Homework 0

This homework is due on Tuesday, August 29th, at 11:59PM. Self-Grades, HW Resubmissions, and HW Resubmission Self-Grades are due on Saturday, September 2, at 11:59PM.

NOTE: All other homeworks follow a Saturday-to-Saturday cycle, in which the homework is due on a given Saturday and the Self-Grades/Resubmission/Resubmission Self-Grades are due the following Saturday.

We are aware that these questions have appeared as past EECS 16A questions. Nevertheless, we recommend that you do the problems in earnest (think through the problems and show all work) as they are meant to reflect concepts that will serve as foundation for the material in EECS 16B.

1. **Administration**

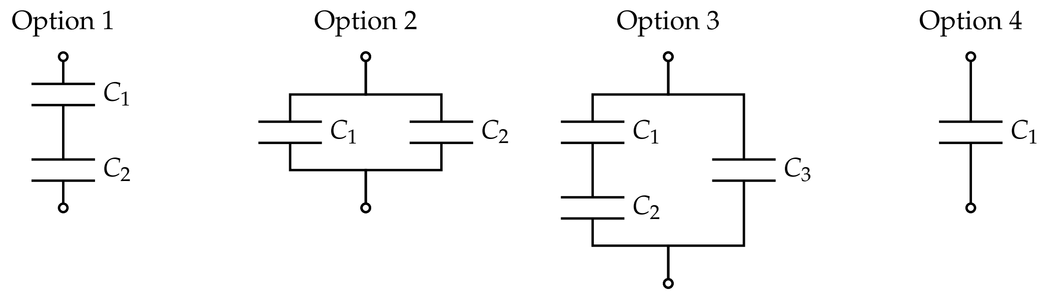
   (a) Please fill out our introductory survey: link to survey. This survey will help us understand our students' prerequisite knowledge for content creation purposes.

   (b) Please complete the Administrative Policy Quiz assignment on Gradescope. The goal is to ensure that everyone is familiar with the course policies, which you can read about here. Take your percent score on the Gradescope assignment, multiply by 10 and round up to either 2, 5, 8, or 10. This is your self-grade score.

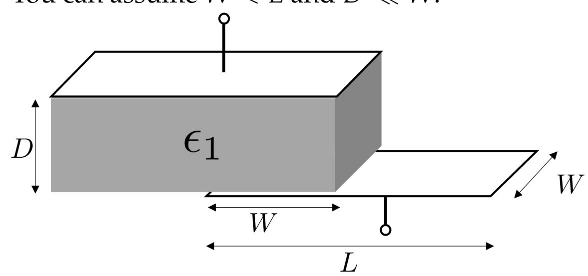
   (c) Please fill out this group formation survey if you are interested in getting matched up in a study group. We highly recommend joining a study group in order to foster a sense of community in the course and learn from others. Within a few weeks, you should get an email informing you of the group you have been matched with. Please follow up with your group members; completing this survey suggests you are interested in joining a group, after all! Please fill out the survey by this Friday so that we can get you your groups as soon as possible. The late deadline to request a group is the HW0 deadline on Tuesday, January 24. Just so you have an answer to put down for this question, write down whether you filled out the survey or not.

2. Modeling Weird Capacitors

For parts (a) - (c) of this problem, **pick the circuit option from below** that best models the given physical capacitor.



(a) A parallel plate capacitor with plate dimensions L and W, separated by a gap D, is filled with an insulator of permittivity ϵ_1, with the bottom plate displaced with overlap W as shown below. You can assume $W < L$ and $D \ll W$.

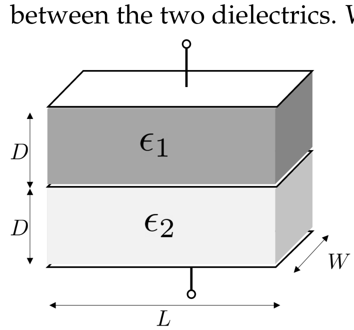


i. What is the circuit option that best models the physical capacitor?
   (A) Option 1
   (B) Option 2
   (C) Option 3
   (D) Option 4

ii. What is the total capacitance, C, for this capacitor? Express your answer in terms of ϵ_1, D, L, and W.

Solution: Option 4, where $C = C_1 = \epsilon_1 \frac{W \cdot W}{D}$

(b) A parallel plate capacitor with plate dimensions L and W, separated by a gap $2 \cdot D$, is filled with two insulators of permittivities ϵ_1 and ϵ_2 as shown below. You can assume there's a plate between the two dielectrics. What is the circuit option that best models the physical capacitor?



(A) Option 1

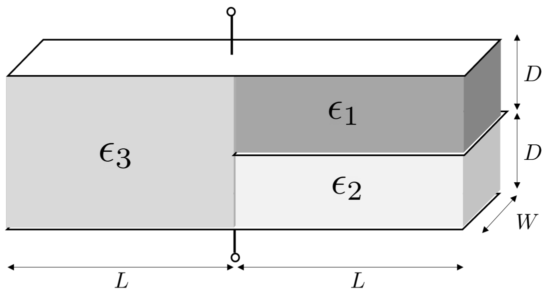
(B) Option 2

(C) Option 3

(D) Option 4

Solution: Option 1, where $C = C_1||C_2 = \frac{L \cdot W}{D} \frac{\epsilon_1 \epsilon_2}{\epsilon_1 + \epsilon_2}$

(c) A parallel plate capacitor with plate dimensions L and W, separated by a gap $2 \cdot D$, is filled with three different materials with permittivities ϵ_1, ϵ_2, and ϵ_3 as shown in the figure below. You can assume there's a plate between the two dielectrics on the right. What is the circuit option that best models the physical capacitor?



