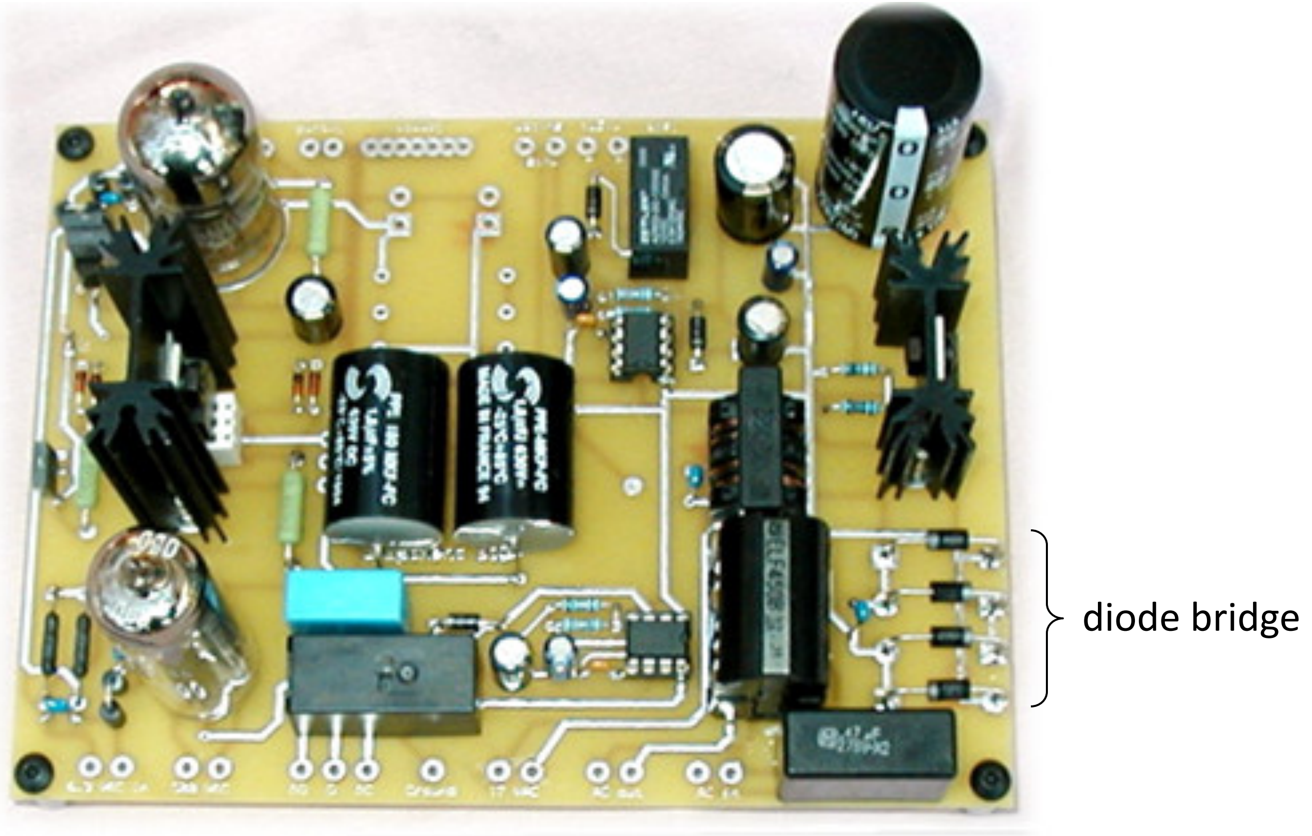


diode bridge

Electronics Overview

Basic Circuits, Power Supplies,
Transistors, Cable Impedance

Basic Circuit Analysis

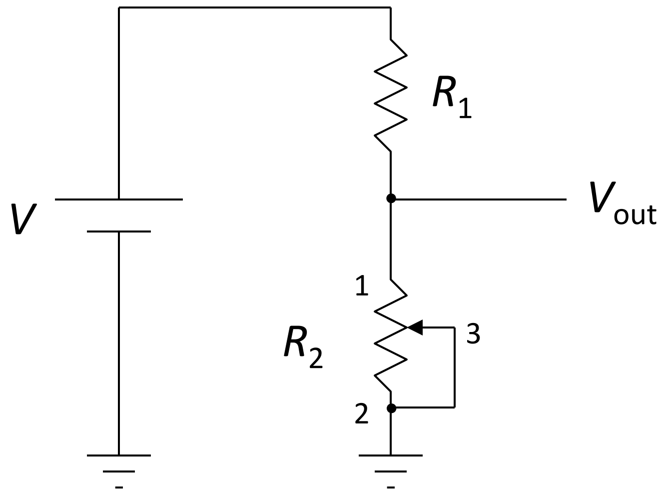
- What we won't do:
  - common electronics-class things: RLC, filters, detailed analysis
- What we will do:
  - set out basic relations
  - look at a few examples of fundamental importance (mostly resistive circuits)
  - look at diodes, voltage regulation, transistors
  - discuss impedances (cable, output, etc.)

The Basic Relations

- V is voltage (volts: V); I is current (amps: A); R is resistance (ohms: Ω); C is capacitance (farads: F); L is inductance (henrys: H)
- Ohm's Law: $V = IR$; $V = \frac{1}{C}\int I dt$; $V = L(dI/dt)$
- Power: $P = IV = V^2/R = I^2R$
- Resistors and inductors in series add
- Capacitors in parallel add
- Resistors and inductors in parallel, and capacitors in series add according to: $\frac{1}{X_{tot}} = \frac{1}{X_1} + \frac{1}{X_2} + \frac{1}{X_3} + \dots$

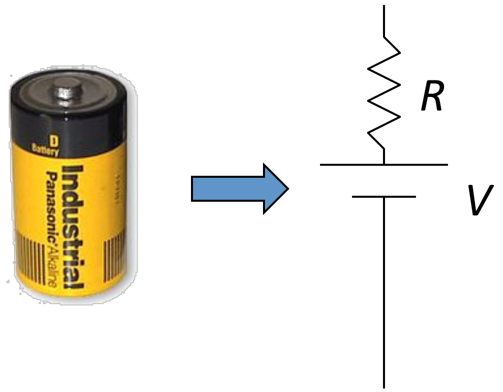
Example: Voltage divider

- Voltage dividers are a classic way to set a voltage
- Works on the principle that all charge flowing through the first resistor goes through the second
  - so $\Delta V \propto R$-value
  - provided any load at output is negligible: otherwise some current goes there too
- So $V_{out} = V(R_2/(R_1 + R_2))$
- R_2 here is a variable resistor, or *potentiometer*, or "pot"
  - typically three terminals: R_{12} is fixed, tap slides along to vary R_{13} and R_{23}, though $R_{13} + R_{23} = R_{12}$ always



Real Batteries: Output Impedance

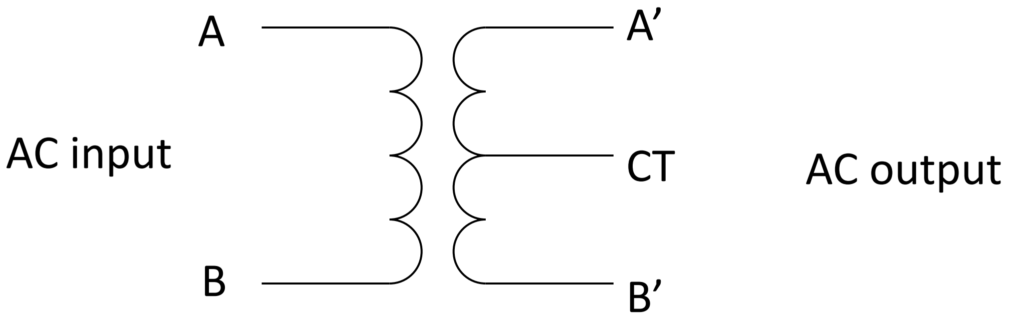
- A power supply (battery) is characterized by a voltage (V) and an output impedance (R)
  - sometimes called *source impedance*
- Hooking up to load: R_{load}, we form a voltage divider, so that the voltage applied by the battery terminal is actually $V_{\text{out}} = V(R_{\text{load}}/(R+R_{\text{load}}))$
  - thus the smaller R is, the "stiffer" the power supply
  - when V_{out} sags with higher load current, we call this "droop"
- Example: If 10.0 V power supply droops by 1% (0.1 V) when loaded to 1 Amp (10 Ω load):
  - internal resistance is 0.1 Ω
  - called *output impedance* or *source impedance*
  - may vary with load, though (not a real resistor)



