The op-amp is ideal, with $V_{CC} = 10\,\text{V}$ and $V_{EE} = -10\,\text{V}$. The diode forward voltage, $V_D = 0.7\,\text{V}$.

- What is the frequency of oscillation.
- Sketch $V_o$ when the oscillation amplitude has stabilized.
- Indicate the approximate voltage of oscillation on the sketch.

This is a Wien bridge sine-wave oscillator. It oscillates because $G = 1 + \frac{91\,\text{k}\Omega}{19\,\text{k}\Omega} = 5.79 > 3$.

- What is the frequency of oscillation.
  
  $\omega = (RC)^{-1} = (39\,\text{k}\Omega \times 37\,\text{nF})^{-1} = 693.0\,\text{rad/s}$
  
  $f = \frac{1}{2\pi}\omega = 110.3\,\text{Hz}$

- Sketch $V_o$ when the oscillation amplitude has stabilized.
  
  The oscillation will be roughly sine shaped at $f = 110.3\,\text{Hz}$

- Indicate the approximate voltage of oscillation on the sketch.
  
  amplitude stabilized at $\pm 0.7\,\text{V}$.
The op-amp is ideal, with $V_{CC} = 2\, \text{V}$ and $V_{EE} = -2\, \text{V}$.

$$\begin{array}{c}
60\, \text{k}\Omega \\
\downarrow
\end{array} \quad \begin{array}{c}
30\, \text{k}\Omega \\
\uparrow
\end{array} \quad \begin{array}{c}
+ \\
\uparrow
\end{array} \quad \begin{array}{c}
- \\
\downarrow
\end{array} \quad 39\, \text{nF} \quad \begin{array}{c}
37\, \text{k}\Omega \\
\uparrow
\end{array} \quad V_o
\end{array}$$

Initial conditions are: $V_- = 0$ and $V_o = +V_{CC}$.

Sketch as a function of time: 1) $V_-$, 2) $V_+$, 3) $V_o$

- $V_o$ will switch between $\pm 2\, \text{V}$
- $V_+$ will switch between $\pm 2\, \text{V}$
  \[\frac{60\, \text{k}\Omega}{60\, \text{k}\Omega + 30\, \text{k}\Omega} = 1.33\, \text{V}\]
- $V_+$ will exponentially rise between $\pm 1.33\, \text{V}$.

Timing will be symmetric between +ve and -ve pulses.

\[(V_f - V_\infty) = (V_i - V_\infty)e^{-t/\tau},\]

where $\tau = RC = 37\, \text{k}\Omega \times 39\, \text{nF} = 1.443\, \text{ms}$

For the -ve transition, $V_i = 1.33\, \text{V}$, $V_f = -1.33\, \text{V}$, an $V_\infty = -2\, \text{V}$.

\[t = \tau \ln \left( \frac{V_f - V_\infty}{V_i - V_\infty} \right) = (1.443\, \text{ms}) \ln \left( \frac{1.33 - (-2)}{-1.33 - (-2)} \right) = 2.31\, \text{ms}\]
Initial conditions are that the charge on the capacitor is zero. $V_{CC} = 9 \text{ V}$.

- Sketch $V_o$, $V_A$ and $V_B$.
- What is the length of the $V_o = \text{high}$ and $V_o = \text{low}$ outputs?

This configuration is similar, but not the same as the configuration discussed in class. Normally $V_+$ of the upper comparator is connected to $V_B$. This means that the upper transitions will not happen at $V_B = \frac{2}{3}V_{CC}$, but instead when $V_A = \frac{2}{3}V_{CC}$. At this time, we calculate

$$i = \left( V_{CC} - \frac{2}{3}V_{CC} \right) / 59 \text{ k}\Omega = \left( 9 \text{ V} - 6 \text{ V} \right) / 59 \text{ k}\Omega = 3 \text{ V} / 59 \text{ k}\Omega = 50.85 \mu\text{A}.$$  

Using $i$, we calculate $V_B = V_A - i(11 \text{ k}\Omega) = 5.44 \text{ V}$.

Another way to see this is to think about Capacitor $C$ charging until $V_A = 2/3V_{CC}$ (RESET) and discharging until $V_B = 1/3V_{CC}$ (SET). In the usual 555 astable configuration, the trigger and threshold pins (pins 2 and 6) are both connected to the top of $C$, so $V_A = V_B$, however in the above circuit $V_A$ and $V_B$ are related by

$$V_A = V_B + (V_{CC} - V_B) \frac{R_B}{R_A + R_B}$$

(voltage divider). Setting $V_A = 2/3V_{CC}$ and rearranging, RESET occurs when $V_B$ reaches voltage $V_R$ given by

$$V_R = \left( \frac{2}{3} - \frac{11 \text{ k}\Omega}{59 \text{ k}\Omega + 11 \text{ k}\Omega} \right) \frac{59 \text{ k}\Omega + 11 \text{ k}\Omega}{59 \text{ k}\Omega} V_{CC}$$

$$V_R = \left( \frac{2}{3} - \frac{11 \text{ k}\Omega}{59 \text{ k}\Omega + 11 \text{ k}\Omega} \right) \frac{59 \text{ k}\Omega + 11 \text{ k}\Omega}{59 \text{ k}\Omega} 9 \text{ V} = 5.44 \text{ V}$$

The durations of the charge and discharge half-cycles are then given by the usual formula

$$t = RC \ln \left( \frac{V_\infty - V_i}{V_\infty - V_f} \right) = (0.52)RC$$
with $V_i = \frac{V_{CC}}{3}$, $V_f = V_R$, $V_\infty = V_{CC}$ and $R = R_A + R_B$ for the charge half-cycle and $V_i = V_R$, $V_f = \frac{V_{CC}}{3}$, $V_\infty = 0$ and $R = R_B$ for the discharge half-cycle. $V_o = V_{CC}$ during the charge period and $V_o = 0$ V during the discharge period. Thus:

- $t_{\text{high}} = 0.52 \times 55 \mu F \times (59 k\Omega + 11 k\Omega) = 2.00 ms$
- $t_{\text{low}} = 0.52 \times 55 \mu F \times (11 k\Omega) = 0.31 ms$

The shape of $V_B$ is essentially the same as that of the regular 555 astable configuration, rising and falling exponentially between the two limits - except that the upper limit is $V_R$ instead of $\frac{2}{3}V_{CC}$. Meanwhile $V_A$ rises exponentially from somewhat above $\frac{1}{3}V_{CC}$ to $\frac{2}{3}V_{CC}$, and then drops immediately to zero for the duration of the discharge half-cycle since it is connected directly to the discharge pin (pin 7).