(A) Option 1

(B) Option 2

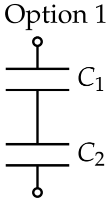
(C) Option 3

(D) Option 4

Solution: Option 3, where $C = (C_1||C_2) + C_3 = \frac{L \cdot W}{D} \frac{\epsilon_1 \epsilon_2}{\epsilon_1 + \epsilon_2} + \frac{L \cdot W \epsilon_2}{2D} = \frac{L \cdot W \cdot \epsilon_2}{2D} \cdot \frac{3\epsilon_1 + \epsilon_2}{\epsilon_1 + \epsilon_2}$

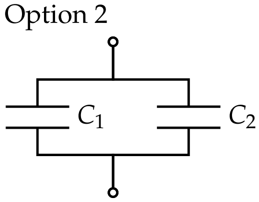
(d) For this final part, please express the equivalent capacitance, C_{eq}, between the top and bottom node for each of the following circuits from the previous parts. Feel free to include the *parallel operator* ("||") in your answer.

i. Option 1



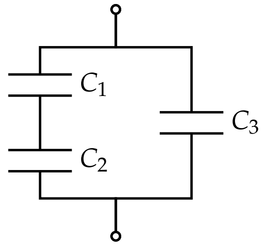
Solution: $C = C_1||C_2$

ii. Option 2



Solution: $C_{eq} = C_1 + C_2$

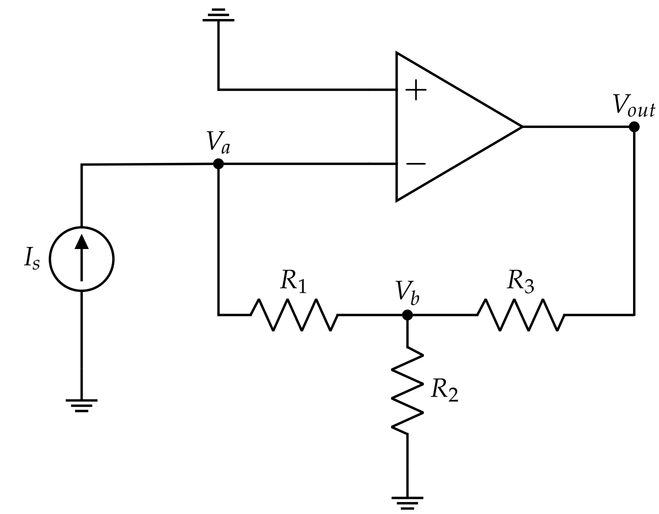
iii. Option 3



Solution: $C_{eq} = (C_1||C_2) + C_3$

3. Op-Amp Analysis!

(a) We want to find a relationship between the output voltage, V_{out}, and the input current, I_s, in the circuit below.



i. Determine the node voltage V_a **in terms of** I_s**,** R_1**,** R_2**, and** R_3.

ii. Determine the node voltage V_b **in terms of** I_s**,** R_1**,** R_2**, and** R_3.

iii. Choose the correct expression for the output voltage V_{out} **in terms of** I_s**,** V_b**,** R_1**,** R_2**, and** R_3.

(A) $V_{out} = \left(1 - \frac{R_3}{R_2}\right) \cdot V_b - I_s \cdot R_1$

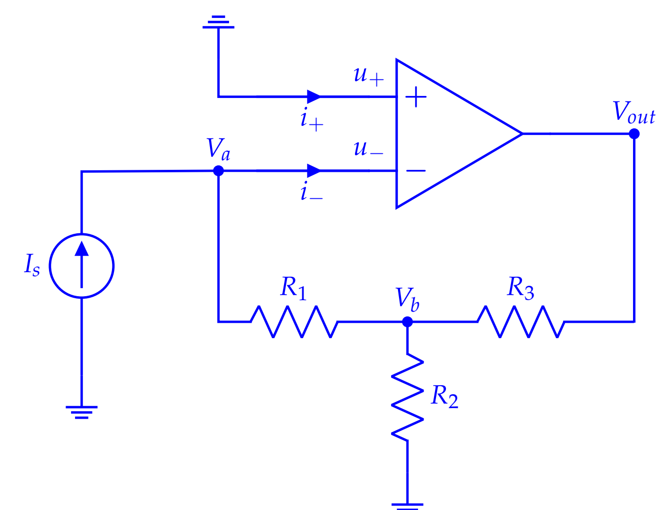
(B) $V_{out} = V_b$

(C) $V_{out} = \left(1 + \frac{R_3}{R_2}\right) \cdot V_b - I_s \cdot R_3$

(D) $V_{out} = \frac{R_3 + R_2}{R_2} V_b$

(E) $V_{out} = \left(1 - \frac{R_3}{R_2}\right) \cdot V_b - I_s \cdot (R_1 + R_3)$

Solution:



After affirming the op-amp circuit is in negative feedback, we can apply both Golden Rules: $u_+ = u_-$ and $i_+ = i_- = 0$.

i. First, the node voltage at V_a is identified as

$$V_a = u_- = u_+ = 0 \tag{1}$$

ii. Second, the node voltage at V_b is determined by writing a KCL equation at node V_a.