D-cell example: 6A out of 1.5 V battery indicates 0.25 Ω output impedance

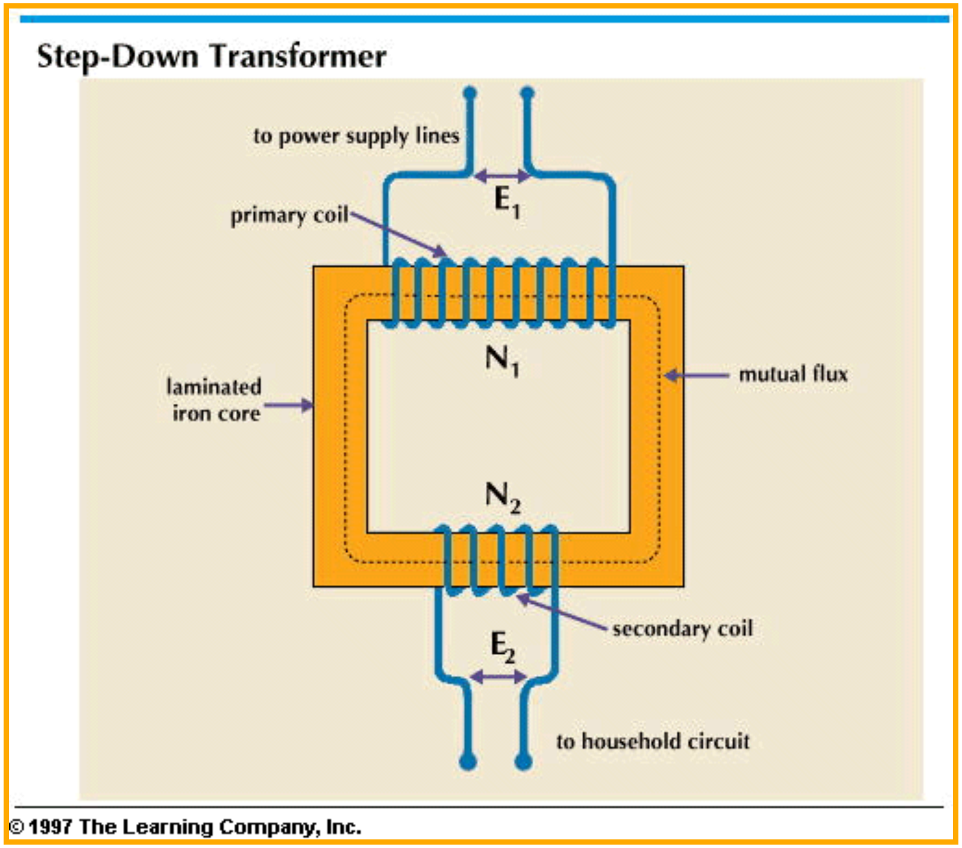
Power Supplies and Regulation

- A power supply typically starts with a transformer
  - to knock down the 340 V peak-to-peak (120 V AC) to something reasonable/manageable
- We will be using a center-tap transformer



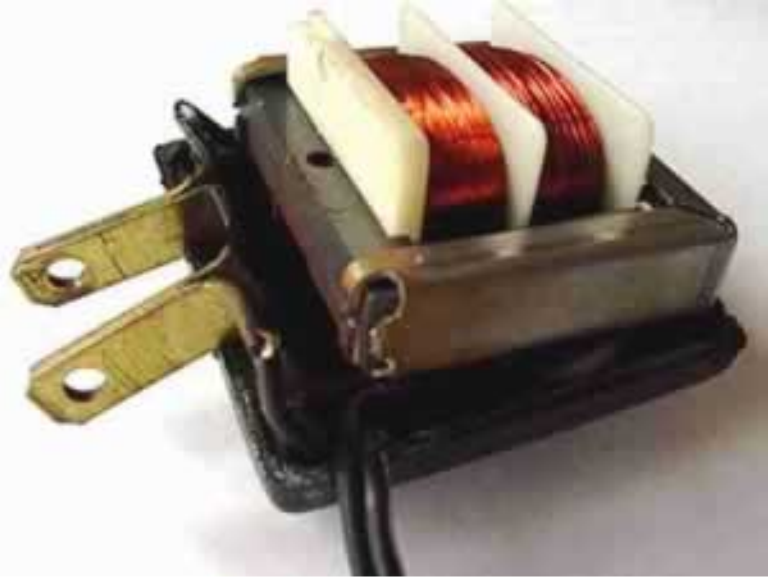
  - (A’ - B’) = (winding ratio)×(A - B)
    - when A > B, so is A’ > B’
  - geometry of center tap (CT) guarantees it is midway between A’ and B’ (frequently tie this to ground so that A’ = -B’)
  - note that secondary side floats: no ground reference built-in

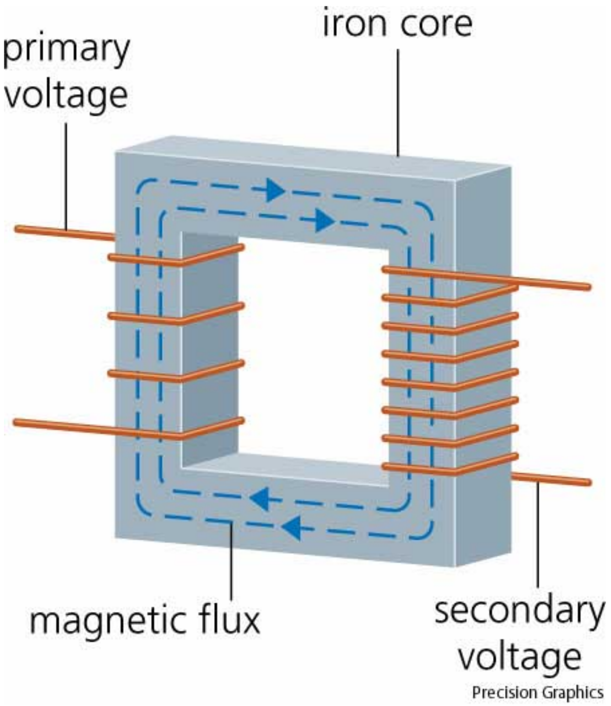
Transformer is just wire coiled around metal



- Magnetic field is generated by current in primary coil
- Iron core channels magnetic field through secondary coil
- Secondary Voltage is $V_2 = (N_2/N_1)\ V_1$
- Secondary Current is $I_2 = (N_1/N_2)\ I_1$
- But Power in = Power out
  - negligible power lost in transformer
- Works only for AC, not DC

Typical Transformers

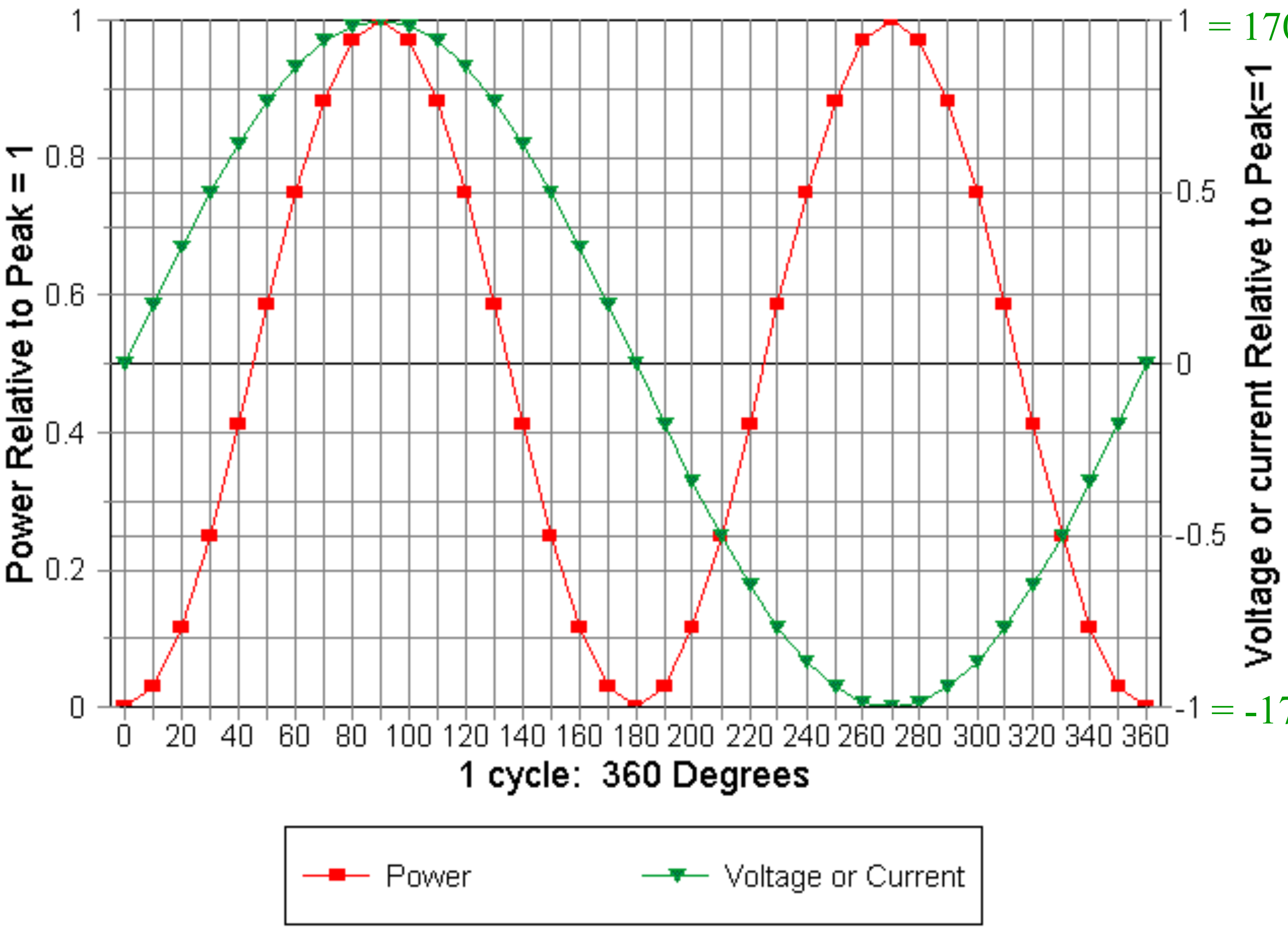




Precision Graphics

transformers usually heavy due to iron core

AC Voltage or Current and AC Power



= 170 Volts

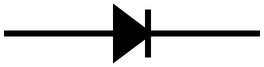
= -170 Volts

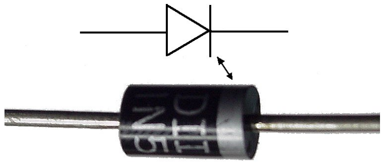
120 VAC is a root-mean-square number: peak-to-peak is 340 Volts!

