- Resonance + Gain = Oscillation.
- Make a crystal (resonator) into an oscillator by adding gain.



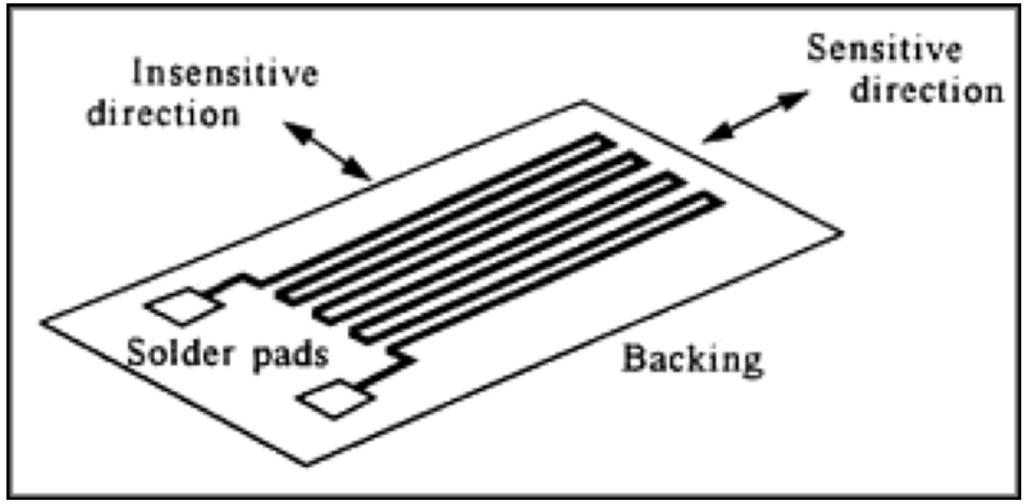
Accelerometers

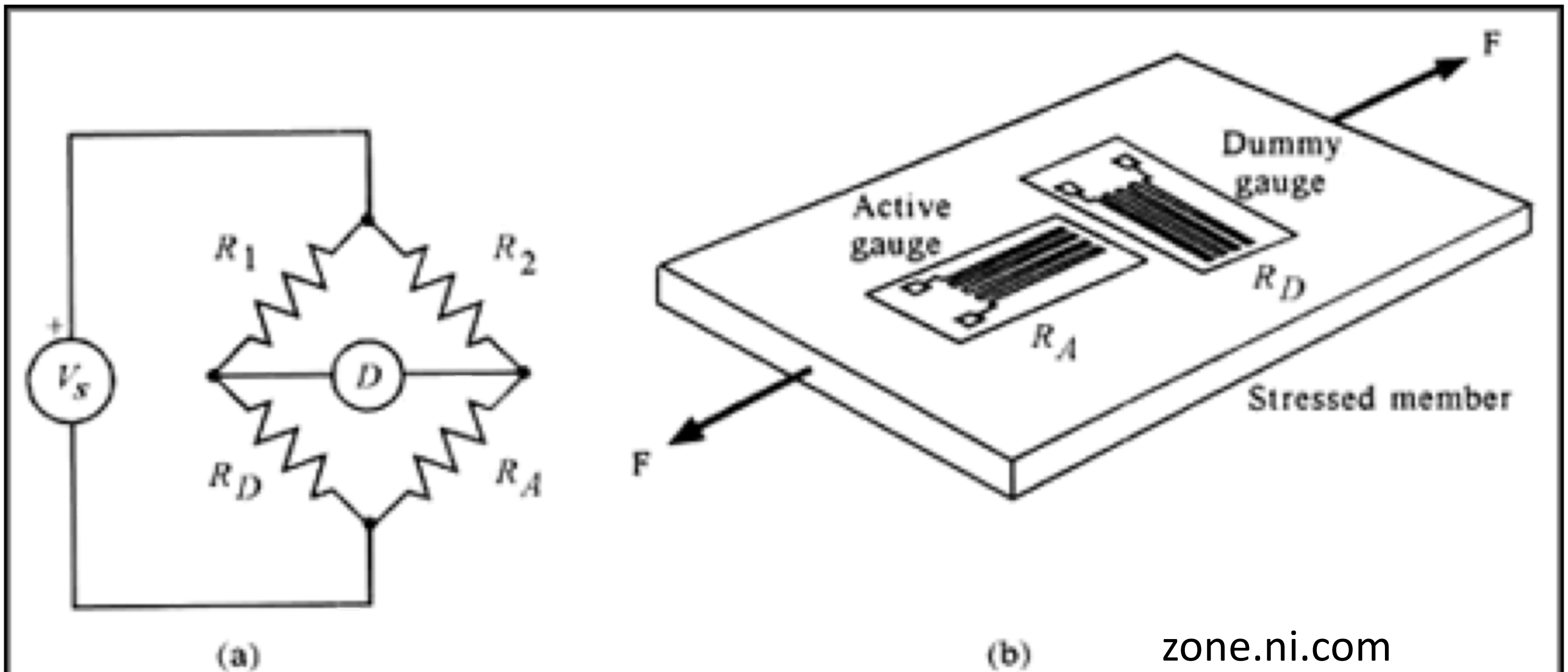
- Generally use inertial force generated by a weight
- Can get 6 degrees of freedom (DOFs)
  - 3 translations (x, y, and z)
  - 3 rotations (pitch, roll, and yaw)
- Error accumulates computing velocity or location.



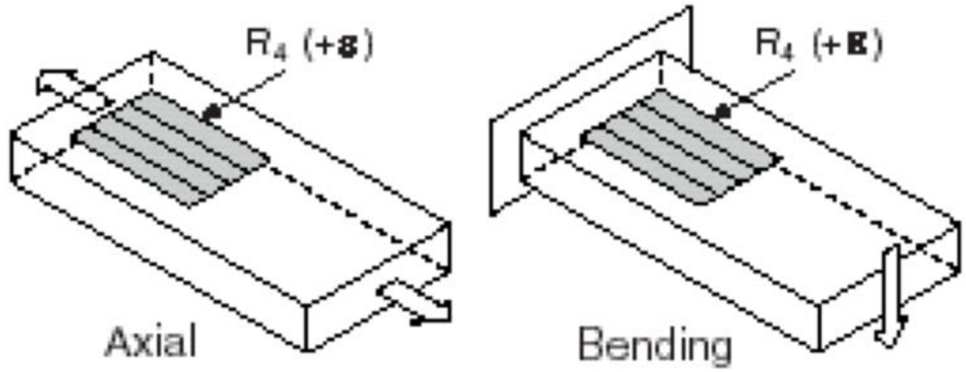
Strain Gages

- Resistance changes with length of trace
- Use 2 in Wheatstone bridge to compensate for temperature changes in resistance

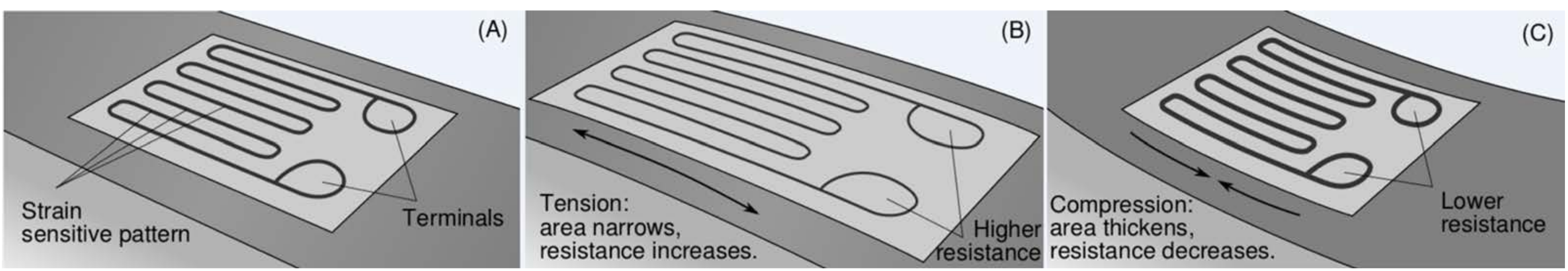




zone.ni.com



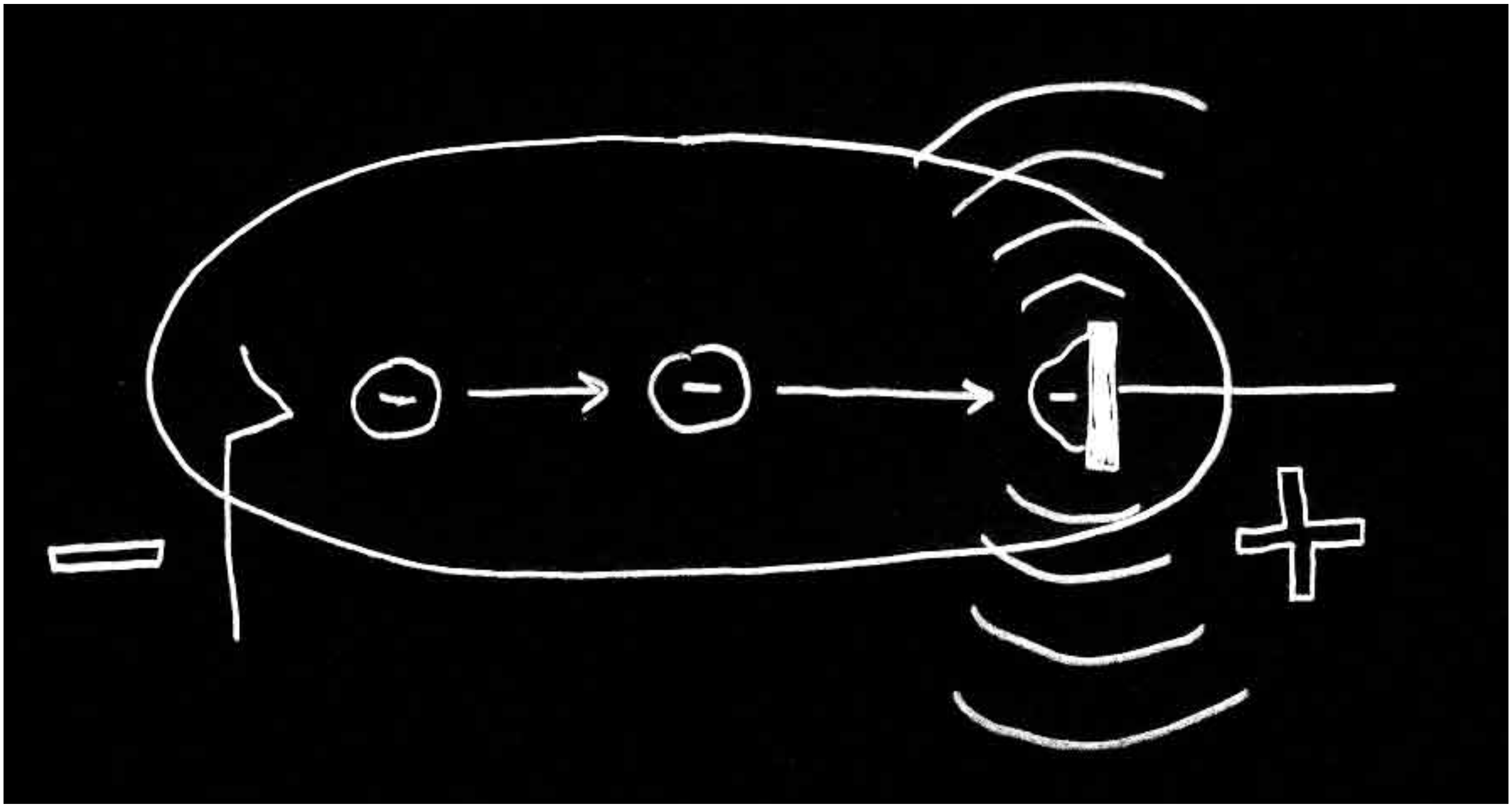
- Strain gages are often attached to a cantilever beam (lever fixed at one end).
- Bending the cantilever stretches the strain gage, mechanical advantage (over axial stretching of the beam) due to the thickness of the beam.



High-Energy Radiation

Variations on the light bulb

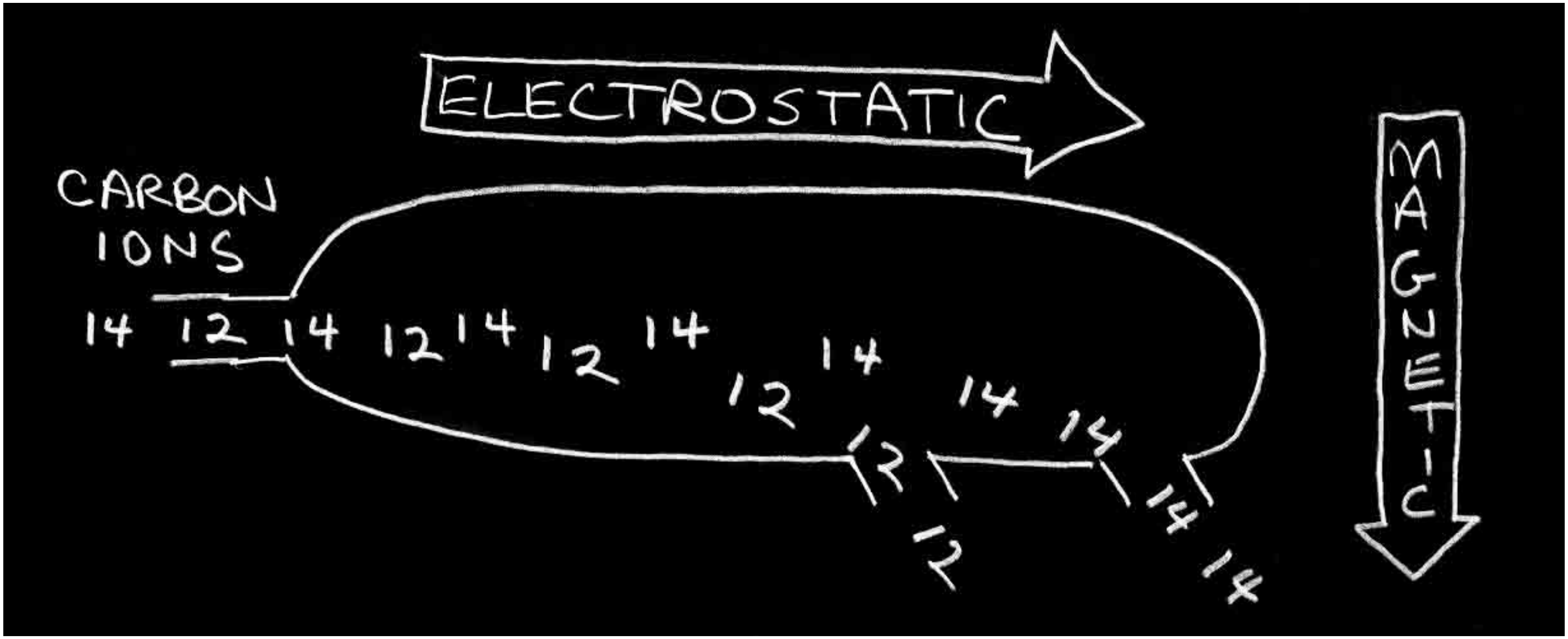
Cathode Ray Tube produces X-rays (Roentgen 1895)



In cathode-ray tube, electrons rapidly decelerates at heavy metal target, giving off X-ray photons.

Variations on the light bulb

Mass Spectrometer (J. J. Thomson 1907)



- Mixture of isotopes accelerated in a beam, separated by difference in inertia by bending the beam in magnetic field.
- Separation of isotopes 1930’s led to discovery of isotopes.

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SOLVAY CONFERENCE 1927

A. PICARD E. HENRIOT P. EHRENFEST Ed. HERSEN Th. DE DONDER E. SCHRÖDINGER E. VERSCHAFFELT W.PAULI W. HEISENBERG R.H FOWLER L. BRILLOUIN

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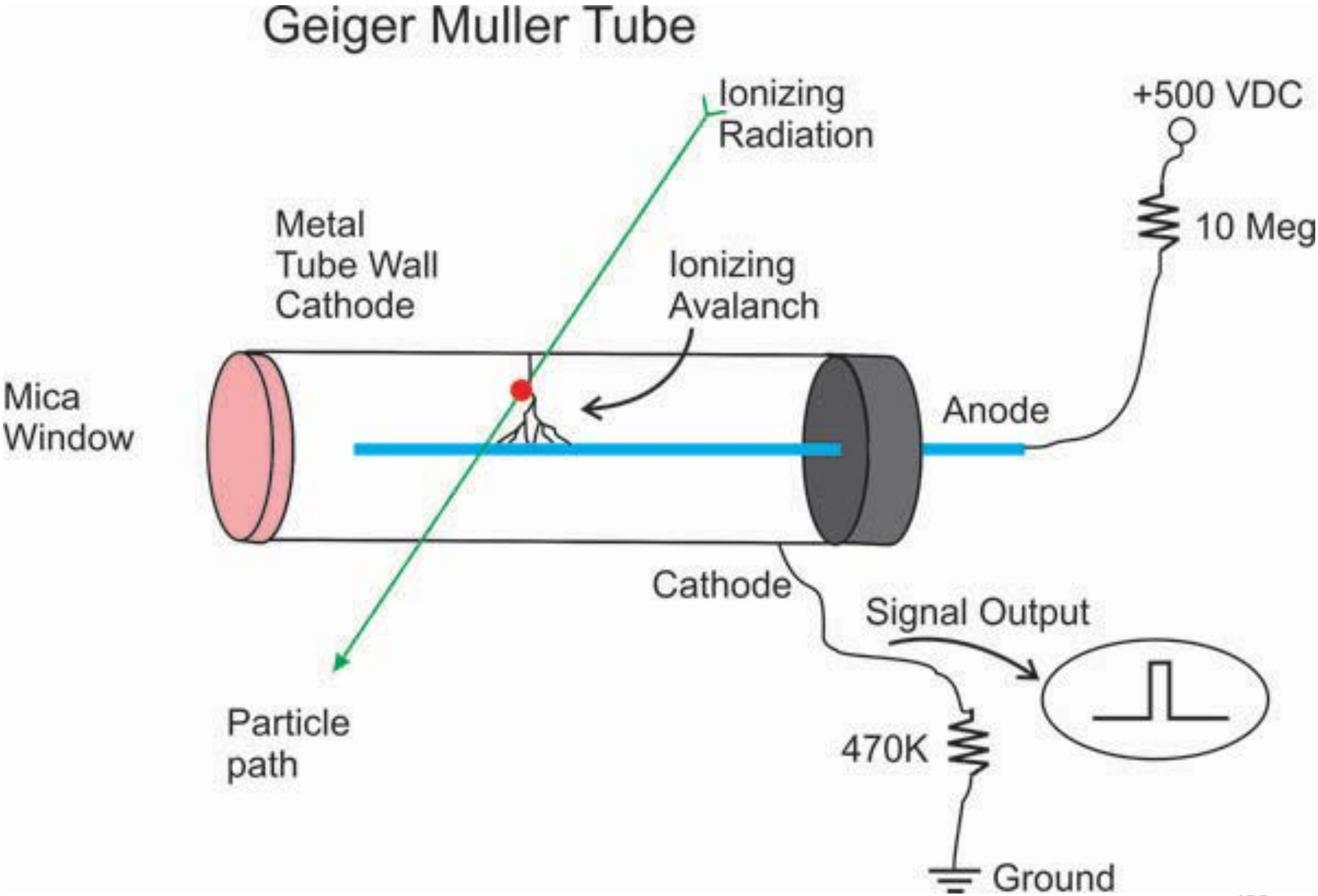
I. LANGMUIR M. PLANCK Mme CURIE H.A.LORENTZ A. EINSTEIN P. LANGEVIN Ch.E. GUYE C.T.R. WILSON O W. RICHARDSON

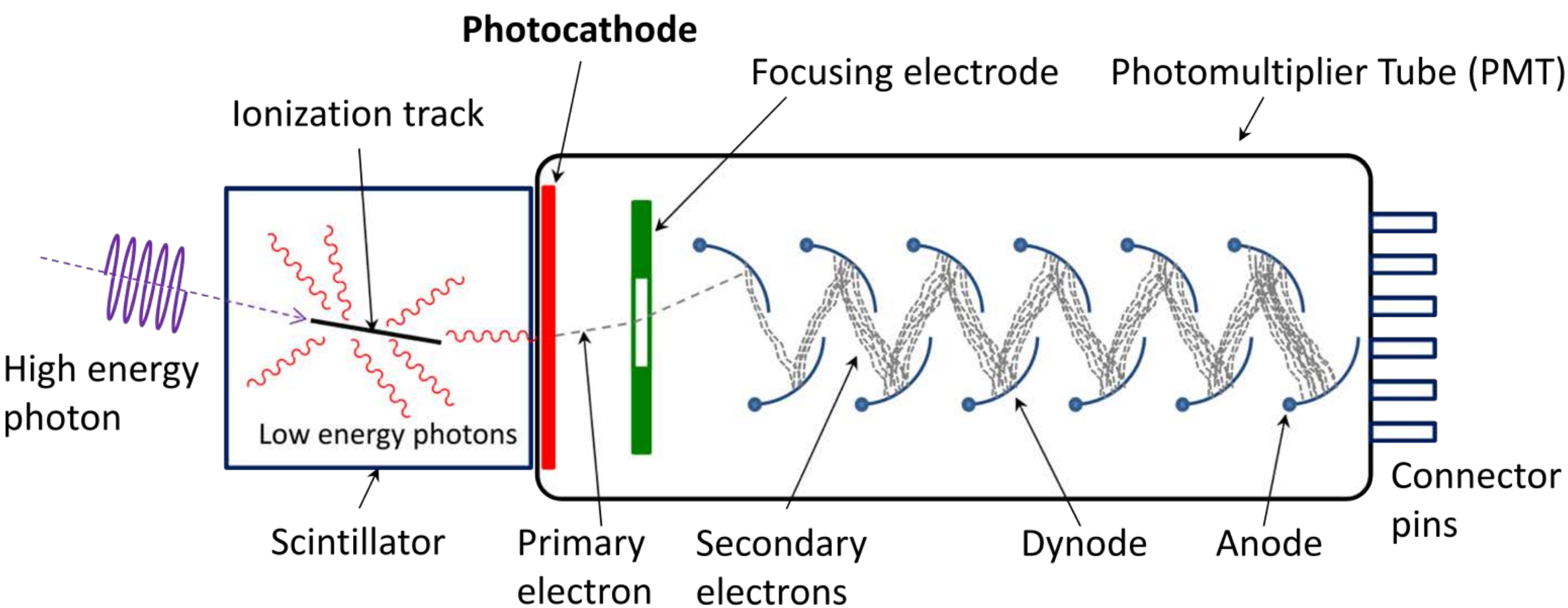
Absents : Sir W.H. BRAGG, H. DESLANDRES et E. VAN AUBEL