$$I_s - i_- - \frac{V_a - V_b}{R_1} = 0 \tag{2}$$

$$I_s + \frac{V_b}{R_1} = 0 \tag{3}$$

$$V_b = -I_s R_1 \tag{4}$$

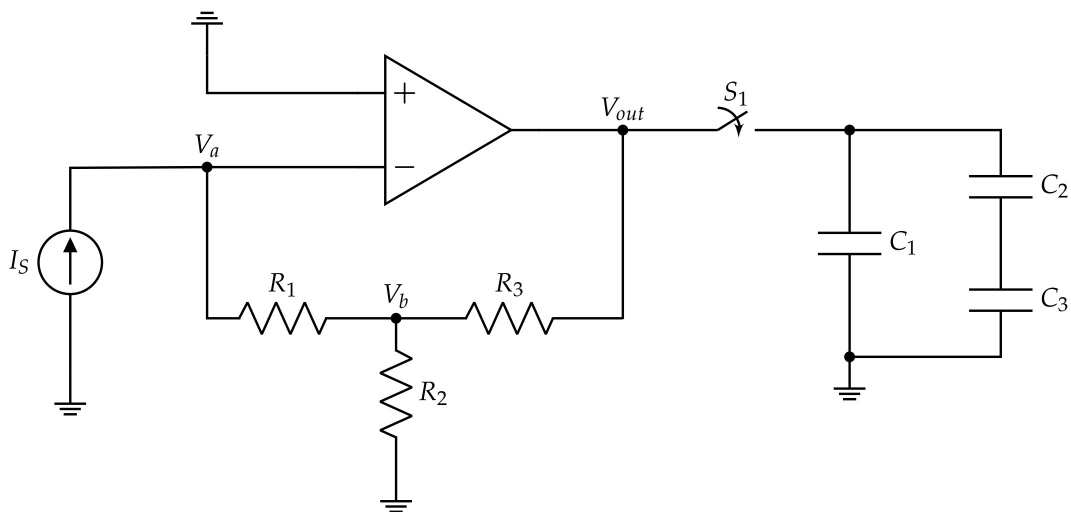
iii. Third, the output voltage, V_{out}, is determined by writing a KCL equation at node V_b. A simplification can be made by recognizing the current through resistor R_1 is I_s.

$$I_s - \frac{V_b}{R_2} - \frac{V_b - V_{out}}{R_3} = 0 \tag{5}$$

$$\frac{V_{out}}{R_3} = \frac{V_b}{R_2} + \frac{V_b}{R_3} - I_s \tag{6}$$

$$V_{out} = \left(1 + \frac{R_3}{R_2}\right) \cdot V_b - I_s \cdot R_3 \tag{7}$$

(b) Now, we will connect a set of capacitors to our previous circuit with an initially open switch S_1, as follows:



Now assume the output voltage is $V_{out} = 5\,\text{V}$. Also, assume the capacitors $C_1 = 4\mu F$, $C_2 = 2\mu F$, and $C_3 = 3\mu F$ are initially discharged. In steady-state after switch S_1 is closed, determine the following quantities. Please provide **numerical** values for your answers.

i. What is the energy stored in **capacitor** C_1?

Solution: In steady-state the voltage across capacitor C_1 will be $V_{C_1} = V_{out} = 5\,\text{V}$. The energy stored in capacitor C_1 is then

$$E_{C_1} = \frac{1}{2} C_1 V_{C_1}^2 = \frac{1}{2}(4\,\mu\text{F})(5\,\text{V})^2 = 50\,\mu\text{J} \tag{8}$$

ii. What is the charge accumulated on **capacitor** C_3?

Solution: Since capacitors in series have equal charge, we first find the equivalent capacitance of C_2 and C_3.

$$C_{23} = C_2 || C_3 = \frac{C_2 C_3}{C_2 + C_3} = \frac{(2\,\mu\text{F})(3\,\mu\text{F})}{(2\,\mu\text{F}) + (3\,\mu\text{F})} = \frac{6}{5}\,\mu\text{F} \tag{9}$$

Next, the charge in the equivalent capacitor (and each constituent series capacitor) is

$$Q_{C_{23}} = C_{23} V_{out} = \left(\frac{6}{5}\,\mu\text{F}\right)(5\,\text{V}) = 6\,\mu\text{C} \tag{10}$$

$$= Q_{C_2} = Q_{C_3} \tag{11}$$

iii. What is the voltage across **capacitor** C_3?

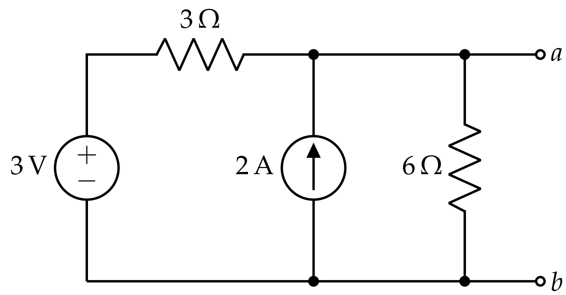
Solution: The voltage in capacitor C_3 is derived from the charge across it.

$$V_{C3} = \frac{Q_{C_3}}{C_3} = \frac{(6\,\mu\text{C})}{(3\,\mu\text{F})} = 2\,\text{V} \tag{12}$$

4. Finding Mr. Thevenin

For the following circuits, find the Thevenin and Norton equivalent resistance, voltage, and current between the nodes a and b.

(a) Consider the circuit below:



i. Can you turn off V_s (5V voltage source) and I_s (2A current source) to find R_{th}?

(A) Yes

(B) No

ii. What is R_{th}?

(A) $R_{th} = 2\,\Omega$

(B) $R_{th} = 3\,\Omega$

(C) $R_{th} = 4.5\,\Omega$

(D) $R_{th} = 6\,\Omega$

(E) $R_{th} = 9\,\Omega$

iii. What is V_{th}?

(A) $V_{th} = 0\,\mathrm{V}$

(B) $V_{th} = 2\,\mathrm{V}$

(C) $V_{th} = 3\,\mathrm{V}$

(D) $V_{th} = 4\,\mathrm{V}$

(E) $V_{th} = 6\,\mathrm{V}$

iv. What is I_{no}?

(A) $I_{no} = 0\,\mathrm{A}$

(B) $I_{no} = 0.67\,\mathrm{A}$

(C) $I_{no} = 1\,\mathrm{A}$

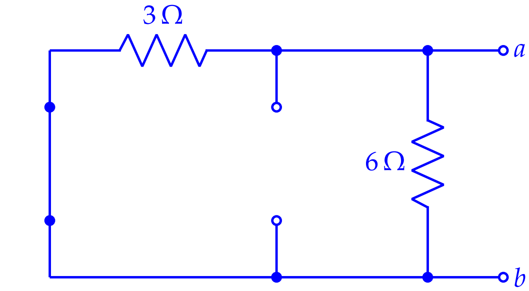
(D) $I_{no} = 2\,\mathrm{A}$

(E) $I_{no} = 3\,\mathrm{A}$

Solution: There are multiple ways to solve this problem, but fundamentally after determining two of R_{th}, V_{th}, or I_{no}, the third can be determined from Ohm's Law: $V_{th} = I_{no}\,R_{th}$.

