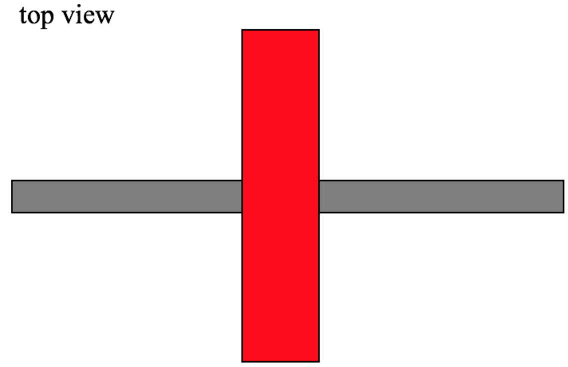
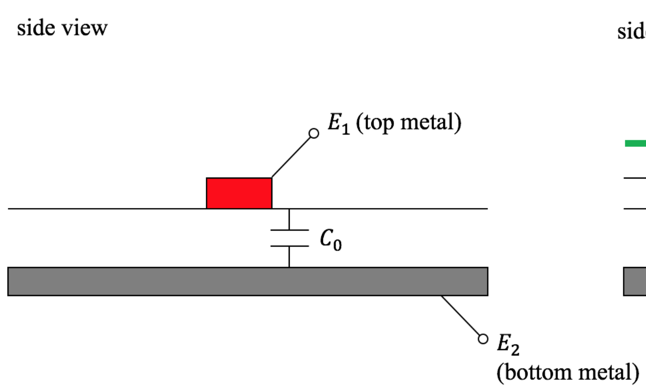
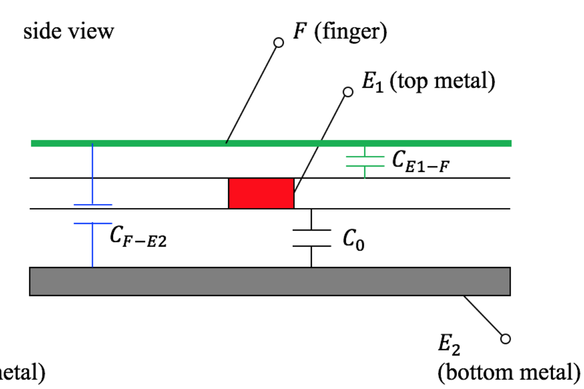
18.1 Capacitive Touchscreen

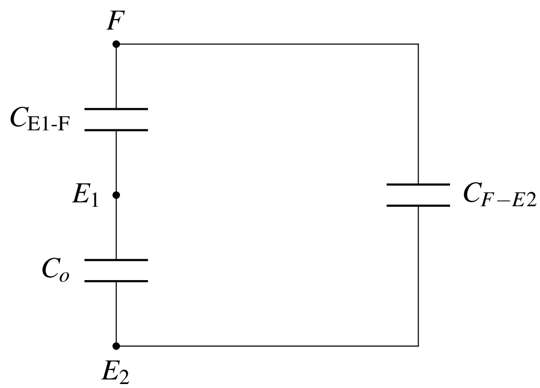
Viewing the physical structure corresponding to one pixel on the capacitive screen, we want to be able to tell if there is a finger touch on top of the pixel.



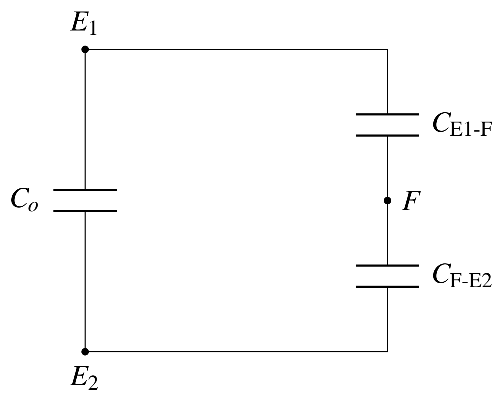




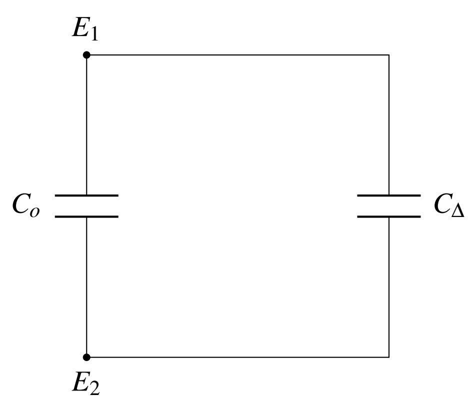
The green line represents our finger touching the dielectric, $C_{\text{F-E2}}$ is the capacitance between our finger (F) and electrode $E2$, and $C_{\text{E1 - F}}$ is the capacitance between our finger (F) and electrode $E1$. Now, we can draw the equivalent circuit model corresponding to the pixel we're looking at:



