4.1. Under the scaling transformation, $W \to W/\kappa$, $L \to L/\kappa$, $t_{ox} \to t_{ox}/\kappa$, $V_{ds} \to V_{ds}/\kappa$, $V_g \to V_g/\kappa$, and $V_t \to V_t/\kappa$, Eq. (3.19) becomes

$$I_{ds} \to \mu_{eff}(\kappa C_{ox})\frac{W/\kappa}{L/\kappa}\left(\frac{V_g}{\kappa}-\frac{V_t}{\kappa}\right)\frac{V_{ds}}{\kappa}=\frac{I_{ds}}{\kappa};$$

and Eq. (3.23) becomes

$$I_{ds} \to \mu_{eff}(\kappa C_{ox})\frac{W/\kappa}{L/\kappa}\frac{1}{2m}\left(\frac{V_g}{\kappa}-\frac{V_t}{\kappa}\right)^2=\frac{I_{ds}}{\kappa}.$$

Note that both $m = 1 + 3t_{ox}/W_{dm}$ and μ_{eff} which is a function of $\mathscr{E}_{eff}$ given by Eq. (3.49) are nearly invariant under constant field scaling.

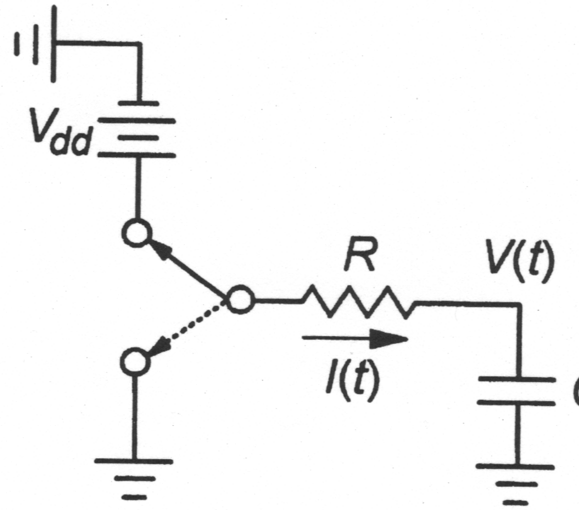
4.2. Under the same scaling rules as above, Eq. (3.36) becomes

$$I_{ds} \to \mu_{eff}(\kappa C_{ox})\frac{W/\kappa}{L/\kappa}(m-1)\left(\frac{kT}{q}\right)^2 e^{q(V_g-V_t)/\kappa mkT}.$$

The $\exp(-qV_{ds}/kT)$ term has been neglected since typically $V_{ds} >> kT/q$. In subthreshold, $V_g < V_t$ and $\exp[q(V_g - V_t)/\kappa mkT] > \exp[q(V_g - V_t)/mkT]$ (note that $\kappa > 1$), therefore, the subthreshold current increases with scaling faster than κI_{ds}.

If the temperature also scales down by the same factor, i.e., $T \to T/\kappa$, then $I_{ds} \to I_{ds}/\kappa$, same as the drift current in Exercise 4.1.

5.2. For the following *RC* circuit,



if the voltage source is switched to V_{dd} at $t = 0$, then

$$V_{dd} = V(t) + RI(t) = V(t) + RC\frac{dV}{dt}.$$

With the initial condition $V(t = 0) = 0$, the solution for $V(t)$ is

$$V(t) = V\ (1 - e^{-t/RC})$$

The energy dissipated in R is

$$E = \int_0^\infty RI^2 dt = \frac{V_{dd}^{\ 2}}{R}\int_0^\infty e^{-2t/RC} dt = \frac{1}{2}CV_{dd}^{\ 2},$$

which is independent of R. The same amount of energy is stored in C.

If the voltage source is now switched to 0, one has

$$V(t) + RC\frac{dV}{dt} = 0.$$

With the initial condition $V(t = 0) = V_{dd}$, the solution for $V(t)$ is

$$V(t) = V_{dd}e^{-t/RC}.$$

The energy stored in C is now all dissipated in R:

$$E = \int_0^\infty RI^2 dt = \frac{V_{dd}^{\ 2}}{R}\int_0^\infty e^{-2t/RC} dt = \frac{1}{2}CV_{dd}^{\ 2}.$$

5.3. From Eq. (3.21) and the inversion charge expression above Eq. (3.54), the transit time is

$$\tau_{tr} = \frac{WLC_{ox}(V_g - V_t - mV_{ds}/2)}{\mu_{eff}C_{ox}(W/L)(V_g - V_t - mV_{ds}/2)V_{ds}} = \frac{L^2}{\mu_{eff}V_{ds}}$$

for a MOSFET device biased in the linear region.

From Eq. (3.23) and the inversion charge expression above Eq. (3.56), the transit time is

$$\tau_{tr} = \frac{(2/3)WLC_{ox}(V_g - V_t)}{\mu_{eff}C_{ox}(W/L)(V_g - V_t)^2/2m} = \frac{4mL^2}{3\mu_{eff}(V_g - V_t)}$$

for a long-channel MOSFET biased in saturation.

5.4. From Eq. (3.78) and the inversion charge expression in Problem 3.10, the transit time is

$$\tau_{tr} \equiv \frac{Q_i}{I_{dsat}} = \frac{L}{v_{sat}} \frac{\sqrt{1 + 2\mu_{eff}(V_g - V_t)/(mv_{sat}L)} + 1/3}{\sqrt{1 + 2\mu_{eff}(V_g - V_t)/(mv_{sat}L)} - 1}$$

for a short-channel MOSFET biased in saturation. The limiting value of τ_{tr} is L/v_{sat} when the device becomes fully velocity saturated as $L \rightarrow 0$.