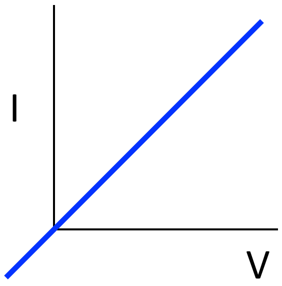
AC Receptacle

- Receptacles have three holes each
- Lower (rounded) hole is earth ground
  - connected to pipes, usually
  - green wire
- Larger slot is "neutral"
  - for current "return"
  - never far from ground
  - white wire
  - if wired correctly
- Smaller slot is "hot"
  - swings to +170 and -170
  - black wire
  - dangerous one

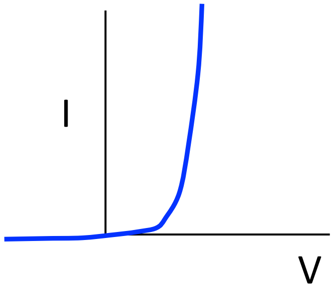
Diodes

- Diodes are essentially one-way current gates
- Symbolized by: 
- Current vs. voltage graphs:

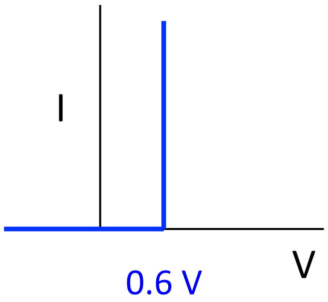




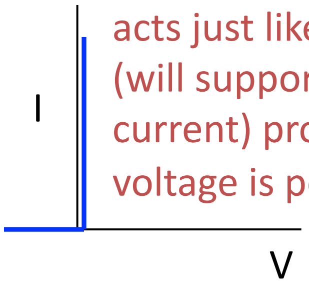
plain resistor



diode

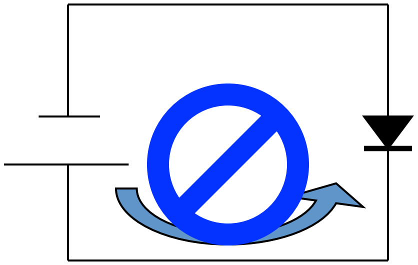


idealized diode

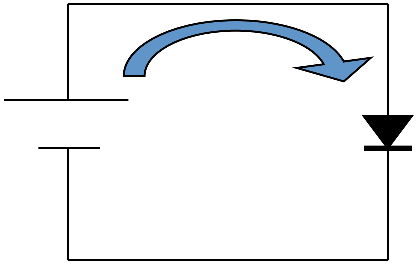


acts just like a wire (will support arbitrary current) provided that voltage is positive

WAY idealized diode



no current flows

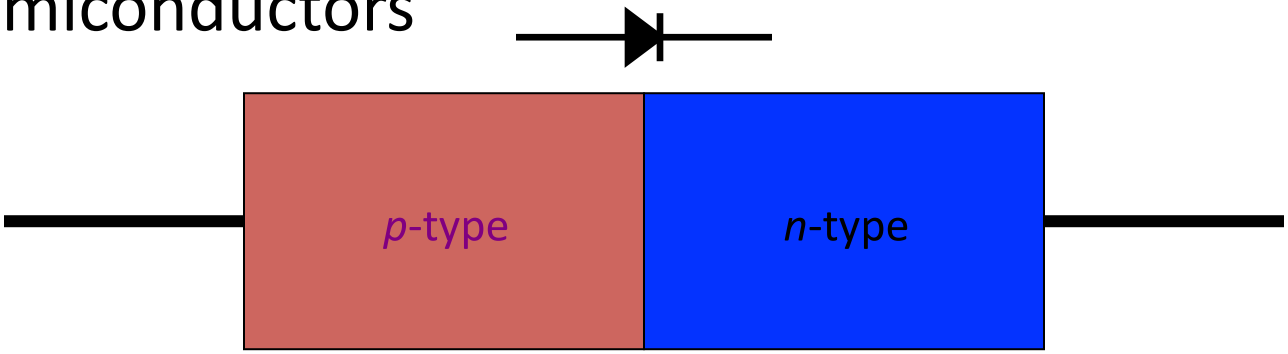


current flows

the direction the arrow points in the diode symbol is the direction that current *will* flow

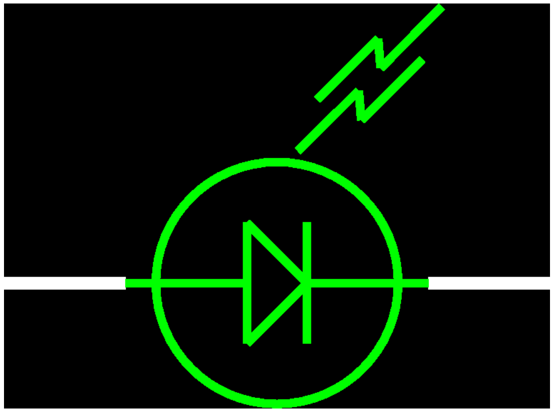
Diode Makeup

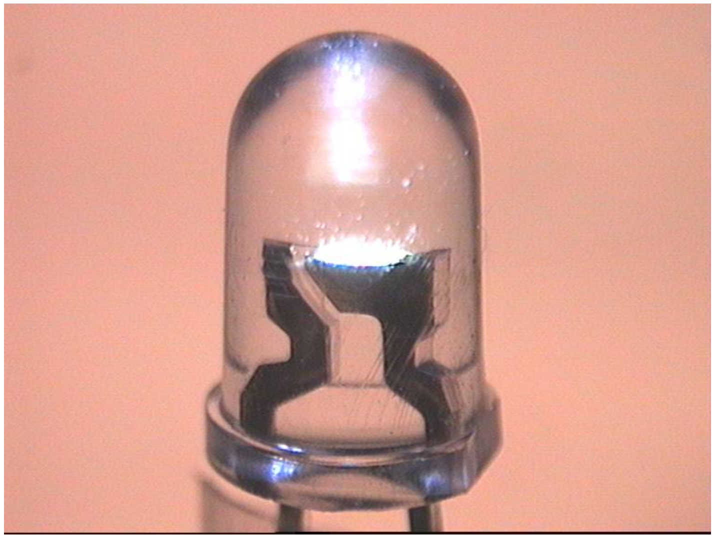
- Diodes are made of semiconductors (usually silicon)
- Essentially a stack of *p*-doped and *n*-doped silicon to form a *p-n junction*
  - doping means deliberate impurities that contribute extra electrons (*n*-doped) or "holes" for electrons (*p*-doped)
- Transistors are *n-p-n* or *p-n-p* arrangements of semiconductors



LEDs: Light-Emitting Diodes

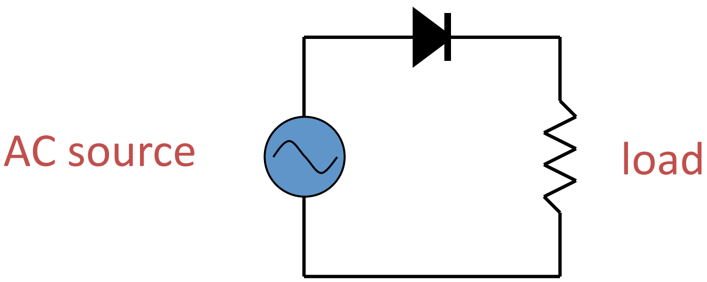
- Main difference is material is more exotic than silicon used in ordinary diodes/transistors
  - typically 2-volt drop instead of 0.6 V drop
- When electron flows through LED, loses energy by emitting a photon of light rather than vibrating lattice (heat)
- LED efficiency is 30% (compare to incandescent bulb at 10%)
- Must supply current-limiting resistor in series:
  - figure on 2 V drop across LED; aim for 1–10 mA of current



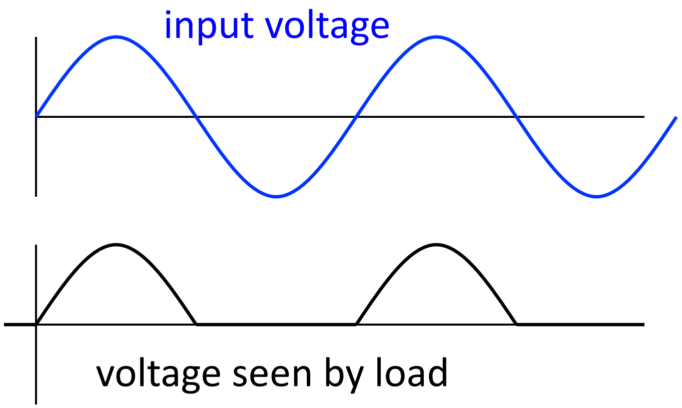


Getting DC back out of AC

- AC provides a means for us to distribute electrical power, but most devices actually *want* DC
  - bulbs, toasters, heaters, fans don't care: plug straight in
  - sophisticated devices care because they have diodes and transistors that require a certain polarity
    - rather than oscillating polarity derived from AC
    - this is why battery orientation matters in most electronics
- Use diodes to "rectify" AC signal
- Simplest (half-wave) rectifier uses one diode:

