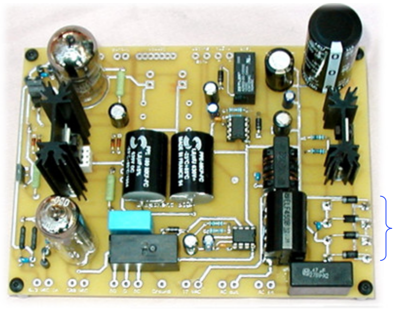


diode bridge

Electronics Overview

Basic Circuits, Power Supplies,
Transistors, Cable Impedance

Basic Circuit Analysis

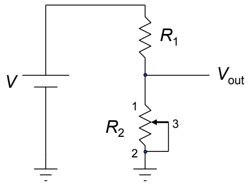
- What we won't do:
  - common electronics-class things: RLC, filters, detailed analysis
- What we will do:
  - set out basic relations
  - look at a few examples of fundamental importance (mostly resistive circuits)
  - look at diodes, voltage regulation, transistors
  - discuss impedances (cable, output,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

The Basic Relations

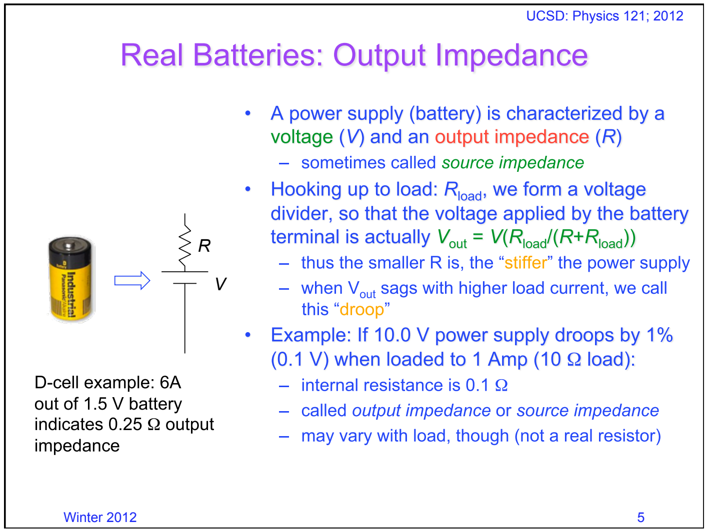
- V is voltage (volts: V); I is current (amps: A); R is resistance (ohms: Ω); C is capacitance (farads: F); L is inductance (henrys: H)
- Ohm's Law: $V = IR$; $V = \frac{1}{C}\int I dt$; $V = L(dI/dt)$
- Power: $P = IV = V^2/R = I^2R$
- Resistors and inductors in series add
- Capacitors in parallel add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

$$\frac{1}{X_{tot}} = \frac{1}{X_1} + \frac{1}{X_2} + \frac{1}{X_3} + \ldots$$

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



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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 $V_{out} = V(R_{load}/(R+R_{load}))$
  - 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

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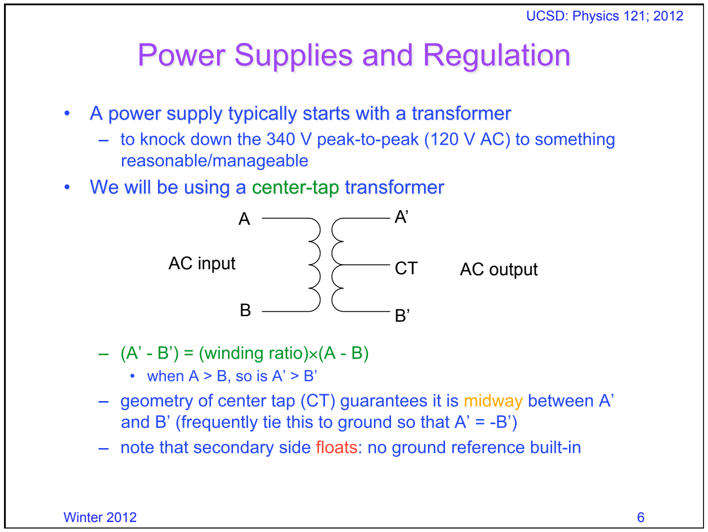

