What is an output stage?
- Desirable behaviors
  - Max power Xfer
  - Large signal linearity

<table>
<thead>
<tr>
<th>Common Emitter/Class A</th>
<th>Push-pull/Class B and Class AB</th>
<th>Class C and beyond</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Large signal Xfer</td>
<td>- Xfer</td>
<td>- Intro to switching regulators and Class C</td>
</tr>
<tr>
<td>- Efficiency + Backoff</td>
<td>- Crosser distortion</td>
<td>- Class D → PWM</td>
</tr>
<tr>
<td>- Introduce class</td>
<td>- Efficiency</td>
<td>- Class E →</td>
</tr>
<tr>
<td>- System</td>
<td>- Thermal runaway</td>
<td>- Later: diamond buffer</td>
</tr>
<tr>
<td>- Linearity × linearity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Output impedance</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We have mostly 7 resistor loads in this class 7 built voltage amplifiers
- loaded all amplifiers / probe - appropriate for low-signal ac
- consider inter-stage loading + swing limitations

But many loads are important:
- Motors look like inductor + small R
- Speakers look like motors ~ rated 4Ω + 8Ω (actual wire inductance)
- Plasmas, phone lines, RF loads, etc.

In general loads want
- Low output Z to minimize loading or maximize swing
- High output power delivered to load
- High efficiency
- High linearity

Pick exact level of Z using max power Xfer Thévenin (real valued version)

\[
V_i = \frac{V_i}{R_s + R_L} \\
I_o = \frac{V_i}{R_s + R_L} \\
V_o = \frac{R_L}{R_s + R_L} V_i \\
P_L = \frac{R_L}{(R_s + R_L)^2} V_i^2 \\
\frac{\partial P_L}{\partial R_s} = 0, \quad (R_s + R_L)^2 = 2 (R_s + R_L) \rightarrow \text{set } R_s = \frac{V_i}{2} \\
\frac{\partial P_L}{\partial R_L} = 0, \quad \text{match load ↔ impedance match} \]

\[
R_s = R_L! 
\]
Lec 23 - output stage

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

\[ V_v = \frac{1}{2} V_{cc} + V_{cc} \]

[Diagram]

- \( V_b \) = \( V_i - V_{be} \) - pretty linear, but potentially such \( V_{be} \) variations

\[ V_{be} = \frac{kT}{q} \ln \left( \frac{\beta I_e}{I_s} \right) \approx \frac{kT}{q} \ln \left( \frac{I_B + V_{ce} / R_e}{I_s} \right) \]

- Swing limited by saturation
- Also by cut-off on low side if all \( I_B \) in load

- Power analysis depends on \( V_i \) sinusoidal

- Max power would deliver both max voltage & current swings

- \( I \neq V \) are in phase

\[ P_L = \frac{(V_{cc} - 2V_{ce}) \cos(\omega t) \cdot I_B \cos(\omega t)}{2} = \frac{1}{2} I_B (V_{cc} - 2V_{ce}) \cos^2(\omega t) \approx \frac{1}{2} \text{ average} \]

\[ P_s = V_{cc} \cdot I_B \] - usually flows \( I_B \)

- Constant supply ignores voltage swings

\[ Z = \frac{R}{P_s} = \frac{1}{4} \left( 1 - \frac{2V_{ce}}{V_{cc}} \right) \approx 25\% \text{ at best} \]

- Back-off hurts \( V_i \) & \( I_B \) sizing
- Non-optimal load hurts

Note: \( P_L = V_{cc} \cdot I_B \)
Lec 23 - Output Stages

Called a Class A Amplifier (usual naming convention)

- Identifying feature: transistor "On" for whole cycle
- Very linear b/c don't flirt w/ cutoff/sat.
- Pays a lot of power in bias current...always flow $I_B$

Let's fix RI 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

$$I_{supply} = \frac{1}{2\pi} \int_{0}^{\pi} \frac{V_{BE}}{r_{BE}} \sin(\theta) \, d\theta$$

$$= \frac{V_{BE}}{\pi r_{BE}}$$

$$P_{supply} = V_{cc} \cdot I_{supply}$$

$$P_{L} = \frac{V_{cc}^2}{2} \cdot max = \left(\frac{V_{cc} - 2V_{BE}}{2}\right)^2 \cdot \frac{1}{r_L}$$

$$Q = \frac{(V_{cc} - 2V_{BE})^2}{4r_L} \cdot \frac{1}{r_L} \cdot \frac{1}{\pi}$$

$$= \frac{\pi (1 - \frac{V_{BE}}{V_{cc}})^2}{78\%}$$

All current in/out of load
Lec 23 - Output Stages

Thermal Runaway

- If $T = 0$ or $V_i = 0$ then both transistors barely cut-off, no current flows.
- If $I > 0$ DC current flows from $Q_1$, forces into $Q_2$.
- DC dissipation heats $Q_1$ → lower $V_{ce}$ → more current.
- Ends w/ explosion.

Fix:
- Add degeneration resistors (1-10 kΩ) in series w/ diodes & emitters.
- Ensure good thermal contact of all parts.

Other Amp Classes

Class C
- Conducts for $T = 0$ but does enter linear region.
- Used in RF where filters select harmonics widely spaced.

Class D
- Switch mode.
- Input is PWM.
- Big output filter.
- Slow, only good for audio.

Class E
- Like class C.
- Switch mode.
- Used in switch mode.
- Strong harmonic filter.
- Zero voltage switching.

Class F
- Common, esp. in MOS.
- Often use LEDs as constant current source.

Diamond Buffer
- Really powerful w/ high bandwidth.
- Anecdotally...