1. KVL/KCL Review

Use Kirchhoff’s Laws on the circuit below to find $V_x$ in terms of $V_{in}, R_1, R_2, R_3$.

(a) Recall Node Voltage Analysis (NVA). Determine $V_x$ by labeling the circuit and writing equations to solve a system of equations in node voltages.

**Solution:**

![Diagram](attachment:image.png)

Applying KCL to the node at $V_x$, we get

$$\frac{V_{in} - V_x}{R_1} - \frac{V_x - 0}{R_2} - \frac{V_x - 0}{R_3} = 0 \quad (1)$$

Solving this equation for $V_x$ yields

$$V_x = V_{in} \frac{R_2 R_3}{R_1 R_2 + R_1 R_3 + R_2 R_3} \quad (2)$$

(b) In EECS16A, you learned you can simplify analysis by replacing series or parallel resistors with equivalents and memorizing common circuit design blocks. Replace two of the resistors in the
circuit with an equivalent resistor and then redraw the circuit. Then, use recognition of a design block to find an expression for $V_x$.

**Solution:** Observe that $R_2$ and $R_3$ are in parallel. We can replace them with a single resistor of value $R_{eq} = \frac{R_2 R_3}{R_2 + R_3}$ in between the ground and the node with node voltage $V_x$.

![Figure 3](image-url)

This circuit is a voltage divider. We can determine $V_{eq}$ as a function of the resistances and the source, then relate $V_x$ to $V_{eq}$.

\[
V_{eq} = \frac{R_{eq}}{R_1 + R_{eq}} V_{in} \quad (3)
\]

\[
V_{eq} = V_x - 0 \quad (4)
\]

\[
V_x = \frac{R_2 R_3}{R_1 + R_2 + R_3} V_{in} \quad (5)
\]

\[
V_x = \frac{R_2 R_3}{R_1 R_2 + R_1 R_3 + R_2 R_3} V_{in} \quad (6)
\]

(c) As a check, as $R_3 \to \infty$, what is $V_x$ for what you found in (a) and (b)? The $V_x$’s of each part should approach the same value. What is the name we used for this type of circuit?

**Solution:** The expressions we show above for (a) and (b) are identical. However, if they do not appear identical without simplification, the limit can be a way to verify that both solution methods inform us of the correct circuit behavior and are consistent with each other. As $R_3 \to \infty$, the $R_1 R_2$ term on the denominator will become insignificant, simplifying our expression.

\[
\lim_{R_3 \to \infty} V_x = \lim_{R_3 \to \infty} V_{in} \frac{R_2 R_3}{R_1 R_2 + R_1 R_3 + R_2 R_3} = \lim_{R_3 \to \infty} V_{in} \frac{R_2}{R_1 R_2 + R_1 + R_2} = V_{in} \frac{R_2}{R_1 + R_2}
\]

When $R_3 \to \infty$, it effectively becomes an open circuit, which makes the rest of the circuit a resistive voltage divider.
2. Current Sources And Capacitors

(Adapted from EECS16A Fall 20 Disc 9A.)

(HINT: Use the I-V relationship for a capacitor (which may involve derivatives). If you do not remember it, you can find it by using the capacitor equation $Q = CV$ and $I = \frac{dQ}{dt}$.)

(HINT: It may also help to note metric prefix examples: $3 \mu F = 3 \times 10^{-6} F$.)

Given the circuit in fig. 4, find an expression for $v_{out}(t)$ in terms of $I_S$, $C$, $V_0$, and $t$, where $V_0$ is the initial capacitor voltage at $t = 0$.

\[ I_S \]

\[ C \]

\[ v_{out} \]

\[ - \]

Figure 4: A current source attached to a capacitor.

Then plot the function $v_{out}(t)$ over time on the graph below for each set of conditions, detailed below.

Use the values $I_S = 1 \text{ mA}$ and $C = 2 \mu F$.