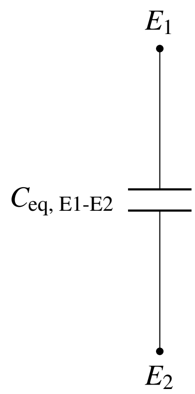
From the standpoint of smart phones, a smart phone can only sense something that is between electrodes E_1 and E_2 as it is impractical to physically connect a measuring device to our finger. So, we redraw our circuit as follows:



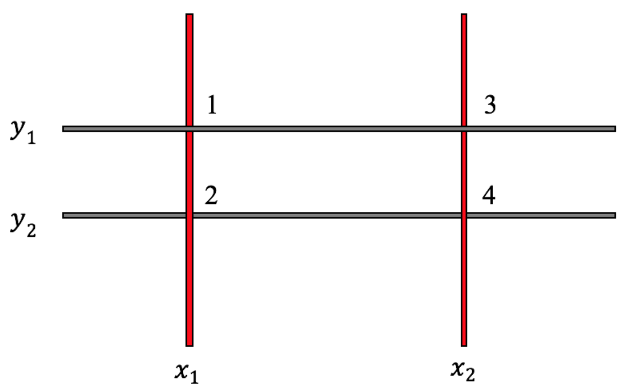
We can further simplify the circuit by replacing the series combination of $C_{\text{E1-F}}$ and $C_{\text{F-E2}}$ by some capacitance C_Δ. Intuitively, we know C_Δ has some finite capacitance and is greater than zero:



If we consider the parallel combination of C_o and C=C_Δ as some equivalent capacitance $C_{\text{eq, E1-E2}}$, we know that $C_{\text{eq, E1-E2}}$ will have some value greater than C_o because $C_{\text{eq, E1-E2}} = C_o + C_\Delta$ and $C_\Delta > 0$.



When a finger presses on top of a pixel, the equivalent capacitance between E_1 and E_2 will become greater than the default capacitance without a finger pressing on top. This characteristic allows us to tell if there is a finger pressing on top of each pixel on our 2D capacitive touchscreen.



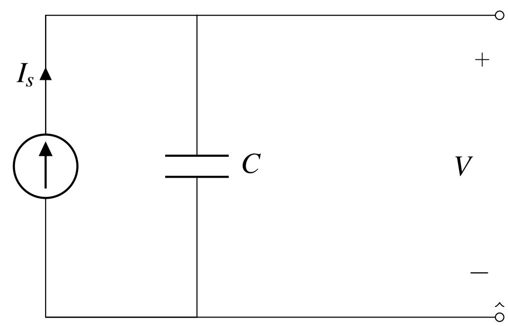
Given 4 pixels 1, 2, 3, 4 and their corresponding locations, we can measure the capacitance at (x_1, y_1) to know if there is a finger pressing on top of pixel 1. Similarly, to know the if there is a finger pressing on top of pixels 2, 3, 4, we can measure the capacitances at (x_1, y_2), (x_2, y_1), (x_2, y_2). If we sense an increase in the capacitance at the pixel location, we know there is a finger pressing on top of this pixel.

18.2 Capacitance Measurement

There are various ways you can use to measure capacitance. In this lecture, we will cover one specific method to measure capacitance. First, let's review some basic physics for a capacitor. As you know:

$$I = C \times \frac{dV}{dt}, Q = C \times V. \tag{1}$$

We can build a circuit with a current source I_s and a capacitor C. If we charge the capacitor C using the current source I_s for a time interval t.

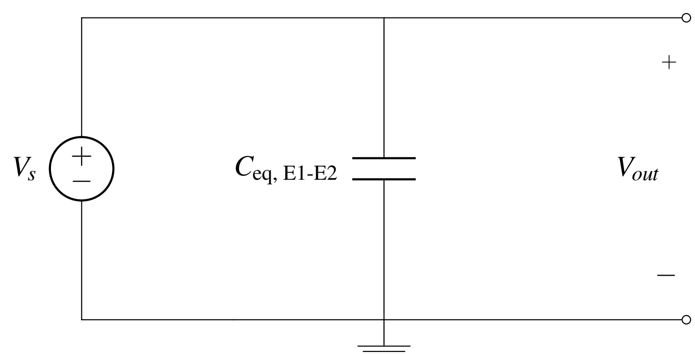


We can then find V to be:

$$V = \frac{I_s \times t}{C} \tag{2}$$

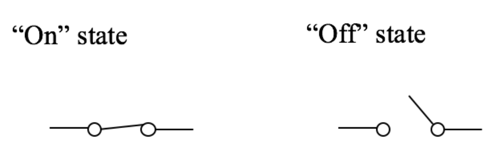
V measured depends on the amount of charge $Q = I_s \times t$ and the capacitance value C. So, if we charge a capacitor using some current source for a finite time period, we can map the voltage across the capacitor to capacitance. However, building a current source is not that easy, so we have to come up with some workarounds to measure capacitance.

