1. \( V_T = \frac{kT}{q} \)

\[ V_T @ 40^\circ C = \frac{kT}{q} = \frac{1.38 \times 10^{-23} \times 233}{1.6 \times 10^{-19}} = 20.096 \text{ mV} \]

\[ V_T @ 85^\circ C = \frac{kT}{q} = \frac{1.38 \times 10^{-23} \times 358}{1.6 \times 10^{-19}} = 30.878 \text{ mV} \]

\( \Delta V_T = 30.878 \text{ mV} - 20.096 \text{ mV} = 10.782 \text{ mV} \)

2. a. \( I_o = I_s e^{\frac{V_{BE}}{V_T}} \)

\( I_{MA} = I_s e^{\frac{600 \text{ mV}}{25 \text{ mV}}} \)

\( I = I_s e^{\frac{620 \text{ mV}}{25 \text{ mV}}} = I_s e^{\left(\frac{600 \text{ mV}}{25 \text{ mV}} - \frac{20 \text{ mV}}{25 \text{ mV}}\right)} = I_s e^{\frac{600 \text{ mV}}{25 \text{ mV}} \cdot 2.4} \)

\( = I_{MA} \cdot e \approx 2.7 \times I_{MA} \)

b. \( I = I_s e^{\frac{V_{BE}}{V_T}} \)

\( I = I_s e^{\frac{600 \text{ mV}}{25 \text{ mV}}} = (I_s e^{\frac{600 \text{ mV}}{25 \text{ mV}}}) e^{\frac{60 \text{ mV}}{25 \text{ mV}}} \)

\( e^{\frac{60 \text{ mV}}{25 \text{ mV}}} \approx 10 \) (The law that 60 mV is one decade)

\( I = I_{MA} \cdot 10 = 10 I_{MA} \)

C. \( I_{MA} = I_s e^{\frac{600 \text{ mV}}{25 \text{ mV}}} \)

\( I_{MA} = I_s e^{\frac{V_{BE}}{25 \text{ mV}}} \)

\( I_{MA} = e^{\frac{600 \text{ mV} - V_{BE}}{25 \text{ mV}}} \)

\( 600 \text{ mV} - V_{BE} = 3.60 \text{ mV} = 180 \text{ mV} \)

\( \therefore V_{BE} = 420 \text{ mV} \)
Problem 2 continued

a) $V_T$ changes as per problem 1, but $I_T$ changes faster. Net change is $-2\text{mV}/\text{°C}$

$1 \mu A = 600 \text{mV}$ @ room temp; cooling it by

$65 ^\circ \text{C}$ means $\text{DUE} = (-2 \text{mV}/\text{°C})(-65 \text{°C}) = +130 \text{mV}$.

Resultant $V_d = 600 \text{mV} + 130 \text{mV} = 730 \text{mV}$.

b) $1 \mu A$ is each diode drop but so each diode drop is $V_d = 630 \text{mV}$. Total voltage will be $10V_d = 6V$.

c) Each diode sees $\frac{1}{10} \mu A$ - that’s an decade less current, so $\text{good less in Vd}$. Total $V_d$ is same for all diodes: $540 \text{mV}$.
Problem 3

(a) When $U_{CE} = 10V$ and $I_B = 60\mu A$
looks like $I_C = 10mA$.
So, $\beta = \frac{I_C}{I_B} = 170 \frac{A}{\mu A}$
$\gamma = \frac{I_C}{U_T} = \frac{10mA}{20mV} = 0.5A$.

$V_A$: looks like slope is $\Delta I_C = 10.7mA \to 9.2mA$
for $\Delta V_{CE} = 15V \to 5V$ so slope = $\frac{1mA}{100V} = 0.01mA/V$.
Extrapolating to $I_C = 0$, need to drop $10mA$ for $U_{CE} = 5V$

$\downarrow \frac{10mA}{100mA/V} = \Delta 1000 \rightarrow U_A = 950V$.

$\eta = \frac{U_A}{I_C} = \frac{950}{10mA} = 95k\Omega$.

Lo should maybe be $\frac{U_A + U_{CE}}{I_C}$ but $U_A \gg U_{CE}$, so
I'm neglecting $U_{CE}$.

(b) Just looking at the slope of the lines, and how
the pixel steps get shorter with more $I_B$,
looks like slope changes by $-10x$ so to will
also change $-10x$. This makes sense because
$I_C$ clearly varies $-1mA \to -13mA$, and
$\eta = \frac{U_A}{I_C}$ so $\eta$'s average can be calculated
that way, too.
Problem 3 continued

(c) The slopes look pretty constant over $U_{CE} = 1.0$ to $15.0$ for all plotted $I_B$ values, so $R_o$ probably doesn't change much.

(d) Looks like the various curves flatten out around $U_{CE} = 0.5.0$. So say $U_{CE, sat} = 0.5.0$. 
Problem 4: see attached plots for lines drawn to get these dot points.