Detecting high-energy photons



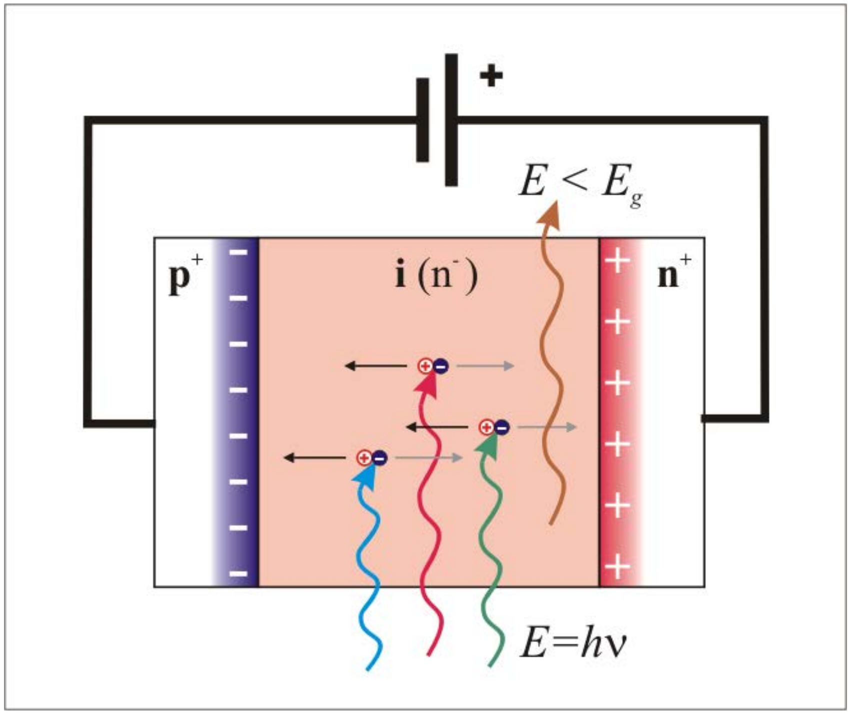
Scintillation Counter

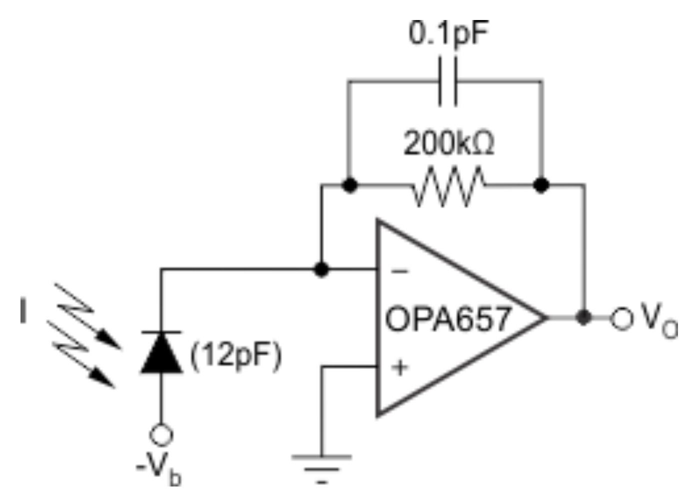
- Production of many “low-energy” light photons from a single high-energy gamma or x-ray photon.
- Usually in a crystal, such as NaCl.
- Photomultiplier tube can detect very few photons by a cascade of electrodes across a high voltage.
- Used in medical imaging



Solid-State Radiation Detector

- Small, can measure photon energy.
- Silicon or germanium "PIN" diode, with undoped *intrinsic* (I) gap layer between usual P and N layers.
- Reversed biased, leaks when irradiated by photon with energy greater than *gap energy* E_g.
- Large surface area like a solar cell.





https://commons.wikimedia.org/wiki/File:Pin-Photodiode.png

Recorded Sound

Edison - 1877

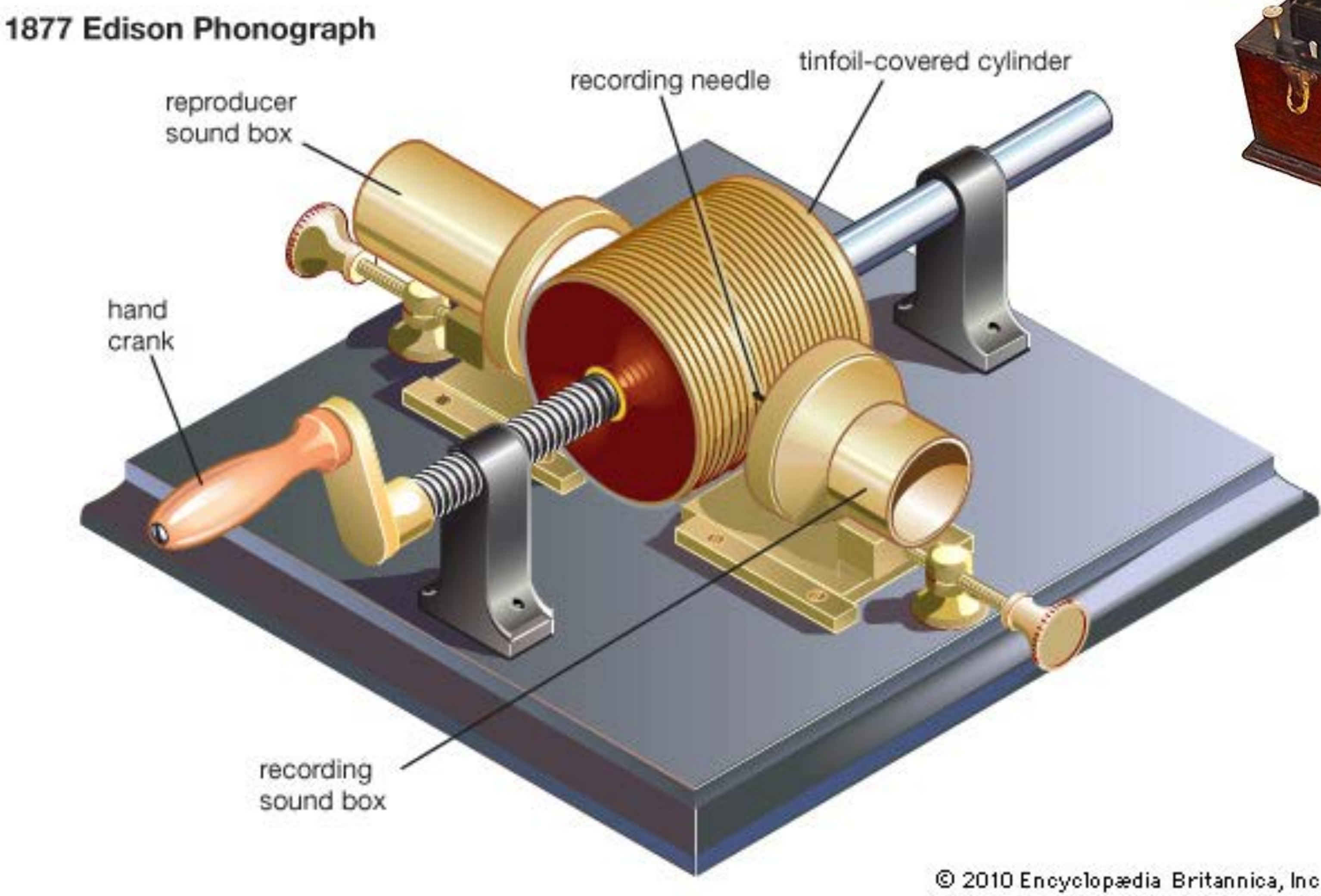
“The phonograph, when first made public, created considerable popular curiosity, and predictions of the most extravagant character were made of the wonders which it would accomplish…

“The truth is that the phonograph is little more than a highly ingenious scientific toy… in the generality of cases, people imagine that they hear from it much more than they actually do… At the present date (1885), seven years after the first production of the instrument, it remains without practical application… It certainly has not fulfilled its inventor’s anticipations...”

Wonders of Acoustics, 1886.

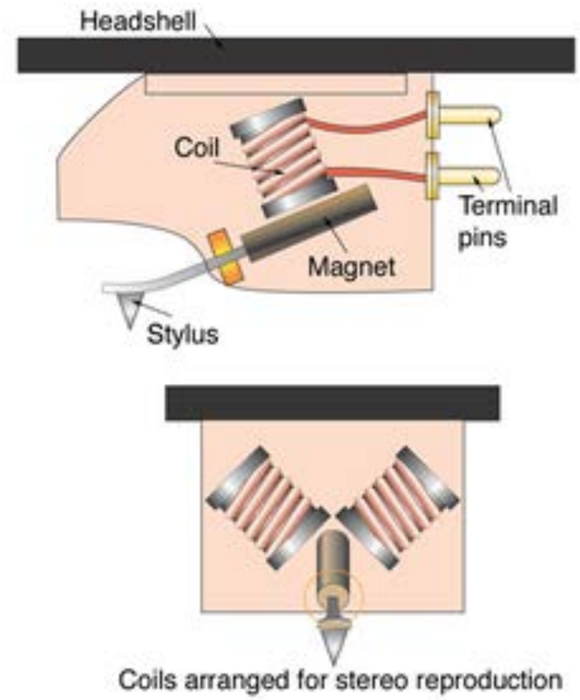
Edison’s Phonograph

- Needle indents waves on metal foil.
- Totally mechanical system.



"Modern" Phonograph

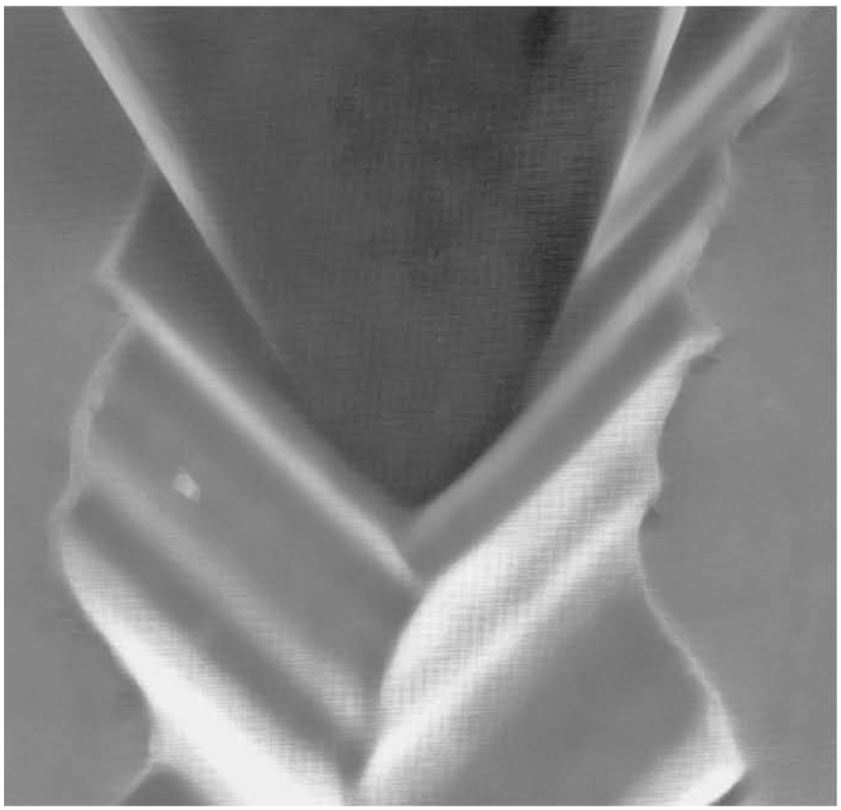
- Electro mechanical recording (~1925)
  - Needle or "Stylus"
    - steel, osmium, sapphire, diamond)
  - Transducers
    - Piezo crystal
    - Magnetic – moving magnet
      - Most common
    - Magnetic – moving coil
      - Better frequency response
      - Smaller signal

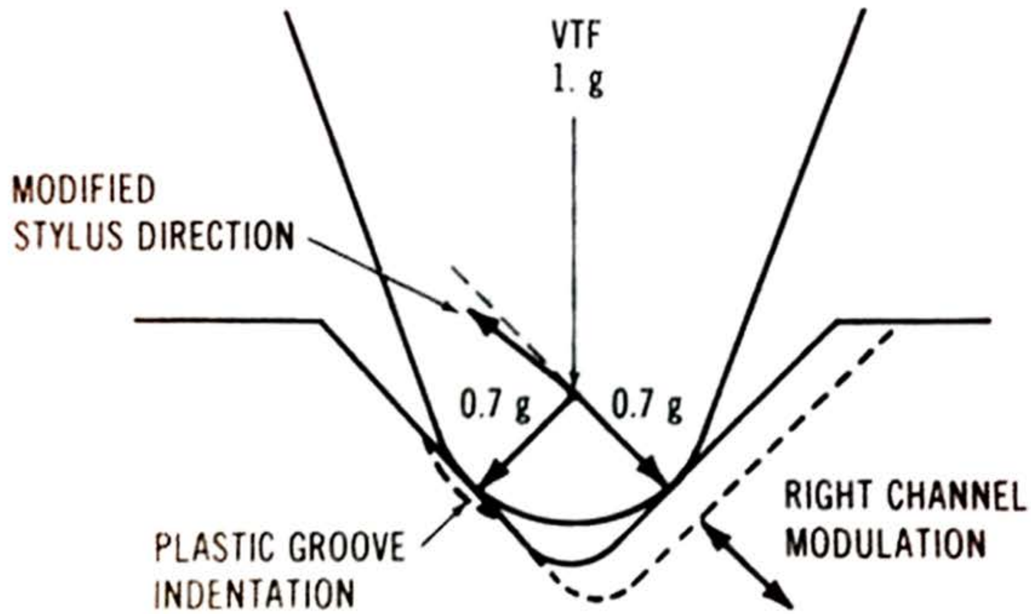


http://www.thefullwiki.org/Magnetic_cartridge

Stereo

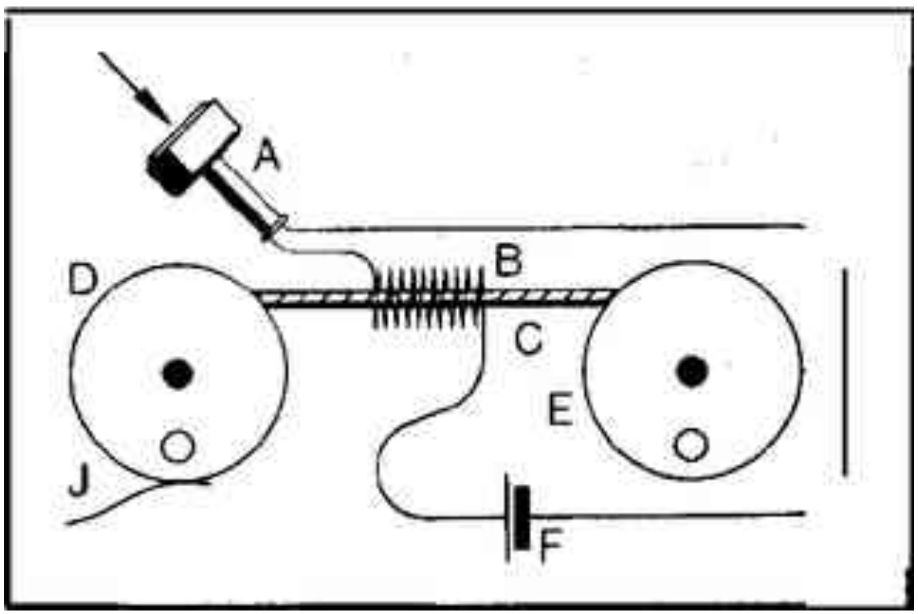
- Two orthogonal surfaces.





Magnetic wire recorder

- Conceived of by Oberin Smith, 1878.
- Successfully built by Valdemar Poulsen, 1898.

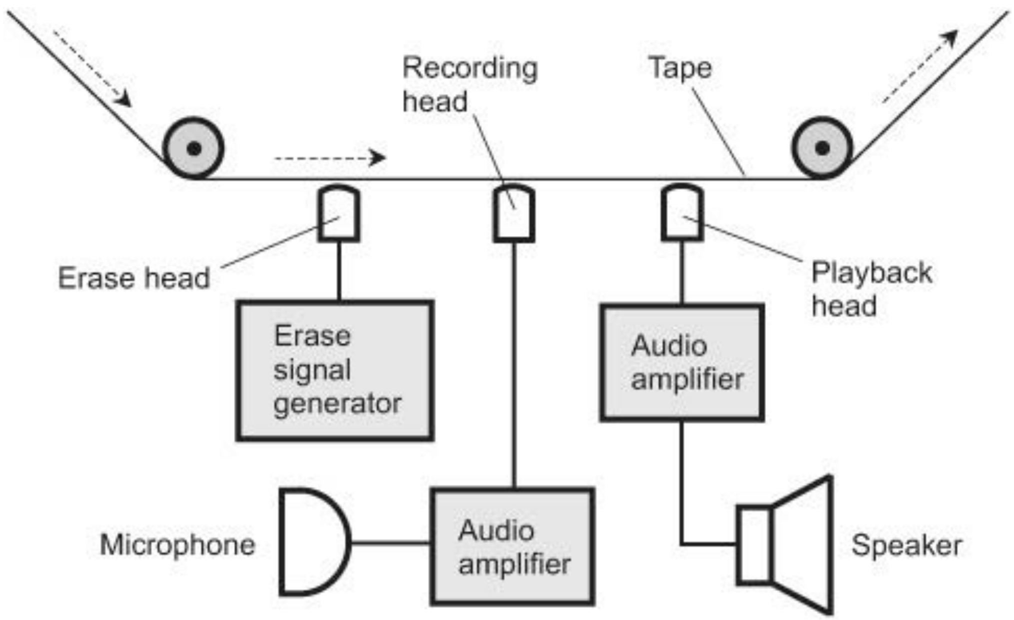


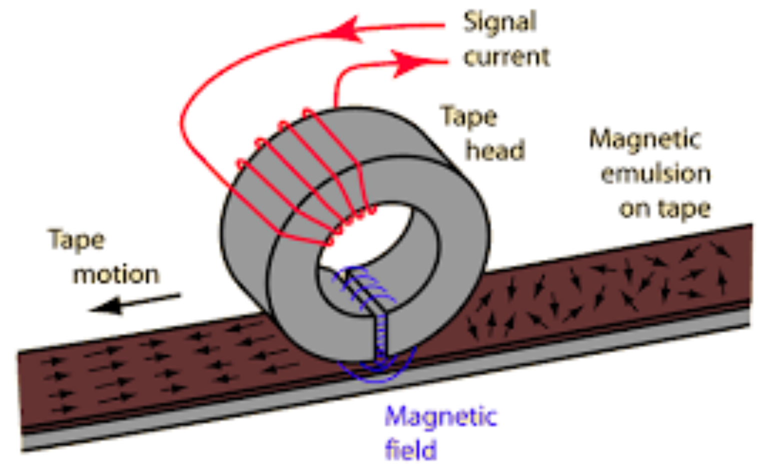
http://museumofmagneticsoundrecording.org/Wire.html

http://www.angelfire.com/wa/stephrenaud/histmagrec.html

Magnetic Tape

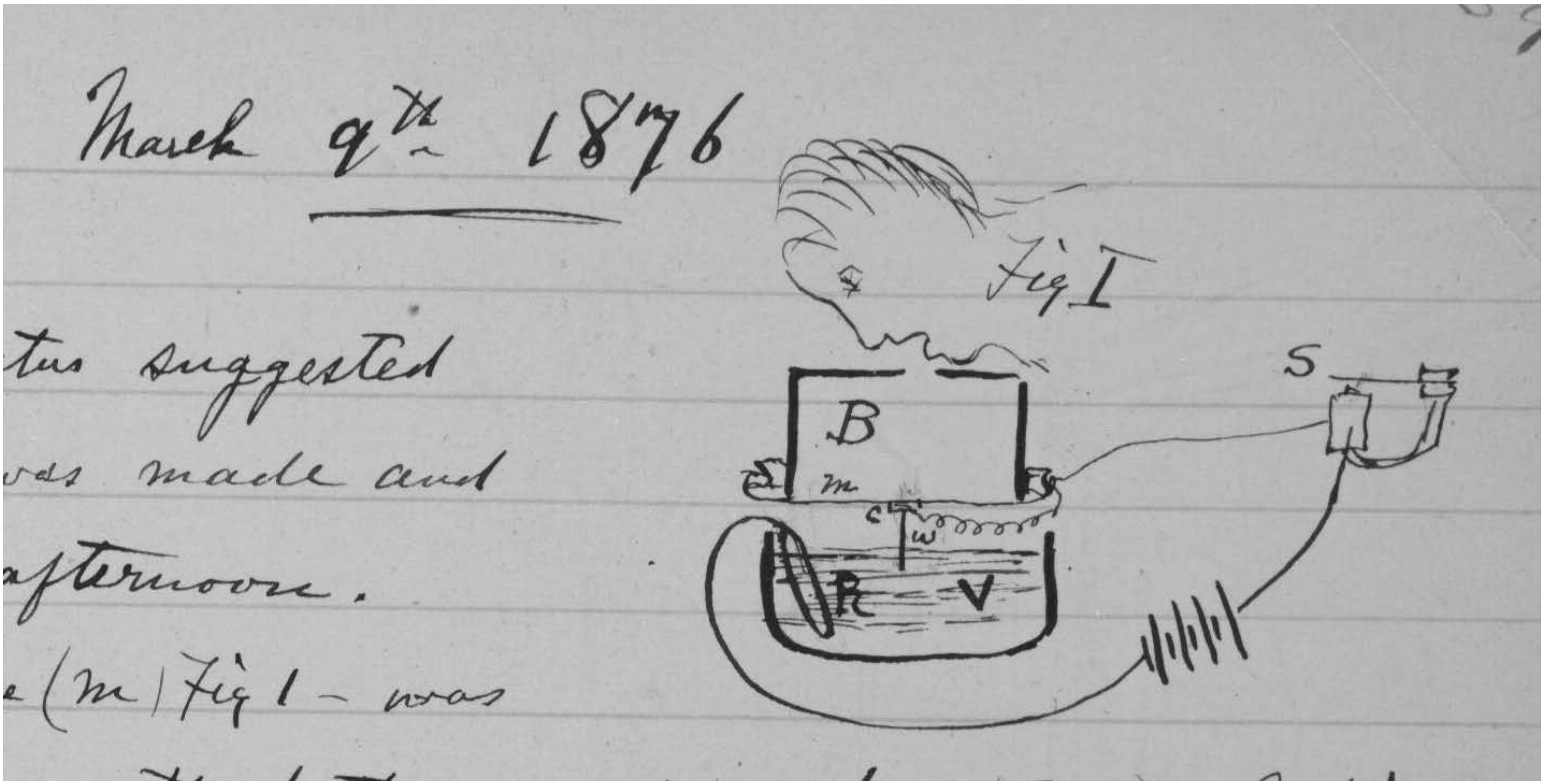
- Invented in Germany in 1930's.





http://hyperphysics.phy-astr.gsu.edu/hbase/audio/imgaud/tape6.gif

- Bell initially used a “water microphone”
- Needle move up and down in water changing resistance
- Independently invented by Elisha Gray, Bell won patent



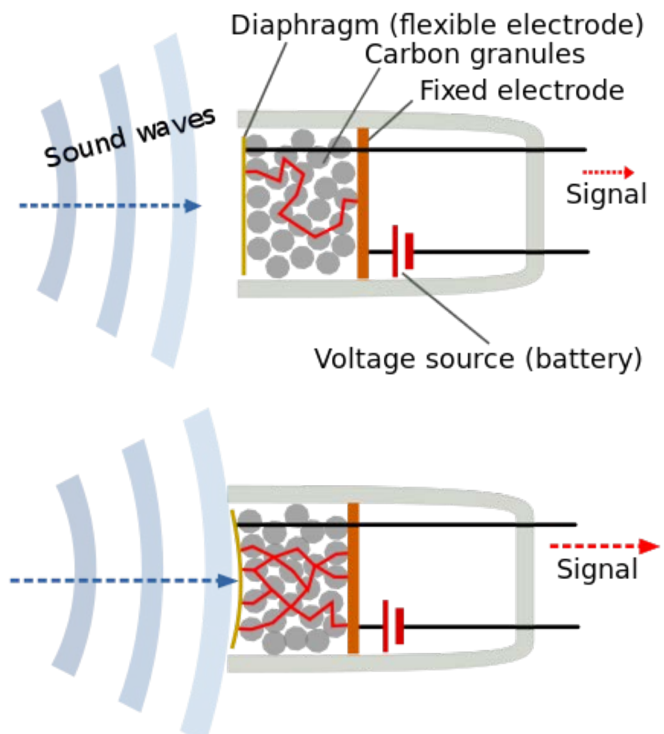
Microphones: Methods of Transduction

Carbon Microphone

Patented by Edison 1877.

