

What is an output stage?

- Desirable behaviors

- ~~max~~ power Xfer TH_L

- Large signal linearity

Common Emitter/
Class A

- Large signal Xfer C
- Efficiency & Backoff
- introduce class system
- (new) Z_{out} ~ output impedance

S.2

push-pull/class B
and class AB

- Xfer
- crossover distortion
- efficiency
- Thermal Runaway

S.4

Class C and beyond

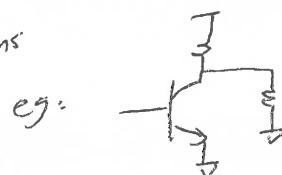
- Intro to switching regulators & class C
- Class D → PWM
- Class E →

- later: diamond buffer

• We've mostly ignored loads in this class & just built voltage amplifiers

- loaded all amplifiers w/ probe - appropriate for low-f signal circ.

- considered interstage loading & swing limitations



• But many loads are important

↳ motors look like inductor + small R

↳ speakers look like motors ~ rated 4Ω or 8Ω (actual wire inductance)

↳ plasmas, phone lines, RF loads, etc.

In general loads want

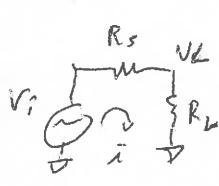
~ low output Z to minimize loading & maximize swing

~ high output power delivered to load $A_p = \frac{V_o^2/R_L}{V_i^2/R_{in}} = \frac{R_{in}}{R_L} A_V^2$... ok for low f

~ high efficiency

~ high linearity

Find exact level of Z using max power Xfer TH_L (real valued version)



$$i_s = \frac{V_L}{R_s + R_L}$$

$$V_L = \frac{R_L}{R_s + R_L} V_i$$

$$\gamma = \frac{R_L}{R_s} = \frac{R_L}{R_s + R_L}$$

$$P_s = \frac{V_i^2}{R_s + R_L}$$

$$P_L = \frac{R_L}{(R_s + R_L)^2} V_i^2$$

Max load power is denoted normalized

- control R_s ?

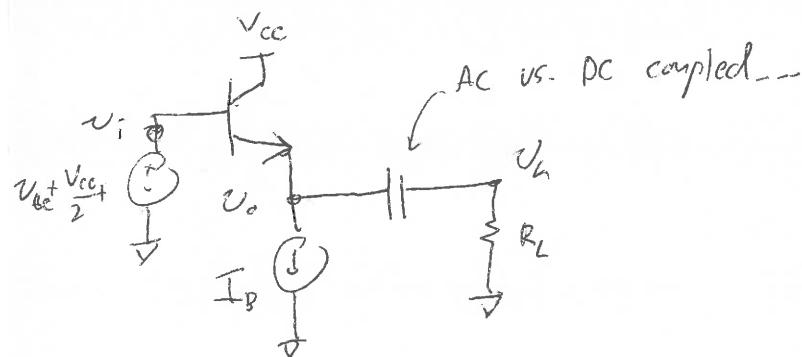
$$\frac{\partial}{\partial R_s} (R_s + R_L)^2 = 2(R_s + R_L) \rightarrow \text{set } R_s = \underline{R_s} \text{ to approach min}$$

- control R_L

$$\frac{\partial}{\partial R_L} E R_L (R_s + R_L)^{-2} = (R_s + R_L)^{-2} + \frac{-2R_L}{(R_s + R_L)^3} = \frac{R_s + R_L}{(R_s + R_L)^3}$$

make ~~min~~
 $R_s = R_L$!

- What's a common example of an output stage - emitter follower

Analysis

- SWING

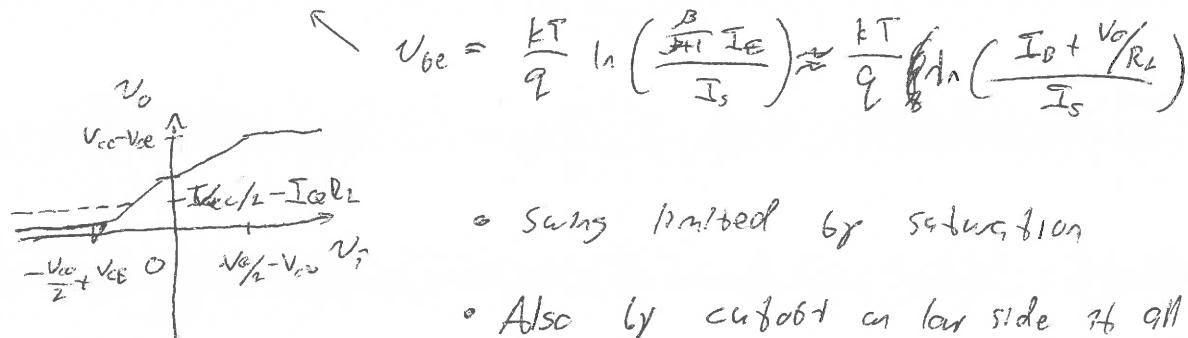
- EFFICIENCY

- Hand-wavy Rout

↳ Quiescent dc for next op.

