1. For the emitter follower shown to the right, let $V_{cc}=10\text{V}$, $I=100\text{mA}$, $R_L=100\text{\Omega}$. Ignore the loss in $Q_3$ and $R$. If the output voltage is an 8V peak sinusoid, find the following:
(a) The power delivered to the load
(b) The average power drawn from the supplies
(c) The power conversion efficiency

\begin{align*}
\text{a. } P_L &= \frac{(\bar{V}_o/\sqrt{2})^2}{R_L} = \frac{(8/\sqrt{2})^2}{100} = 0.32 \text{ W} \\
&= 2 \text{ W} \\
\text{Efficiency } \eta &= \frac{P_L}{P_S} \times 100 \\
&= \frac{0.32}{2} \times 100 \\
&= 16\%
\end{align*}

2. A class B output stage operates from $\pm 5\text{V}$ supplies. Assuming relatively ideal transistors, what is the output voltage for maximum power conversion efficiency? What is the output voltage for maximum device dissipation? If each of the output devices is individually rated for 1W dissipation, and a factor-of-2 safety margin is to be used, what is the smallest value of load resistance that can be tolerated, if operation is always at full output voltage? If operation is allowed at half the full output voltage, what is the smallest load permitted? What is the greatest possible output power available in each case?

\begin{align*}
V_{cc} &= 5 \text{ V} \\
\text{For maximum } \eta, \quad \bar{V}_o &= V_{cc} - 5 \text{ V} \\
\text{The output voltage that results in maximum device dissipation is given by} \\
\bar{V}_o &= \frac{2}{\pi} V_{cc} \\
&= \frac{2}{\pi} \times 5 = 3.18 \text{ V}
\end{align*}
If operation is always at full output voltage, 
\[ \eta = 78.5\% \text{ and thus} \]
\[ P_{\text{dissipation}} = (1 - \eta) P_{l} \]
\[ = (1 - \eta) \frac{P_{L}}{\eta} = 1 - \frac{0.785}{0.785} P_{L} = 0.274 P_{L} \]
\[ P_{\text{dissipation/device}} = \frac{1}{2} \times 0.274 P_{L} = 0.137 P_{L} \]

For a rated device dissipation of 1 W, and using a factor of 2 safety margin,
\[ P_{\text{dissipation/device}} = 0.5 \text{ W} \]
\[ = 0.137 P_{L} \]
\[ \Rightarrow P_{L} = 3.65 \text{ W} \]
3.65 = \frac{1}{2} \times \frac{25}{R_{L}}
\[ \Rightarrow R_{L} = 3.425 \Omega \text{ (i.e. } R_{L} \geq 3.425 \Omega \text{)} \]
The corresponding output power (i.e., greatest possible output power) is 3.65 W.

If operation is allowed at \( V_{oc} = \frac{1}{2} V_{cc} = 2.5 \text{ V}, \)
\[ \eta = \frac{\pi}{4} \frac{V_{oc}}{V_{cc}} \text{ (Eq. 12.15)} \]
\[ = \frac{\pi}{4} \times \frac{1}{2} = 0.393 \]
\[ P_{\text{dissipation/device}} = \frac{1}{2} \frac{1 - \eta}{\eta} P_{L} = 0.772 P_{L} \]
0.5 = 0.772 \( P_{L} \)
\[ \Rightarrow P_{L} = 0.647 \text{ W} \]
\[ = \frac{1}{2} \frac{2.5^2}{R_{L}} \]
\[ \Rightarrow R_{L} = 4.83 \Omega \text{ (i.e., } \geq 4.83 \Omega \text{)} \]

3. A particular transistor having a thermal resistance \( \theta_{ja}=0.5^\circ\text{C/W} \) is operating at an ambient temperature of 30°C with a collector-emitter voltage of 20V. If long life requires a maximum junction temperature of 130°C, what is the corresponding device power rating? What is the greatest average collector current that should be considered?

Power rating = \( \frac{130 - 30}{2} = 50 \text{ W} \)
\[ I_{ca} \leq \frac{50}{20} = 2.5 \text{ A} \]
4. A power transistor for which $T_{J_{\text{max}}}=180^\circ\text{C}$ can dissipate 50W at a case temperature of 50°C. If it is connected to a heat sink using an insulating washer for which the thermal resistance is $0.6^\circ\text{C}/\text{W}$, what heat-sink temperature is necessary to ensure safe operation at 30W? For an ambient temperature of 39°C, what heat-sink thermal resistance is required? If, for a particular extruded-aluminum-finned heat sink, the thermal resistance in still air is $4.5^\circ\text{C}/\text{W}$ per centimeter of length, how long a heat sink is needed?

\[
\theta_{JC} = \frac{T_J - T_C}{P_D} = \frac{180^\circ - 50^\circ}{50} = 2.6^\circ\text{C}/\text{W}
\]

\[
T_J - T_S = \theta_{JS} P_D
\]

\[
180^\circ - T_S = (\theta_{JC} + \theta_{CS}) P_D
\]

\[\Rightarrow T_S = 180 - (2.6 + 0.6) \times 30 = 84^\circ\]

\[
T_S - T_A = \theta_{SA} P_D
\]

\[84 - 39 = 0.5 \times 30 \]

\[\Rightarrow \theta_{SA} = 1.5^\circ\text{C}/\text{W}\]

**Required heat-sink length** = \[
\frac{4.5^\circ\text{C}/\text{W}/\text{cm}}{1.5^\circ\text{C}/\text{W}} = 3 \text{ cm}
\]

Use the following circuit for the rest of the problems.