Varying pressure on carbon granules changes the electrical resistance

Very early amplifier for telephone repeaters (speaker and high-voltage carbon mike)

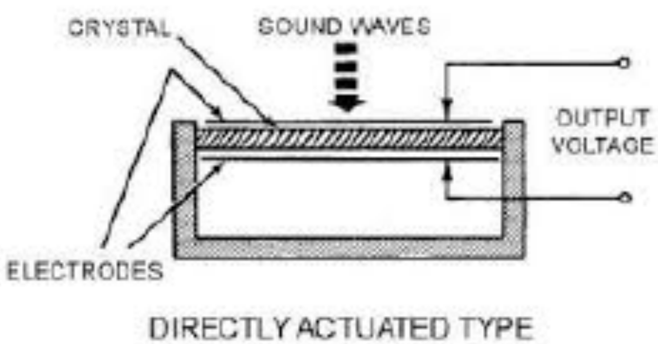


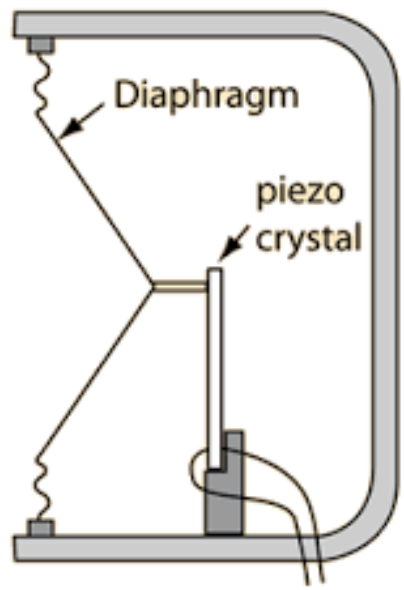
Piezoelectric Microphone

Very high electrical impedance (mostly voltage, very small current), not used much any more.

Can be very small if directly actuated.

Still used in Ultrasound, where they are both the detectors and actuators.



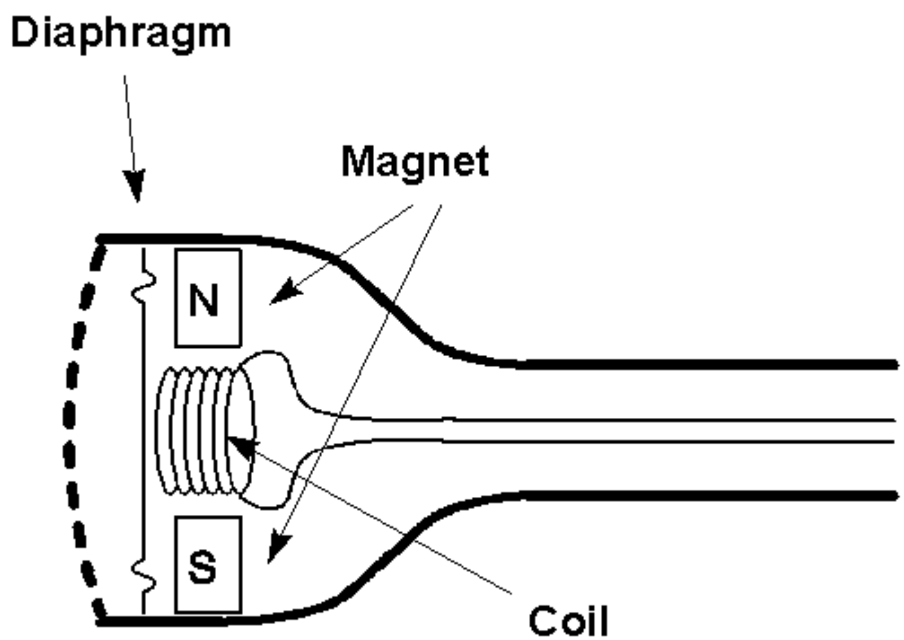


Dynamic Microphone

Permanent magnet and moving coil generates current.

Basically a speaker in reverse.

Self powered. Still used in vocal microphones.

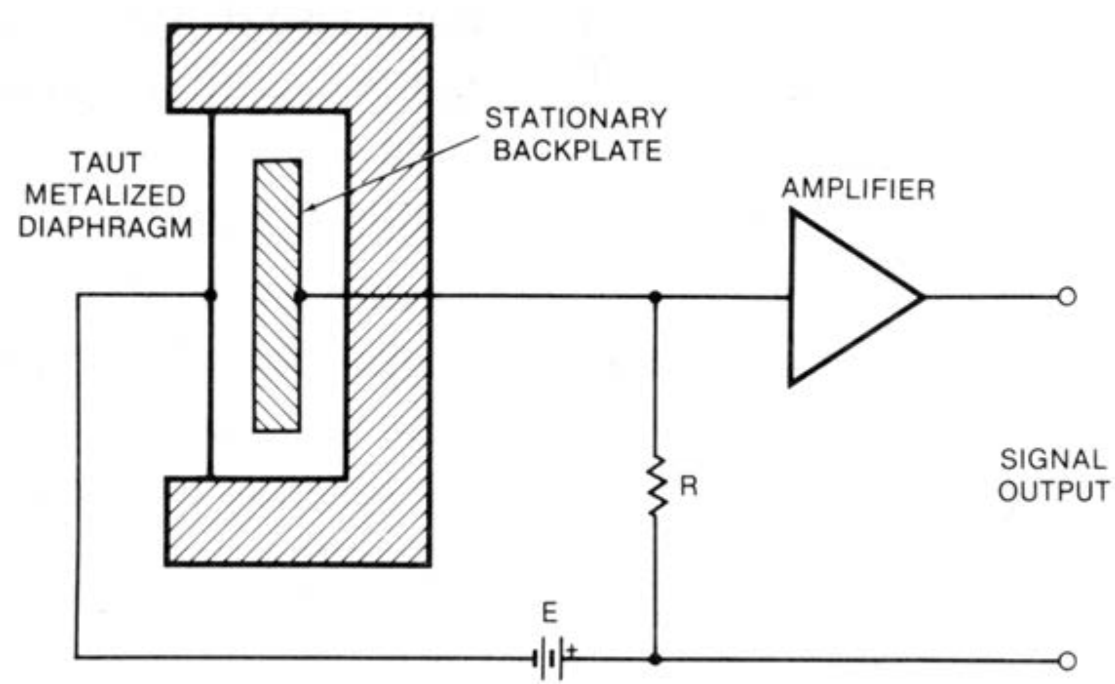


Condenser Microphone

Varying the distance between plates containing a constant charge chances capacitance and creates a varying voltage.

Most common microphone, both in inexpensive and high-end applications.

Miniature version called "electret" mike ubiquitous in computers and cell phones.



- $Q = CV$

which leads to

- $I = C\dfrac{dV}{dt}$

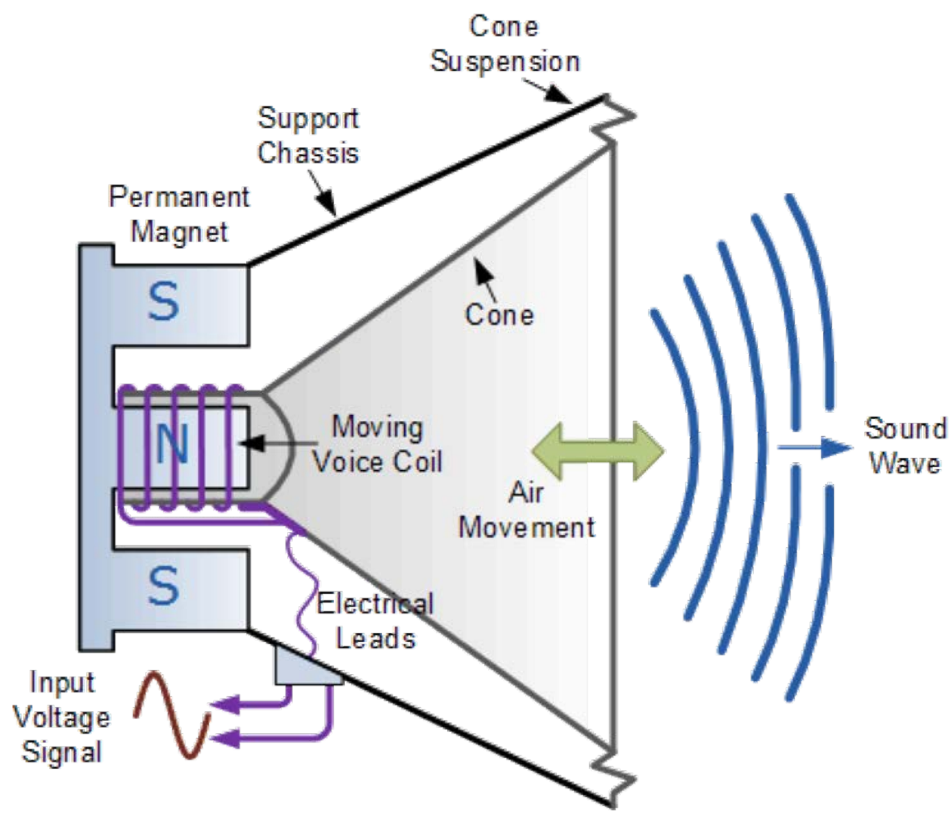
but also to

- $\dfrac{dV}{dt} = \dfrac{1}{Q}\dfrac{dC}{dt}$

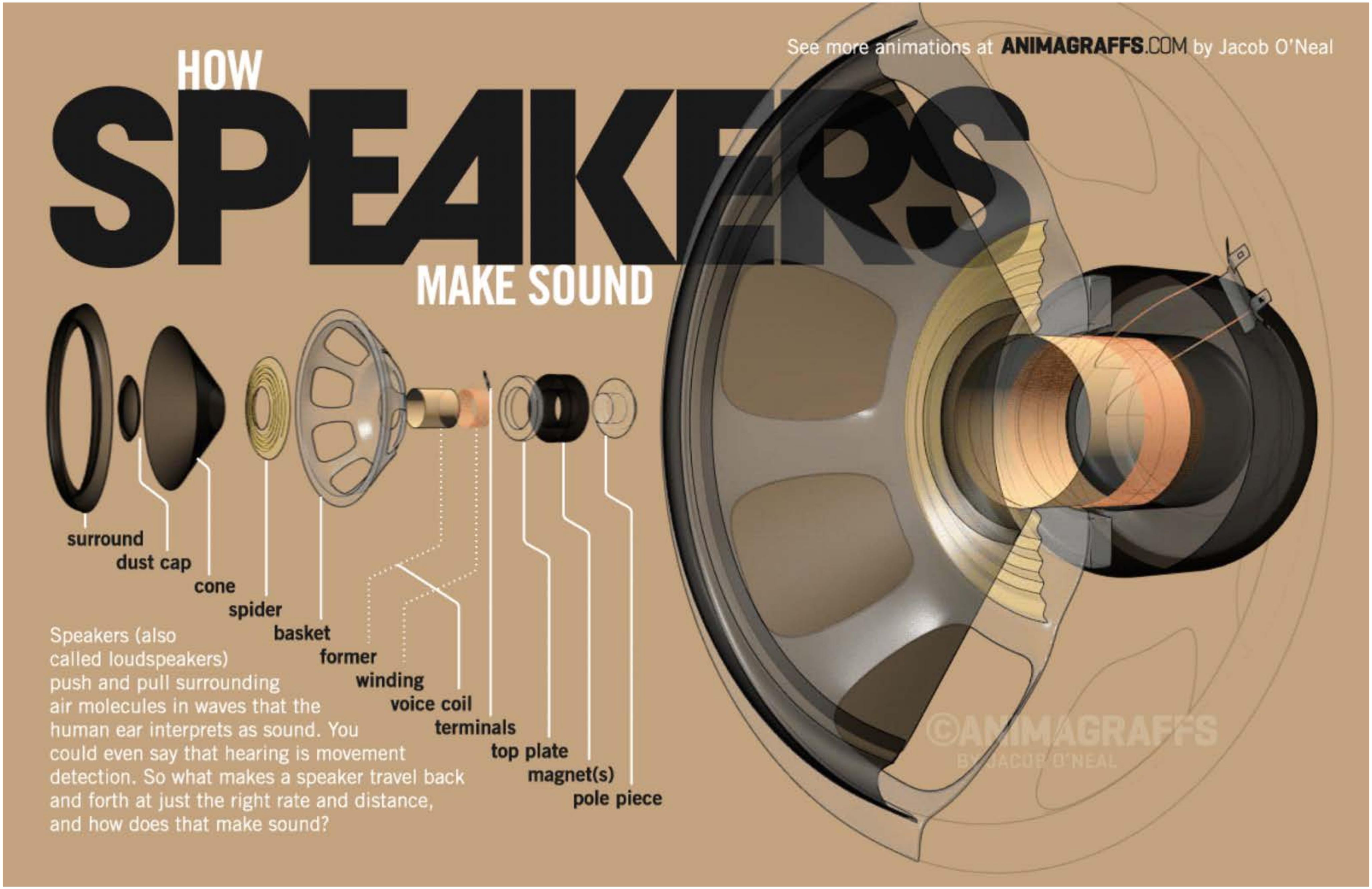
Changing the capacitance with constant charge changes voltage.

Loudspeaker

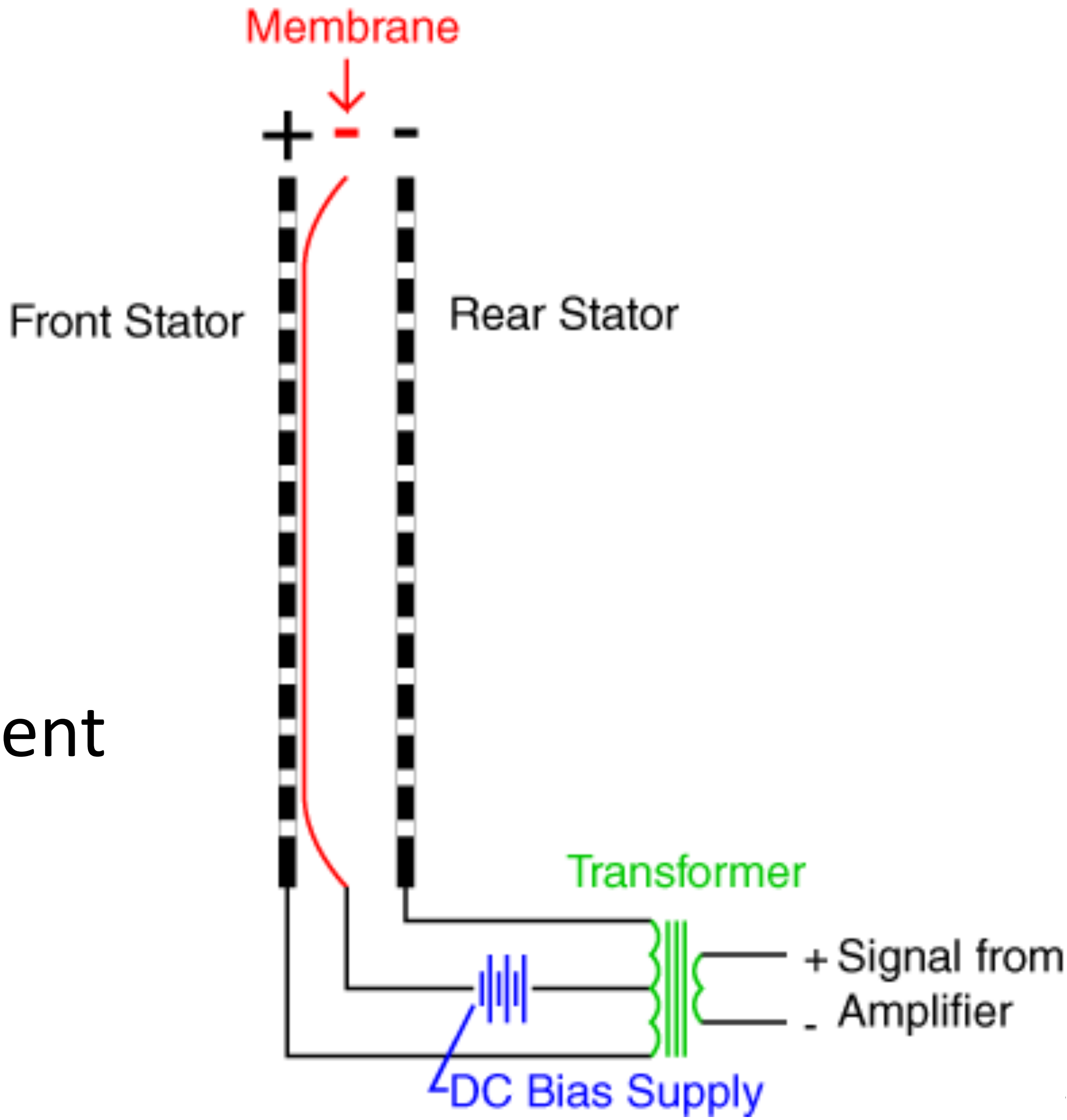
- Moving coil transducer invented by Ernst Siemens in 1874.
- Used by Bell in telephone in 1876.



quora.com

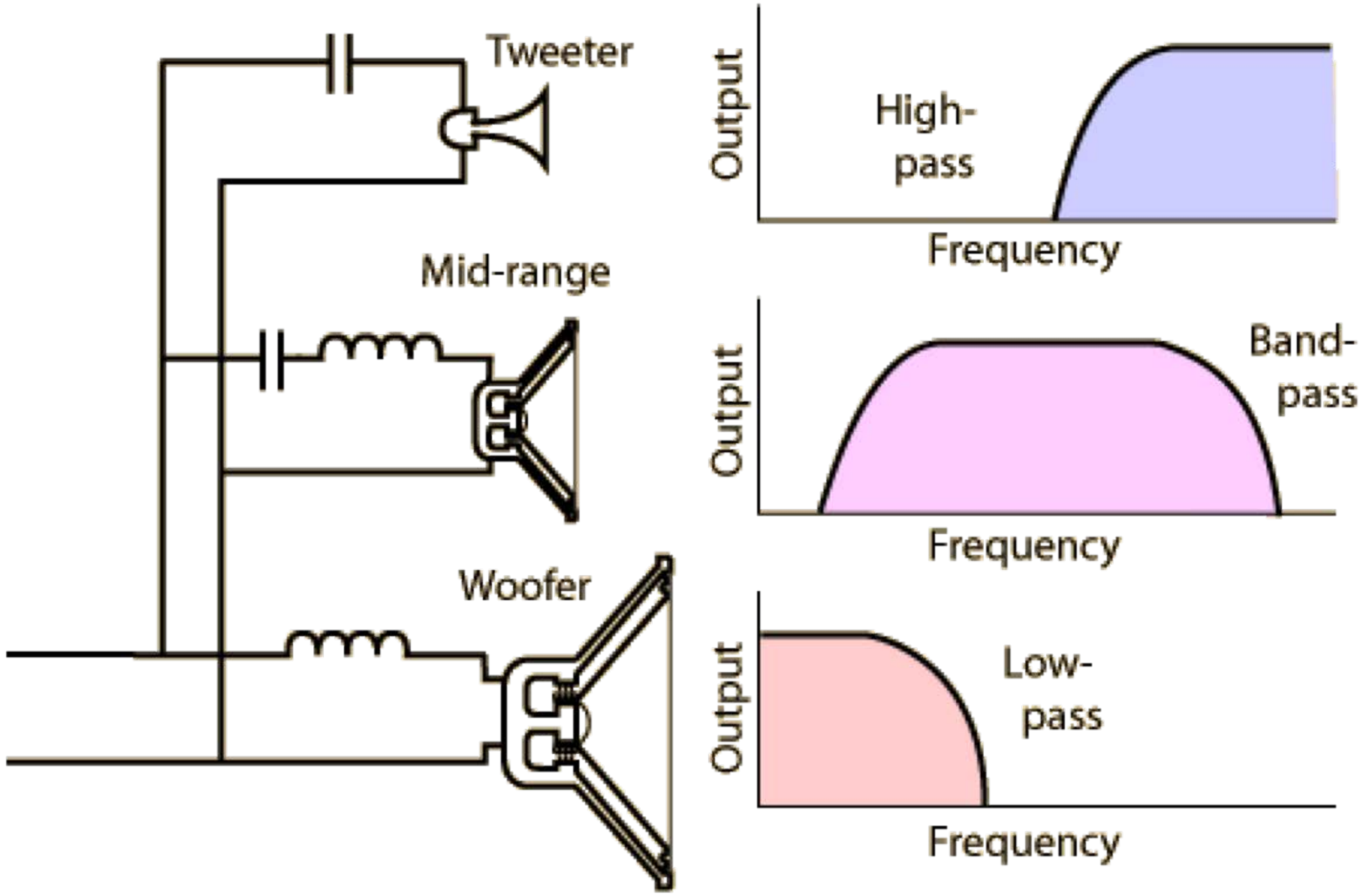

See more animations at ANIMAGRAFFS.COM by Jacob O'Neal
HOW
SPEAKERS
MAKE SOUND
surround
dust cap
cone
spider
basket
former
winding
voice coil
terminals
top plate
magnet(s)
pole piece
Speakers (also called loudspeakers) push and pull surrounding air molecules in waves that the human ear interprets as sound. You could even say that hearing is movement detection. So what makes a speaker travel back and forth at just the right rate and distance, and how does that make sound?
©ANIMAGRAFFS
BY JACOB O'NEAL

Electrostatic Speaker

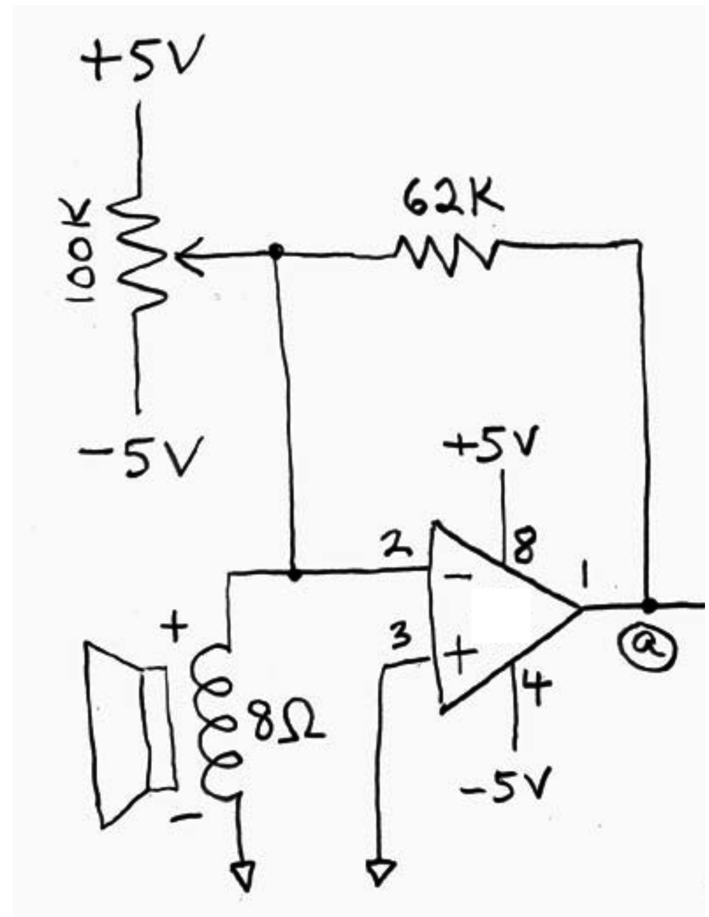


- Not very efficient
- High voltage

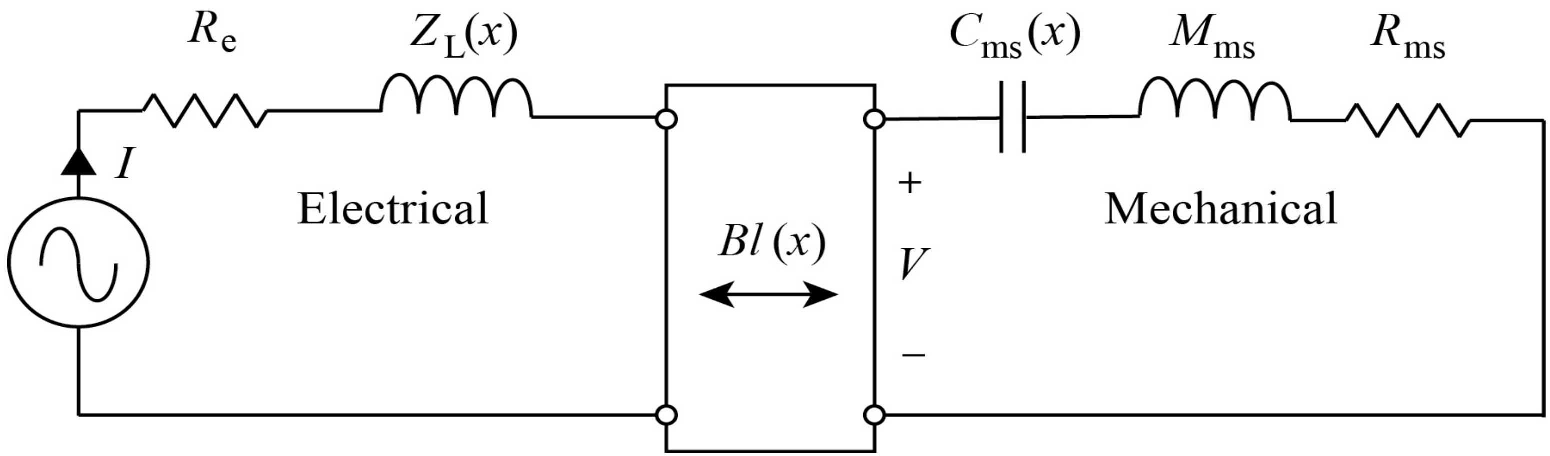
Multi-speaker system divided by frequency



Speakers can act as microphones with great low-frequency response, as in this carotid artery pulse detector.



