• Sketch $V_o$.

• At what times does $V_o$ reach $\pm 10 \text{ V}$?

• Does this circuit suffer from multiple transitions?

(Notes: voltage axis not to scale. The slope of the voltage may be approximated as $5 \text{ V/100 ms}$. Op amps are ideal)

This is a non-inverting amplifier with a gain of $G = 1 + \frac{469}{1.15} = 408.8$. With such a large gain, it will saturate when $V_i = \pm 10 \text{ V}/G = \pm 0.024 \text{ V}$.

Times when $|V_i| < 0.024$, V, are

$T_1 = \pm \frac{0.1-0.024}{5\text{ V/100 ms}} = \pm 1.520 \text{ ms}$.

$T_2 = \pm \frac{0.1+0.024}{5\text{ V/100 ms}} = \pm 2.480 \text{ ms}$.

• Sketch $V_o$.

1) From start to $-2.480 \text{ ms}$, $V_o = -10 \text{ V}$

2) From $-2.480 \text{ ms}$ to $-1.520 \text{ ms}$, $V_o =$ transitions from $-10 \text{ V}$ to $+10 \text{ V}$

3) From $-1.520 \text{ ms}$ to $0 \text{ ms}$, $V_o = +10 \text{ V}$

4) From $0 \text{ ms}$ to $+1.520 \text{ ms}$, $V_o = -10 \text{ V}$

5) From $+1.520 \text{ ms}$ to $+2.480 \text{ ms}$, $V_o =$ transitions from $-10 \text{ V}$ to $+10 \text{ V}$

6) From $+2.480 \text{ ms}$ to end, $V_o = +10 \text{ V}$

• At what times does $V_o$ reach $\pm 10 \text{ V}$?

1) From start to $-2.480 \text{ ms}$, $V_o = -10 \text{ V}$

3) From $-1.520 \text{ ms}$ to $0 \text{ ms}$, $V_o = +10 \text{ V}$

4) From $0 \text{ ms}$ to $+1.520 \text{ ms}$, $V_o = -10 \text{ V}$

6) From $+2.480 \text{ ms}$ to end, $V_o = +10 \text{ V}$

• Does this circuit suffer from multiple transitions?

[Yes]
• Sketch $V_o$.

• At what times does $V_o$ reach $\pm 10$ V?

• Does this circuit suffer from multiple transitions?

(Notes: voltage axis not to scale. The slope of the voltage may be approximated as 5 V/100 ms. Op amps are ideal)

Thresholds at $\pm \frac{1.56 \text{kΩ}}{369+1.56 \text{kΩ}} \times 10 \text{V} = \pm 0.042 \text{V}$.

Conditions:
1) If $V_i < V_+ \implies V_o = +10 \text{V}$ and $V_+ = +0.042 \text{V}$.
2) If $V_i > V_+ \implies V_o = -10 \text{V}$ and $V_+ = -0.042 \text{V}$.

• Sketch $V_o$.
  1) Initially, $V_o = +10$ and $V_+ = +0.042 \text{V}$
  2) when $V_i$ crosses $+0.042 \text{V}$, then $V_o = -10$ and $V_+ = -0.042 \text{V}$
  3) when $V_i$ crosses $-0.042 \text{V}$, then $V_o = +10$ and $V_+ = +0.042 \text{V}$
  4) when $V_i$ crosses $+0.042 \text{V}$, then $V_o = -10$ and $V_+ = -0.042 \text{V}$

• At what times does $V_o$ reach $\pm 10$ V?
  Transitions at $\pm \frac{0.1-0.042}{5 \text{V}/100 \text{ms}} = \pm 1.16 \text{ms}$.
  1) Beginning until $-1.16 \text{ms} \implies V_o = +10 \text{V}$.
  2) $-1.16 \text{ms}$ until $0 \text{ms} \implies V_o = -10 \text{V}$.
  3) $0 \text{ms}$ until $+2.84 \text{ms} \implies V_o = +10 \text{V}$.
  4) $+2.84 \text{ms}$ until end $\implies V_o = -10 \text{V}$.

• Does this circuit suffer from multiple transitions?
  Yes
This is a low pass filter with a gain of $G = -\frac{401\,\text{k}\Omega}{12.0\,\text{k}\Omega} = -33.42$.
With such a large gain, it will saturate when $V_i = \pm 10\,\text{V}/G = \pm 0.299\,\text{V}$.
The time constant is $\tau = 401\,\text{k}\Omega \times 346\,\text{nF} = 138.7\,\text{ms}$.

- At what times does $V_o$ reach $\pm 10\,\text{V}$?
  Transitions at $\pm \frac{0.1+0.299}{5\,\text{V}/100\,\text{ms}} = \pm 8.0\,\text{ms}$.
  Thus: 1) Beginning until $-8.0\,\text{ms} \implies V_o = +10\,\text{V}$.
    2) $+8.0\,\text{ms}$ until end $\implies V_o = -10\,\text{V}$.

- Sketch $V_o$ (this is difficult because of the exponential – indicate the main features of the curve)
  Begin until $-8.0\,\text{ms} \implies V_o = +10\,\text{V}$. Then, from $+8.0\,\text{ms}$ until $-8.0\,\text{ms}$ the will go from $+10\,\text{V}$ to $-10\,\text{V}$, following the flipped the blue line (with gain) but with a slight delay. However, it will only deviate slightly at the zigzag. The time constant $\tau$ is longer than the gap in the zigzag. Finally, from $+8.0\,\text{ms}$ until end $\implies V_o = -10\,\text{V}$.

- Does this circuit suffer from multiple transitions?
  [No]

*Explanation:* In the above case, the response is linear throughout the +/-0.1V transition of the input signal. The addition of the capacitor turns the circuit into a “lossy integrator”. Its step response would be an exponential with time constant $RC = 138.7\,\text{ms}$. We don’t have exactly a step at the input; however, if the input transitions are short compared to the time constant we can approximate the output as an exponential (perhaps with a “bump” $V_i$ briefly changes sign). Assuming the input transitions are short compared to $RC$, then $V_o$ will NOT suffer from multiple transitions.