$V^+$ 

 $I_{\text{REF}} \downarrow \lessgtr R_1$ 

 ${}_{R_{E1}}$ 

 $V^-$ 

 $I_0$ 

 $Q_2$ 

 $\circ V_{C2}$ 

1. (20%) The transistors are matched. Assume that base currents are negligible and that  $V_A = \infty$ . Show that

$$I_O R_{E2} - I_{REF} R_{E1} = V_T \ln\left(\frac{I_{REF}}{I_O}\right).$$





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3. (30%) Let  $I_{\text{REF}} = 0.2 \text{ mA}$ ,  $K_n = 0.2 \text{ mA/V}^2$ ,  $V_{TN} = 1 \text{ V}$ , and  $\lambda = 0.02 \text{ V}^{-1}$ . (All transistors are matched.) Determine the output resistance looking into the drain of  $M_6$ .



4. (25%) Assume all transistors are matched. Draw the small-signal model and use the small-signal hybrid- $\pi$  parameter notations such as  $g_m$ ,  $r_{o1}$ , etc. for transistors to derive the voltage gain  $A_v = v_o / v_I$ .