Lumped Parameter Model - Loudspeaker



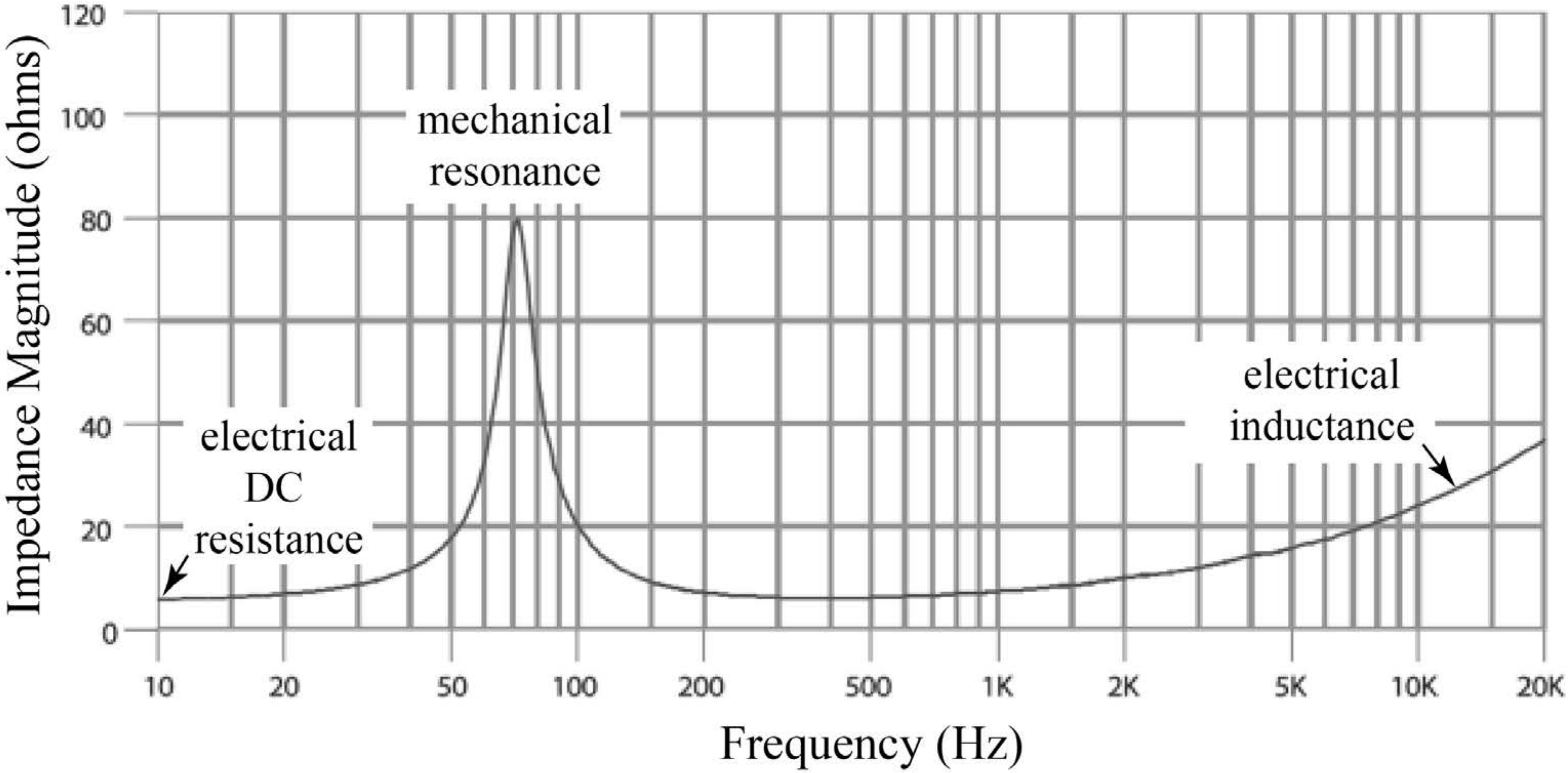
- I Electrical current in speaker voice-coil.
- V Mechanical force 'voltage' caused by electrical current.
- R_e Electrical resistance at DC.
- $Z_L(x)$ Electrical inductance, varies with displacement *x.*
- $C_{ms}(x)$ Compliance of mechanical suspension.
- M_{ms} Mechanical mass of loudspeaker diaphragm.
- R_{ms} Mechanical friction and drag of loudspeaker (sound).
- $Bl(x)$ Transduction between electrical I and mechanical "V".

Energy goes both ways:

Electrical current causes mechanical force (shown)

Speaker motion causes electrical force (not shown).

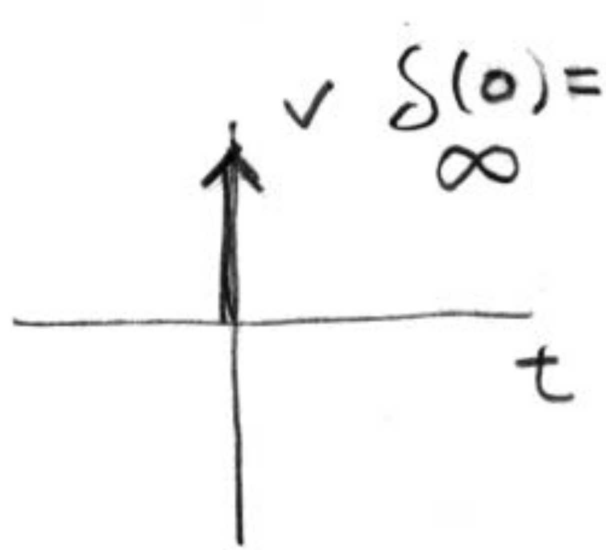
Resulting Electrical Impedance

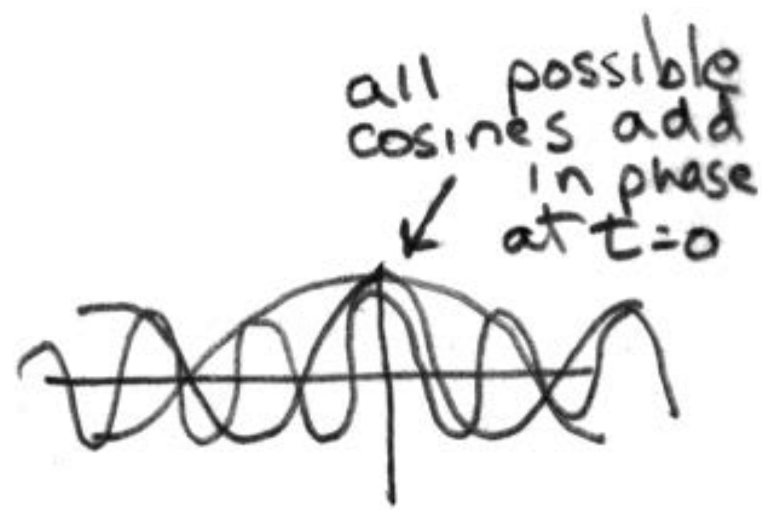


- Electrical impedance results from both electrical and mechanical parts.
- Mechanical resonance generates a *positive* peak, even though mechanically it is *negative* (L and C in series approach zero).
- This is because electrical current causes mechanical ‘voltage’.

Early Radio

- Used “spark gap” transmitters.
- Sparks are basically impulses, transmit on all frequencies (lightning is heard on all channels).
- Saved more than 700 lives on the Titanic.





An impulse consists of the sum of equally weighted cosines at every frequency, in phase only at t = 0.

Modulation / Demodulation

- With more stations, needed to restrict each channel to a different frequency.
- Put information onto a “carrier” signal.
- Two basic methods of modulating the radiofrequency (RF) carrier:
  - Amplitude Modulation (AM)
  - Frequency Modulation (FM)

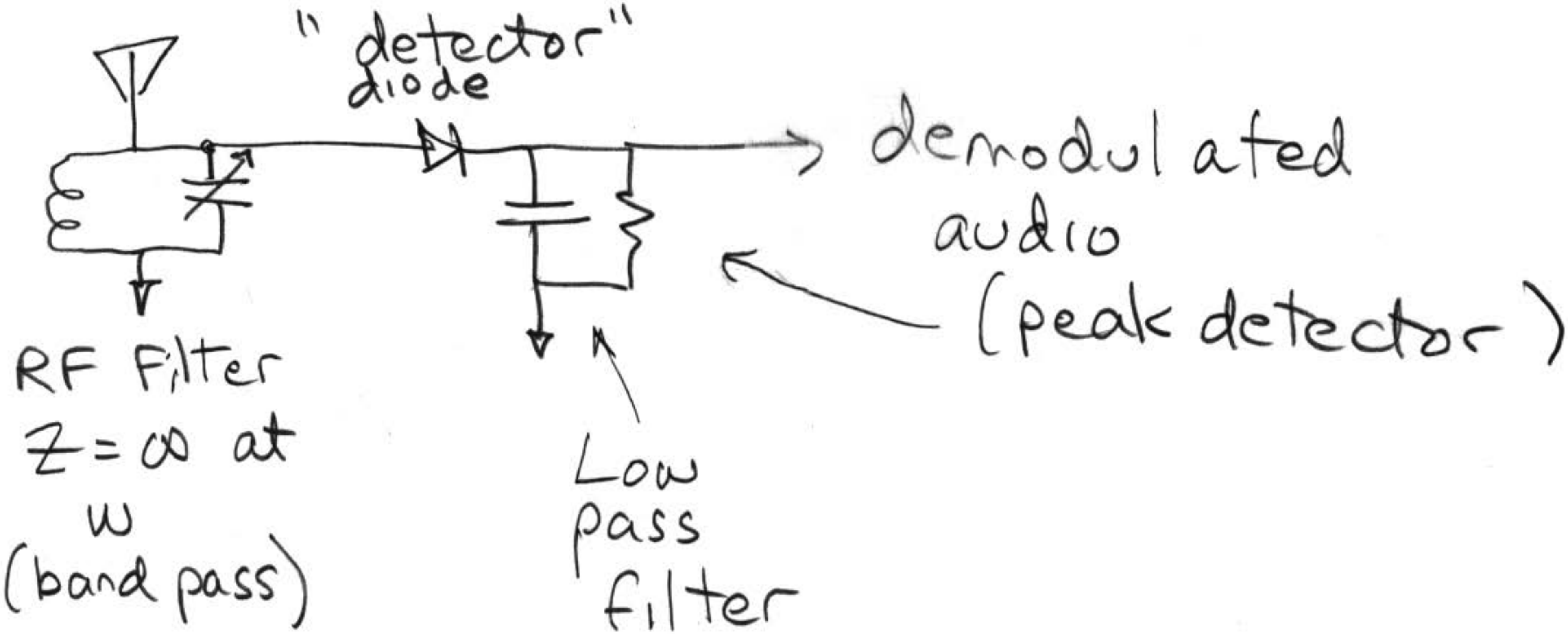
Amplitude Modulation (AM)

- The audio voltage (from the microphone) determines (modulates) the amplitude of the RF sinusoid.
- Allows for transmitters on different frequencies to be distinguished from each other and coexist.

"One, two, three, four.
Is it snowing where you are?"
First voice transmission by radio,
December 23, 1906,
Reginald Fessendon.
Chair EE U. Pitt

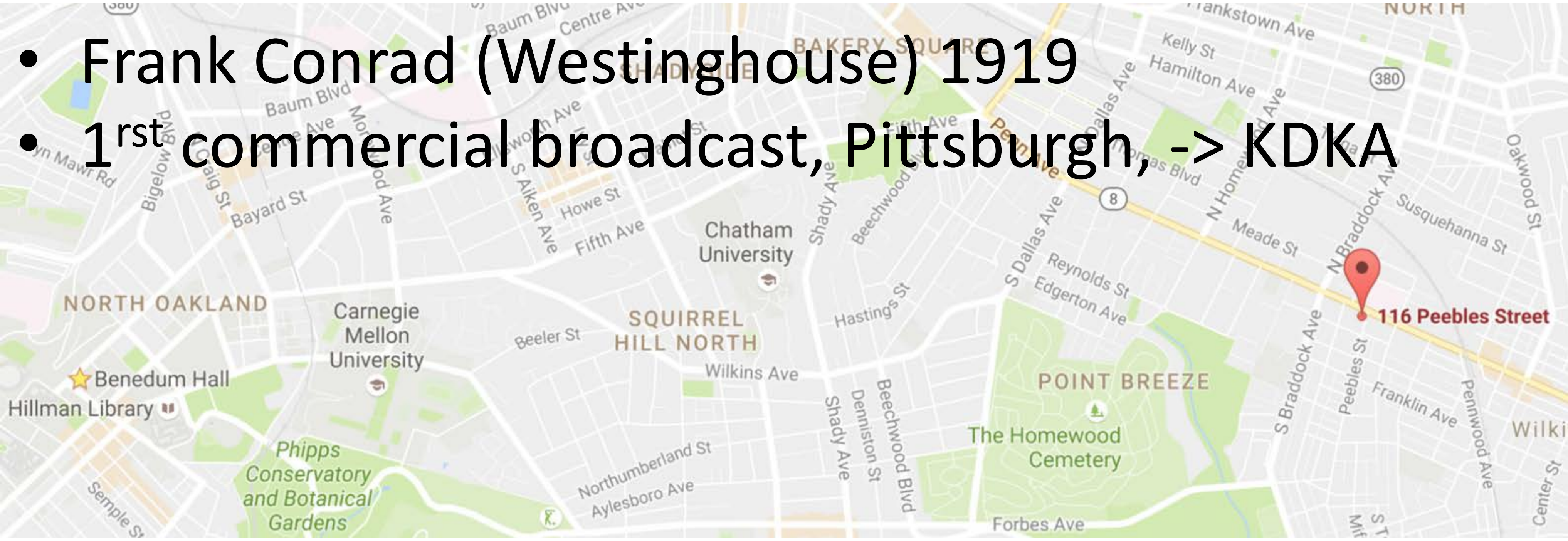
AM Receiver can be a simple peak detector

First method to *demodulate* AM radio



Invented by Reginald Fessenden

- Frank Conrad (Westinghouse) 1919
- 1^{rst} commercial broadcast, Pittsburgh, -> KDKA



Superheterodyning

A better way to demodulate AM radio

- Recall how two phasors multiply

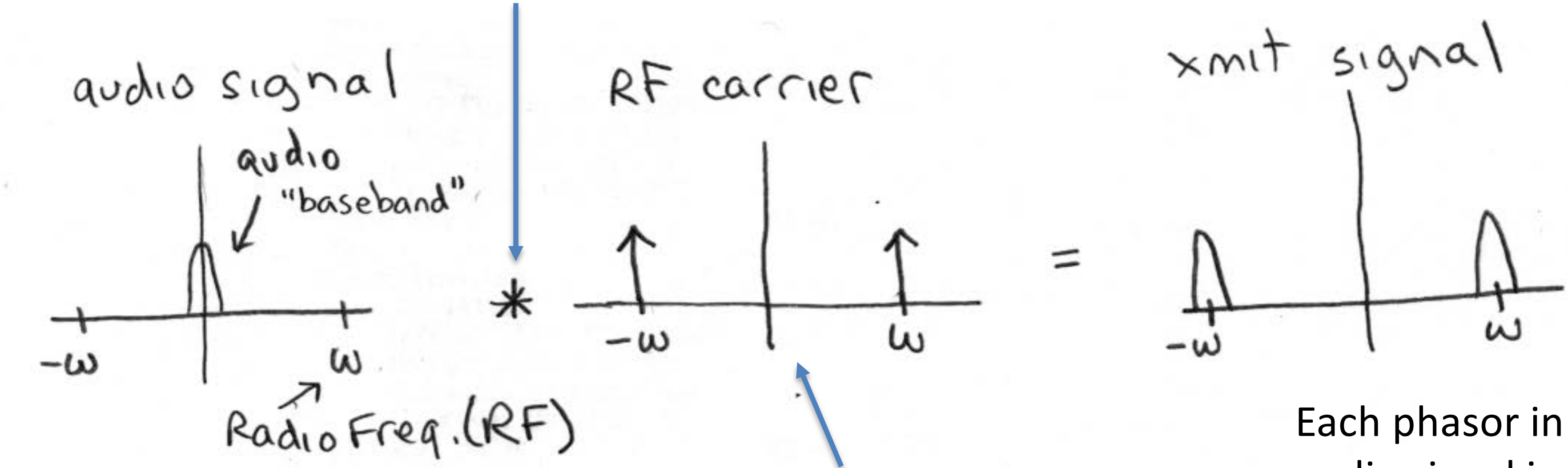
$$e^{j\omega_1 t} \times e^{j\omega_2 t} = e^{j(\omega_1+\omega_2)t}$$

- When multiplying two signals together, each phasor in one signal rotates *all* the phasors in the other signal, shifting their frequencies by its own frequency.
- This amounts to convolution in the frequency domain.
- *Multiplication* in time equals *Convolution* in frequency.

AM in the Frequency Domain

- Amplitude Modulation can be viewed as shifting the audio spectrum up to the radio band by multiplying it by a sinusoid at radio frequency (RF), the "RF carrier".

convolution

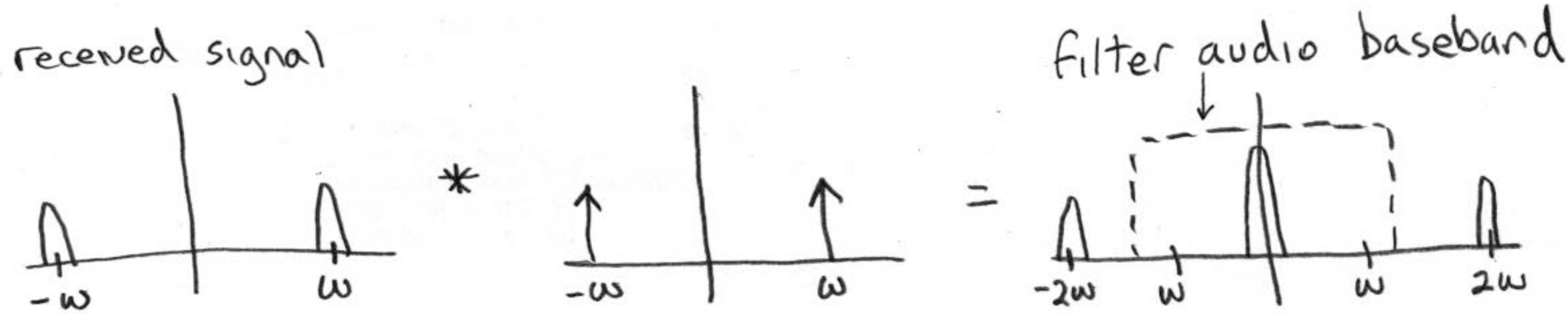


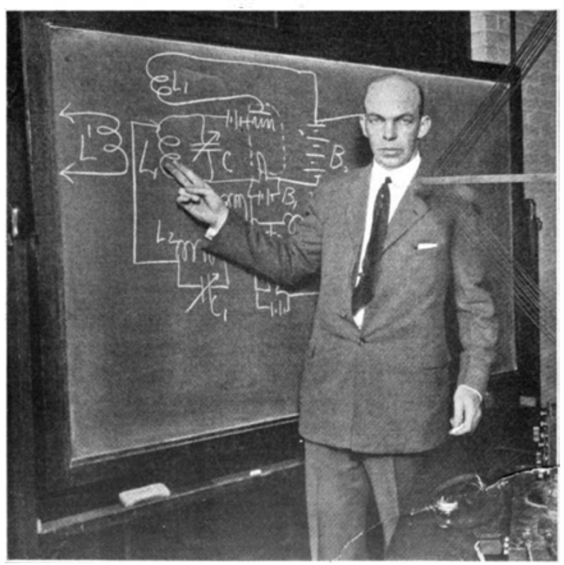
The sinusoidal RF carrier at frequency ω consists of a pair of complex conjugate phasors at $\pm\omega$.

Each phasor in the audio signal is shifted in frequency by $\pm\omega$.

Demodulating by Superheterodyning

- Multiplying the received radio signal by a sinusoid at the carrier frequency shifts the audio back down to the baseband (as well as up to twice the carrier frequency, which can easily be filtered off).