- Let V_i be sinusoidal $V_i = V_A \cos(\omega t)$

- $V_b = V_i - V_{BE}$ ← pretty linear, but potentially small V_{BE} variations



- Swing limited by saturation

- Also by cutoff on low side if all \$I_B\$ in load

- Power analysis depends on V_i sinusoidal

- Max power could deliver both max voltage & current swings
(same resistors does this)
- I & V are in phase

$$P_L = \frac{(V_{CC} - 2V_{CE}) \cos(\omega t) \cdot I_B \cos(\omega t)}{2} = \frac{1}{2} I_B (V_{CC} - 2V_{CE}) \cos^2(\omega t) \xrightarrow[\text{average}]{\frac{1}{2}}$$

$$= \frac{1}{2} I_B (V_{CC} - 2V_{CE})$$

can save and since this

$$P_S = V_{CC} \cdot I_B \quad (\cancel{\text{current}}) \leftarrow \text{always flows } I_B$$

- Constant supply ignores voltage swings

$$\eta = \frac{P_L}{P_S} = \frac{1}{2} \left(1 - \frac{2V_{CE}}{V_{CC}} \right) \approx 25\% \quad \text{at best}$$

\hookrightarrow backoff hurts b/c I_B stays

\hookrightarrow non-optimal load hurts

Note: $P_L = V_{CE} \cdot I_B$

$(V_{CC} - \frac{V_{CC}}{2} \cos(\omega t)) I_B \cos(\omega t)$

 $\frac{V_{CC}}{2} I_B (2 \cos^2(\omega t) - \cos(\omega t))$
 $\frac{V_{CC} I_B}{4} \text{ on avg.}$

\downarrow less than quiescent

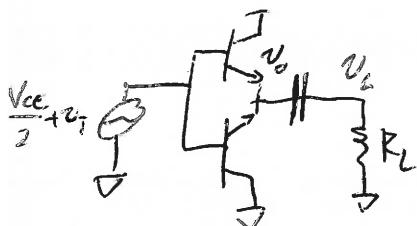
= called a class A amplifier (weird naming convention)

↳ identifying feature ~ transistor "On" for whole cycle

↳ very linear b/c don't fluct w/ cutoff/sat.

↳ pay a lot of power in bias current ... always flow I_B

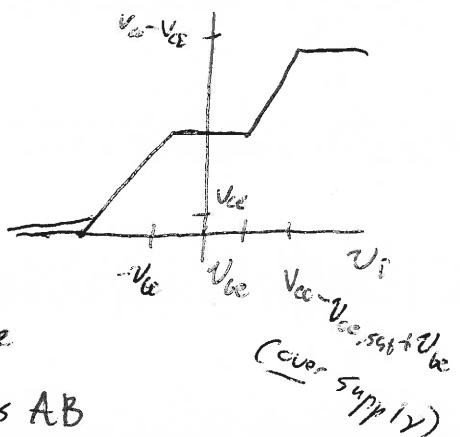
Let's fix it w/ class B



↳ defined as current flows in transistor for 50% cycle

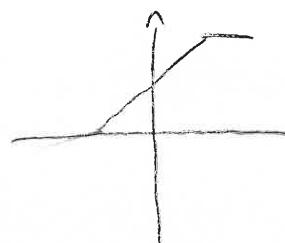
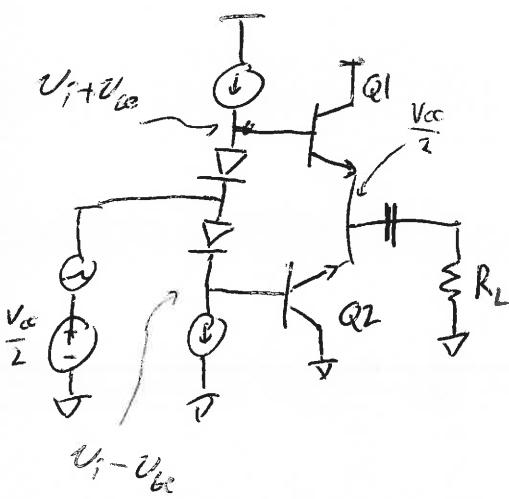
↳ Also called a push-pull