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Power Supplies and Regulation

- 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

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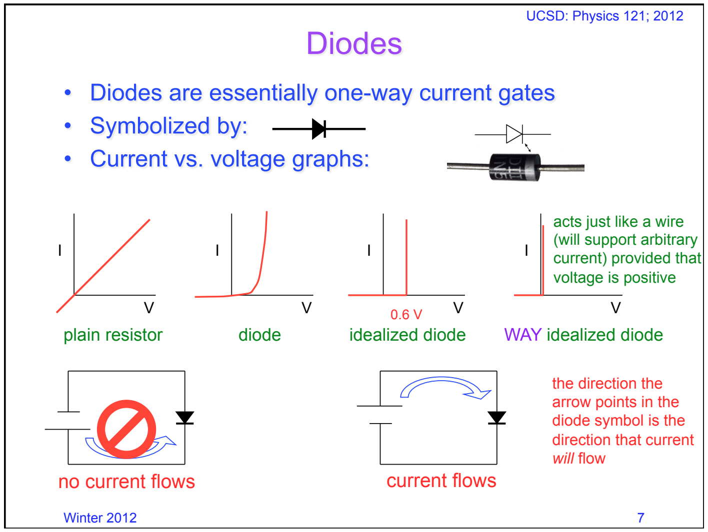

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Diodes

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

plain resistor

diode

idealized diode

WAY idealized diode

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

no current flows

current flows

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

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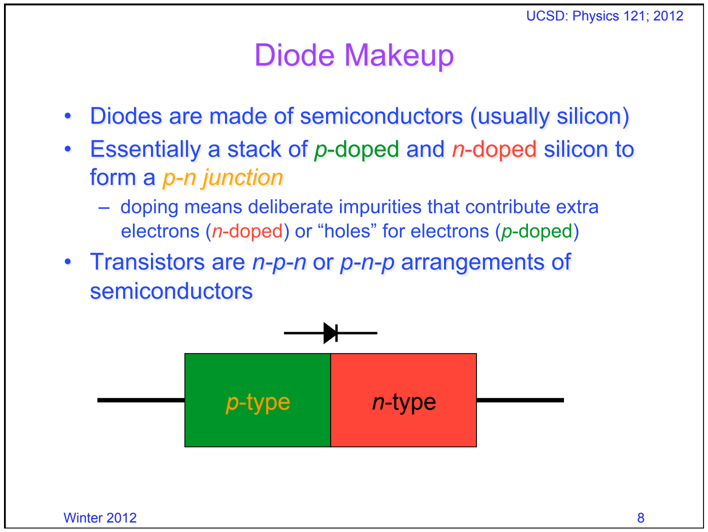

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Diode Makeup

- 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

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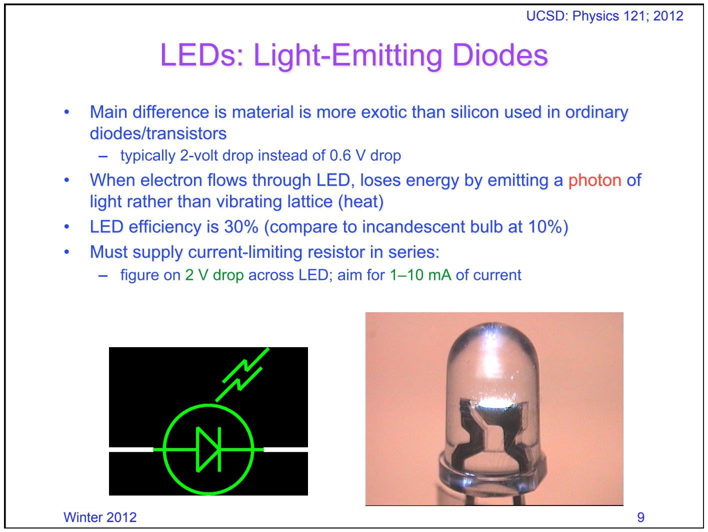