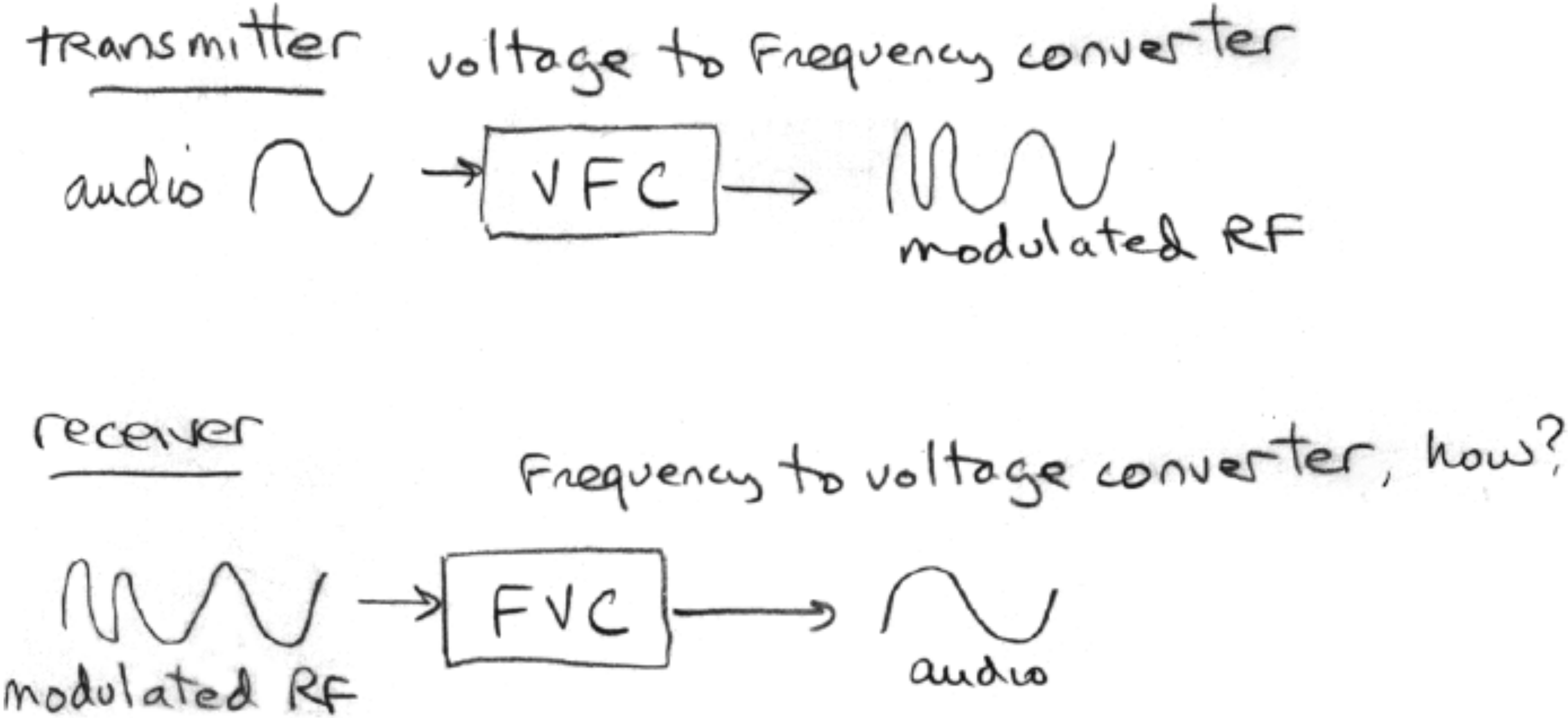




Invented by
Edwin Armstrong 1919

Frequency Modulations (FM) Radio

Audio modulates the *frequency* of the carrier.



FM has better fidelity and can be differentiated better from noise.

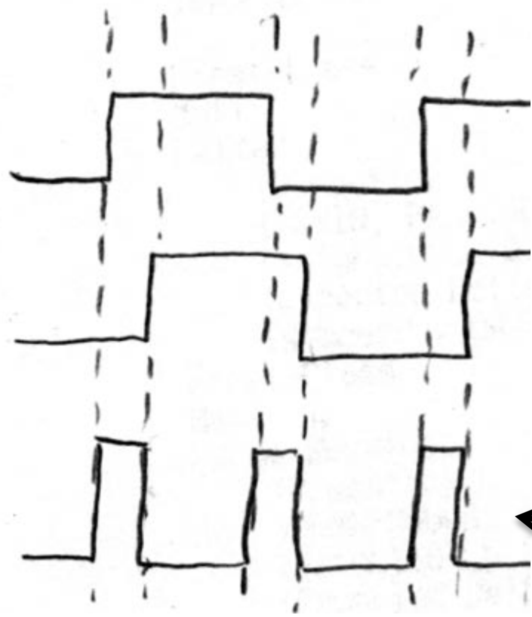
Also invented by Edwin Armstrong - 1928

FM Receiver using *Phase Lock Loop*

Input signal

Local VCO

Exclusive OR



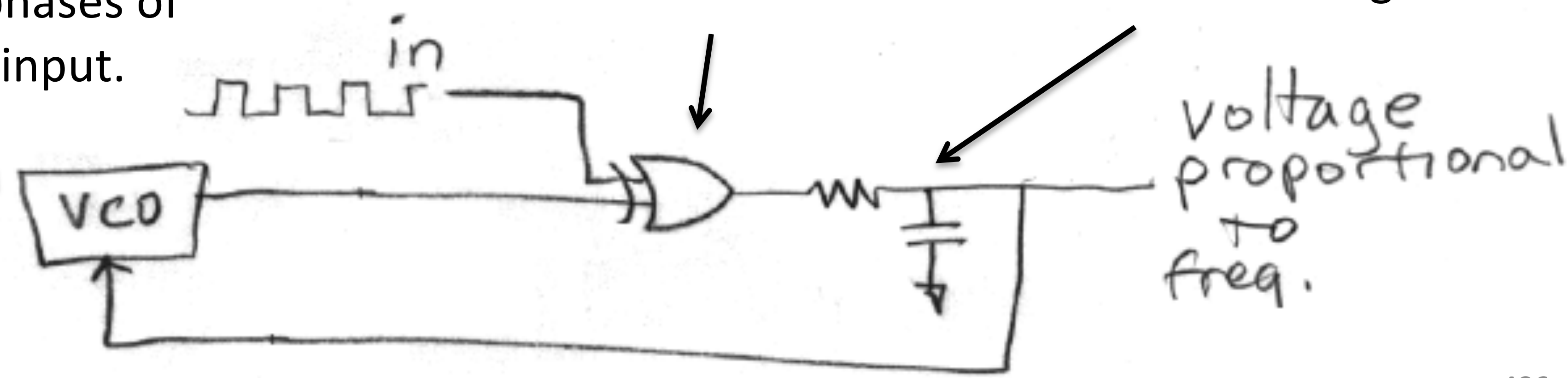
Local Voltage-Controlled Oscillator (VCO) *phase locked* to keep it same frequency as input signal

Duty Cycle (% time high) varies with relative phases of input signal and local VCO

Frequency of VCO controlled by relative phases of VCO and input.

exclusive OR

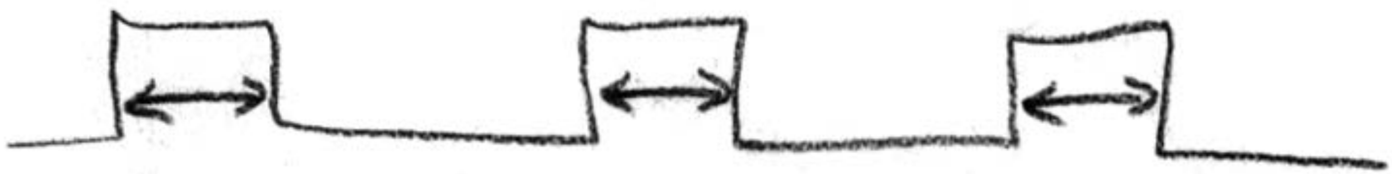
filter to find average value



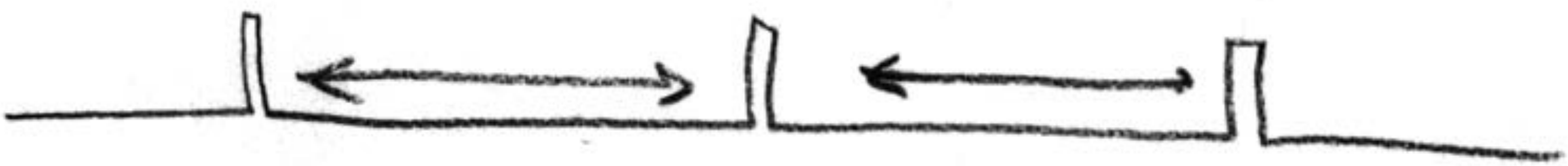
CD4046 chip

Other methods of Modulation

- Pulse-Width Modulation (model cars)



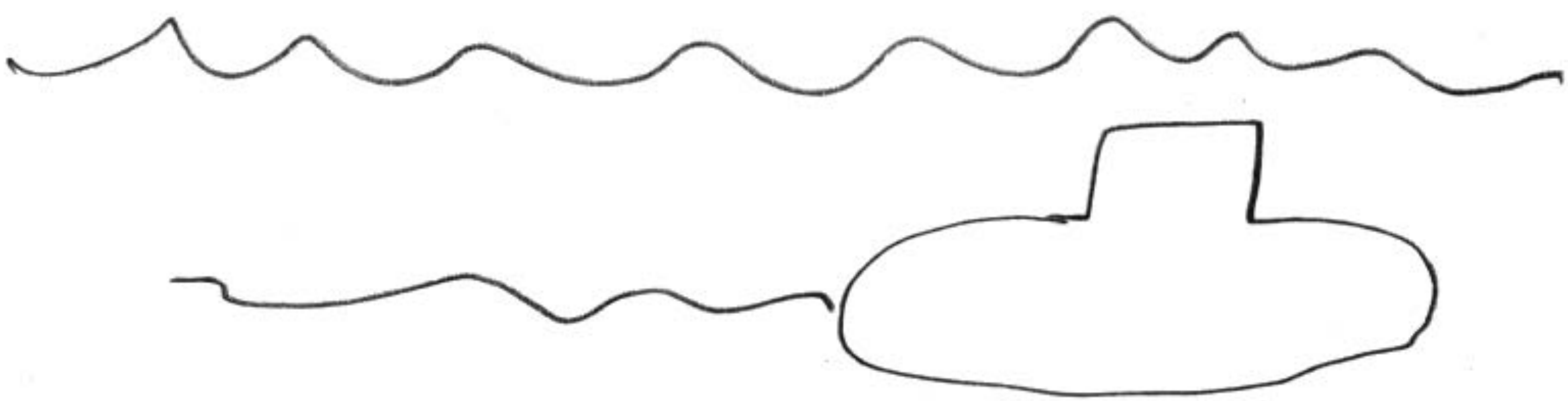
- Pulse-Interval Modulation (least power)



Very Low Frequency

VLF 3-30 KHz

you can go 1/2 wavelenth into anything with EM Radiation, So can reach submarines at 20 meters



Extremely Low Frequency

ELF 3 - 3000 Hz

ONLY TWO EVER BUILT

RUSSIAN 82 HZ

US 76 HZ

2 huge electrodes in wet areas of earth

one in WISCONSIN, ONE in MICHIGAN

uses the earth between

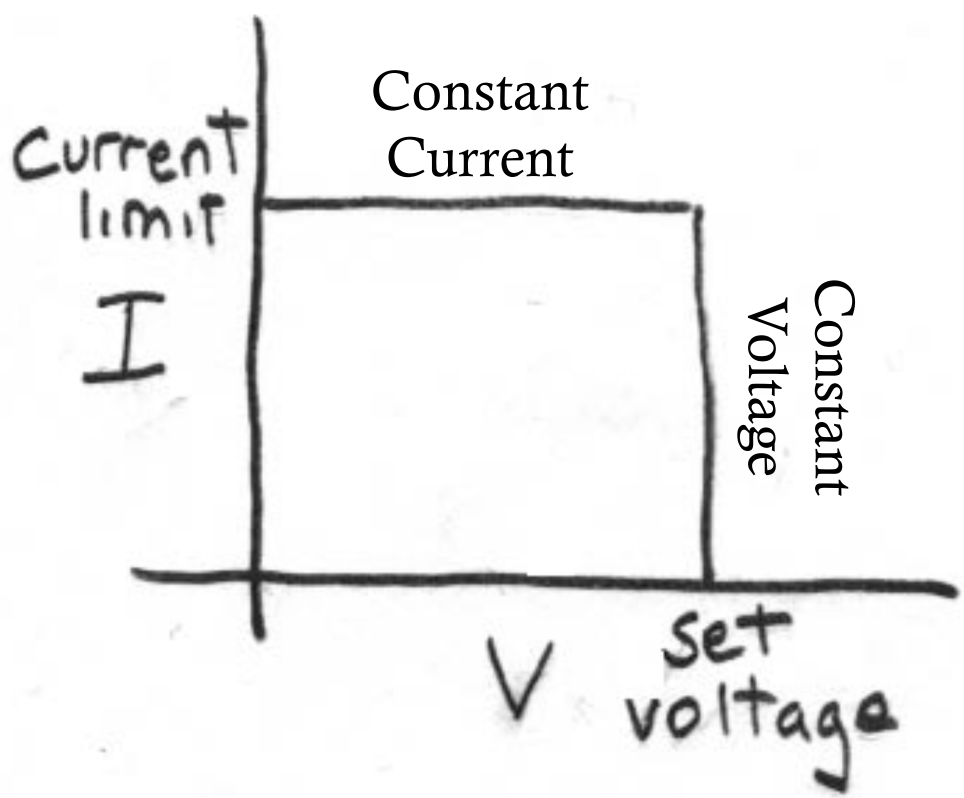
as antenna

Big Power Supplies in Lab – Don't use with MicroBLIP!

- Two 30 V supplies (grounded to the green terminals by metal strips to be $\pm$).
- One 4-6.5 V supply, FLOATING (you must ground it yourself, by connecting a wire between its black terminal and one of the green terminals).
- "Current knobs" set current limit at which turns on the red LED.
- Push V/A buttons to see voltage or current (leave other buttons *out*).
- Leave connector strips between ground (green) and neighbor (red or black).

Regulated Power Supply

- Provides constant voltage up to a certain current limit.
- Thereafter, provides constant current over voltage range.
- Not a linear system.



set voltage & current limit

"CV"
Constant Voltage
during normal operation.

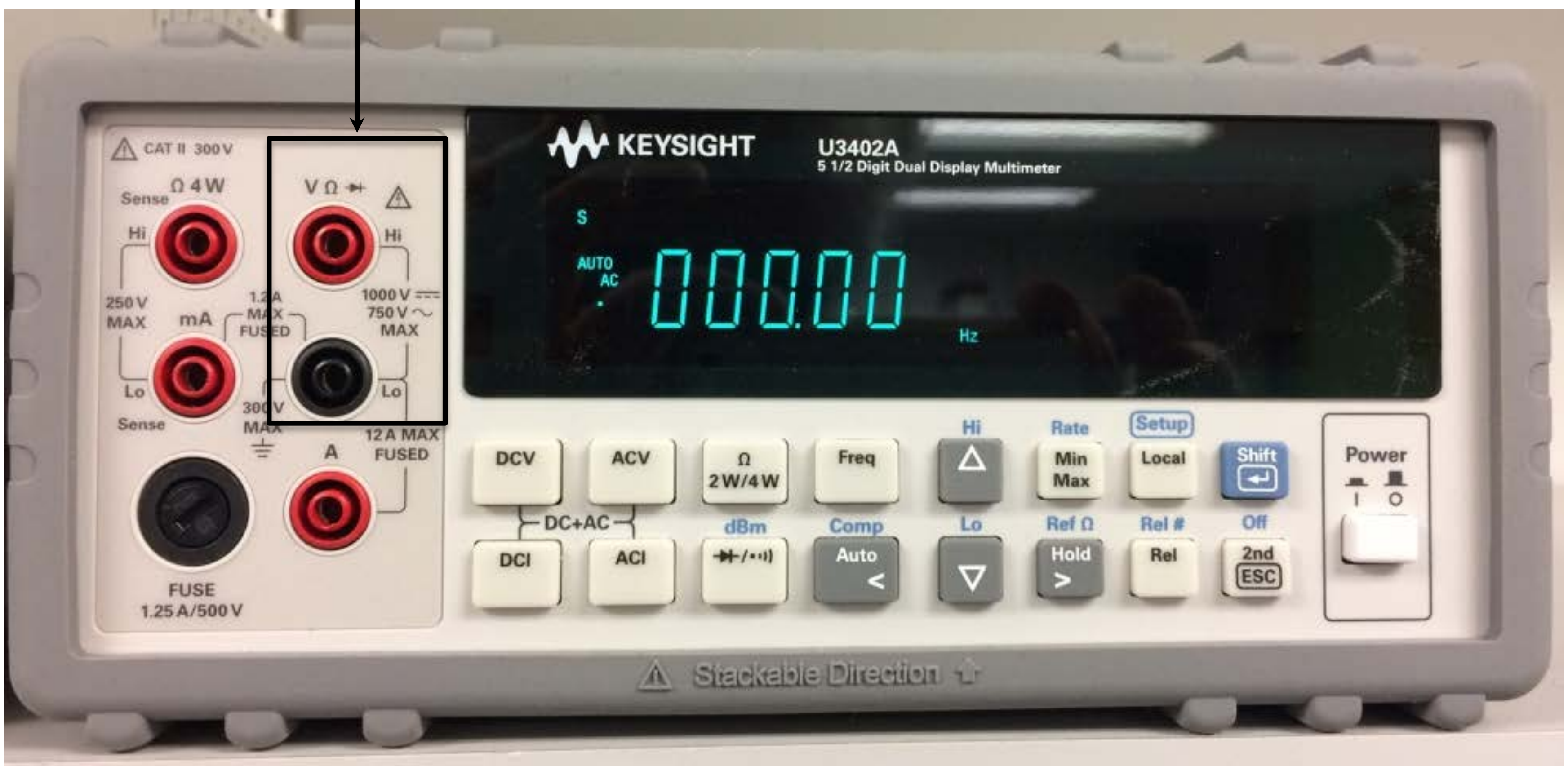
"CC"
Constant Current
when current limit is reached.

Fancy Multi-meters in lab

- Higher accuracy and greater range for voltages, current, resistance.
- Auto-ranging.
- Measures Frequency more accurately than scope.
- Lots of other fancy features, see manual.

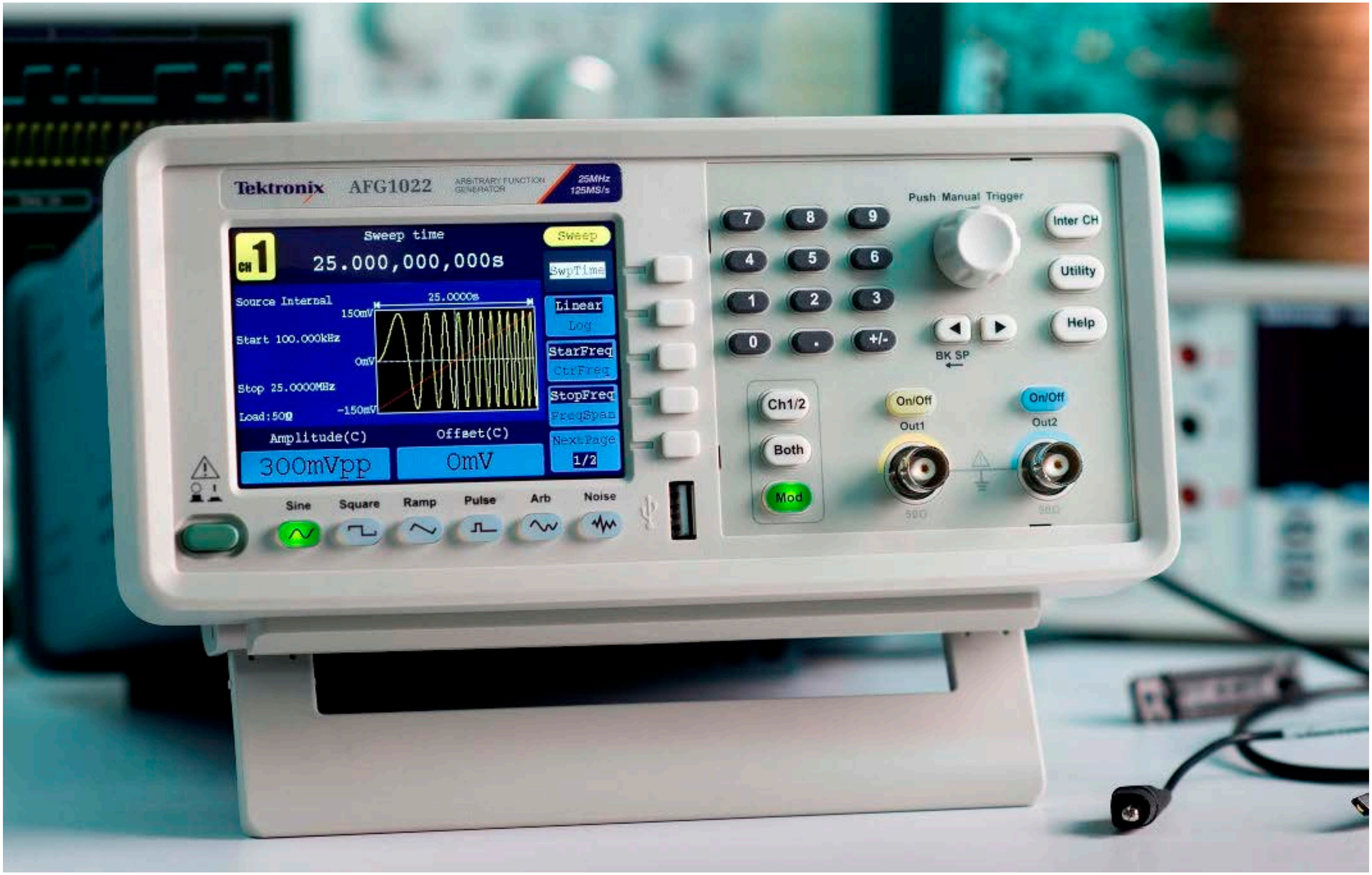
Keysight is really *Hewlett Packard*, a top name in instruments, founders of Silicon Valley.

Generally use these for Volts, Ohms, Frequency, black as ground.