↳ crossover distortion



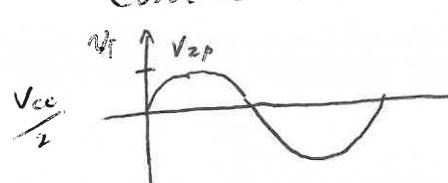
Crossover distortion is very bad & usually avoidable

so you tend to use a topology called class AB



Fixes crossover distortion

Current flow different in each device



$$\begin{aligned} I_{\text{Supply}} &= \frac{1}{2\pi} \int_0^{\pi} \frac{V_{2P}}{R_L} \sin(\theta) d\theta \\ &= \frac{V_{2P}}{\pi R_L} \end{aligned}$$



$$P_{\text{Supply}} = V_{ce} \cdot I_{\text{Supply}}$$

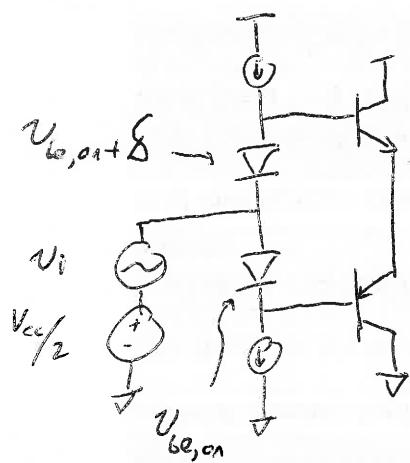


$$P_L = \frac{V_{2P}^2}{2R_L} \quad \text{max} = \left(\frac{V_{ce} - 2V_{ce}}{2} \right)^2 \cdot \frac{1}{R_L}$$

All current in/out of load

$$\begin{aligned} \gamma &= \frac{(V_{ce} - 2V_{ce})^2 / 4R_L}{V_{ce} (V_{ce} - V_{ce}) / R_L + \gamma_0} \\ &= \frac{\pi}{2} \left(1 - \frac{V_{ce}}{V_{ce}} \right) = 78\% \end{aligned}$$

Thermal Runaway



- If $\delta = 0$ & $V_i = 0$ then both transistors barely cutoff → no current flows
- If $\delta > 0$ DC current flows from Q_1 , forces into Q_2
- DC dissipation heats $Q_1 \rightarrow$ lower $V_{be} \rightarrow$ more current
↳ ends w/ explosion

Fix

- Add degeneration resistors ($1-10\ \Omega$) in series w/ diodes & emitters
- Ensure good thermal contact of all parts

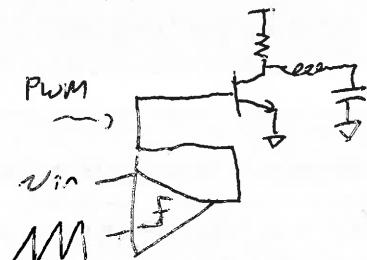
Other Amp Classes

class C



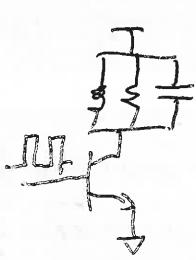
- conducts for $< \pi$
but does enter linear region
- used in RF where filters small harmonics widely spaced

class D



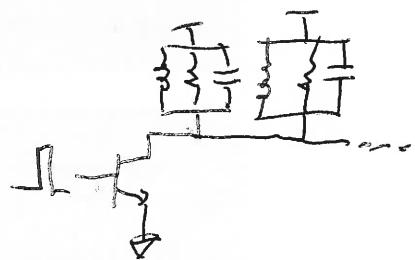
- switch mode
- input is PWM
- big output filter
- slow, only good for audio

class E



- Like class C but in switch mode
- zero voltage switching
- common, esp. in MOS

class F

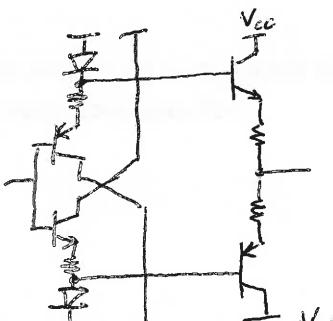


- switch mode
- do harmonic filter

Diamond Buffer

↳ really powerful &
high bandwidth

↳ Anecdote



↳ often use LEDs
as constant current source