(A) Yes. Since $V_s = 3\,\mathrm{V}$ and $I_s = 2\,\mathrm{A}$ are both independent sources, they can be turned off to determine the Thevenin resistance R_{th} or equivalent resistance between nodes a and b.

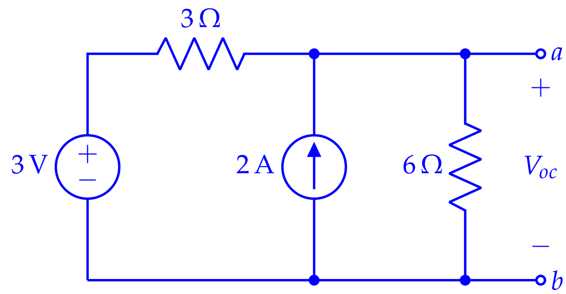
(B) To find R_{th}, we turn off independent sources ($V \to$ short circuit and $I \to$ open circuit) and determine the equivalent resistance.



For this circuit, the two resistors 3 Ω and 6 Ω are equivalently in parallel with respect to nodes a and b.

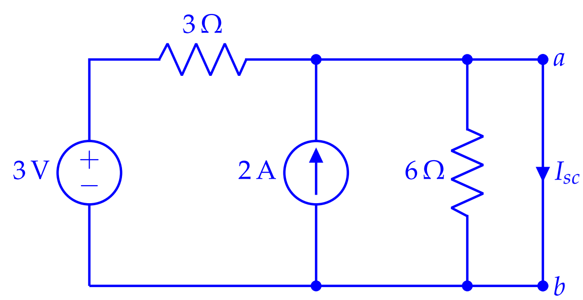
$$R_{th} = 3\,\Omega || 6\,\Omega = \frac{(3\,\Omega)\,(6\,\Omega)}{(3\,\Omega) + (6\,\Omega)} = 2\,\Omega \tag{13}$$

(C) Using superposition, we can find the open circuit voltage (i.e., V_{th}) between nodes a and b



$$V_{th} = V_{oc} = \frac{(6\,\Omega)}{(3\,\Omega) + (6\,\Omega)} V_s + (6\,\Omega) \cdot \frac{(3\,\Omega)}{(3\,\Omega) + (6\,\Omega)} I_s = 2\,\text{V} + 4\,\text{V} = 6\,\text{V} \tag{14}$$

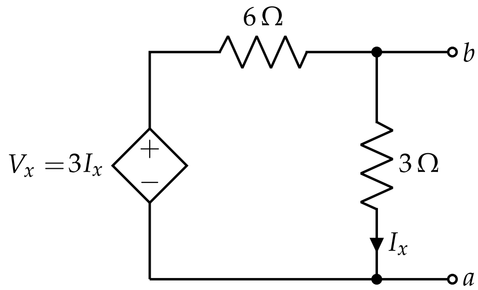
(D) Using superposition, we can find the short circuit current (i.e., I_{no}) between nodes a and b



$$I_{no} = I_{sc} = \frac{1}{(3\,\Omega)} V_s + I_s = 1\,\text{A} + 2\,\text{A} = 3\,\text{A} \tag{15}$$

(b) Consider this new circuit with a current-dependent voltage source (that depends on I_x, the current through the 3 Ω resistor): $V_x = 3\Omega \cdot I_x$ [V].

(HINT: To find R_{th}, you will need to use a test voltage V_{test} (or test current) and find the relationship to its current I_{test} (or voltage).)



i. Should you turn off V_x to find R_{th}?

(A) Yes

(B) No

ii. What is R_{th}?

(A) $R_{th} = 2\,\Omega$

(B) $R_{th} = 3\,\Omega$

(C) $R_{th} = 4.5\,\Omega$

(D) $R_{th} = 6\,\Omega$

(E) $R_{th} = 9\,\Omega$

iii. What is V_{th}?

(A) $V_{th} = 0\,\text{V}$

(B) $V_{th} = 2\,\text{V}$

(C) $V_{th} = 3\,\text{V}$

(D) $V_{th} = 4\,\text{V}$

(E) $V_{th} = 6\,\text{V}$

iv. What is I_{no}?

(A) $I_{no} = 0\,\text{A}$

(B) $I_{no} = 0.67\,\text{A}$

(C) $I_{no} = 1\,\text{A}$

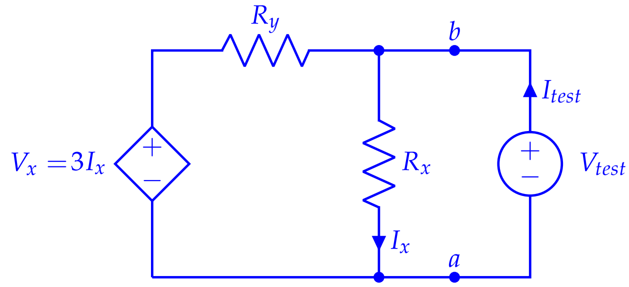
(D) $I_{no} = 2\,\text{A}$

(E) $I_{no} = 3\,\text{A}$

Solution: There are multiple ways to solve this problem, but fundamentally after determining two of R_{th}, V_{th}, or I_{no}, the third can be determined from Ohm's Law: $V_{th} = I_{no}\,R_{th}$.

(A) No. In general, turning off dependent sources to determine the equivalent resistance does not work.

(B) Since there are dependent sources, we need to apply a test voltage (or current) source across terminals a and b and measure the current (voltage) through it. Then we can use $R_{th} = V_{test}\,/\,I_{test}$ to determine the Thevenin resistance.



