In the two circuits shown below, V_B and R_B are adjusted such that $I_{o1} = I_{o2} = I_o = 1\,\text{mA}$ at 300 K for the following nominal parameters: $V_{CC} = 5\,\text{V}$, $R_{L1} = R_{L2} = R_L = 1\,\text{k}\Omega$, and $I_s = 10\,\text{fA}$, $\beta \to \infty$, $V_A \to \infty$ for all transistors.

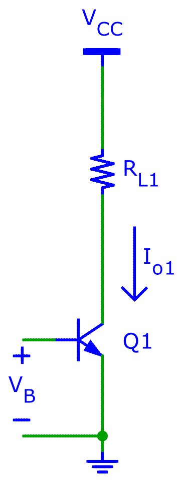
Now the temperature, supply voltage, load resistance and transistor parameters change as specified in the table below. Assuming V_B and R_B are kept constant, calculate the relative change of the currents I_{o1} and I_{o2} from their nominal value, $I_o = 1\,\text{mA}$. No entry in the table means "no change".

	T	V_{CC}	R_L	I_s at 300K	β	V_A	$\frac{I_{o1}}{I_o} - 1$ [%]	$\frac{I_{o2}}{I_o} - 1$ [%]
a)							0 %	0 %
b)			2 kΩ				0 %	0 %
c)		6 V					0 %	23 %
d)	240 K						big decrease	little change!
e)	360 K						big increase*	little change!
f)				20 fA			100 %	0 %
g)					50		0 %	-4 %
h)						50 V	6.6 %	6.6 %

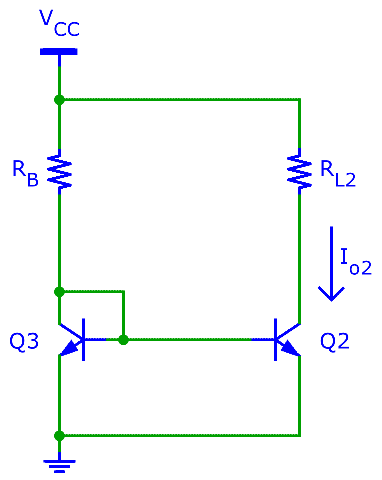
For each case, give a brief explanation what's going on and how this is relevant for circuit design.

This circuit (especially the one on the right) is a core building block used in many more complicated circuits (operational amplifier, A/D converters, etc.). You will use it frequently in your designs and recognizing it will help you understand circuit operations without resorting to long calculations.

Note: specify answers to 5 % accuracy except cases d) and e) where its sufficient to specify the direction and order-of-magnitude of the change. Keeping this in mind lets you avoid lots of senseless nonlinear equation solving.



(a)



(b)

Comments:

b) No change. Q1 and Q2 act as (ideal, since $V_A \to \infty$) current sources: I_C is independent of V_{CE}, as long as the transistor is in the forward active region.
Check: $V_{CE} = V_{cc} - 2\,\text{k}\Omega \times 1\,\text{mA} = 3\,\text{V} \gg V_{ce(sat)} \approx 200\,\text{mV}$.

c) No change for circuit (a), same reason as case b).
In circuit (b) the current through R_B increases by $\frac{6\,\text{V} - V_{BE(on)}}{5\,\text{V} - V_{BE(on)}} \approx 23\,\%$. This change is "mirrored" to Q2 since both have the same V_{BE}.

d) In circuit (a), the lower tempature changes both I_s and V_t. The change of I_s dominates and causes the current to decrease significanty. The accurate value can be calculated from the full equation for I_s and modeling the temperature dependencies of all its parameters. Using a circuit simulator (SPICE) is a simpler alternative.
In circuit (b) the current through R_B changes only slightly since $V_{BE3(on)}$ increases by approximately $120\,\mathrm{mV}$ ($dV_{BE(on)}/dT \approx -2\,\mathrm{mV/K}$ for constant I_C). Since that current is mirrored to Q2, I_{o2} remains almost constant. This is a significant advantage over circuit (a).

e) Same arguments as in case d), except that now I_{o1} increases substantially. For $\Delta T = 60\,\mathrm{K}$ the increase is sufficient to bring Q1 into saturation, and then the current actually decreases, hinted in the solution by the * qualifier.

f) In this case, we design for $I_s = 10\,\mathrm{fA}$, but then use a transistor with $I_s = 20\,\mathrm{fA}$. The value of I_s is not well controlled—datasheets specify a range of values. Typical variations are $\pm 20\,\%$, the example here with $+100\,\%$ is a bit excessive.
In circuit (a) the current is proportional to I_s and therefore doubles. In circuit (b) the change is minimal since the current is set by R_B. Since V_{BE3} drops slightly (bigger transistor), we see a small increase of the voltage across R_B and corresponding increase in current, but the change is negligible.

g) For circuit (a) we see absolutely no change since the base current is delivered from the source V_B.
In circuit (b), the current through R_B is $4\,\%$ larger than I_{C2} since it includes the base currents of Q2 and Q3, each $2\,\%$ of the collector currents. Why do we get -4 %? The current through R_B does not change (the voltage across it remains the same) but I_{C2} is now $4\,\%$ less.

h) If we designed the circuit for $V_A \to \infty$ but then built it in the lab with real transistors with $V_A = 50\,\mathrm{V}$ we would see a small current increase due to the $1 + V_{CE}/V_A$ factor in the equation for I_C. For $V_{CE} \approx V_{cc} - 1\,\mathrm{V} - 0.7\,\mathrm{V}$ the increase is 6.6 %.

Both circuits implement current sources. Circuit (b) with “replica biasing” (transistor Q3 replicates the current source Q2 and is used to set the value of V_{BE2}) is preferable since it is much less sensitive to variations, especially of temperature.
Often emitter degeneration (placing a resistor in series with the emitters of Q2 and Q3) is also used to further use sensitivity. We will study emitter degeneration extensively.