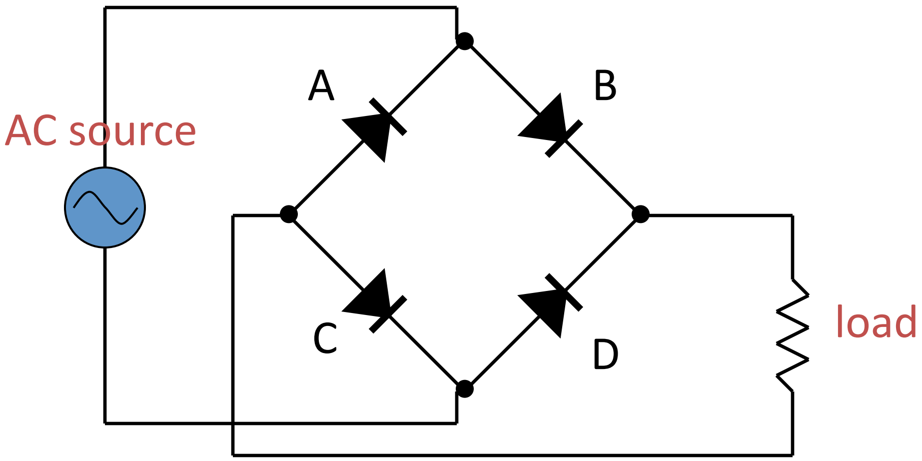


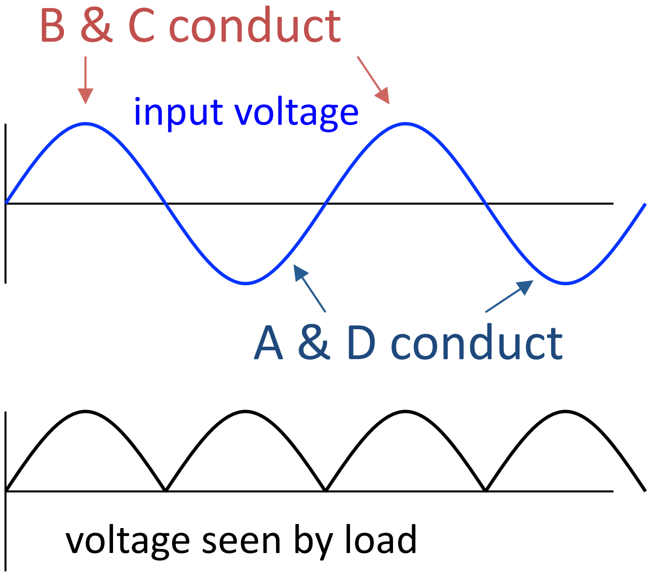
diode only conducts
when input voltage is positive



Doing Better: Full-wave Diode Bridge

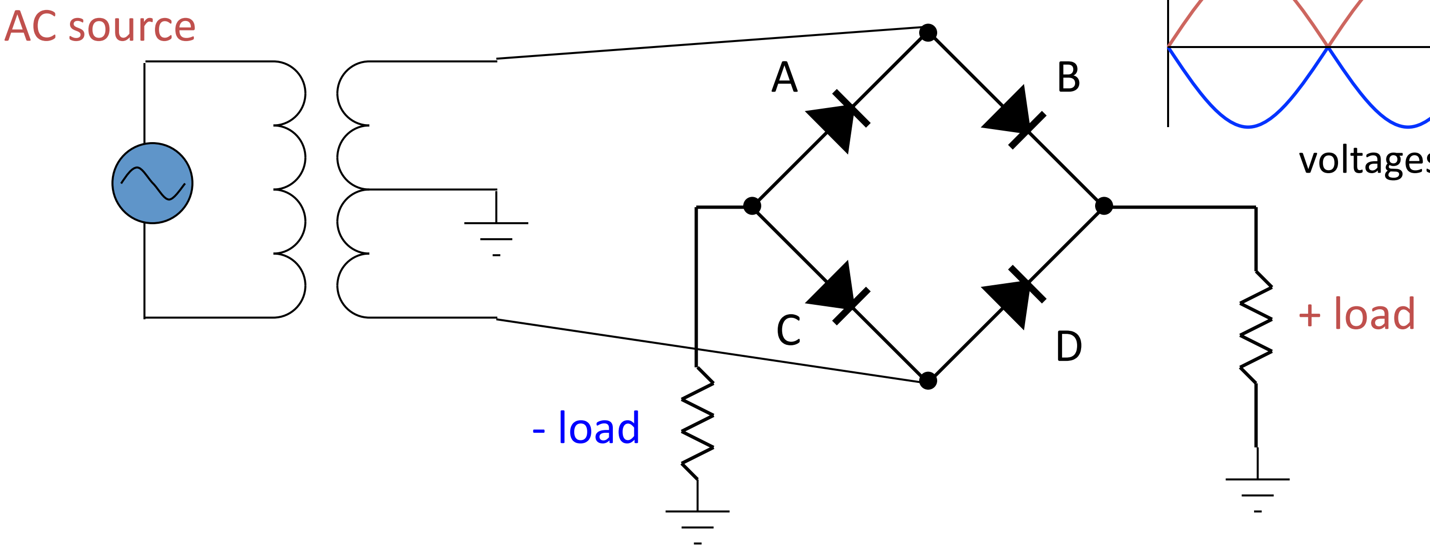
- The diode in the rectifying circuit simply prevented the negative swing of voltage from conducting
  - but this wastes half the available cycle
  - also very irregular (bumpy): far from a "good" DC source
- By using four diodes, you can recover the negative swing:

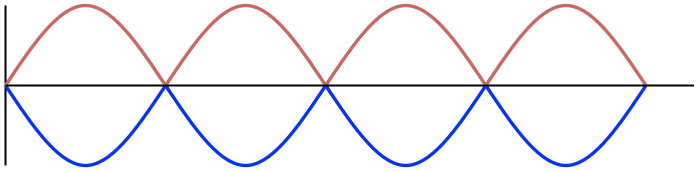




Full-Wave Dual-Supply

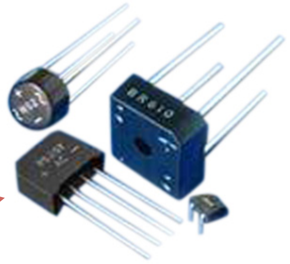
- By grounding the center tap, we have two opposite AC sources
  - the diode bridge now presents + and - voltages relative to ground
  - each can be separately smoothed/regulated
  - cutting out diodes A and D makes a half-wave rectifier





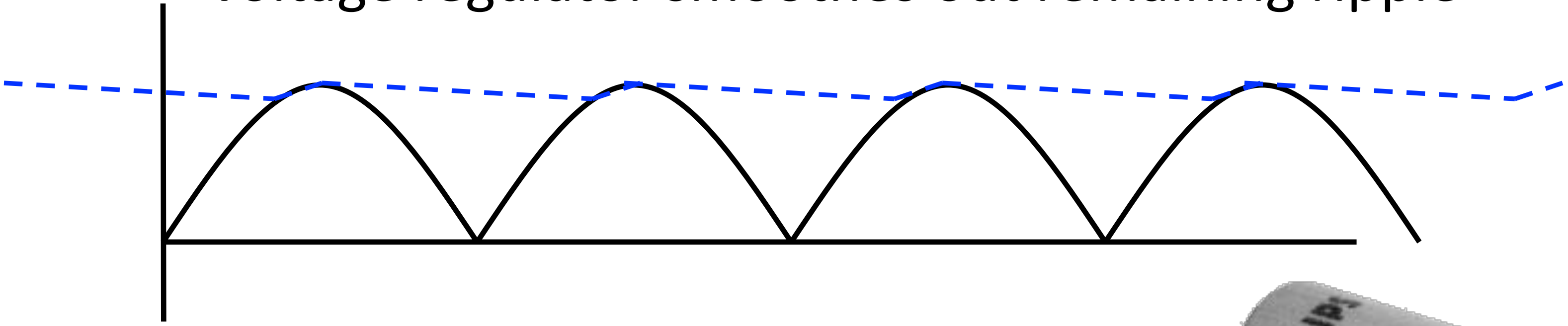
voltages seen by loads

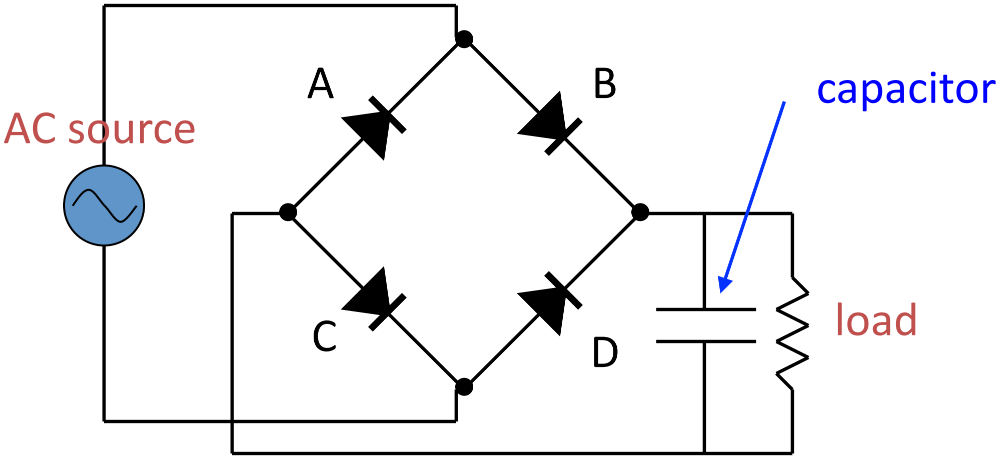
can buy pre-packaged diode bridges

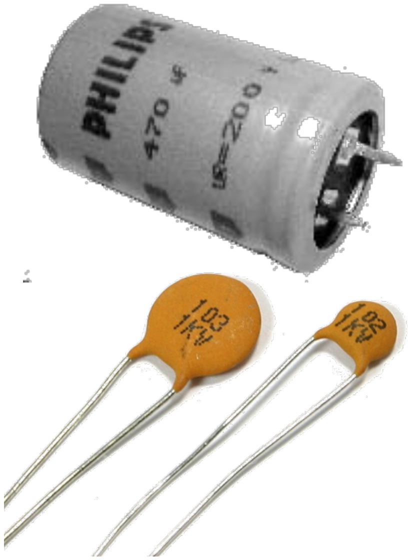


Smoothing out the Bumps

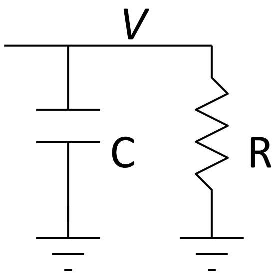
- Still a bumpy ride, but we can smooth this out with a capacitor
  - capacitors have capacity for storing charge
  - acts like a reservoir to supply current during low spots
  - voltage regulator smoothes out remaining ripple