First, the current I_x through resistor $R_x = 3\,\Omega$ is

$$I_x = \frac{V_{test}}{R_x} \tag{16}$$

thus the voltage V_x of the current dependent voltage source is

$$V_x = 3I_x = \frac{3}{R_x} V_{test} \tag{17}$$

Defining the resistor $R_y = 6\,\Omega$, a KCL equation can then be written at node b and solved for $\frac{V_{test}}{I_{test}}$.

$$\frac{V_x - V_{test}}{R_y} - I_x + I_{test} = 0 \tag{18}$$

$$\frac{1}{R_y}\left(\frac{3}{R_x} V_{test} - V_{test}\right) - \frac{1}{R_x} V_{test} + I_{test} = 0 \tag{19}$$

$$\left(3 - R_x - R_y\right) V_{test} + R_x R_y\, I_{test} = 0 \tag{20}$$

Finally,

$$R_{th} = \frac{V_{test}}{I_{test}} = \frac{R_x R_y}{R_x + R_y - 3} \tag{21}$$

$$= \frac{(3\,\Omega)(6\,\Omega)}{(3\,\Omega) + (6\,\Omega) - 3} \tag{22}$$

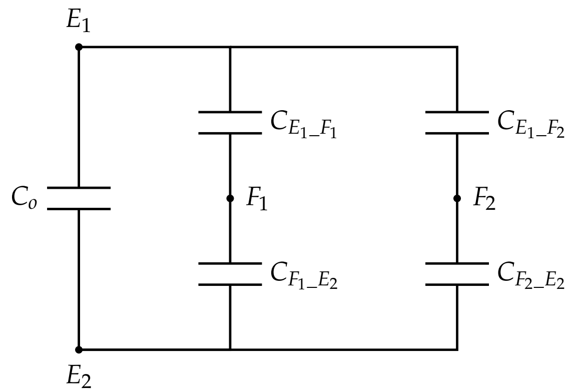
$$= 3\,\Omega \tag{23}$$

(C) We have no independent sources, therefore the open circuit voltage and short circuit current are both zero: $V_{th} = 0\,\text{V}$, $I_{no} = 0\,\text{A}$.

(D) We have no independent sources, therefore the open circuit voltage and short circuit current are both 0: $V_{th} = 0\,\text{V}$, $I_{no} = 0\,\text{A}$.

5. Please don't burn your fingers

One day, hidden somewhere deep within Cory 140, you discover an ancient capacitive circuit.



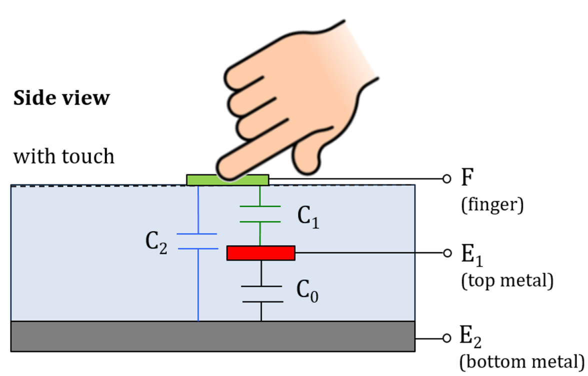
(a) Calculate the equivalent capacitance C_e between E_1 and E_2 given $C_0 = C_{E_1\_F_1} = C_{F_1\_E_2} = C_{E_1\_F_2} = C_{F_2\_E_2} = 40\,\text{pF}$.

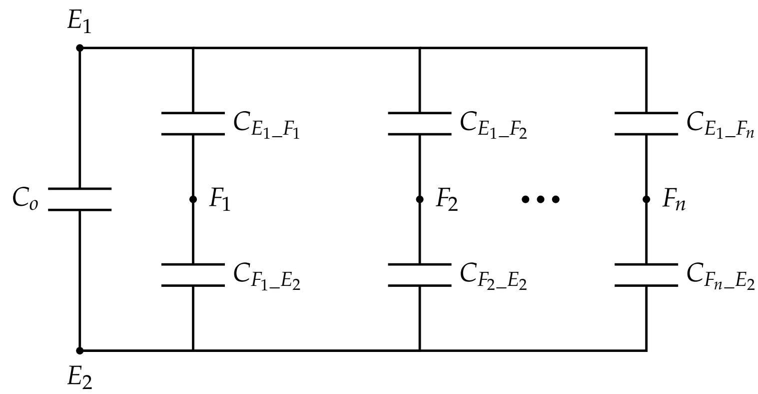
(A) 20 pF
(B) 40 pF
(C) 60 pF
(D) 80 pF
(E) 120 pF

Solution:

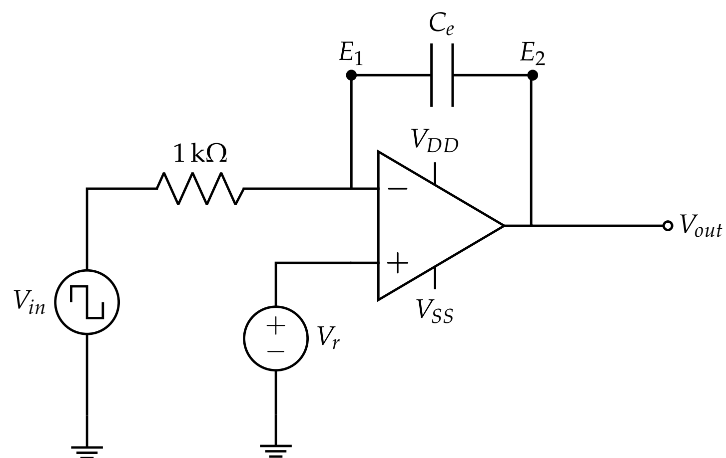
$$C_e = C_o + C_{E_1\_F_1}||C_{F_1\_E_2} + C_{E_1\_F_2}||C_{F_2\_E_2} \tag{24}$$
$$= (40\,\text{pF}) + (40\,\text{pF})||(40\,\text{pF}) + (40\,\text{pF})||(40\,\text{pF}) \tag{25}$$
$$= 40\,\text{pF} + (20\,\text{pF}) + (20\,\text{pF}) \tag{26}$$
$$= 80\,\text{pF} \tag{27}$$

(b) What you found was in fact a multi-finger touchscreen that forms different capacitive circuits depending on how many fingers we place.