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LEDs: Light-Emitting Diodes

- 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

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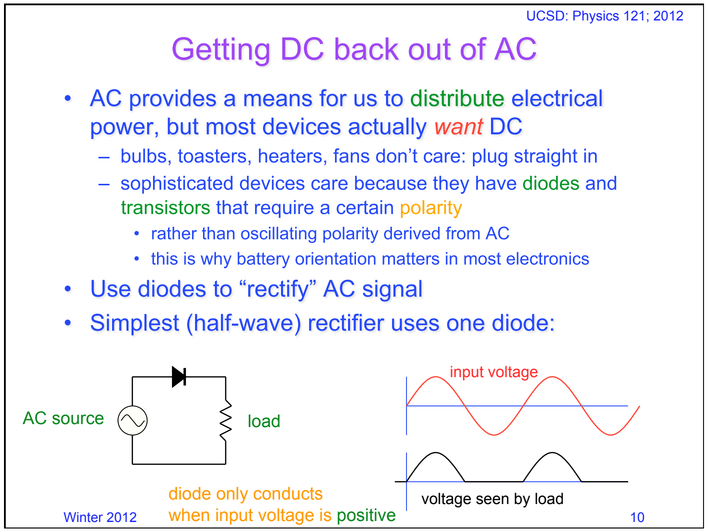

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Getting DC back out of AC

- 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

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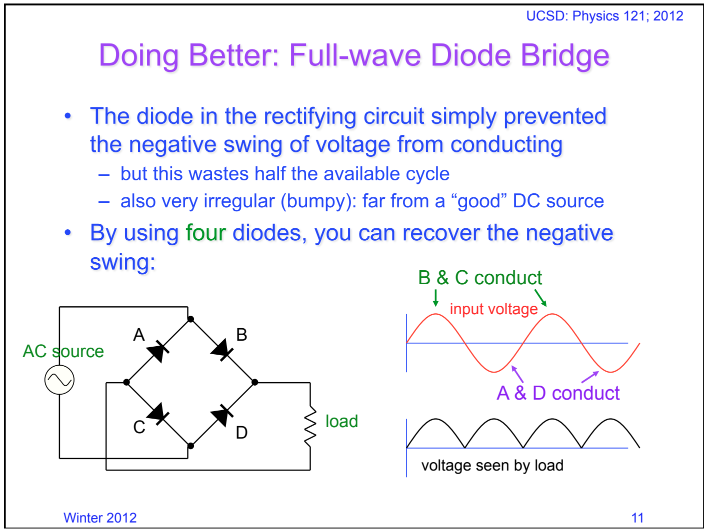

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Doing Better: Full-wave Diode Bridge

- 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:

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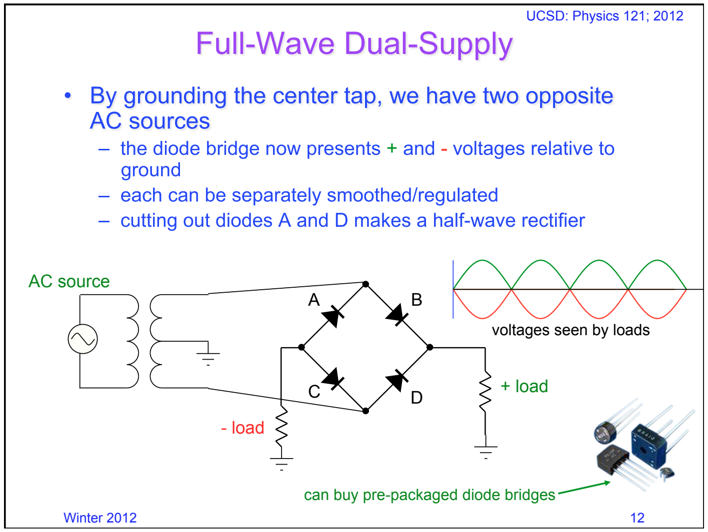