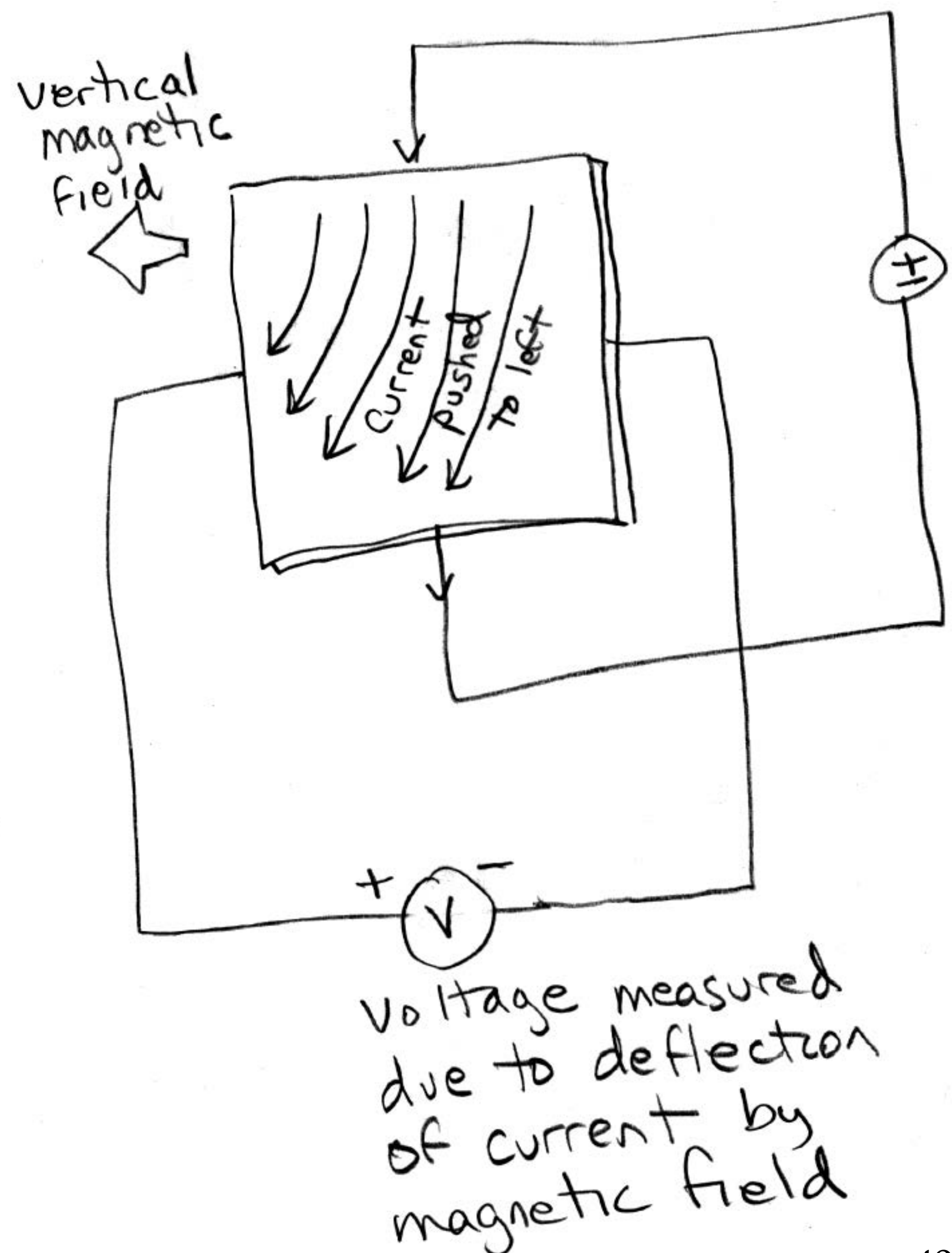
Tektronix AFG10022 Function Generator

- Now in B10: Sin, Square, Ramp, Swept, Arbitrary, Noise

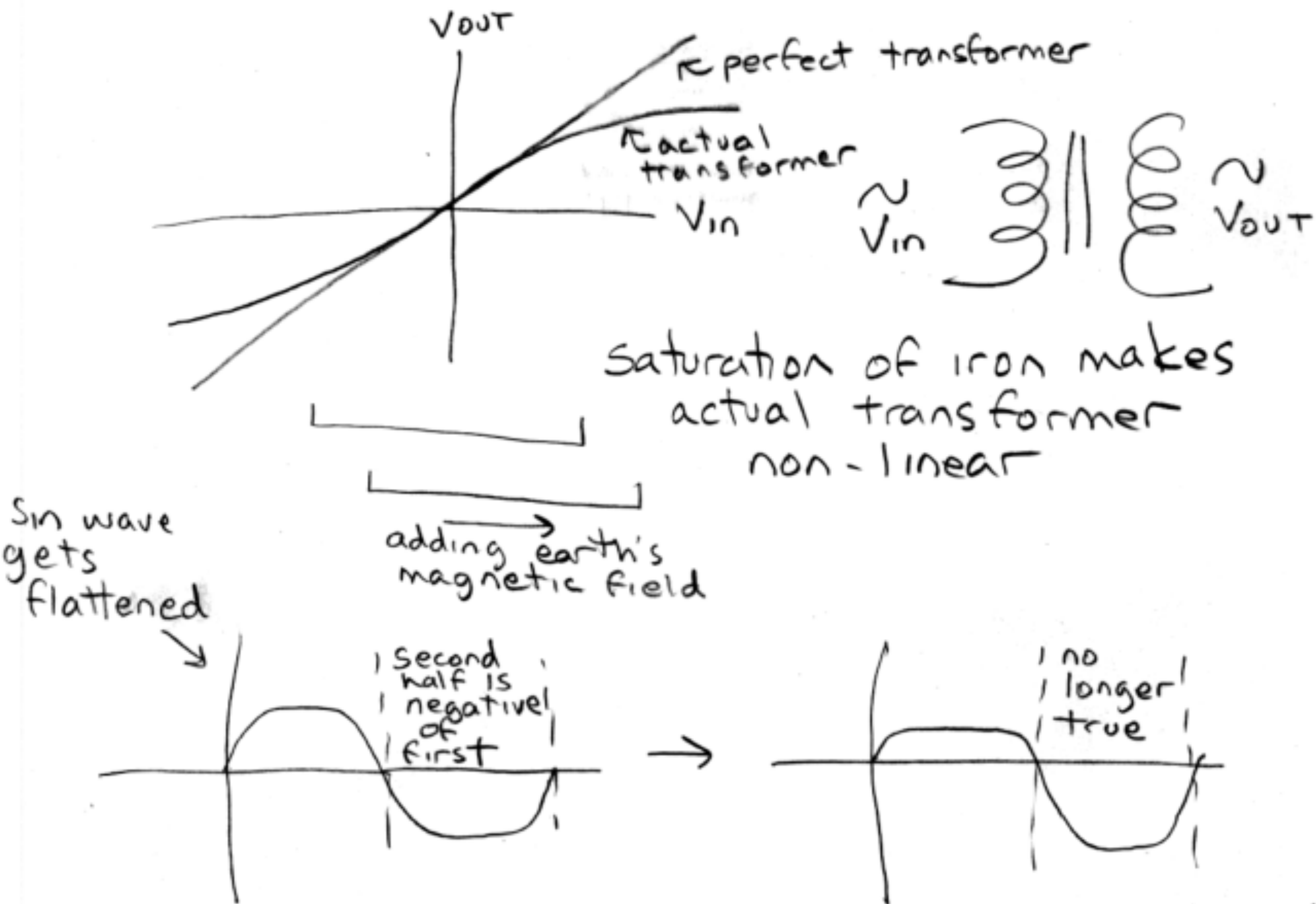


Measuring Magnetism

- Hall Effect Sensor.
- Not that sensitive, but cheap, good enough for sensing Earth's field.
- Used in "brushless" motors, which don't wear out as fast.



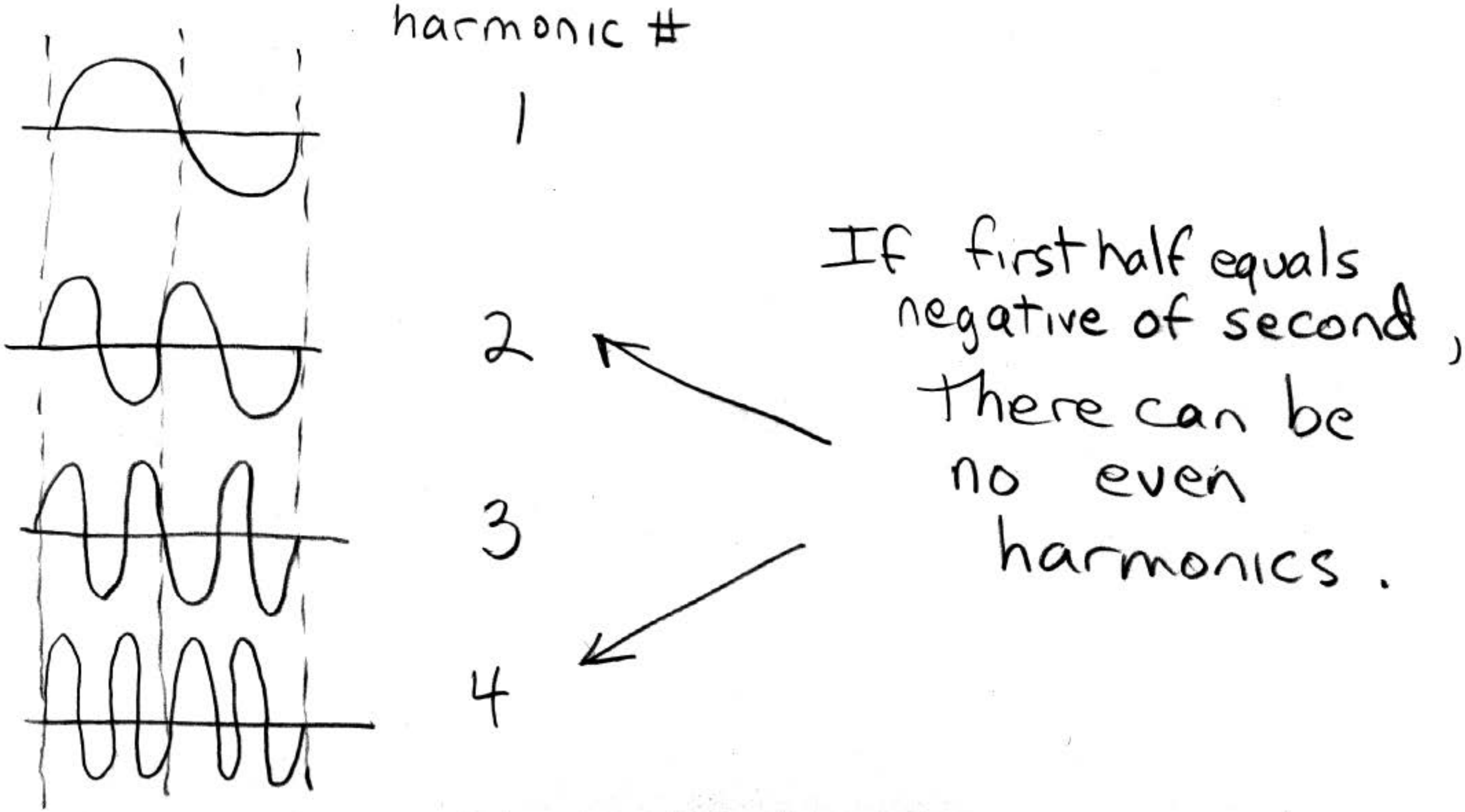
Flux Gate Magnetometer



adding earth's field make distortion asymmetrical

Flux Gate Magnetometer

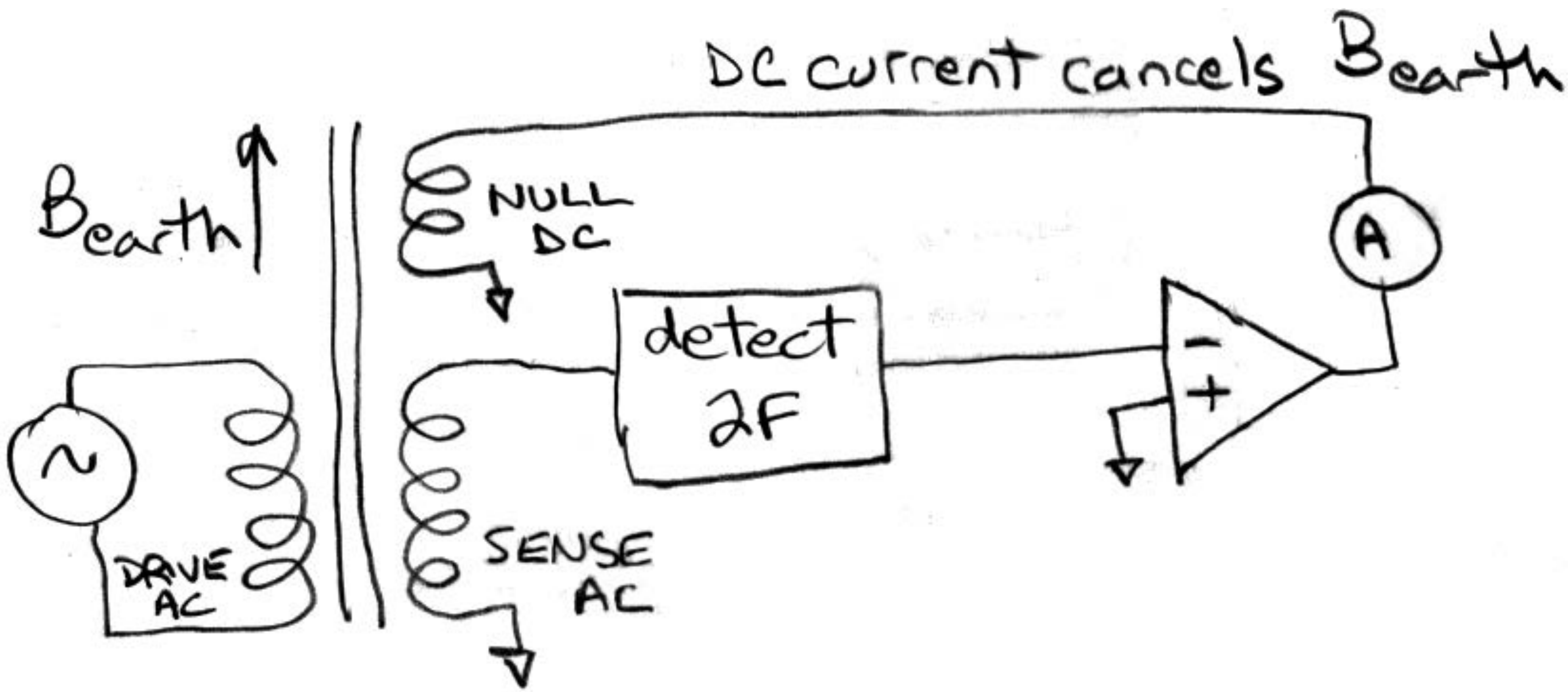
- Detect asymmetrical distortion by even harmonics



- Add coil to transformer to cancel ambient magnetic field

Flux-Gate Magnetometer

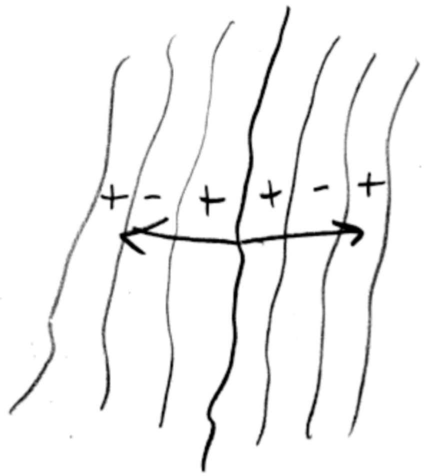
- Used to measure slight variations in the Earth's magnetic field (B_{earth})



Earth Magnetic Field
is a big FLIP FLOP!

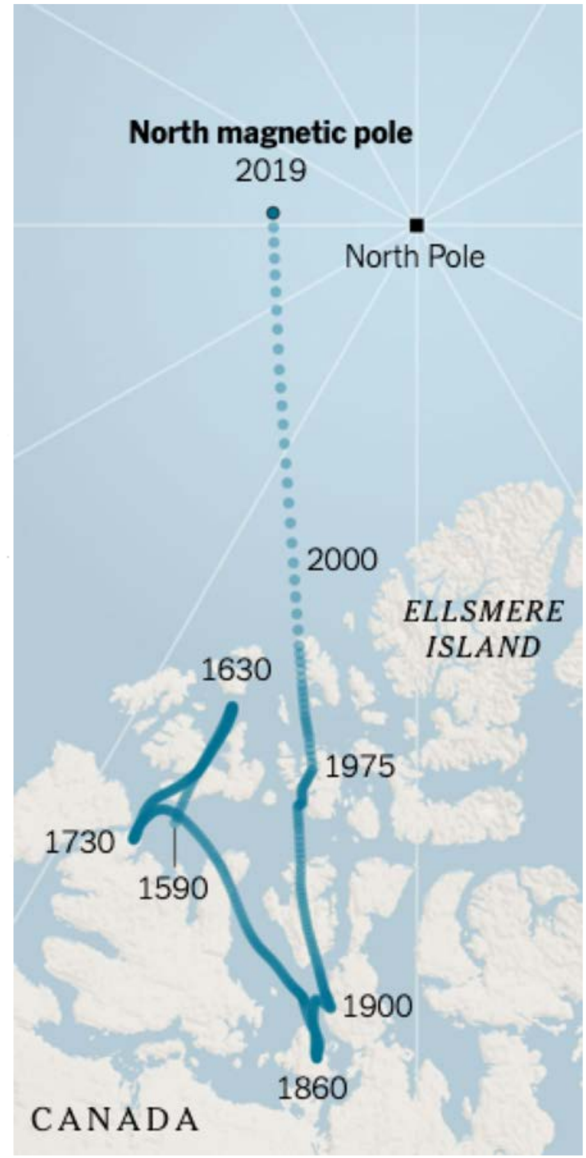
moving iron core and ionosphere

mid-atlantic ridge



magnetic
field flips
on the order of
every ½ million years

Same pattern on opposite
sides of ridge



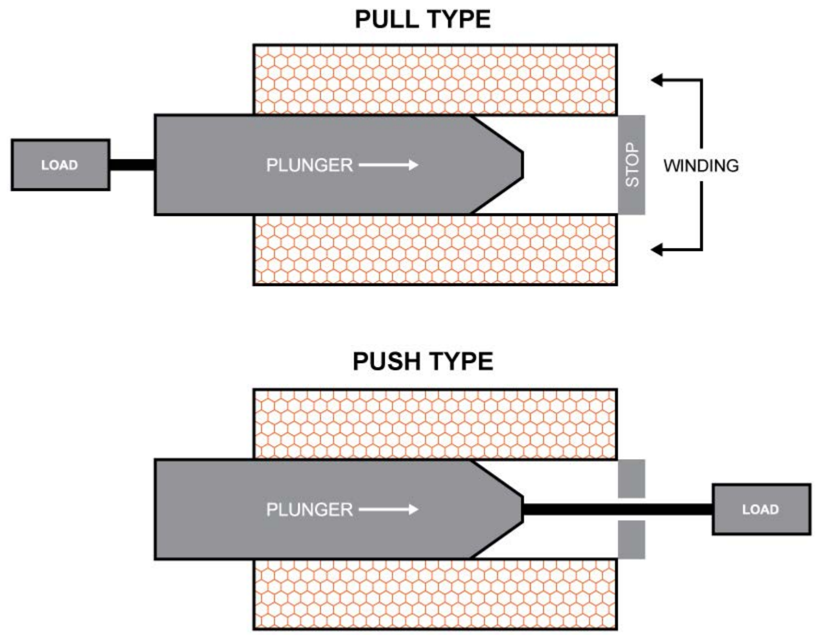
Superconducting Quantum Interference Detector (SQUID)

- Very sensitive magnetic detector.
- Originally to detect submarines, now used in Magnetoencephalography (MEG) to detect brain waves.
- Meissner Effect: currents arise in a superconductor to exactly cancel external *magnetic* fields (equivalent to shielding of *electrostatic* fields by conducting box).
- Blocking these currents with a thin "quantum" barrier permits detection of sufficient external magnetic field to overcome the barrier.

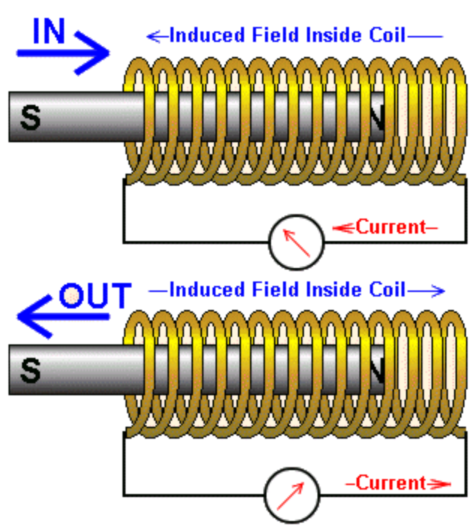
http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/meis.html#c1
https://en.wikipedia.org/wiki/SQUID

Linear Actuators

- Solenoids (stationary coil)
  - Non-magnetized iron plunger
    - Iron always pulled into coil
    - Most commercial solenoids
    - Can be either pull or push type
    - Usually has a spring



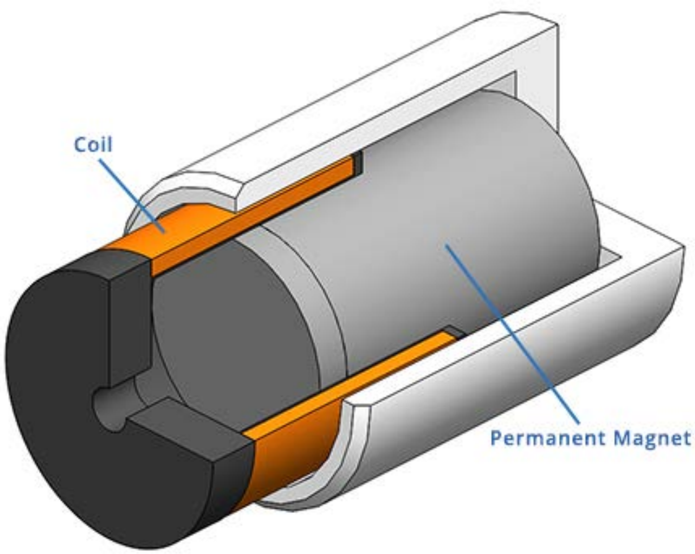
  - Magnetized plunger
    - Less common (make your own?)
    - Can push or pull depending on direction of current.



https://www.allaboutcircuits.com/technical-articles/solenoids-understanding-actuation-and-voltage-polarity/
http://www.societyofrobots.com/actuators_solenoids.shtml

Linear Actuators

- Voice Coils (coil moves through permanent magnet)
  - Used in speakers
  - Faster than solenoids (coil is lighter than iron plunger)
  - Less powerful than solenoids (coil is usually single layer)
  - Coil must be held straight while it moves, by bearing, bushing, or suspension (in speaker).