1. Capacitor is initially uncharged $V_0 = 0$ at $t = 0$.
2. Capacitor has been charged with $V_0 = 1.5 \text{ V}$ at $t = 0$.
3. (PRACTICE) Swap this capacitor for one with half the capacitance $C = 1 \mu F$, which is initially uncharged $V_0 = 0$ at $t = 0$.

(HINT: Recall the calculus identity $\int_a^b f'(x) \, dx = f(b) - f(a)$, where $f'(x) = \frac{df}{dx}$.)
**Solution:** The key here is to exploit the capacitor equation by taking its time-derivative.

\[ Q = C v_{\text{out}} \quad \rightarrow \quad \frac{dQ}{dt} = I_C = I_s = C \frac{dv_{\text{out}}}{dt}. \tag{7} \]

From here we can rearrange and show that:

\[ \frac{dv_{\text{out}}}{dt} = \frac{I_s}{C}, \tag{8} \]

Thus the voltage has a constant slope!

Our solution is

\[ v_{\text{out}}(t) = V_0 + \left( \frac{I_s}{C} \right) t \tag{9} \]

Formally, we are solving a differential equation that happens to return a linear function for \( v_{\text{out}}(t) \):

\[ \frac{dv_{\text{out}}}{dt} = \frac{I_s}{C} \tag{10} \]

\[ \int_0^t \frac{dv_{\text{out}}}{dt} \, dt = v_{\text{out}}(t) - v_{\text{out}}(0) \tag{11} \]

\[ \int_0^t \frac{I_s}{C} \, dt = \frac{I_s}{C} \int_0^t 1 \, dt = \frac{I_s}{C} t \tag{12} \]

Thus we arrive at the same statement as seen earlier: \( v_{\text{out}}(t) = v_{\text{out}}(0) + \left( \frac{I_s}{C} \right) t \).

From this stage we can compute the slope of \( v_{\text{out}}(t) \) in each scenario.

\[ \frac{I_s}{C} = \frac{1 \text{ mA}}{2 \mu\text{F}} = \frac{1000 \mu\text{C}}{2 \mu\text{V}} = 500 \frac{\text{V}}{\text{s}} = 0.5 \frac{\text{V}}{\text{ms}} \tag{13} \]

For part (c):

\[ \frac{I_s}{C} = \frac{1 \text{ mA}}{1 \mu\text{F}} = \frac{1000 \mu\text{C}}{1 \mu\text{V}} = 1000 \frac{\text{V}}{\text{s}} = 1 \frac{\text{V}}{\text{ms}} \tag{14} \]

When plotting, make sure to recall (a) and (c) start at the origin, while (b) has initially charged plates by \( V_0 = 1.5\text{V} \). Results are shown below:
3. Linear Algebra Review

For the following matrices, find the following properties:

i. What is the column space of the matrix?

ii. What is the null space of the matrix?

iii. What are the eigenvalues and corresponding eigenspaces for the matrix?

(a) \[
\begin{bmatrix}
2 & 4 \\
0 & 3
\end{bmatrix}
\]

Solution:

i. \(\mathbb{R}^2\). Inspection: the columns of the matrix cannot be written as multiples of each other, so they are linearly independent. Since these vectors are in \(\mathbb{R}^2\) and there are 2 linearly independent vectors, these are enough to span \(\mathbb{R}^2\), which must then be the column space.

ii. \(\{\vec{0}\}\). The linear independence of the columns also implies \(\{\vec{0}\}\) as the solution set of \(A\vec{x} = \vec{0}\) where \(A\) is the matrix, and thus the null space is \(\{\vec{0}\}\).

iii. \(\lambda_1 = 2\) has the corresponding eigenspace: \(\text{Span} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}\)

\(\lambda_2 = 3\) has the corresponding eigenspace: \(\text{Span} \begin{pmatrix} 0 \\ 4 \\ 1 \end{pmatrix}\)