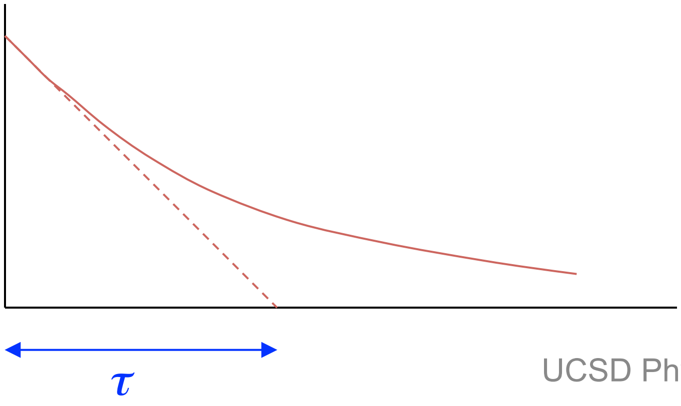




How smooth is smooth?

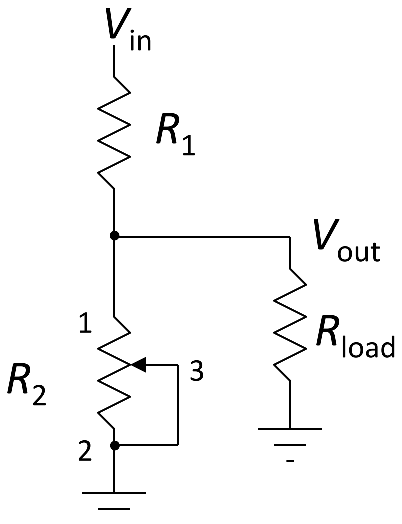


- An RC circuit has a time constant $\tau = RC$
  - because $dV/dt = I/C$, and $I = V/R \rightarrow dV/dt = V/RC$
  - so V is $V_0\exp(\pm t/\tau)$
- Any exponential function starts out with slope = Amplitude/τ
- So if you want < 10% ripple over 120 Hz (8.3 ms) timescale…
  - must have $\tau = RC > 83$ ms
  - if $R = 100\ \Omega$, $C > 830\ \mu\text{F}$



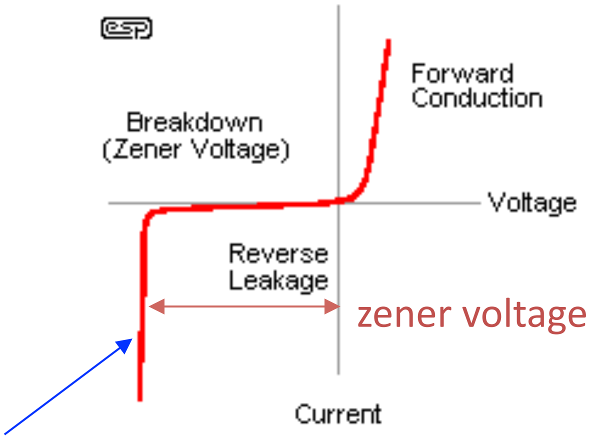
Regulating the Voltage

- The unregulated, ripply voltage may not be at the value you want
  - depends on transformer, etc.
  - suppose you want 15.0 V
- You *could* use a voltage divider to set the voltage
- But it would droop under load
  - output impedance → $R_1 \,||\, R_2$
  - need to have very small R_1, R_2 to make "stiff"
  - the divider will draw a lot of current
  - perhaps straining the source
  - power expended in divider >> power in load
- Not a "real" solution
- Important note: a "big load" means a small resistor value: 1 Ω demands more current than 1 MΩ



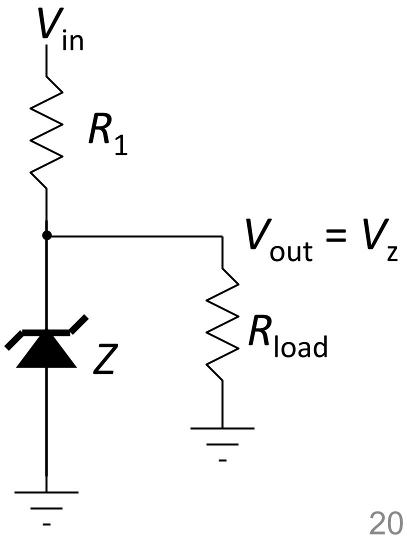
The Zener Regulator

- Zener diodes break down at some reverse voltage
  - can buy at specific breakdown voltages
  - as long as *some* current goes through zener, it'll work
  - good for rough regulation
- Conditions for working:
  - let's maintain some minimal current, I_z through zener (say a few mA)
  - then $(V_{in} - V_{out})/R_1 = I_z + V_{out}/R_{load}$ sets the requirement on R_1
  - because presumably all else is known
  - if load current increases too much, zener shuts off (node drops below breakdown) and you just have a voltage divider with the load



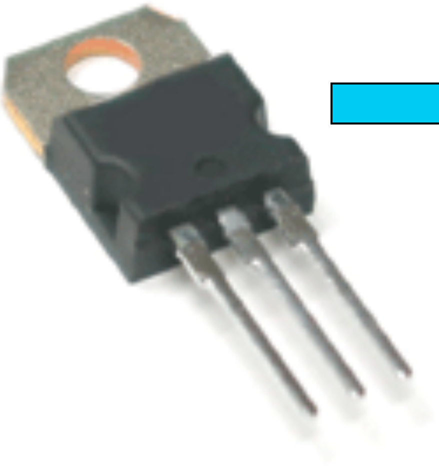
zener voltage

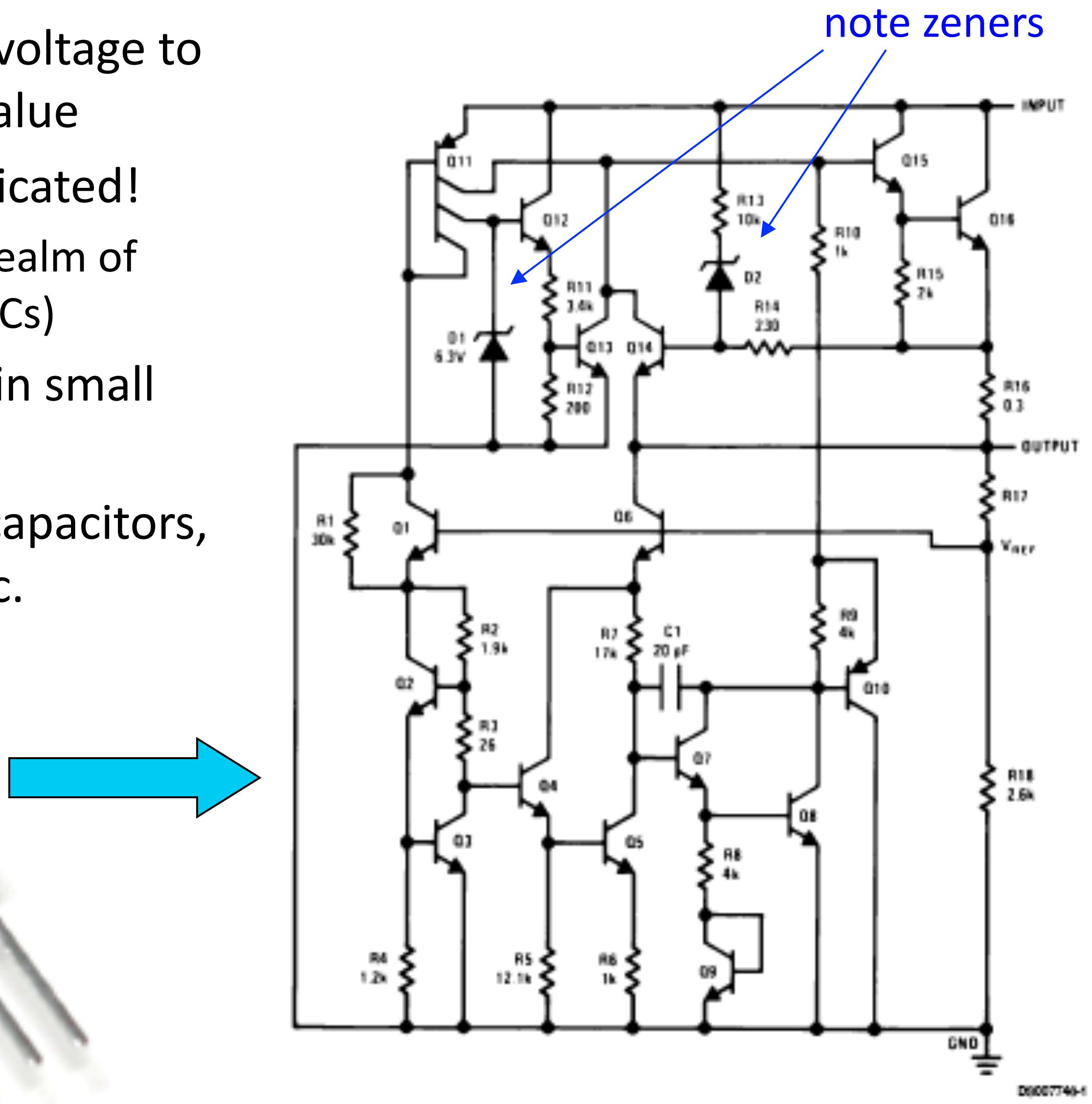
high slope is what makes the zener a decent voltage regulator



