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.
  \[
  \omega = (RC)^{-1} = (30\, \text{k}\Omega \times 24\, \text{nF})^{-1} = 1388.9\, \text{rad/s}
  \]
  \[
  f = \frac{1}{2\pi}\omega = 221.1\, \text{Hz}
  \]
- Sketch $V_o$ when the oscillation amplitude has stabilized.
  The oscillation will be roughly sine shaped at $f = 221.1\, \text{Hz}$
- Indicate the approximate voltage of oscillation on the sketch.
  amplitude stabilized at $\pm 0.7\, \text{V}$. 

\[
\begin{array}{c}
\text{24 nF} \\
\text{30 k}\Omega \\
\text{24 nF} \\
\text{30 k}\Omega \\
\end{array}
\begin{array}{c}
19\, \text{k}\Omega \\
\text{91 k}\Omega \\
\end{array}
\begin{array}{c}
\end{array}
\begin{array}{c}
\text{Vo} \\
\end{array}
\end{array}
\]
The op-amp is ideal, with $V_{CC} = 2$ V and $V_{EE} = -2$ V.

![Circuit Diagram]

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 $\pm 2$ V
- $V_+$ will switch between $\pm 2$ V $\frac{69 \text{k} \Omega}{69 \text{k} \Omega + 23 \text{k} \Omega} = 1.50$ V
- $V_+$ will exponentially rise between $\pm 1.50$ V.

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

$$(V_f - V_\infty) = (V_i - V_\infty) e^{-t/\tau},$$
where $\tau = RC = 24 \text{k} \Omega \times 30 \text{nF} = 0.720 \text{ ms}$

For the -ve transition, $V_i = 1.50$ V, $V_f = -1.50$ V, an $V_\infty = -2$ V.

$$t = \tau \ln \left( \frac{V_f - V_\infty}{V_i - V_\infty} \right) = (0.720 \text{ ms}) \ln \left( \frac{1.50 - (-2)}{-1.50 - (-2)} \right) = 1.40 \text{ ms}$$
Initial conditions are that the charge on the capacitor is zero. $V_{CC} = 9\, V$.

- 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 $V_B = \frac{2}{3}V_C C$, but instead when $V_A = \frac{2}{3}V_C C$. At this time, we calculate

$$i = \frac{(V_{CC} - \frac{2}{3}V_{CC})}{45\, k\Omega} = \frac{9\, V - 6\, V}{45\, k\Omega} = \frac{3\, V}{45\, k\Omega} = 66.67\, \mu A.$$  

Using $i$, we calculate $V_B = V_A - i(11\, k\Omega) = 5.27\, V$.

Another way to see this is to think about Capacitor $C$ charging until $V_A = \frac{2}{3}V_{CC}$ (RESET) and discharging until $V_B = \frac{1}{3}V_{CC}$ (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 $V_A = \frac{2}{3}V_{CC}$ and rearranging, RESET occurs when $V_B$ reaches voltage $V_R$ given by

$$V_R = \left(\frac{2}{3} - \frac{R_B}{R_A + R_B}\right)\left(\frac{R_A + R_B}{R_A}\right)V_{CC}$$

$$V_R = \left(\frac{2}{3} - \frac{11\, k\Omega}{45\, k\Omega + 11\, k\Omega}\right)\left(\frac{45\, k\Omega + 11\, k\Omega}{45\, k\Omega}\right)9\, V = 5.27\, V$$

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

$$t = RC\ln\left(\frac{V_{\infty} - V_i}{V_{\infty} - V_f}\right) = (0.48)RC$$
with $V_i = V_{CC}/3$, $V_f = V_R$, $V_{\infty} = V_{CC}$ and $R = R_A + R_B$ for the charge half-cycle and $V_i = V_R$, $V_f = V_{CC}/3$, $V_{\infty} = 0$ 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:

- $t_{\text{high}} = 0.48 \times 55 \mu F \times (45 \, k\Omega + 11 \, k\Omega) = 1.48 \text{ ms}$
- $t_{\text{low}} = 0.48 \times 55 \mu F \times (11 \, k\Omega) = 0.29 \text{ ms}$

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 $2/3V_{CC}$. Meanwhile $V_A$ rises exponentially from somewhat above $1/3V_{CC}$ to $2/3V_{CC}$, 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).