Efficiency: want most of the power delivered to the load, not dissipated in the output stage.
At high power levels, we need to worry about heating, often damaging the transistor in the output stage.

Output Stage Classification:

- Output stages are classified into several categories.
- Classified by the current waveform for the output transistor.
  - Equivalently, the proportion of each cycle for which the output transistor is “on” (supply-level current).
- This is also called the “conduction angle” (ranges from 0° to 360°).

1) Class A: device is on for entire period (360° conduction angle)
   - All of the amplifiers we have discussed up until now have been Class A due to small signal assumption.

2) Class B: device is on for half of period (180° conduction angle)
   - Bias current is zero.
   - Need filtering to recover the intended output signal.

3) Class AB: device is on for over half the period, but not full (conduction angle > 180° < 360°)

4) Class C: device is on for less than half the period (conduction angle < 180°)
   - Like a negative bias current.
How do we recover the original signal from an amplifier with an output conduction angle <360°?

- Consider output of class B stage:

\[ V(t) \]

- What frequency components is the output composed of?

- Find Fourier series expansion:

\[ a_0 = \frac{1}{\pi} \int_0^{\pi} \sin(t) \cdot dt = \frac{2}{\pi} \]

\[ b_1 = \frac{1}{\pi} \int_0^{\pi} \sin(t) \cdot \sin(t) \cdot dt = \frac{1}{2} \]

\[ a_1 = \frac{1}{\pi} \int_0^{\pi} \sin(t) \cdot \cos(t) \cdot dt = 0 \]

\[ b_2 = \frac{1}{\pi} \int_0^{\pi} \sin(t) \cdot \sin(2t) \cdot dt = 0 \]

\[ a_2 = \frac{1}{\pi} \int_0^{\pi} \sin(t) \cdot \cos(2t) \cdot dt = -\frac{2}{3\pi} \]

\[ b_3 = 0, \quad b_4 = 0, \quad \text{etc.} \]

\[ a_3 = 0, \quad a_4 = -\frac{2}{15\pi}, \quad a_5 = 0, \quad \text{etc.} \]

- Spectrum is composed of dc, fundamental, odd harmonics.

- Can recover original signal with blocking cap. to eliminate dc, and low-pass filter to eliminate harmonics.

- Freq. spectrum:

\[ \text{Fundamental} = \frac{1}{2} \quad \text{(desired)} \]

\[ \text{DC (block)} \]

\[ \text{Harmonics (filter out)} \]

- Conduction angle (and therefore class) is determined by biasing.

- Next consider class A \& B in more detail (with examples).

- Use BJTs since that is what the test uses, and that will provide some exposure to them.

Brief review of BJTs:

- Much like MOSFETs: voltage controlled current source.

\[ V \quad \text{dc} \]

\[ E \]
\[ i_c \text{ vs. } V_{BE} : \]

- in active region, acts like a diode

\[ i_c = I_s e^{\frac{V_{BE}}{V_T}} \]

\( V_T = kT/q \)

(Compare with square law for MOSFET)

\[ i_c \text{ vs. } V_{CE} \]

Saturation Region

Active Region (desired operating region)

- Note naming convention is different than for MOSFETs:
  - with MOSFETs we wanted the saturation region
  - with BJTs we went the active region

(review Section 5.1 and 5.2 in text if necessary)

Nov. 19.

Class A Output Stage

-Emitter follower (common collector) is a good output stage
  - low output resistance

\[ V_{in} \rightarrow \]

\[ \frac{1}{2} \]

\[ \text{Input} \]

\[ \text{Output} \]

\[ \text{Use small signal model to find output resistance} \]

\[ V_{out} = \frac{I_c}{g_m} + V_T \]

\[ R_0 \]

\[ \text{Like MOSFET, but } R_0 \text{ replaces open circuit} \]

\[ g_m = \frac{I_c}{V_T} \]

\[ \text{for MOS} \]

\[ R_T = \frac{\beta}{g_m} \]

\[ \text{for MOS} \]

\[ R_0 = \frac{V_T}{I_c} \]

\[ \text{Output resistance: } I_c = \frac{V_T}{g_m} + \frac{V_T}{R_0} \]

\[ \Rightarrow \text{Output } = \frac{V_T}{I_c} = \left( V_T I_T \parallel I_T R_0 \right) \]

- Can make output resistance as small as possible by making \( g_m \) small

- Requires larger \( I_c \) \rightarrow more power consumption.