(b) \[
\begin{bmatrix}
1 & -2 \\
2 & -4
\end{bmatrix}
\]

Solution:

i. \(\text{Span} \begin{pmatrix} 1 \\ 2 \end{pmatrix}\). If proceeding by inspection, note that the matrix columns are multiples, so their span is equivalent to the span of one column. Note that it does not matter which column is chosen. Thus the column space can be written as the span of one column from the matrix.

ii. \(\text{Span} \begin{pmatrix} 2 \\ 1 \end{pmatrix}\). Since the columns are integer multiples of each other, a solution to \(A\vec{x} = \vec{0}\) can be constructed, and then extrapolated to the null space.

iii. \(\lambda_1 = -3\) has the corresponding eigenspace: \(\text{Span} \begin{pmatrix} 1 \\ 2 \end{pmatrix}\)

\(\lambda_2 = 0\) has the corresponding eigenspace: \(\text{Span} \begin{pmatrix} 2 \\ 1 \end{pmatrix}\)
4. (OPTIONAL) Op-Amp Summer

Consider the following circuit (assume the op-amp is ideal):

![Op-amp Summer Circuit Diagram]

Figure 5: Op-amp Summer

What is the output $V_o$ in terms of $V_1$ and $V_2$? You may assume that $R_1$, $R_2$, and $R_f$ are known.

(For extra practice, solve this problem twice: once using Node Voltage Analysis (NVA) with both $V_1$ and $V_2$ and another time using superposition of $V_1$ and $V_2$.)

**Solution:**

We can show that the op-amp is in negative feedback (as a quick check, increasing $V_o$ would increase $V^-$, which results in a decrease for $V_o$). Thus, $V^- = V^+ = 0$.

Using Node Voltage Analysis (NVA):

![Node Voltage Analysis Diagram]

Let $I_-$ be the current flowing into the (-) terminal of the op-amp. Since the op-amp is ideal, $I_- = 0$.

We can use KCL at node with the (-) terminal of the op-amp to solve for $V_o$:

\[
I_{R_f} + I_- = I_{R_1} + I_{R_2} \quad \text{(15)}
\]

\[
I_{R_f} + 0 = I_{R_1} + I_{R_2} \quad \text{(16)}
\]

\[
\frac{0 - V_o}{R_f} + 0 = \frac{V_1 - 0}{R_1} + \frac{V_2 - 0}{R_2} \quad \text{(17)}
\]

\[
V_o = -\left(\frac{R_f}{R_1} \cdot V_1 + \frac{R_f}{R_2} \cdot V_2\right) \quad \text{(18)}
\]
Using Superposition:

First, analyze the system with $V_1$. $V_2$ is set to 0, or ground.

![Figure 7](image-url)

Since $V^- = 0$, there is no voltage drop across $R_2$ and thus no current through $R_2$.

We can use KCL at the node with the (-) terminal of the op-amp to solve for $V_{o1}$ (output with only $V_1$):

\[
\frac{V_1 - V^-}{R_1} = \frac{V^- - V_{o1}}{R_f}
\]

(19)

\[
\frac{V_1 - 0}{R_1} = \frac{0 - V_{o1}}{R_f}
\]

(20)

\[
V_{o1} = \frac{R_f}{R_1} \cdot V_1
\]

(21)

Note that you can recognize that this scenario represents an inverting op-amp and the solution for $V_{o1}$ matches this result.

Next, analyze the system with $V_2$. $V_1$ is set to 0, or ground.

![Figure 8](image-url)

Similarly, we can solve for $V_{o2} = -\frac{R_f}{R_2} \cdot V_2$.

Thus, using superposition, with both $V_1$ and $V_2$ present:

\[
V_o = V_{o1} + V_{o2} = \left( \frac{R_f}{R_1} \cdot V_1 + \frac{R_f}{R_2} \cdot V_2 \right)
\]