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Full-Wave Dual-Supply

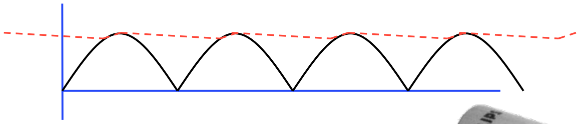
- By grounding the center tap, we have two opposite AC sources
  - the diode bridge now presents + and - voltages relative to ground
  - each can be separately smoothed/regulated
  - cutting out diodes A and D makes a half-wave rectifier

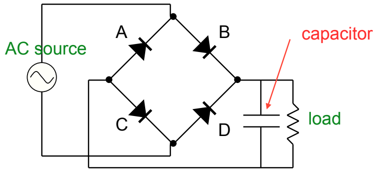
can buy pre-packaged diode bridges

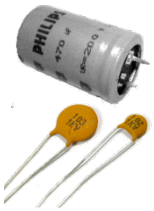
Winter 2012 12

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

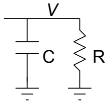


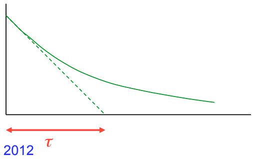




How smooth is smooth?

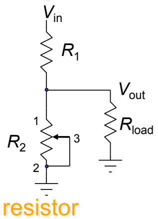
- An RC circuit has a time constant $\tau = RC$
  - because $dV/dt = I/C$, and $I = V/R \rightarrow dV/dt = V/RC$
  - so V is $V_0\exp(\pm t/\tau)$
- Any exponential function starts out with slope = Amplitude/τ
- So if you want < 10% ripple over 120 Hz (8.3 ms) timescale…
  - must have $\tau = RC > 83$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





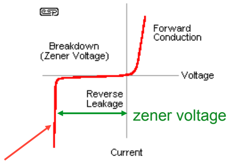
Regulating the Voltage

- 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 → $R_1 \parallel R_2$
  - 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