To figure out how this multi-finger touchscreen works, you decide to connect it to your op-amp setup from the Touch 3 labs. The circuit between terminals E_1 and E_2 is modeled as equivalent capacitance C_e, and V_{in} is a function generator with alternating square wave voltage between $V_{in} = 0\,\text{V}$ and $V_{in} = 2V_r$.



Assume an ideal op-amp and the circuit is in negative feedback.

i. After experimenting with the circuit for a bit, you notice a sudden increase in the positive peaks of V_{out}. How must the equivalent capacitance C_e have changed?

(A) C_e increased

(B) C_e decreased

Solution: Since the circuit is in negative feedback, $u_{E_1} = V_r$ and $V_{C_e} = V_{out} - V_r$. If V_{out} increases, then V_{C_e} must increase and C_e must decrease since the derivative of capacitor voltage is inversely proportional to its capacitance (for fixed applied current) as $i_{C_e} = C_e \frac{dV_{C_e}}{dt}$.

ii. How are the equivalent capacitance C_e and the number of fingers touching related?

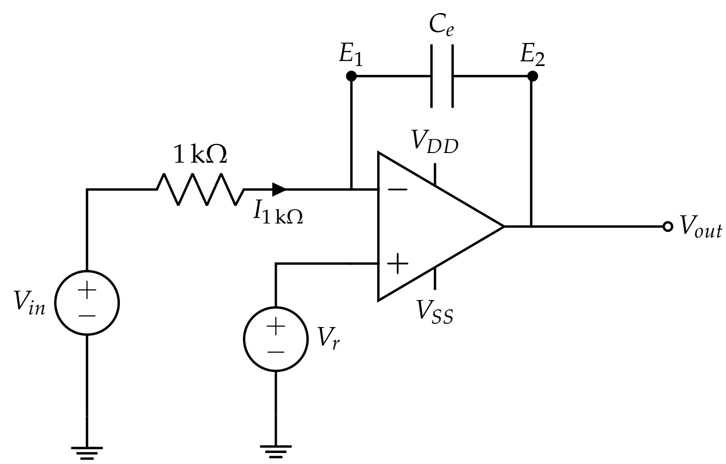
(A) More fingers increases C_e

(B) More fingers decreases C_e

(C) C_e does not depend on the number of fingers

Solution: For the multi-finger touchscreen presented, increasing the number of touch points increases the total equivalent capacitance.

(c) Oops! Instead of a function generator, we accidentally used a constant voltage source V_{in} instead. We will find out how long it will take before the circuit breaks! Here is the circuit with the new voltage source V_{in}.



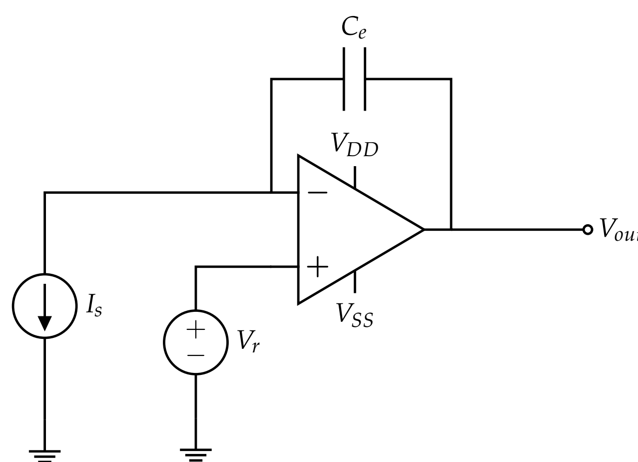
For the following problems, **assume the circuit is in negative feedback**.

i. First, what is the current flowing in the $1\,\mathrm{k\Omega}$ resistor ($I_{1\,\mathrm{k\Omega}}$ in the circuit)? Assume $V_{in} = 2\,\mathrm{V}$, $V_r = 1\,\mathrm{V}$. **Express your answer in mA (numerical value), and make sure your sign is correct** (according to the labeled current in the circuit.).

Solution:

$$I_{1\,\mathrm{k\Omega}} = \frac{V_{in} - V_r}{R} = \frac{2\,\mathrm{V} - 1\,\mathrm{V}}{1\,\mathrm{k\Omega}} = 1\,\mathrm{mA} \tag{28}$$

ii. Now assume a *constant* current source I_s (instead of V_{in} and the $1\,\mathrm{k\Omega}$ resistor), as shown in the circuit below.



If the initial voltage across the capacitor is zero at time $t = 0$, **what is the value of V_{out} over time**? Assume the output does not saturate (i.e., $V_{DD} > V_{out} > V_{SS}$). Express your answer **in terms of the variables I_s, V_r, C_e, and t** by simplifying any integrals or derivatives (i.e. your final answer should not have any integrals or derivatives in it.)

Solution: According to the golden rule of opamp with negative feedback (NFB): $i_- = i_+ = 0$ and $u_- = u_+$.

$$I_s = C_e \frac{dV_{C_e}}{dt} \quad \rightarrow \quad V_{C_e} = \frac{1}{C_e}\int_0^t I_s \, dt \tag{29}$$

$$V_{out} - V_r = \frac{I_s}{C_e} t \tag{30}$$

$$V_{out} = V_r + \frac{I_s}{C_e} t \tag{31}$$

iii. If the op-amp is connected to supply sources $V_{DD} = -V_{SS}$, **1)** how long does it take for V_{out} to saturate the op-amp? and **2)** what is the value of V_{out} in saturation? (Assume $I_s > 0$, $V_r > 0$, and $V_{DD} > V_r > V_{SS}$)