Voltage Regulator IC

- Can trim down ripply voltage to precise, rock-steady value
- Now things get complicated!
  - We are now in the realm of integrated circuits (ICs)
- ICs are whole circuits in small packages
- ICs contain resistors, capacitors, diodes, transistors, etc.

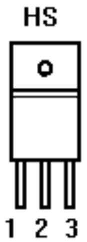




note zeners

Voltage Regulators

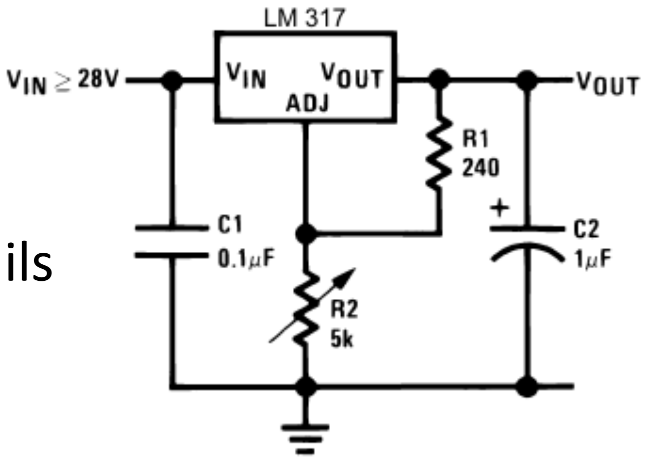
- The most common voltage regulators are the LM78XX (+ voltages) and LM79XX (- voltages)
  - XX represents the voltage
    - 7815 is +15; 7915 is -15; 7805 is +5, etc
  - typically needs input > 3 volts above output (reg.) voltage



PIN	7915	7815	LM317
1	GND	IN	ADJ.
2	IN	GND	OUT
3	OUT	OUT	IN
HS	IN	GND	OUT

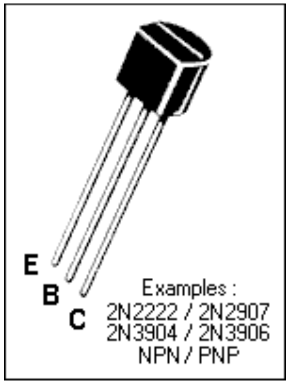
← beware that housing is not always ground

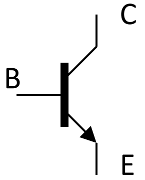
- A versatile regulator is the LM317 (+) or LM337 (-)
  - 1.2–37 V output
  - $V_{out} = 1.25(1+R_2/R_1) + I_{adj}R_2$
    - I_{adj} is small: 50 μA
  - Up to 1.5 A
  - picture at right can go to 25 V
  - datasheetcatalog.com for details



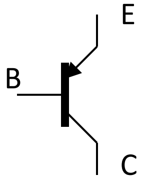
Transistors

- Transistors are versatile, highly non-linear devices
- Two frequent modes of operation:
  - amplifiers/buffers
  - switches
- Two main flavors:
  - npn (more common) or pnp, describing doping structure
- Also many varieties:
  - bipolar junction transistors (BJTs) such as npn, pnp
  - field effect transistors (FETs): n-channel and p-channel
  - metal-oxide-semiconductor FETs (MOSFETs)
- We'll just hit the essentials of the BJT here
  - MOSFET in later lecture





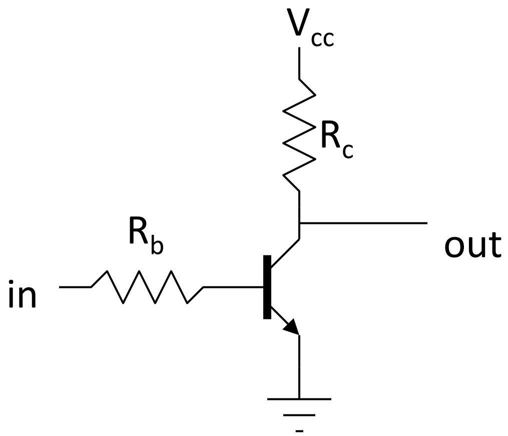
npn

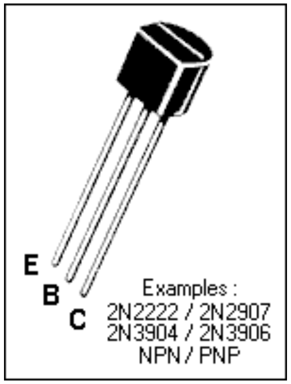


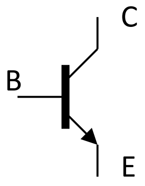
pnp

BJT Amplifier Mode

- Central idea is that when in the right regime, the BJT collector-emitter current is proportional to the base current:
  - namely, $I_{ce} = \beta I_b$, where β (sometimes h_{fe}) is typically ~100
  - In this regime, the base-emitter voltage is ~0.6 V
  - below, $I_b = (V_{in} - 0.6)/R_b$; $I_{ce} = \beta I_b = \beta(V_{in} - 0.6)/R_b$
  - so that $V_{out} = V_{cc} - I_{ce}R_c = V_{cc} - \beta(V_{in} - 0.6)(R_c/R_b)$
  - ignoring DC biases, wiggles on V_{in} become $\beta\,(R_c/R_b)$ bigger (and inverted): thus amplified

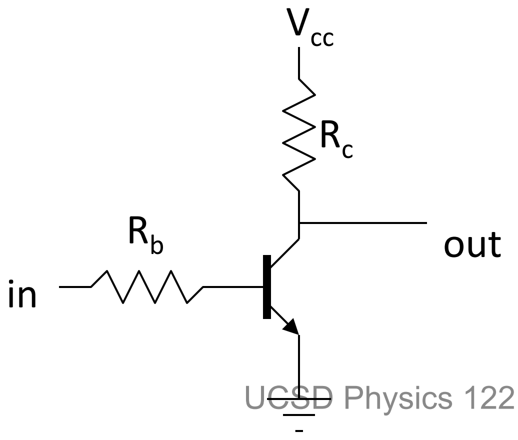


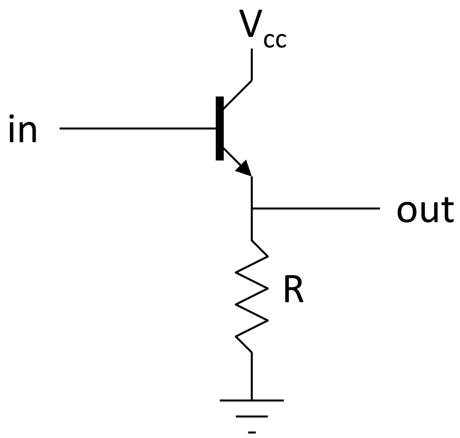




Switching: Driving to Saturation

- What would happen if the base current is so big that the collector current got so big that the voltage drop across R_c wants to exceed V_{cc}?
  - we call this saturated: $V_c - V_e$ cannot dip below ~0.2 V
  - even if I_b is increased, I_c won't budge any more
- The example below is a good logic inverter
  - if $V_{cc} = 5$ V; $R_c = 1$ kΩ; $I_c(\text{sat}) \approx 5$ mA; need $I_b > 0.05$ mA
  - so $R_b < 20$ kΩ would put us safely into saturation if $V_{in} = 5$V
  - now 5 V in → ~0.2 V out; < 0.6 V in → 5 V out



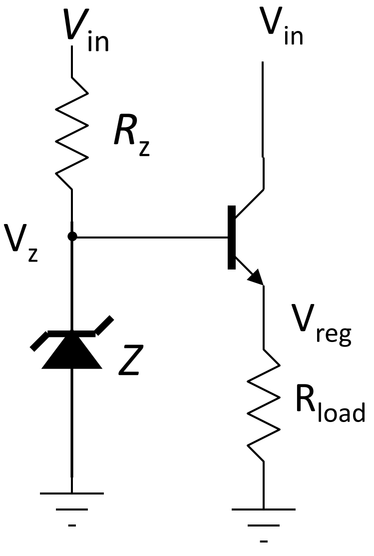


Transistor Buffer

- In the hookup above (emitter follower), $V_{out} = V_{in} - 0.6$
  - sounds useless, right?
  - there is no voltage "gain," but there *is* current gain
  - Imagine we wiggle V_{in} by ΔV: V_{out} wiggles by the same ΔV
  - so the transistor current changes by $\Delta I_e = \Delta V/R$
  - but the base current changes $1/\beta$ times this (much less)
  - so the "wiggler" *thinks* the load is $\Delta V/\Delta I_b = \beta{\cdot}\Delta V/\Delta I_e = \beta R$
  - the load therefore is less formidable
- The "buffer" is a way to drive a load without the driver feeling the pain (as much): it's impedance isolation