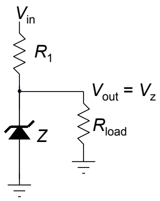


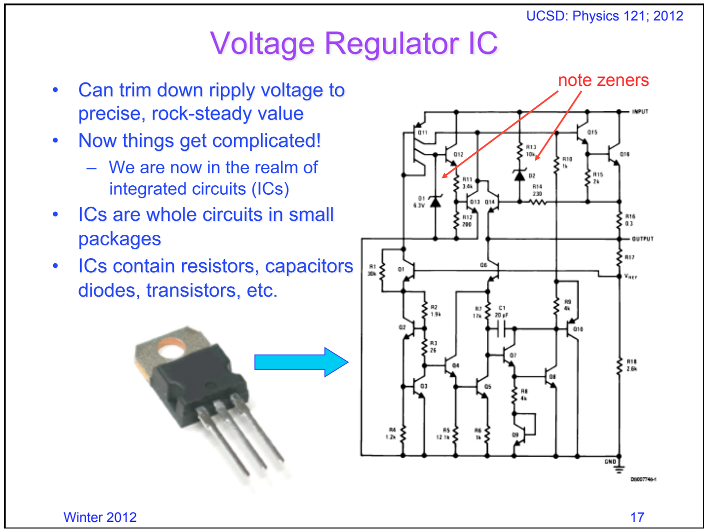
The Zener Regulator

- 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



high slope is what makes the zener a decent voltage regulator

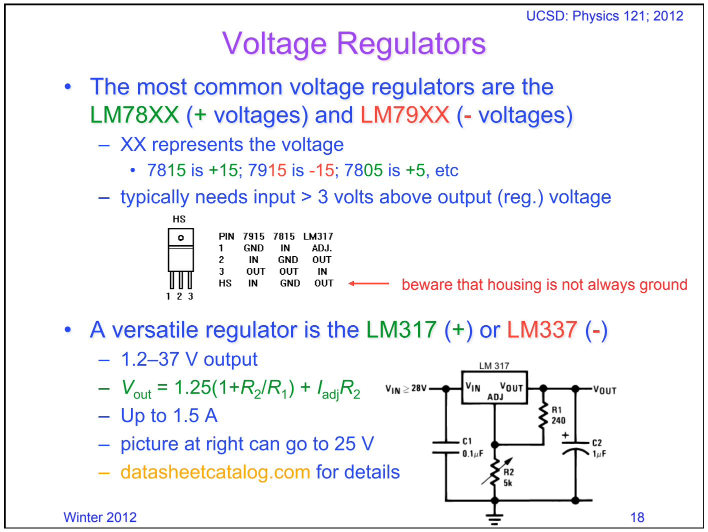




Voltage Regulator IC

- 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



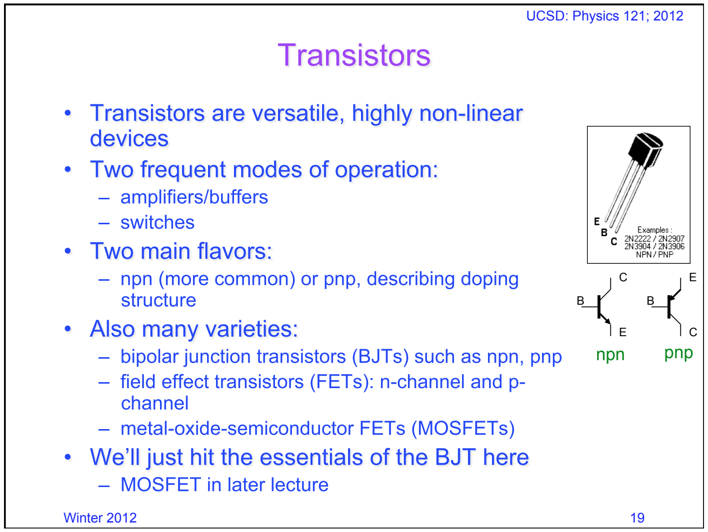
Voltage Regulators

- 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

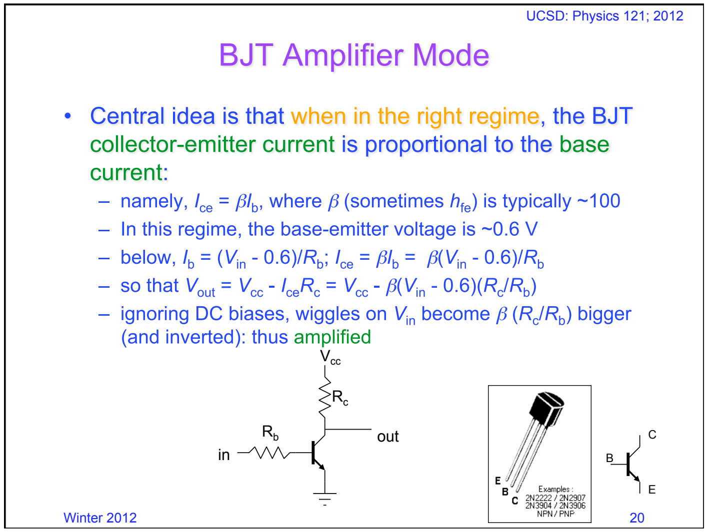
beware that housing is not always ground

- A versatile regulator is the LM317 (+) or LM337 (-)
  - 1.2–37 V output
  - $V_{out} = 1.25(1+R_2/R_1) + I_{adj}R_2$
  - 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