5. The CMOS op amp shown above is fabricated in a process for which Let $V_{A(n\text{ type})}=12.5\text{V}$ and $V_{A(p\text{ type})}=10\text{V}$. Find $A1$, $A2$, and the overall gain if all devices are operated at equal overdrive voltages of 0.2V. Also, determine the op-amp output resistance obtained when the second stage is based at 0.4mA. What do you expect the output resistance of a unity-gain voltage amplifier to be, using this op amp?
Example #8

\[ A_0 = A_1 A_2 \]
\[ A_v = g_m (r_{e2} \parallel r_{o4}) g_m (r_{o3} \parallel r_{o7}) \]
\[ (r_{e2} \parallel r_{o3}) = \frac{V_A}{I} \times \frac{V_P}{I} \times \frac{I}{V_A + V_P} \]
\[ = \frac{12.5 \times 10}{0.4 \text{ mA}(12.5 + 10)} = 13.9 \text{ k}\Omega \]

To avoid systematic output dc offset, we assume:
\[ \left( \frac{W}{L} \right)_4 = 2 \times \left( \frac{W}{L} \right)_5^2, \quad Q_5, Q_6, Q_7 \text{ carry I} \]
while \( Q_4 \) carries \( I/2 \), therefore to satisfy the above requirement, \( Q_4 \) should have \( \left( \frac{W}{L} \right)_4^4 \). 

\[ g_m = \sqrt{2 \mu_C \omega \frac{W}{L} I} = 2 K V_{oV} \text{ thus:} \]
\[ g_m = 2 \frac{I}{V_{oV}} = 2 \times \frac{I/2}{V_{oV}} = 0.4 \text{ mA} \]
\[ = 2 \text{ mA/V} \]
\[ g_m = 2 \frac{J_0}{V_{oV}} = 2 \times \frac{I}{V_{oV}} = 2 \times 0.4 \text{ mA} \]
\[ = 4 \text{ mA/V} \]
\[ A_1 = 2 \times 13.9 \times 2 \]
\[ A_1 = 55.6 \]
\[ A_2 = 4 \times 13.9 \]
\[ A_2 = 55.6 \]

\[ A_v = 2 \times (13.9 \times 2) \times 4 \times 13.9 = 3091.36 \text{ V/V} \]

For Unity-gain amplifier:
\[ 1 - \frac{A_v}{1 + A \beta} \Rightarrow 1 + A \beta = A_v = 3091.36 \]
\[ R_{of} = \frac{R_O}{1 + A \beta} = \frac{13.9 \text{ k}\Omega}{3091.36} = 4.5 \Omega \]

6. The CMOS op amp shown above is fabricated in a process for which \( |V_a| = 12 \text{ V} \). If all transistors are operated at equal overdrive voltages, find the magnitude of the overdrive voltage required to obtain a dc open-loop gain of 6400 V/V.

\[ A = A_1 A_2 = g_m (r_{o2} \parallel r_{o4}) g_m (r_{o3} \parallel r_{o7}) \]
\[ = \frac{2I_1}{V_{oV}} \left( \frac{V_A}{2 T_1} \right) \frac{2I_2}{V_{oV}} \left( \frac{V_A}{2 T_2} \right) \]
7. A two-stage CMOS op amp as shown above is found to have a capacitance between the output node and ground of 0.5pF. If it is desired to have a unity-gain bandwidth $f_t$ of 150MHz with a phase margin of $75^\circ$ what must $g_{m6}$ be set to? Assume that a resistance $R$ is connected in series with the frequency compensation capacitor $C_C$ and adjusted to place the transmission zero at infinity. What value should $R$ have?

$$C_2 = 0.5\ \text{pF}, f_t = 150\ \text{MHz}, PM = 75^\circ$$

$$Q_{p2} = 90^\circ - 75^\circ = 15^\circ$$

$$Q_{p1} = \tan^{-1}\frac{f_t}{f_{p2}}$$

$$\therefore f_{p2} = \frac{f_t}{\tan 15^\circ} = \frac{150}{0.27} = 555.6\ \text{MHz}$$

$$f_{p2} = \frac{G_{m2}}{2\pi C_2}$$ and in order to place the transmission zero at infinity we have to select

$$R = \frac{1}{G_{m2}}$$

$$f_{p2} = \frac{1}{2\pi C_2 R}$$

$$R = \frac{1}{2\pi \times 0.5 \times 10^{-12} \times 555.6 \times 10^6}$$

$$= 573\ \Omega$$

8. A CMOS op amp as shown above but with a resistance $R$ included in series with $C_C$ is designed to provide $G_{m1}=1\text{mA/V}$ and $G_{m2}=2\text{mA/V}$.

(a) Find the value of $C_C$ that results in $f_t=100\text{MHz}$.

(b) For $R=500\Omega$ what is the maximum allowed value of $C_2$ for which a phase margin of at least $60^\circ$ is obtained?
Example #8

\[ G_{m1} = 1 \text{ mA/V}, G_{m2} = 2 \text{ mA/V}, \]
\[ R = 500 \ \Omega \]
\[ f_1 \approx \frac{G_{m1}}{2\pi C_c} \Rightarrow C_c = \frac{G_{m2}}{2\pi f_1} \]
\[ = \frac{1 \times 10^{-3}}{2\pi 100 \times 10^6} \Rightarrow 1.59 \text{ pF} \]

For \[ \frac{1}{G_{m2}} - R = \frac{10^3}{2} - 500 = 0 \]
Zero has been moved to \( \infty \)

For \( PM = 60 \): \[ f_1 = f_{P2} \tan(90 - 60)^\circ \]
\[ \Rightarrow f_{P2} = \frac{f_1}{\tan30^\circ} = 173 \ \text{MHz} \]
\[ C_2 = \frac{G_{m2}}{2\pi f_{P2}} = \frac{2 \times 10^{-3}}{2\pi (173 \times 10^6)} = 1.84 \ \text{pF} \]