Improved Zener Regulator

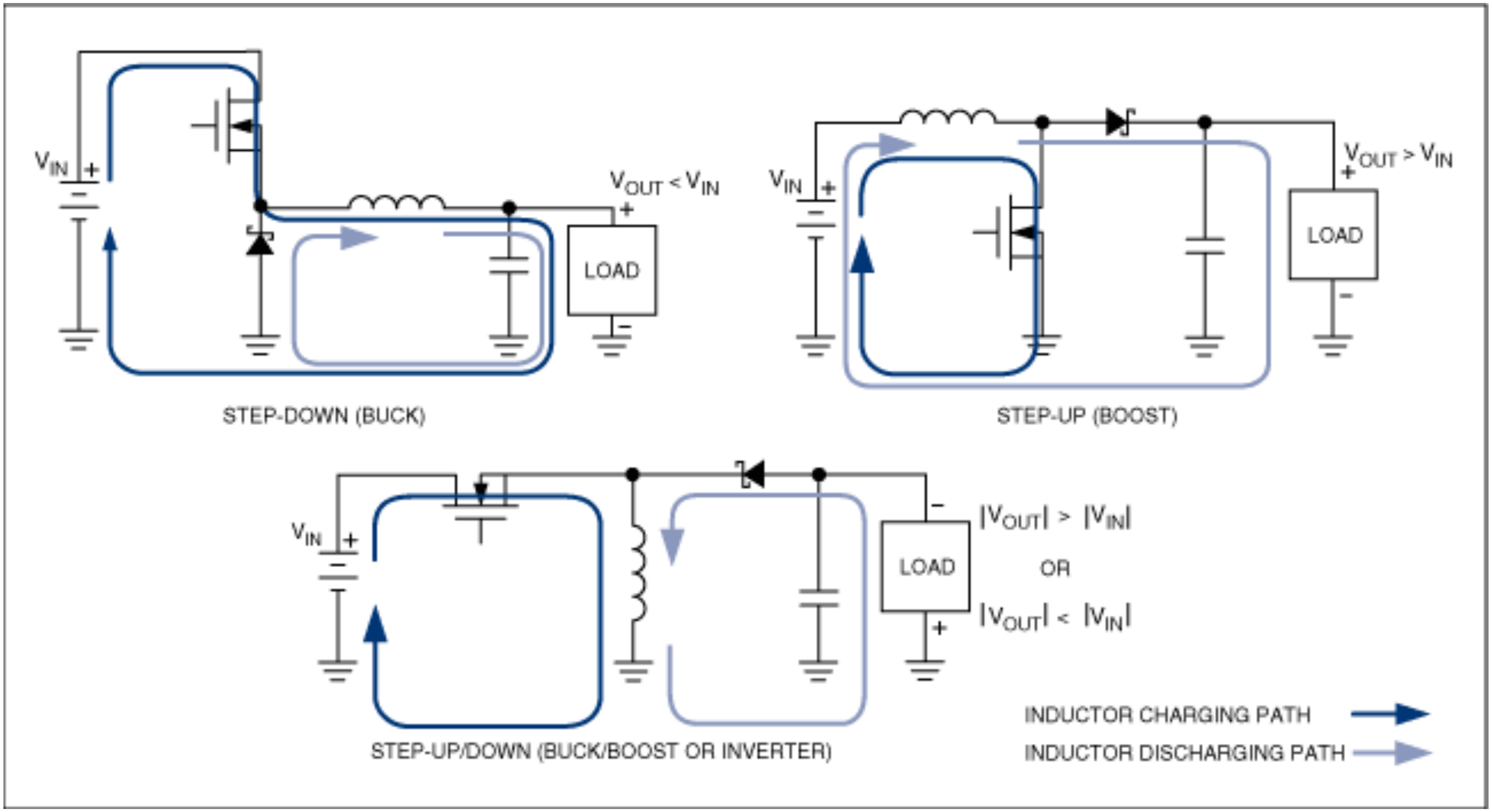
- By adding a transistor to the zener regulator from before, we no longer have to worry as much about the current being pulled away from the zener to the load
  - the base current is small
  - R_{load} effectively looks β times bigger
  - real current supplied through transistor
- Can often find zeners at 5.6 V, 9.6 V, 12.6 V, 15.6 V, etc. because drop from base to emitter is about 0.6 V
  - so transistor-buffered V_{reg} comes out to 5.0, 9.0, etc.
- I_z varies less in this arrangement, so the regulated voltage is steadier



Switching Power Supplies

- Power supplies without transformers
  - lightweight; low cost
  - can be electromagnetically noisy
- Use a DC-to-DC conversion process that relies on flipping a switch on and off, storing energy in an inductor and capacitor
  - regulators were DC-to-DC converters too, but lossy: lose $\Delta P = I\Delta V$ of power for voltage drop of ΔV at current I
  - regulators only down-convert, but switchers can also up-convert
  - switchers are reasonably efficient at conversion

Switcher topologies



The FET switch is turned off or on in a pulse-width-modulation (PWM) scheme, the duty cycle of which determines the ratio of V_{out} to V_{in}

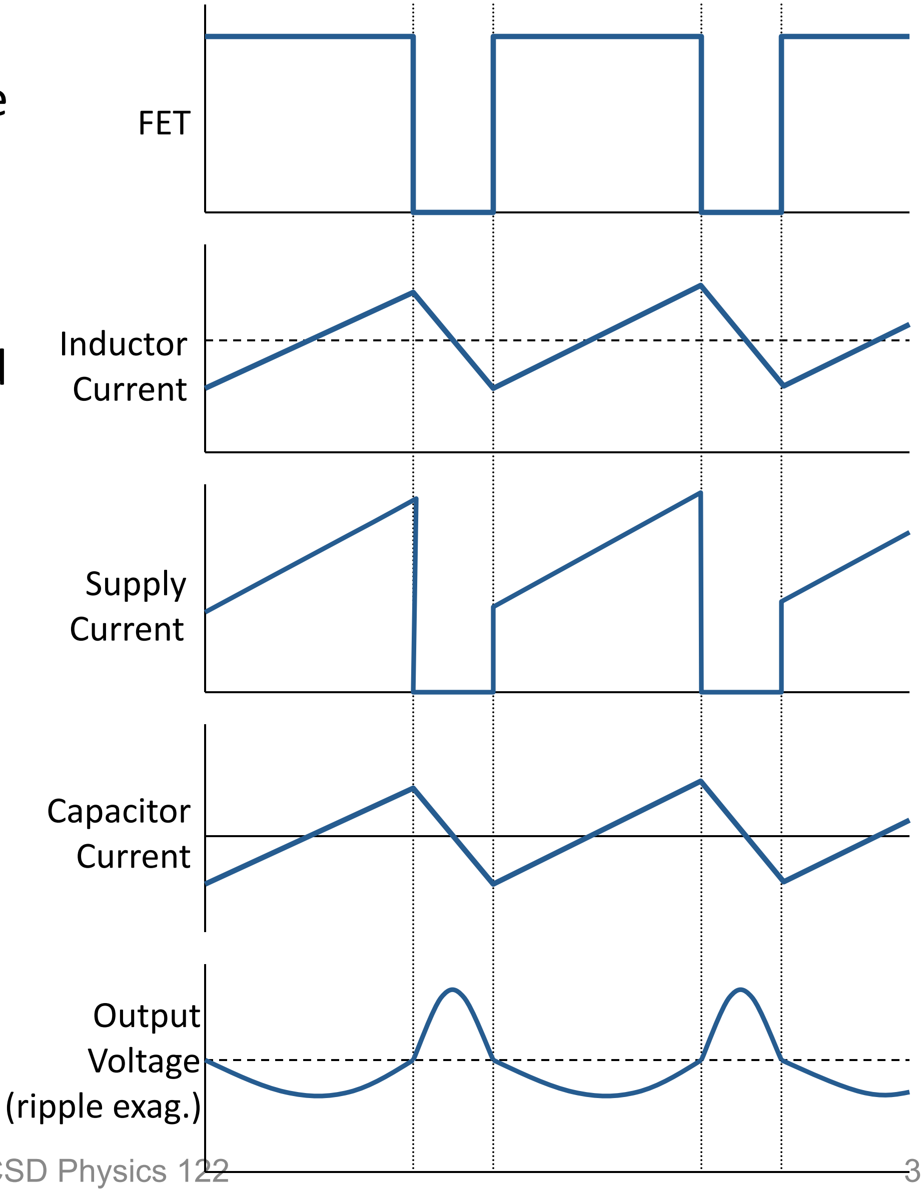
from: http://www.maxim-ic.com/appnotes.cfm/appnote_number/4087

Step-Down Calculations

- If the FET is on for duty cycle, *D* (fraction of time on), and the period is *T*:
  - the average output voltage is $V_{\text{out}} = DV_{\text{in}}$
  - the average current through the capacitor is zero, the average current through the load (and inductor) is 1/*D* times the input current
  - under these idealizations, power in = power out