(A) $t = C_e \frac{-V_{SS} + V_r}{I_s}$ $\quad V_{out} = V_{SS}$

(B) $t = C_e \frac{V_{DD} - V_r}{I_s}$ $\quad V_{out} = V_{DD}$

(C) $t = \frac{-V_{SS} + V_r}{C_e I_s}$ $\quad V_{out} = V_{SS}$

(D) $t = \frac{V_{DD} - V_r}{C_e I_s}$ $\quad V_{out} = V_{DD}$

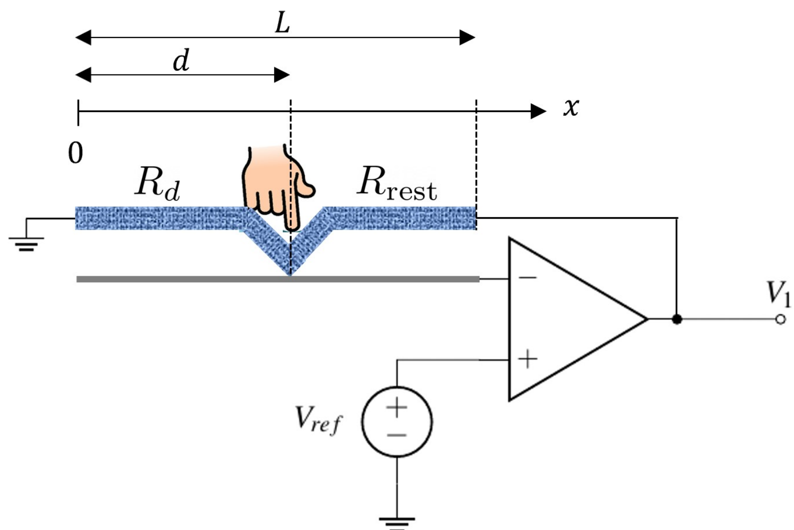
Solution: The output V_{out} will keep increasing linearly until it saturates at $V_{out} = V_{DD}$

$$V_{out} = V_r + \frac{I_s}{C_e} t = V_{DD} \tag{32}$$

$$t = C_e \frac{V_{DD} - V_r}{I_s} \tag{33}$$

6. Ask Opamps Anything

We've decided to design a 1D resistive touch-screen using an ideal opamp. The resistive touchscreen has a total length of L, a cross sectional area of A and resistivity of ρ.



(a) First, we want to find V_1, because we will use this block in a larger design.

i. What are the values for the resistance between the touch point and ground (R_d) and between the touch point and V_1 (R_{rest})?

(A) $R_d = \rho \frac{A}{d}$ $\quad R_{rest} = \rho \frac{A}{L-d}$

(B) $R_d = \rho \frac{d}{A}$ $\quad R_{rest} = \rho \frac{L-d}{A}$

(C) $R_d = \rho \frac{L-d}{A}$ $\quad R_{rest} = \rho \frac{d}{A}$

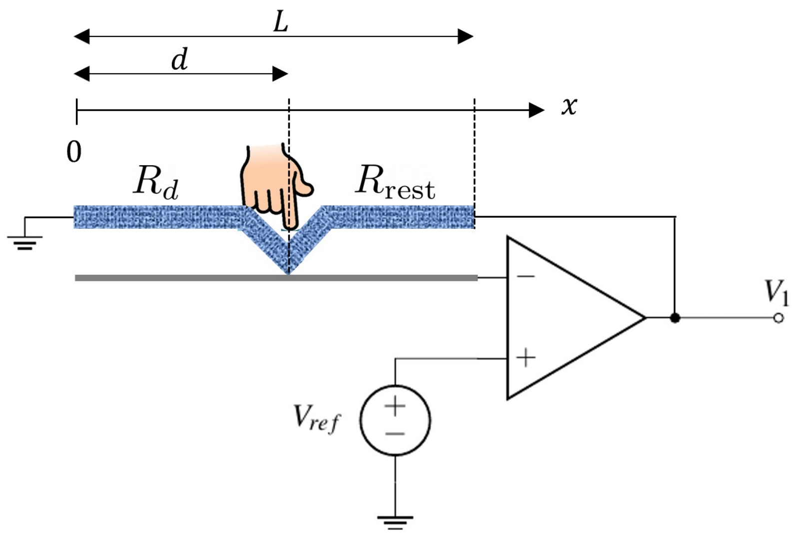
(D) $R_d = \rho \frac{A}{L-d}$ $\quad R_{rest} = \rho \frac{A}{d}$

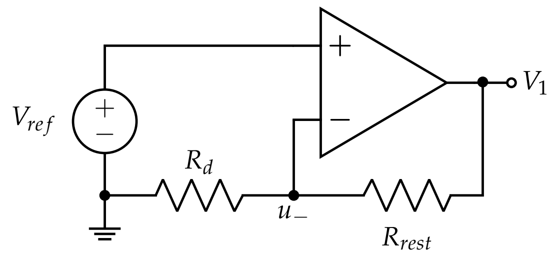
Solution: An object with resistivity ρ, cross-sectional area A, and length l has resistance $R = \rho \frac{l}{A}$. The two resistive segments only differ by the length

$$R_d = \rho \frac{d}{A} \tag{34}$$

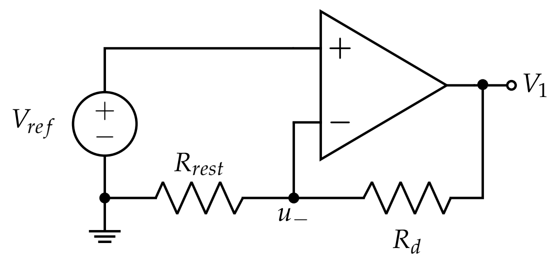
$$R_{rest} = \rho \frac{L-d}{A} \tag{35}$$

ii. Identify a correct equivalent topology for this scenario:





(A)



(B)

Solution: A.

iii. What is the value of V_1 if the resistive touch screen, as a function of R_d and R_{rest}?