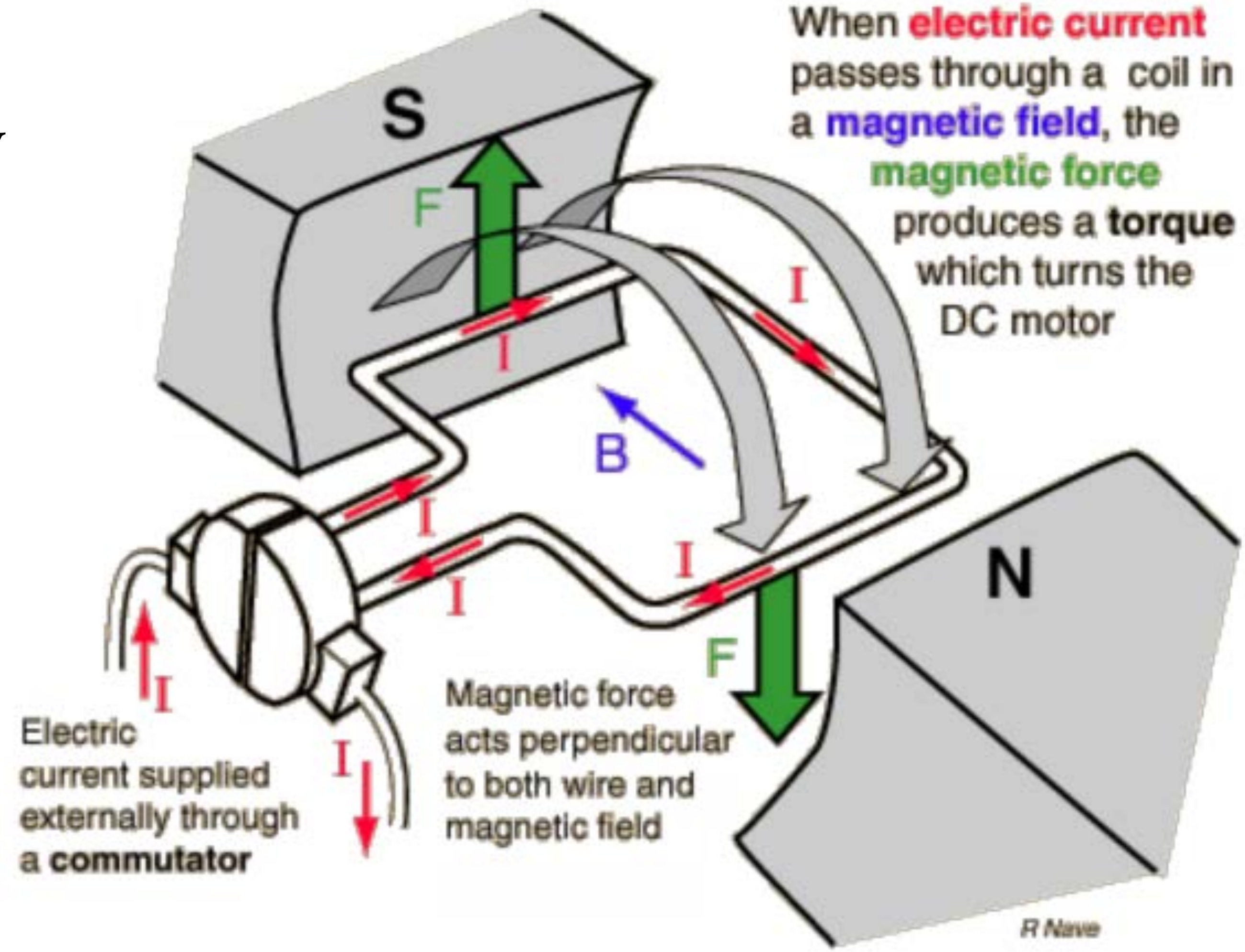


http://www.moticont.com/voice-coil-motor.htm
https://www.h2wtech.com/article/what-is-a-voice-coil-actuator

Conventional DC Motor

Stator – stationary part of a motor

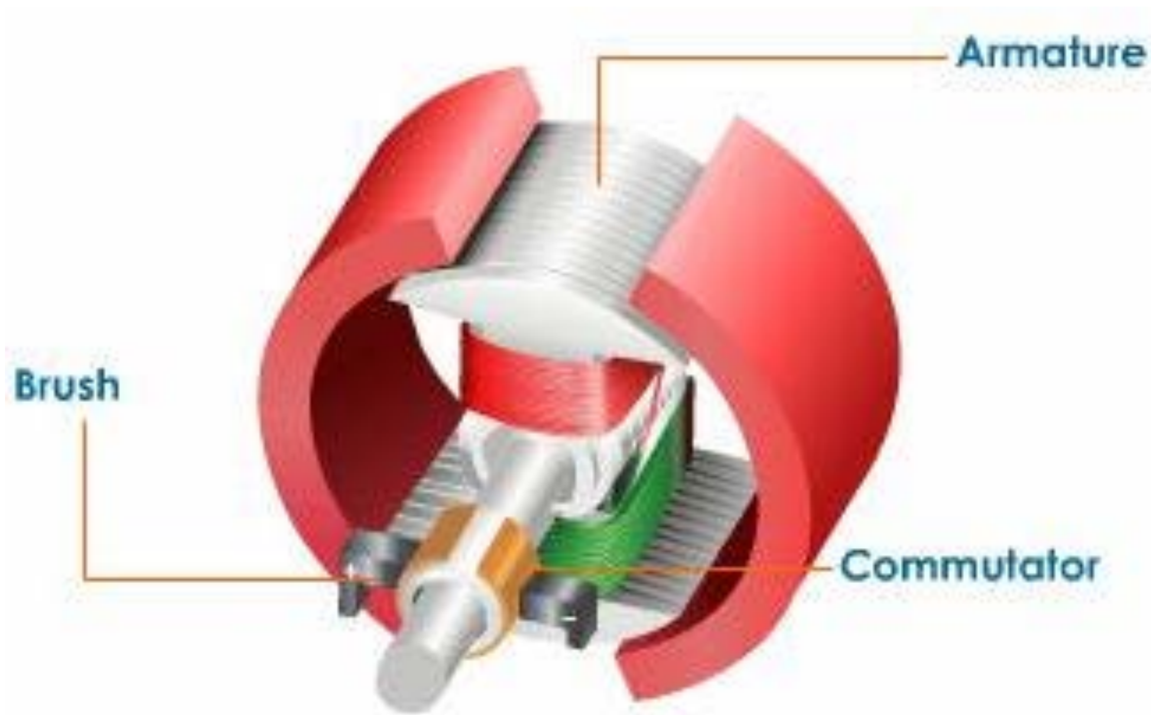
Rotor – rotating part of a motor



hyperphysics.phy-astr.gsu.edu

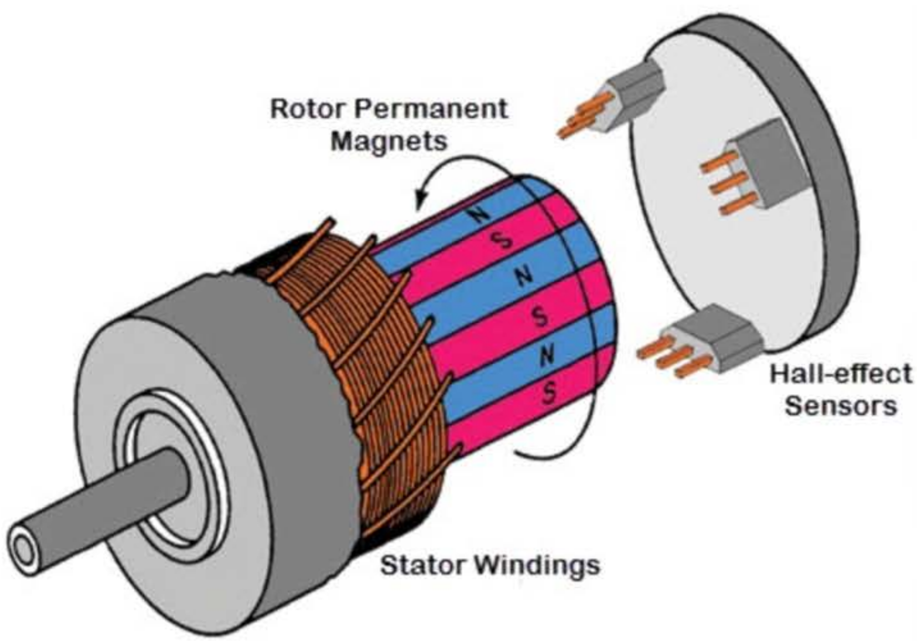
Conventional DC Motor

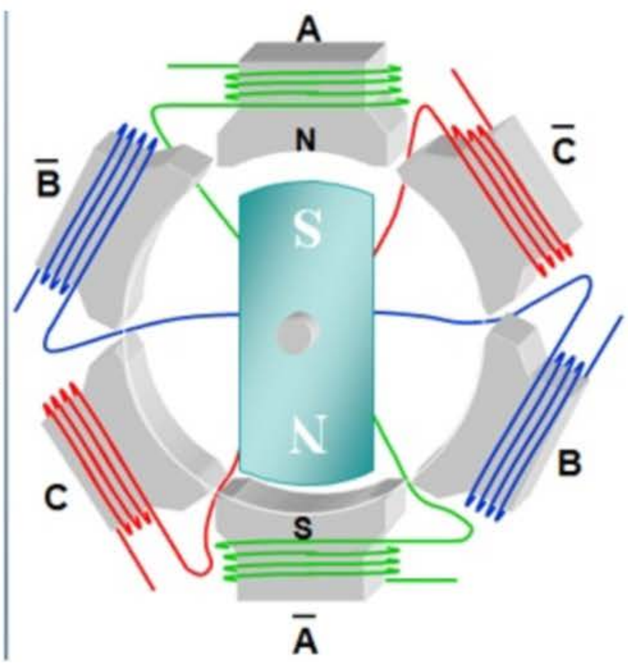
- Brushes touch metal contacts on the commutator.
- With only 2 coils and contacts, motor may go either direction or not at all, depending on resting orientation.
- Most DC motors thus have at least 3 coils and contacts.

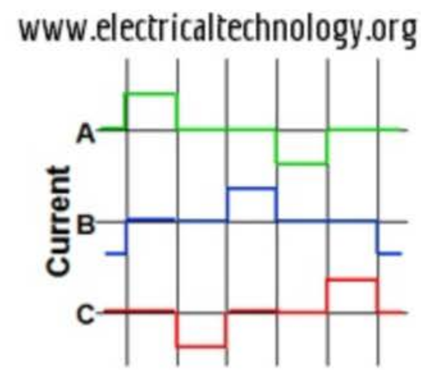


Brushless Motor

- Stationary Hall effect sensors (or sensing coils) sense rotating permanent magnets, replacing mechanical switches (brushes) to control coil activation.
- Longer lifetime. More expensive.







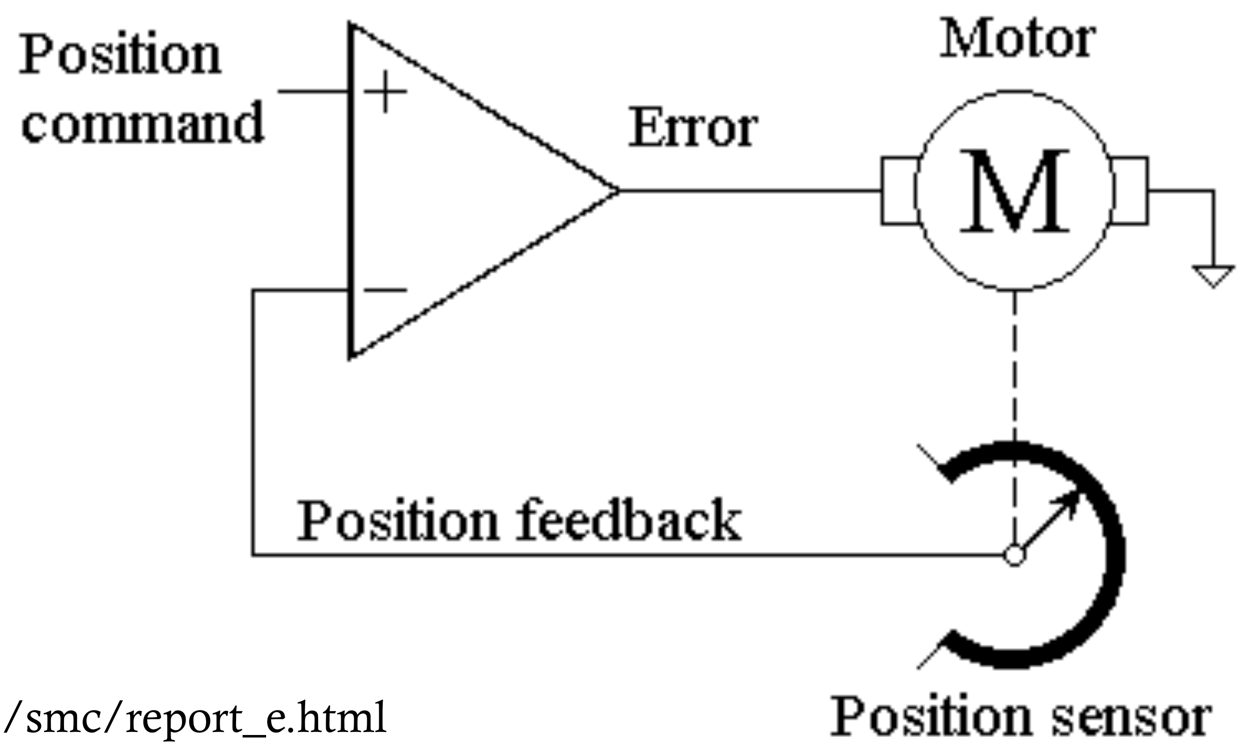
Synchronous AC motor

- No commutator or sensors, uses AC power source to change magnetic fields.
- Rotates at a rate locked to the line frequency, (60 Hz in the US).
- Used in analog clocks (and Hammond organ).
- AC power-line generators are timed to average exactly 60 Hz, by slowing down or speeding up at the end of each day, so that synchronous motors can be used in clocks.

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

Servomotors

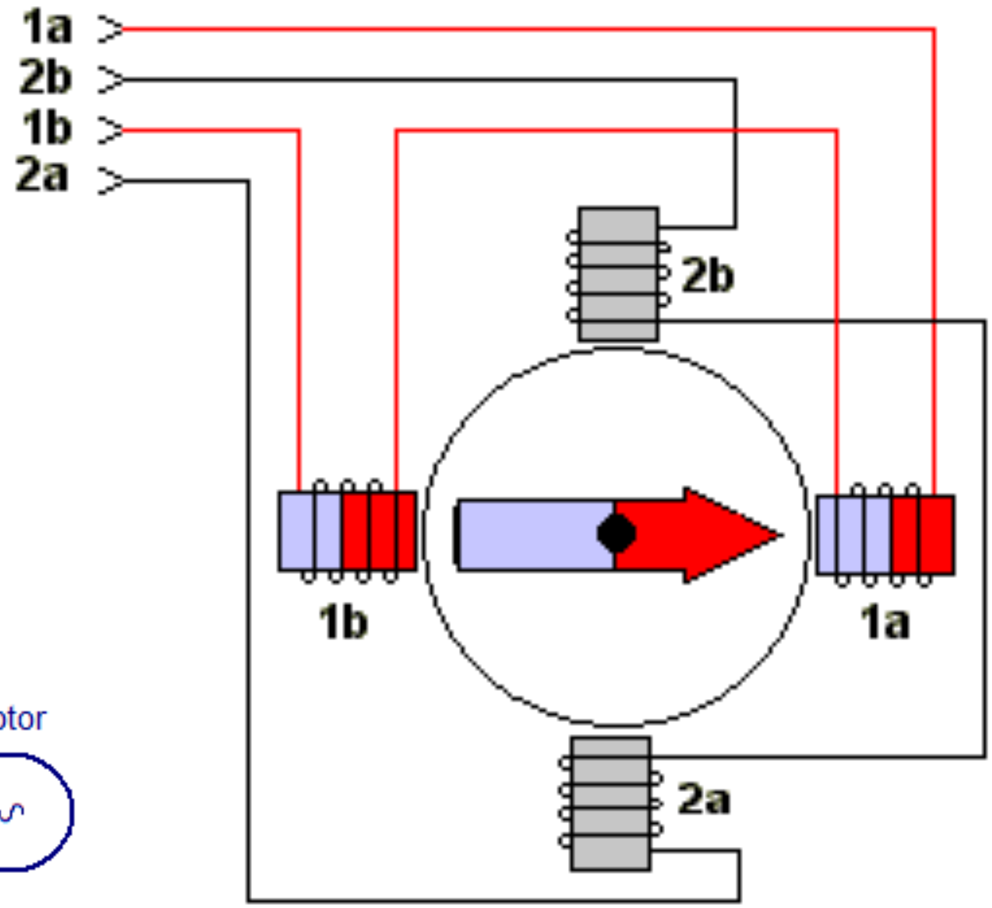
- Motor controlled using feedback from a measured position (orientation) to achieve a given position.
- If position differs from that commanded, an error signal causes the motor to rotate in the correct direction to reach the appropriate position.

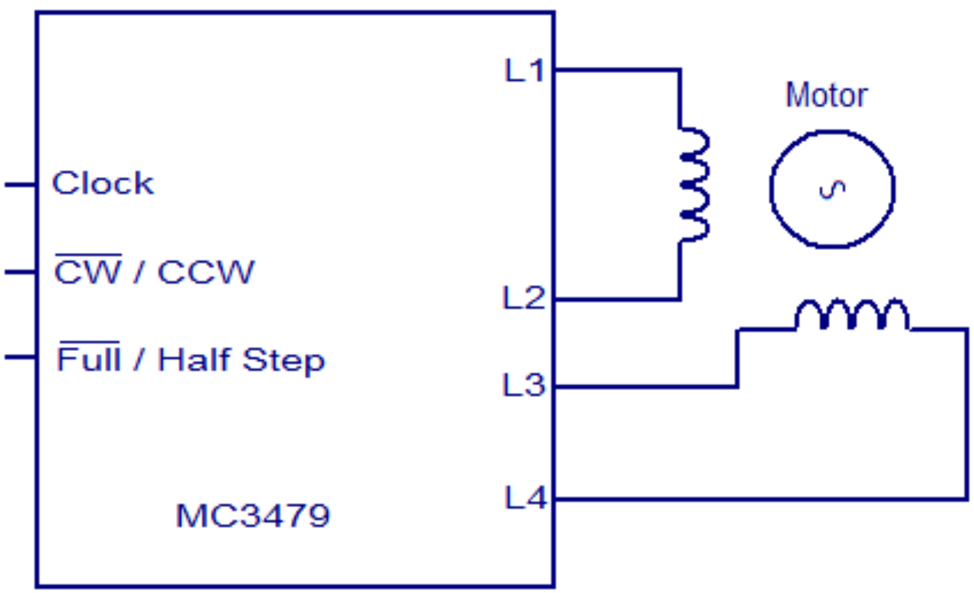


http://elm-chan.org/works/smc/report_e.html

Stepper Motors

- Sequential activation of different sets of magnets.
- Computer can keep track of exactly how many rotations and in which direction.
- Good for robotics.

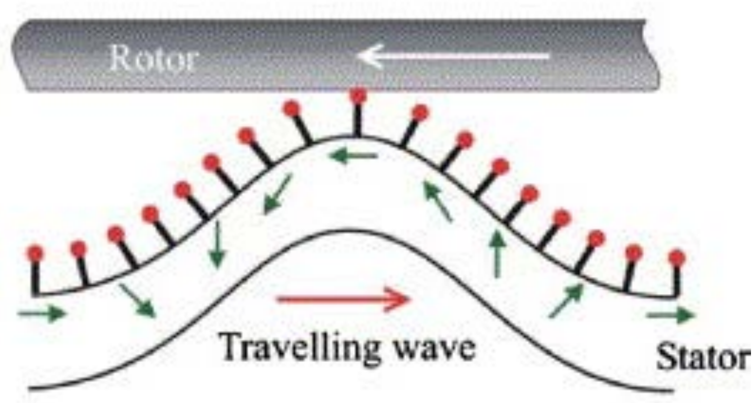


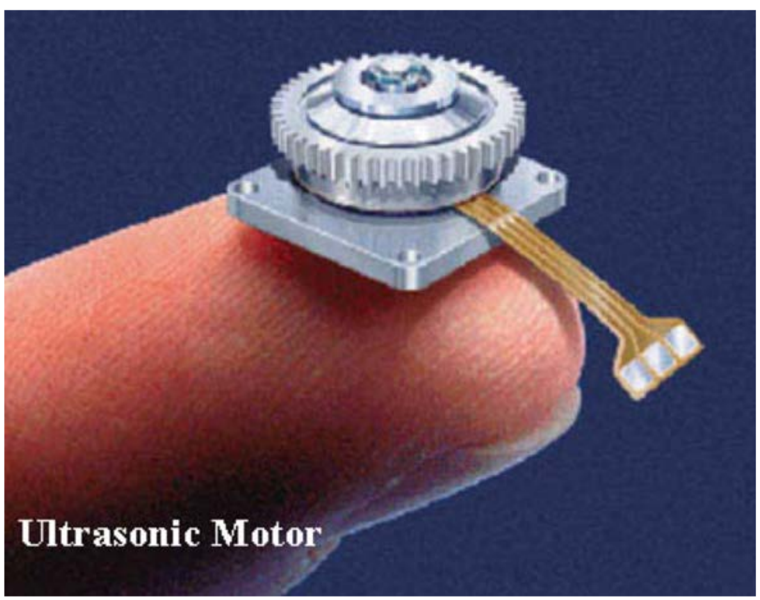


www.stepperworld.com
www.circuitstoday.com

Ultrasonic Motors

- Ultrasonic waves propel rotor.
- Can be made extremely small.
- Used in camera lenses.
- Linear motors can also be made.



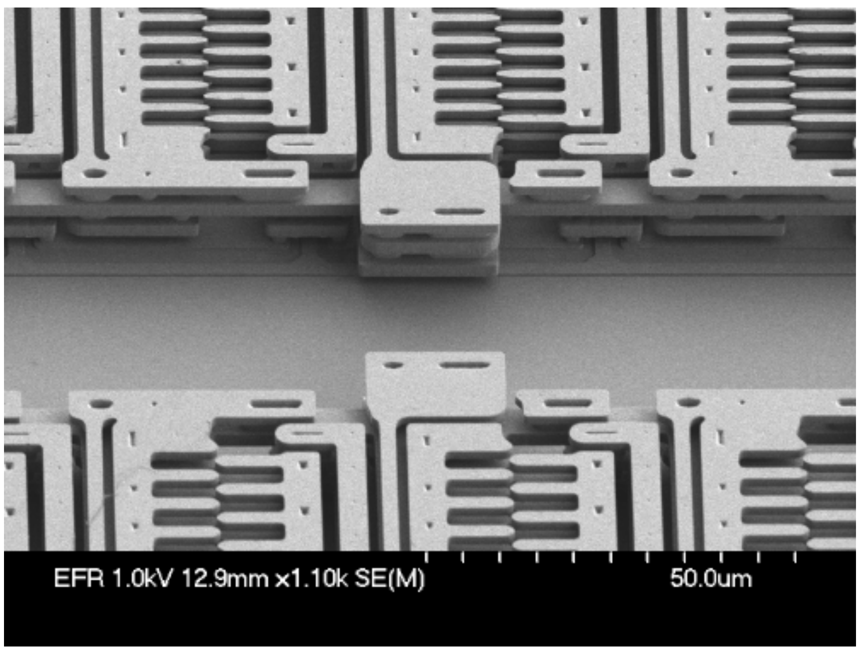


web.mst.edu

www.sciencedirect.com

Micro Electro-Mechanical Systems (MEMS)

- Photoetched like Integrated Circuits (IC)
- Electrostatically actuated.