Step-down waveforms

- Shown here is an example of the step-down with the FET duty cycle around 75%
- The average inductor current (dashed) is the current delivered to the load
  - the balance goes to the capacitor
- The ripple (parabolic sections) has peak-to-peak fractional amplitude of $T^2(1-D)/(8LC)$
  - so win by small T, large L & C
  - 10 kHz at 1 mH, 1000 μF yields ~0.1% ripple
  - means 10 mV on 10 V



Cable Impedances

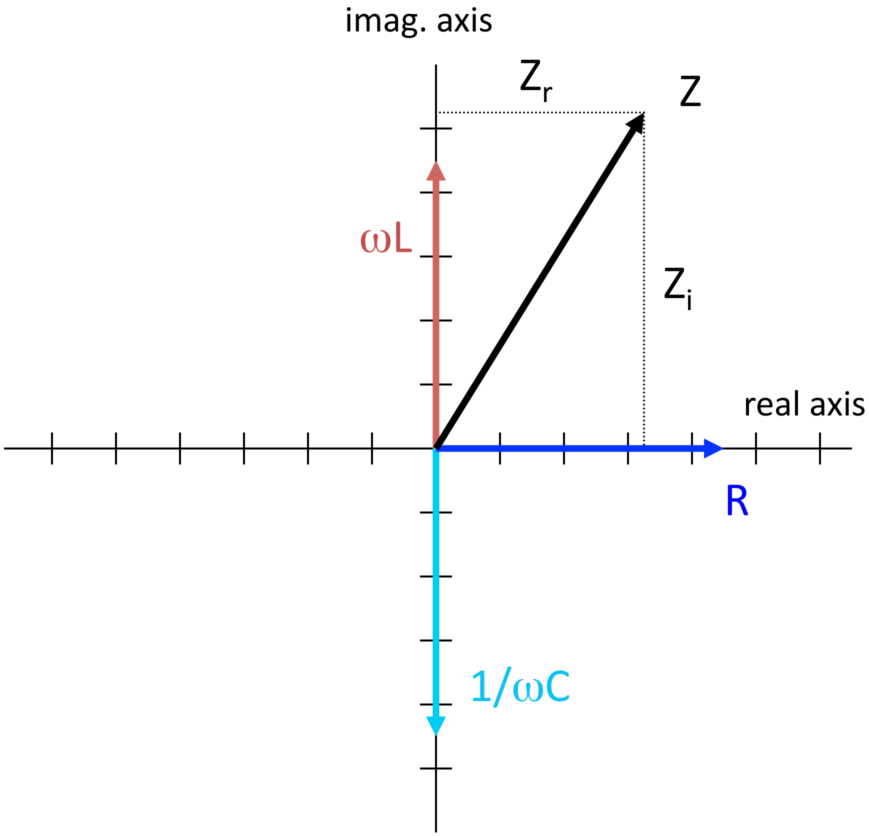
- RG58 cable is characterized as 50 Ω cable
  - RG59 is 75 Ω
  - some antenna cable is 300 Ω
- Isn't the cable nearly zero resistance? And shouldn't the length come into play, somehow?
- There is a distinction between resistance and impedance
  - though same units
- Impedances can be real, imaginary, or complex
  - resistors are real: $Z = R$
  - capacitors and inductors are imaginary: $Z = -i/\omega C$; $Z = i\omega L$
  - mixtures are complex: $Z = R - i/\omega C + i\omega L$

Impedances, cont.

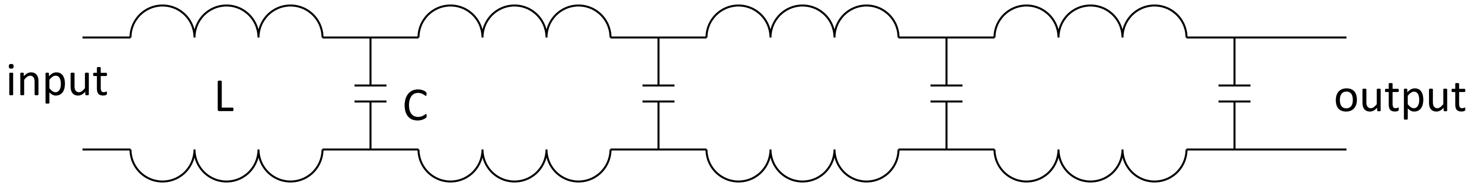
- Note that:
  - capacitors become less "resistive" at high frequency
  - inductors become more "resistive" at high frequency
  - bigger capacitors are more transparent
  - bigger inductors are less transparent
  - i (√-1) indicates 90° phase shift between voltage and current
    - after all, *V = IZ*, so *Z = V/I*
    - thus if *V* is sine wave, *I* is ±cosine for inductor/capacitor
    - and given that one is derivative, one is integral, this makes sense (slide # 3)
  - adding impedances automatically takes care of summation rules: add *Z* in series
    - capacitance adds as inverse, resistors, inductors straight-up

Impedance Phasor Diagram

- Impedances can be drawn on a complex plane, with pure resistive, inductive, and capacitive impedances represented by the three cardinal arrows
- An arbitrary combination of components may have a complex impedance, which can be broken into real and imaginary parts
- Note that a system's impedance is frequency-dependent



Transmission Line Model



- The cable has a finite capacitance per unit length
  - property of geometry and dielectric separating conductors
  - $C/\ell = 2\pi\varepsilon/\ln(b/a)$, where b and a are radii of cylinders
- Also has an inductance per unit length
  - $L/\ell = (\mu/2\pi)\ln(b/a)$
- When a voltage is applied, capacitors charge up
  - thus draw current; propagates down the line near speed of light
- Question: what is the ratio of voltage to current?
  - because this is the characteristic impedance
- Answer: $Z_0 = \mathrm{sqrt}(\omega L/\omega C) = \mathrm{sqrt}(L/C) = (1/2\pi)\mathrm{sqrt}(\mu/\varepsilon)\ln(b/a)$
  - note that Z_0 is frequency-independent

Typical Transmission Lines

- RG58 coax is abundant
  - 30 pF per foot; 75 nH per foot; 50 Ω; $v = 0.695c$; ~5 ns/m
- RG174 is the thin version
  - same parameters as above, but scaled-down geometry
- RG59
  - used for video, cable TV
  - 21 pF/ft; 118 nH per foot; 75 Ω; $v = 0.695c$; ~5 ns/m
- twisted pair
  - 110 Ω at 30 turns/ft, AWG 24–28
- PCB (PC-board) trace
  - get 50 Ω if the trace width is 1.84 times the separation from the ground plane (assuming fiberglass PCB with $\varepsilon = 4.5$)

Why impedance matters

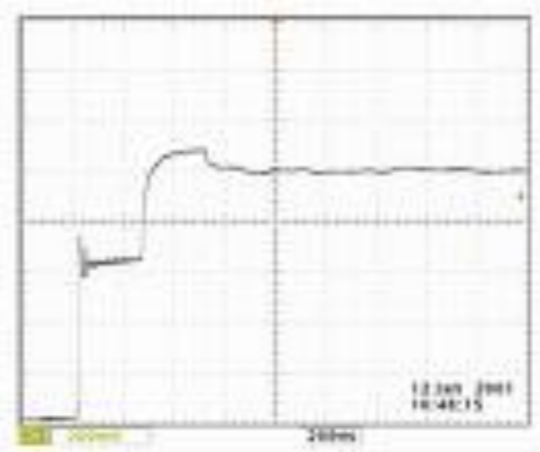
- For fast signals, get bounces (reflections) at every impedance mismatch
  - reflection amplitude is $(Z_t - Z_s)/(Z_t + Z_s)$
    - s and t subscripts represent source and termination impedances
    - sources intending to drive a Z_0 cable have $Z_s = Z_0$
- Consider a long cable shorted at end: insert pulse
  - driving electronics can't know about the termination immediately: must charge up cable as the pulse propagates forward, looking like Z_0 of the cable at first
  - surprise at far end: it's a short! retreat!
  - in effect, negative pulse propagates back, nulling out capacitors (reflection is −1)
  - one round-trip later (10 ns per meter, typically), the driving electronics feels the pain of the short

Impedance matters, continued

- Now other extreme: cable un-terminated: open
  - pulse travels merrily along at first, the driving electronics seeing a Z_0 cable load
  - at the end, the current has nowhere to go, but driver can't know this yet, so keeps loading cable as if it's still Z_0
  - effectively, a positive pulse reflects back, double-charging capacitors (reflection is +1)
  - driver gets word of this one round-trip later (10 ns/m, typically), then must cease to deliver current (cable fully charged)
- The goldilocks case (reflection = 0)
  - if the end of the cable is terminated with resistor with $R = Z_0$, then current is slurped up perfectly with no reflections
  - the driver is not being lied to, and hears no complaints

So Beware!

- If looking at fast (tens of ns domain) signals on scope, be sure to route signal to scope via 50 Ω coax and terminate the scope in 50 Ω
  - if the signal can't drive 50 Ω, then use active probes
- Note that scope probes terminate to 1 MΩ, even though the cables are NOT 1 MΩ cables (no such thing)
  - so scope probes can be very misleading about shapes of fast signals



References and Reading

- References:
  - The canonical electronics reference is Horowitz and Hill: *The Art of Electronics*
  - Also the accompanying lab manual by Hayes and Horowitz is highly valuable (far more practically-oriented)
- Reading
  - Sections 6.1.1, 6.1.2
  - Skim 6.2.2, 6.2.3, 6.2.4
  - Sections 6.3.1, 6.5.1, 6.5.2
  - Skim 6.3.2