(A) $V_1 = V_{ref}\dfrac{R_d}{R_{rest}}$

(B) $V_1 = V_{ref}\dfrac{R_{rest}}{R_d}$

(C) $V_1 = V_{ref}\left(1 + \dfrac{R_d}{R_{rest}}\right)$

(D) $V_1 = V_{ref}\left(1 + \dfrac{R_{rest}}{R_d}\right)$

Solution: The circuit is in a negative feedback configuration, thus in addition to $i_- = i_+ = 0$ the op-amp "Golden Rule" $u_+ = u_-$ can be applied. In this circuit, $u_- = u_+ = V_{ref}$. Writing a KCL equation at node u_- and solving for V_1 yields

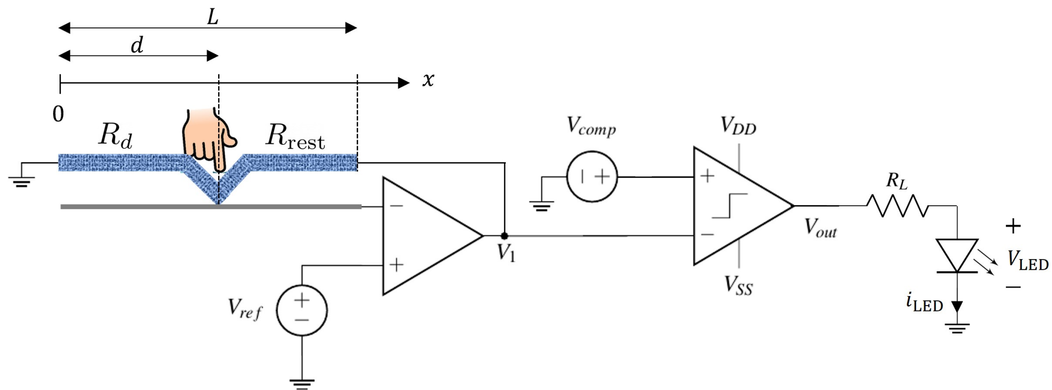
$$\frac{u_-}{R_d} + \frac{u_- - V_1}{R_{rest}} = 0$$

$$\left(1 + \frac{R_{rest}}{R_d}\right) u_- = V_1$$

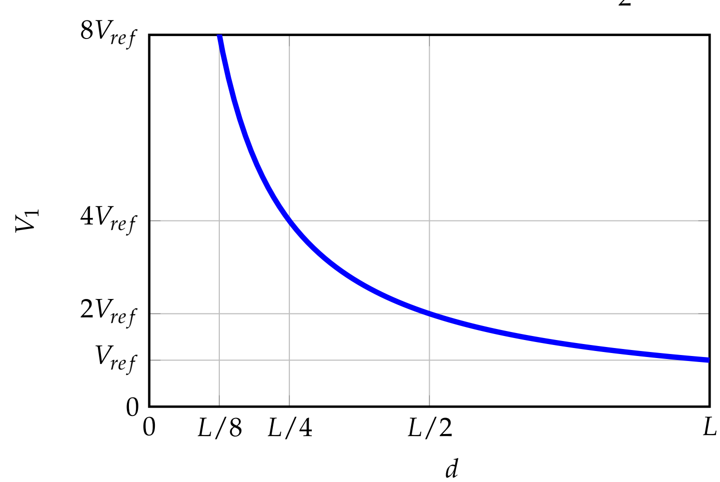
$$\left(1+\frac{R_{rest}}{R_d}\right) V_{ref} = V_1$$

This also matches the known gain of a conventional non-inverting amplifier circuit.

(b) Next, an LED indicator driven by a comparator is added to the output of the prior circuit.



i. You are provided the curve for the voltage V_1 as a function of the touch distance d. What should the value of V_{comp} be to ensure the LED turns on when $d > \frac{L}{2}$?



(A) $V_{comp} = +V_{ref}$

(B) $V_{comp} = -V_{ref}$

(C) $V_{comp} = +2\,V_{ref}$

(D) $V_{comp} = -2\,V_{ref}$

(E) $V_{comp} = +4\,V_{ref}$

(F) $V_{comp} = -4\,V_{ref}$

Solution: The output of the comparator will be V_{DD} and the LED will turn on when the touch distance $d > \frac{L}{2}$. This will occur when $V_+ = V_{comp}$ of the op-amp is greater than $V_- = V_1$. From the plot of d versus V_1, since $V_1 = 2V_{ref}$ when $d = \frac{L}{2}$, the voltage V_{comp} should be $2V_{ref}$.

ii. When the LED shown in the diagram is turned on the voltage across it is $V_{LED} = 1\,\text{V}$, **what is the current,** i_{LED}**, through it**? Consider the load resistance $R_L = 1\,\text{k}\Omega$, and voltages supplies $V_{DD} = 5\,\text{V}$ and $V_{SS} = 0\,\text{V}$. Your answer should be a **numerical** value.

Solution: When the LED is on, the output voltage of the comparator is $V_{out} = V_{DD} = 5\,\text{V}$. Thus the LED current is

$$I_{\text{LED}} = \frac{V_{out} - V_{\text{LED}}}{R_L} = \frac{5\,\text{V} - 1\,\text{V}}{1\,\text{k}\Omega} = 4\,\text{mA} \tag{36}$$

iii. Now, assume $i_{\text{LED}} = 1\,\text{mA}$, $V_{\text{LED}} = 2\,\text{V}$, $R_L = 3\,\text{k}\Omega$, $V_{DD} = 5\,\text{V}$, and $V_{SS} = 0\,\text{V}$.
How much power P_{out} is delivered by the output of the comparator? Your answer should be a **numerical** value.
Solution: When the LED is on, the output voltage of the comparator is still $V_{out} = V_{DD} = 5\,\text{V}$. Additionally the output current of the comparator is $I_{out} = I_{\text{LED}} = 1\,\text{mA}$.
The power delivered by the output of the comparator is

$$P_{out} = V_{out}\, I_{out} = (5\,\text{V})(1\,\text{mA}) = (5\,\text{mW}) \tag{37}$$