(a) NMOS:  \[ \frac{V_{DS}}{I_D} = \frac{0.2V}{0.04mA/\mu m} = 5 \text{ k}\Omega/\mu m \]

\[ g_m = \frac{\Delta I_D}{\Delta V_{gs}} = \frac{0.2mA/\mu m}{0.1V} = 2 \text{ mA/\mu m} \]

\[ A_v = -\frac{2\text{mA}}{5.52 \text{ k\Omega}} = -10.8\% \]

PMOS: \[ r_{op} = \frac{0.2V}{0.05mA/\mu m} = 4 \text{ k}\Omega/\mu m \]

\[ g_m = \frac{0.27mA/\mu m}{0.1V} = 2.7 \text{ mS/\mu m} \]

\[ A_v, n = -\frac{4.52 \mu m}{2.7 \text{ mS/\mu m}} = -10.8\% \]

(b) Put a dot where it looks like the quadratic section ends and the linear section begins, like:

Eyeballing that dot:

NMOS: for \( V_{gs} = 0.5V \), \( V_{bss} = 0.22V \)

so \( V_{t, n} = 0.28V \)

PMOS: for \( |V_{gs}| = 0.5V \), \( V_{bss} = 0.25V \)

so \( V_{t, p} = 0.25V \)

(c) Annotate on figure. \( n_n = 1.3 \), \( n_p = 1.3 \rightarrow \text{VERY approximate.} \)
Figure 5: Transistor I-V Curves

Figure 6: Subthreshold Curves
5. (a) $I_D = \frac{1}{2} M \frac{C}{l} \cdot \frac{W}{L} \cdot (V_{GS} - V_T)^2 \cdot (1 + \lambda V_{DS})$

$V_{GS} = 0 \Rightarrow I_D = 0$

$V_{GS} = 1 \Rightarrow I_D = 0$

$V_{GS} = 2 \Rightarrow I_D = \frac{1}{2} \cdot 100 \cdot 100 \cdot (2 - 1)^2 \cdot (1 + \frac{1}{10} V_{DS})$

$= 5 \times 10^{-3} \cdot (1 + \frac{1}{10} V_{DS})$

$I_D^* = \frac{M \cdot C}{l} \cdot \frac{W}{L} \cdot ((V_{GS} - V_{TH}) V_{DS} - \frac{V_{DS}^2}{2})$

$= 100 \cdot 100 \cdot (V_{DS} - \frac{V_{DS}^2}{2})$

$= 0.01 \cdot (V_{DS} - \frac{V_{DS}^2}{2})$

$V_{GS} = 3, \ I_D = 2 \times 10^{-2} \cdot (1 + \frac{1}{10} V_{DS})$

(b) $V_{GS} = 0, -1 \Rightarrow I_D = 0$

$V_{GS} = -2 \Rightarrow I_D = 2 \times 10^{-2} \cdot 100 \cdot (-2 - (-1))^2 \cdot (1 + \frac{1}{10} V_{DS})$

$V_{GS} = -3 \Rightarrow I_D = \frac{1}{2} \cdot 100 \cdot 100 \cdot (-3 - (-1))^2 \cdot (1 + \frac{1}{10} V_{DS})$
6. a. \[ I_D = \frac{1}{2} M_n C_{ox} \left( \frac{W}{L} \right) \cdot (V_{gs} - V_{th})^2 \]

\[ S_m = \frac{M_n C_{ox}}{2} \left( \frac{W}{L} \right) (V_{gs} - V_{th})^3 \]

\[ \text{Graph:} \quad I_D \text{ vs. } \frac{W}{L} \]

\[ \text{Graph:} \quad S_m \text{ vs. } \frac{W}{L} \]

b. \[ I_D = \frac{1}{4} M_n C_{ox} \left( \frac{W}{L} \right) (V_{gs} - V_{th})^2 \]

\[ S_m = \frac{M_n C_{ox}}{4} \left( \frac{W}{L} \right) (V_{gs} - V_{th}) \]

\[ \text{Graph:} \quad I_D \text{ vs. } V_{gs} \]

\[ \text{Graph:} \quad S_m \text{ vs. } V_{gs} \]

c. \[ V_{ov} = \sqrt{\frac{2 I_D}{\frac{1}{2} M_n C_{ox} \left( \frac{W}{L} \right)}} \]

\[ S_m = \frac{M_n C_{ox}}{2} \left( \frac{W}{L} \right) V_{ov} \]

\[ V_{ov} = \sqrt{\frac{2 I_D}{\frac{1}{2} M_n C_{ox} \left( \frac{W}{L} \right)}} \]

\[ \text{Graph:} \quad V_{ov} \text{ vs. } I_D \]

\[ \text{Graph:} \quad S_m \text{ vs. } I_D \]

d. \[ I_D = \frac{1}{2} M_n C_{ox} \left( \frac{W}{L} \right) (V_{gs} - V_{th})^2 \]

\[ \frac{W}{L} = \frac{2 I_D}{M_n C_{ox} (V_{gs} - V_{th})^2} \]

\[ S_m = \frac{2 I_D}{V_{gs} - V_{th}} \]

\[ \text{Graph:} \quad \frac{W}{L} \text{ vs. } I_D \]

\[ \text{Graph:} \quad S_m \text{ vs. } I_D \]
HW2 rubric

1) 2pts
2) 12 pts

3a) 10 pts
3b) 2pts
3c) 2pts
3d) 2pts

4a) 6 pts
We should point out that the vertical axis is mislabeled (should be mA/um, not A/um) but that it's fine you didn't realize that. So $r_o = 5\text{kOhm*um}$ (not $5\text{ Ohm*um}$) and $g_m = 2\text{mS/um}$ (not $2\text{S/um}$)
4b) 6pts total; 1 pt each of $V_t$, $V_{tp}$; 1 pt each for quadratic vs. velocity, and 1pt each for a reason
4c) 4 pts

5a) 6 pts: 1 each for $V_{gs}=0,1$; 2 each for $V_{GS}=2,3$: 1 pt for roughly the right shape, 1 pt for getting the triode/saturation transition point in the right spot.
5b) 6 pts, as above
* This should actually be negative drain current so it fits the hint in the homework set, "exactly the same plot just rotated 180 degrees".

6) 8 pts total, 2 pts each