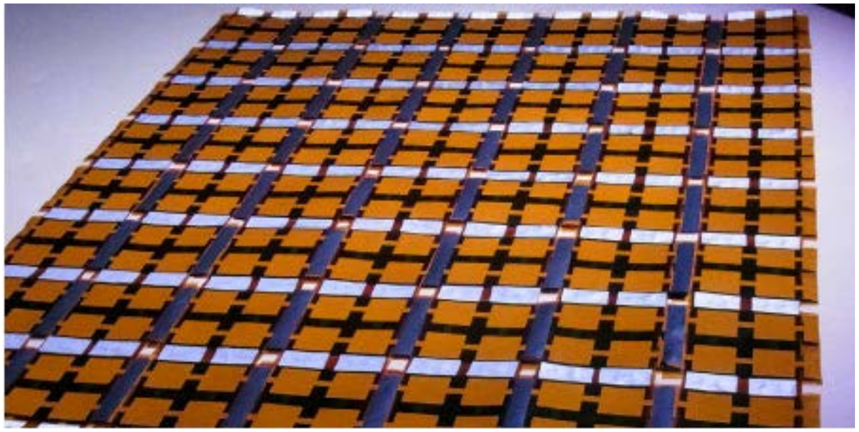


Electrostatic Actuator

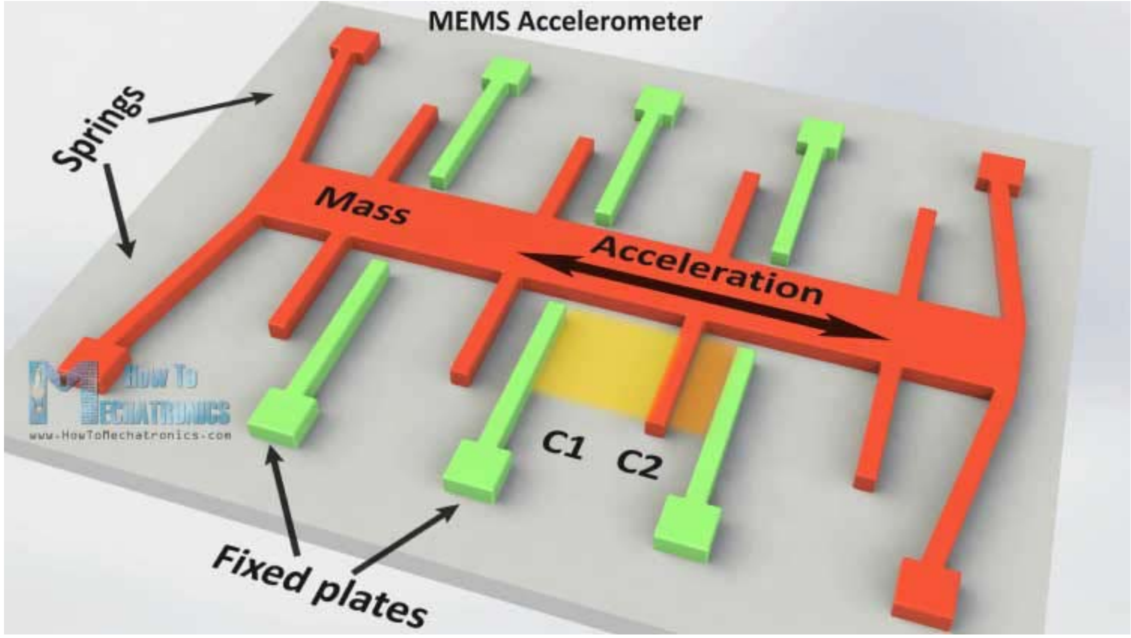
Ratchet Gear

memx.com

MEMS ultrasound transducer array



MEMS accelerometer (in smart phones)

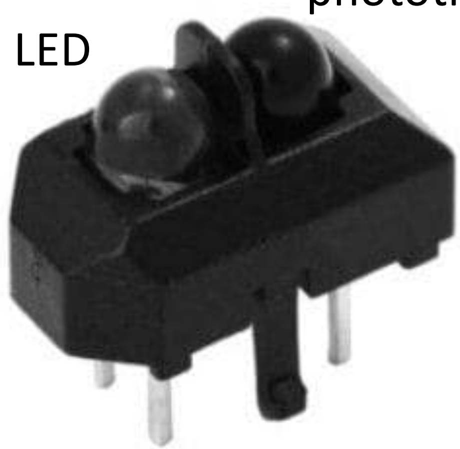


Optical Distance measurement

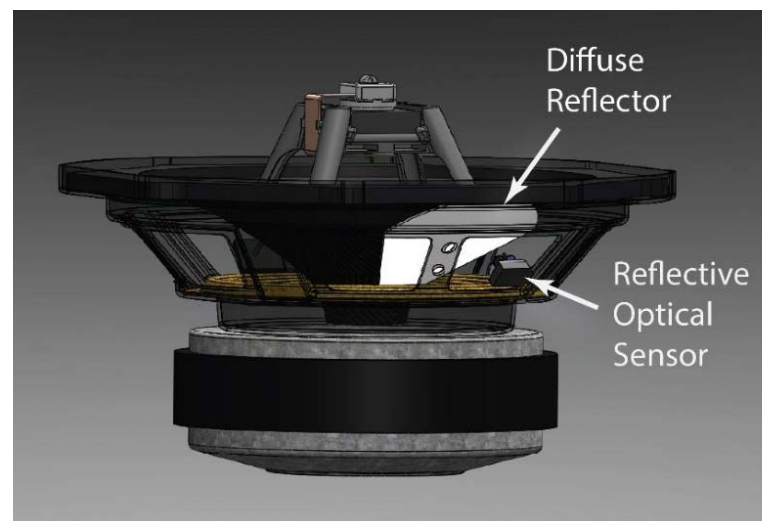
- Magnitude of reflectance
  - Infrared (IR) LED and photodiode or phototransistor.
  - Quite (surprisingly) immune to ambient lighting.
  - Non-calibrated: depends on surface material, shape, orientation.

phototransistor

IR LED



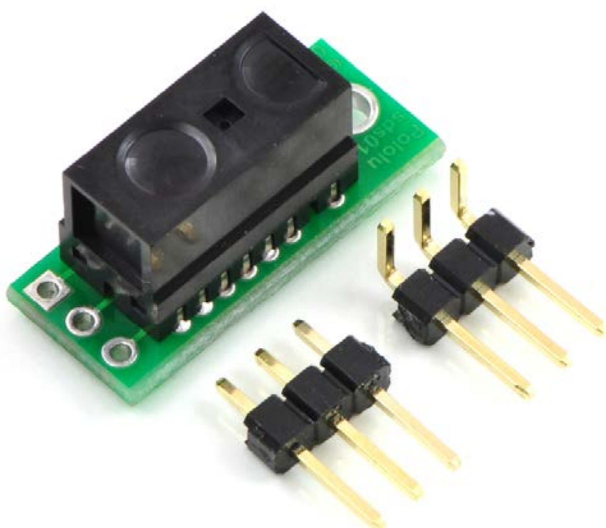
Example: measure speaker displacement with white paper target.



Vishay TRCT500 https://www.vishay.com/optical-sensors/list/product-83760/

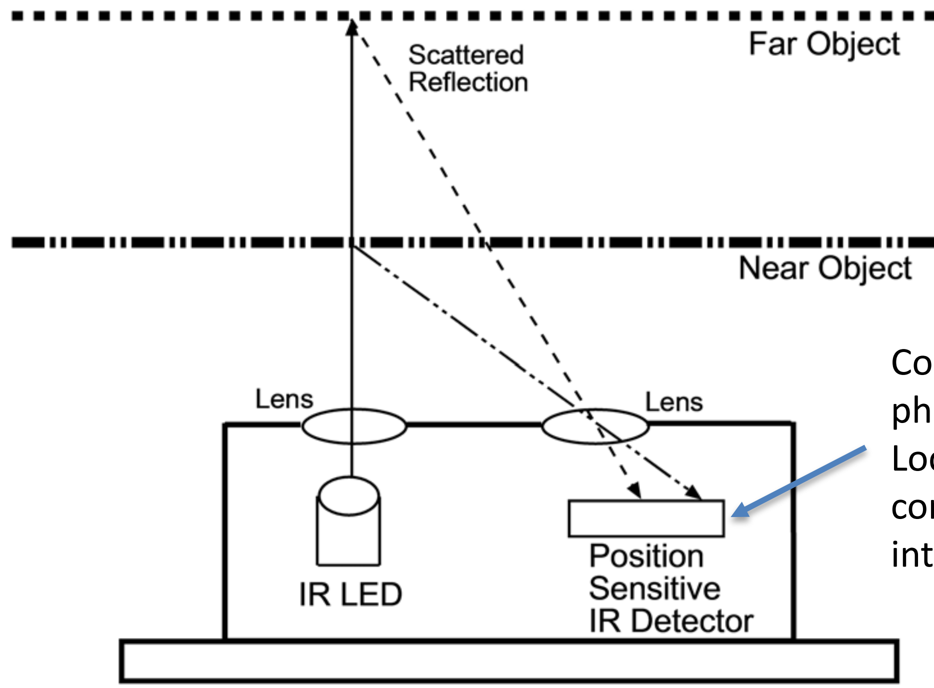
Structured light (one example).

- Triangulates using LED and two photodiodes.
- Up to 15 cm range.
- Insensitive to surface material, shape, or orientation.
- Contains microprocessor to compare intensities of photodiodes.
- Very cheap ($10) and low power (5 mA).



Sharp GP2Y0D815Z0F
https://www.pololu.com/product/2465

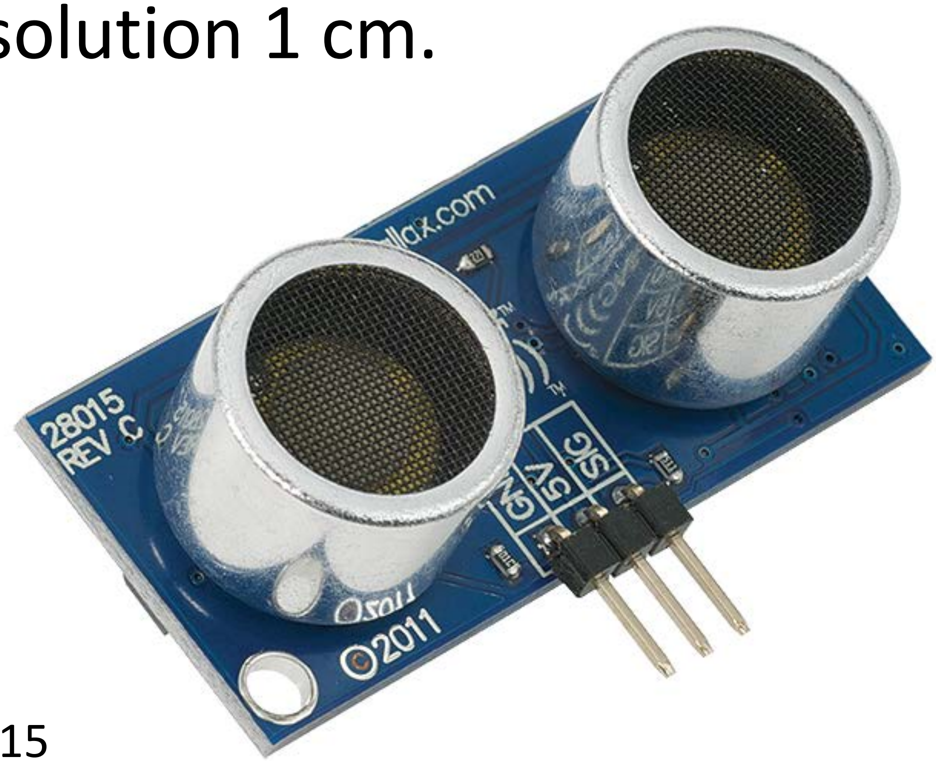
https://os.mbed.com/forum/mbed/topic/1048/?page=1#comment-5063



Contains two photodiodes. Locates dot by comparing intensity.

Ultrasound Ranging

- Transmits and received ultrasound pulse.
- Time of flight distance measurement.
- Could use MicroBLIP Period Duration Mode.
- Target must be closest and large enough.
- Range 3-5 meters, resolution 1 cm.
- Cheap ($30).



https://www.parallax.com/product/28015

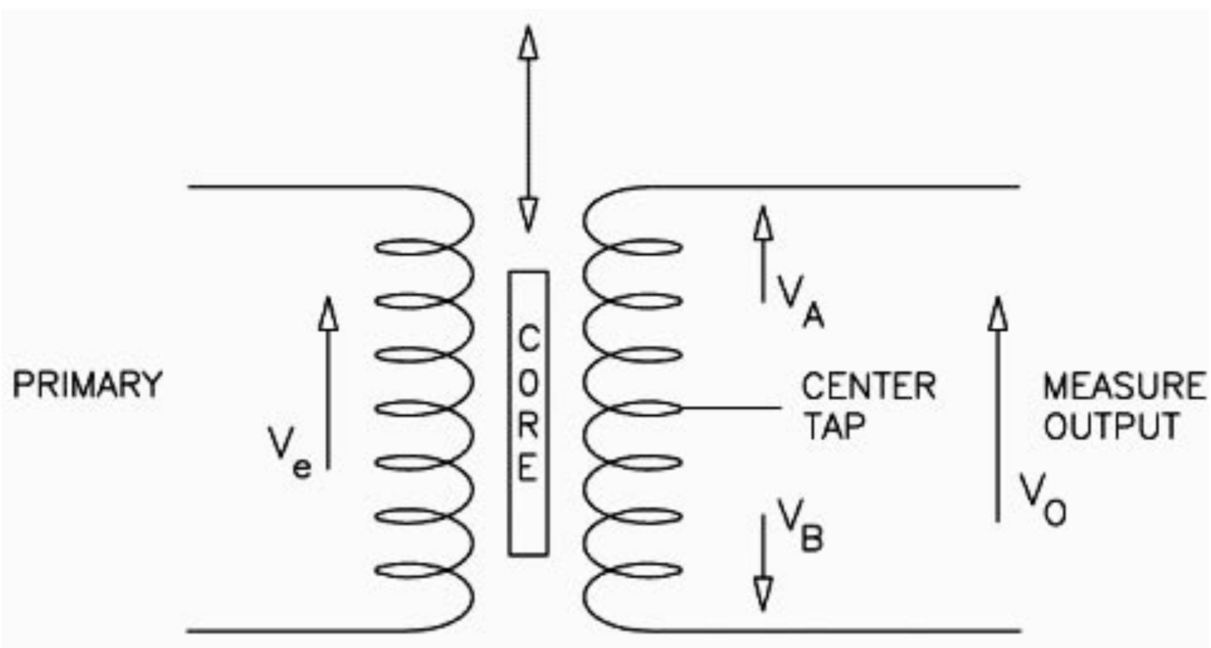
Magnetic Reluctance

- Complex number, like impedance, but for magnetism

$$\text{MagneticReluctance} = \frac{\text{Magnetomotive Force}}{\text{Magnetic Flux}}$$

like Ohm's law

  - Magnetomotive Force (unit = *ampere*)
  - Magnetic Flux (unit = *weber*)

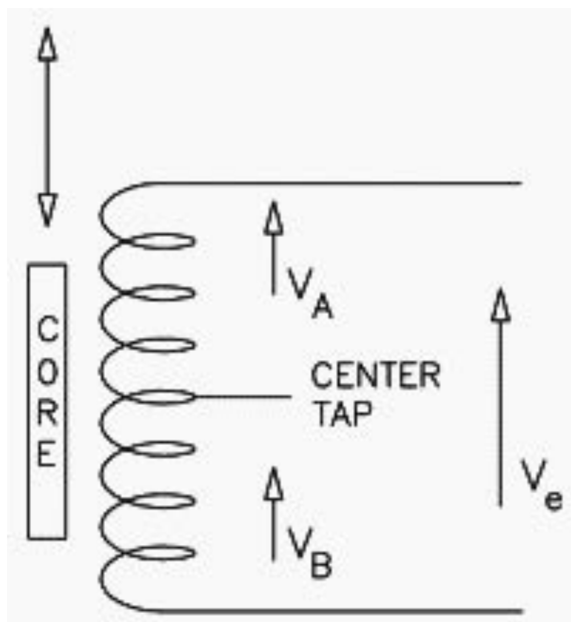


Linear Variable Differential Transformer (LVDT)

www.microstrain.com

Magnet Reluctance

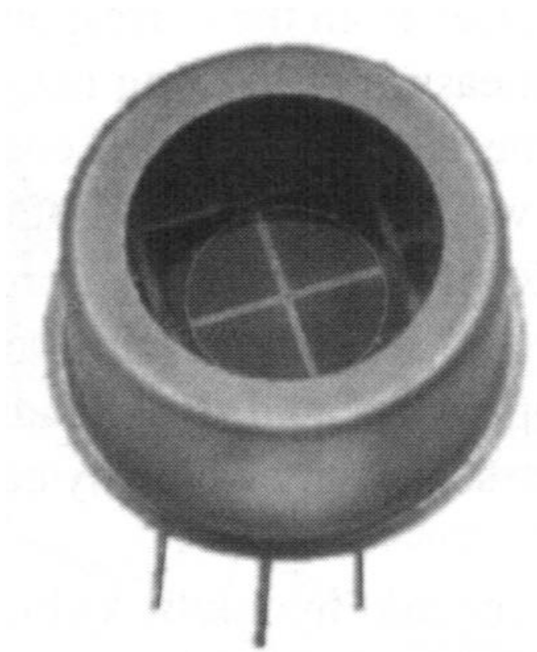
- Sensor can be made with a single coil
  - Both excites and detects.
  - Can be made very small.
  - Can also be made to accurately measure distance to "non-contact" aluminum surface.

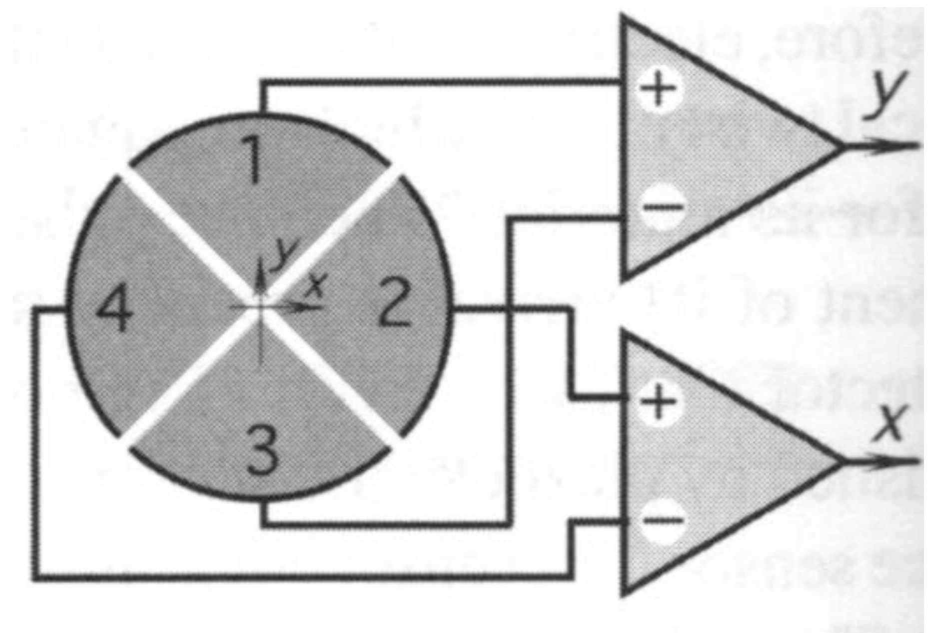


Differential Variable Reluctance Transducer (DVRT)

Four-Quadrant Photodetector

- Very accurate x-y location detection
  - Can tell when laser is at the center.
  - Separate *x* and *y* measurement.
  - Good for aiming missiles.

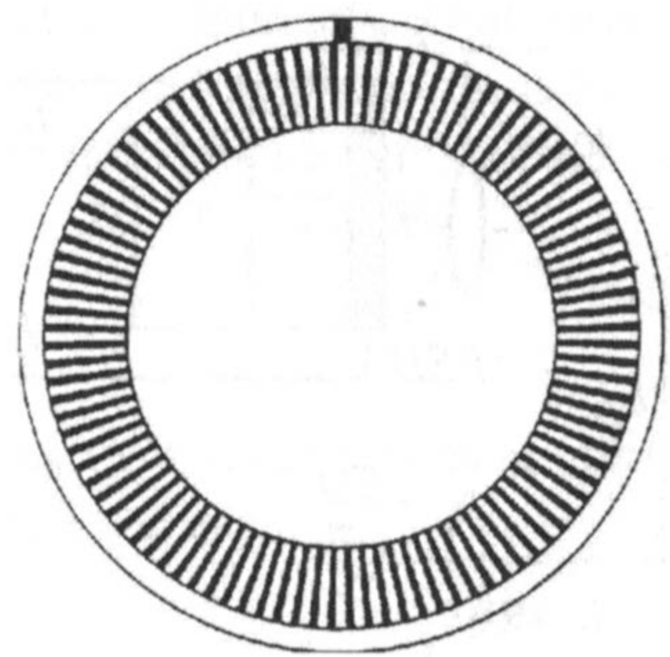


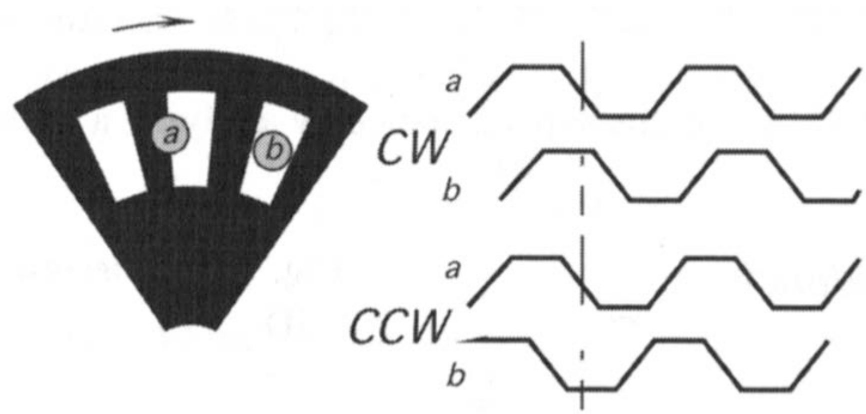


Handbook of Modern Sensors, Fraden

Incremental Optical Encoders

- Counts number of transitions but doesn't know starting orientation
  - More common (cheaper) than absolute encoders.
  - Uses 2 sensors in *quadrature* (sin and cos) to tell CW from CCW.



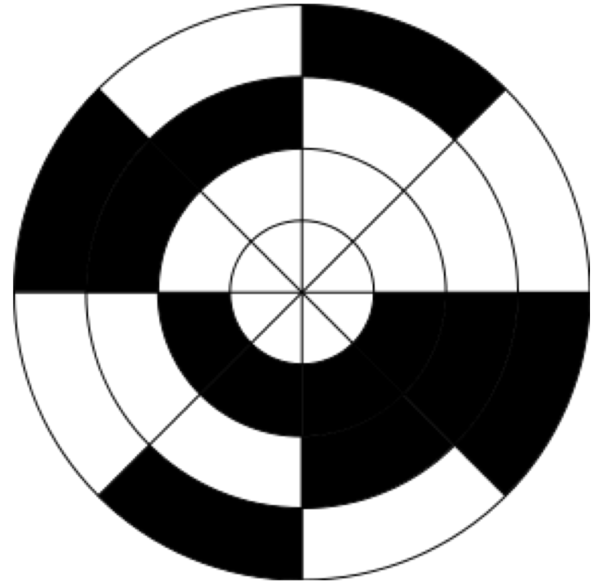


Handbook of Modern Sensors, Fraden

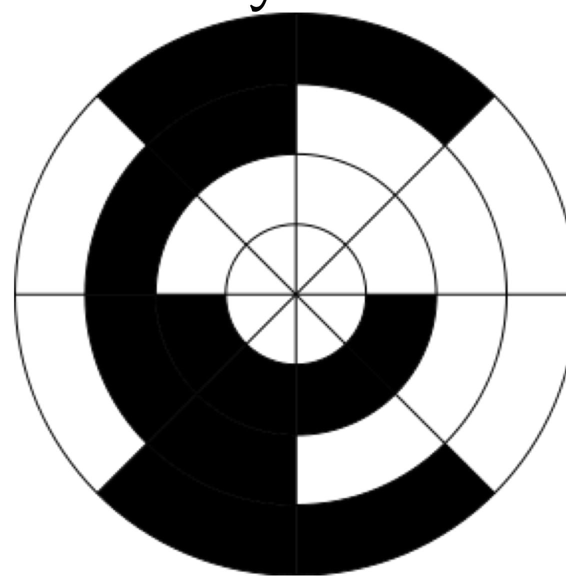
Absolute Optical Encoders

- Unique angle identified
  - Binary number code
    - Prone to problems with non-simultaneous transitions between sectors.
  - Gray code
    - Solves this problem by only permitting one bit to change at a time, between adjacent sectors.

Binary number code



Gray code



World’s Largest Optical Encoder