Output Stages

- So far, our designs have high output impedance
  
  → Generally termed "operational transconductance amplifiers" due to current source output (OTA)

- To drive resistive loads or large capacitance loads, need an output stage w/ low output impedance to buffer the load from our high gain stages → "operational amplifier"

  Equivalent models:

  OTA: \( R_{out} \rightarrow \text{large} \)
  
  Op-Amp: \( R_{out} \rightarrow \text{small} \)

- Next: Add buffer to OTA to realize low output impedance op-amp.
Op-Amp Stages:

- OTA.
- Complete op-amp.

Output Stages:

1) Common-Drain (source follower)

\[ \frac{V_0}{V_{o2}} \approx 1, \quad R_{out} \approx \frac{1}{g_m}, \]

- Can source only \( I_0^+ = I_{B2} \)
- Can sink \( I_0^- = I_{D1, \text{max}} - I_{B2} \)
  \( \Rightarrow \) can be large \( w/L \)

\( \Rightarrow \) Class A: Constant power consumption
- \( I_0 \) limited by bias \( I_{B2} \)
- Highly linear (all devices active)
2) **Two Source Followers:**

- Has "cross-over" distortion for $V_{O2}$ near $V_0$ with $M_1$ and $M_2$ cut-off:

  ![Diagram]

- @ $I_0 = 0 \Rightarrow$ zero power loss (or quiescent power)

- $(I_0)_{\text{max}}$: can be large in both directions by design (large $W/L$, 1 + 2).

- Small-signal:

  \[ \frac{\Delta V_0}{\Delta V_{O2}} = 1 \] if $M_1$ and $M_2$ active; $B = \frac{1}{g_m}$ or $\frac{1}{g_{m2}}$

\[ \Rightarrow \text{Class B: } -\text{ no quiescent current} \]

- $I_0$ not limited by bias current

- Cross-over distortion (non-linear)
3) Two source followers w/ biasing:

- Use $V_{b1} + V_{b2}$ to "pre-bias" $M_1$, $M_2$ into active region
- Reduce or eliminate crossover distortion depending on how much $I_{Q}$ is allowed.
- Quiescent current ($@ I_{O} = 0$)
  
  Possible realization:

- $M_{1b} + M_{2b}$ bias $M_1$, $M_2$ with $I_{Q_{1,2}} = n \cdot I_{Q}$ so both are active @ $I_{O} = 0$
- For large $I_{O}^+$ $\Rightarrow M_2$ active $M_1$ cutoff
- For large $I_{O}^-$ $\Rightarrow$ reverse.

- $V_{SS} \Rightarrow$ Class A/B: Compromise between distortion + bias current
- $I_{Q}$ not limited by bias current.
- $I_{Q} = $ Small (not Zero)
- Limited distortion