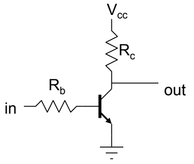


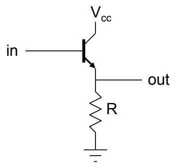
BJT Amplifier Mode

- 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



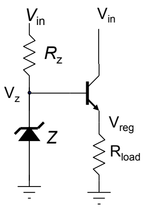


Transistor Buffer

- 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

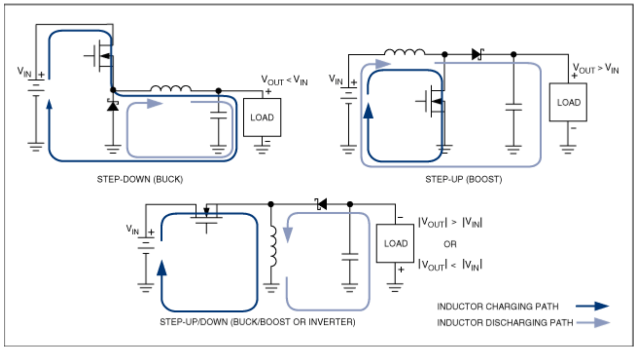
- By adding a transistor to the zener regulator from before, we no longer have to worry as much about the current being pulled away from the zener to the load
  - the base current is small
  - R_{load} effectively looks β times bigger
  - real current supplied through transistor
- Can often find zeners 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}

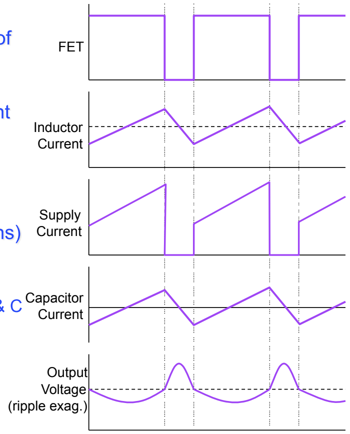
from: http://www.maxim-ic.com/appnotes.cfm/appnote_number/4087

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 $V_{out} = DV_{in}$
  - 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

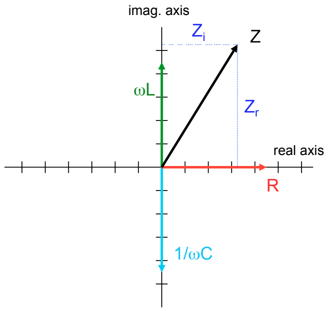
- RG58 cable is characterized as 50 Ω cable
  - RG59 is 75 Ω
  - some antenna cable is 300 Ω
- Isn't the cable nearly zero resistance? And shouldn't the length come into play, somehow?
- There is a distinction between resistance and impedance
  - though same units
- Impedances can be real, imaginary, 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.

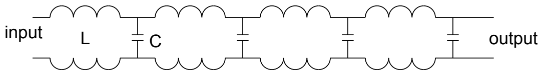
- Note that:
  - capacitors become less “resistive” at high frequency
  - inductors become more “resistive” at high frequency
  - bigger capacitors are more transparent
  - bigger inductors are less transparent
  - i (√-1) indicates 90° phase shift between voltage and current
    - after all, $V = IZ$, 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 = sqrt($\omega L/\omega C$) = sqrt(L/C) = (1/2π)sqrt(μ/ε)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 ε = 4.5)

Why impedance matters

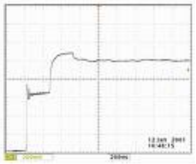
- For fast signals, get bounces (reflections) at every impedance mismatch
  - reflection amplitude is $(Z_t - Z_s)/(Z_t + Z_s)$
    - s and t subscripts represent source and termination impedances
    - sources intending to drive a Z_0 cable have $Z_s = Z_0$
- Consider a long cable shorted at end: insert 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 Assignment

- 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)
  - And of course: Electronics for Dogs (just ask Gromit)
- 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