- **Attempt #1** Our first attempt is connecting a capacitor to some voltage source and we measure the voltage across the capacitor directly:

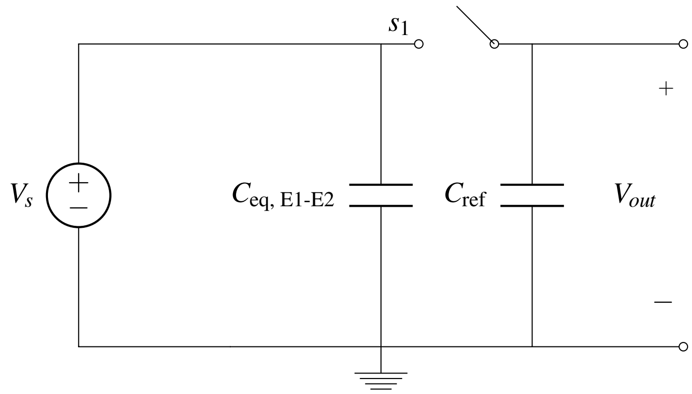


We can immediately see that no matter how C changes, the voltage measured V_{out} is always going to be equal to V_s.

- **Attempt #2** In order to measure something different from V_s while stilling using the voltage source as the power source in our circuit, we must somehow disconnect V_{out} from V_s when we measure V_{out}. How? We can add a switch to the circuit. A switch has two states, at its on state, the switch becomes a perfectly conducting wire with zero resistance, and when the switch is turned off, it becomes an open circuit.

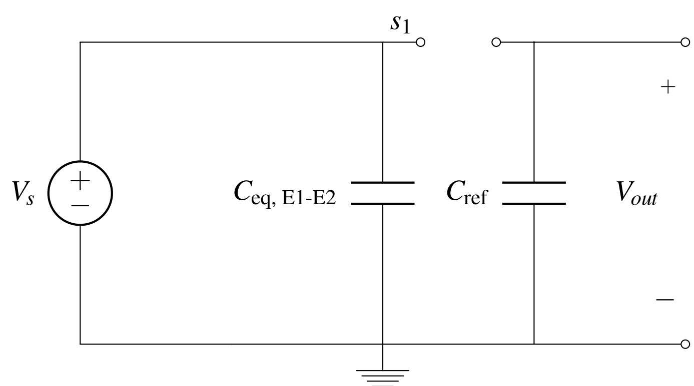


For our second attempt, we will add a reference capacitor C_{ref} and a switch to the circuit, and we will measure the voltage across C_{ref}.

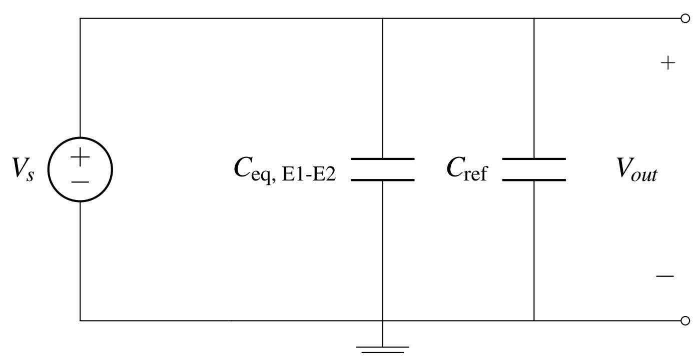


There are two phases of this circuit.

– **Phase 1:** s_1 is off. $C_{\text{eq, E1-E2}}$ is connected to V_s and C_{ref} is not connected to anything.

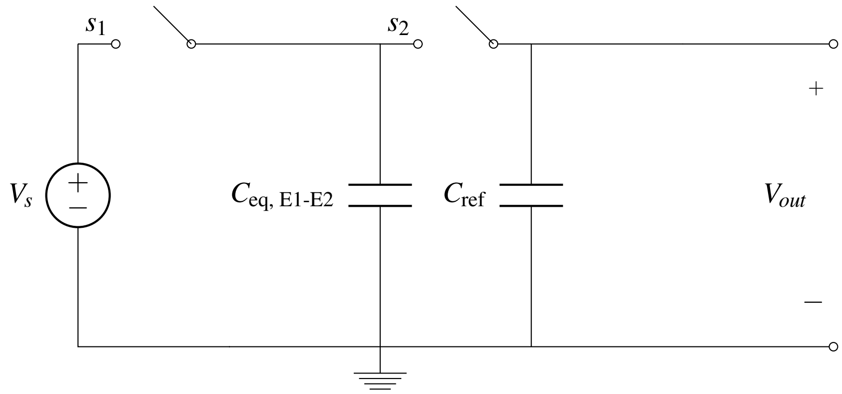


– **Phase 2:** s_1 is on, we can replace s_1 with a perfect wire.

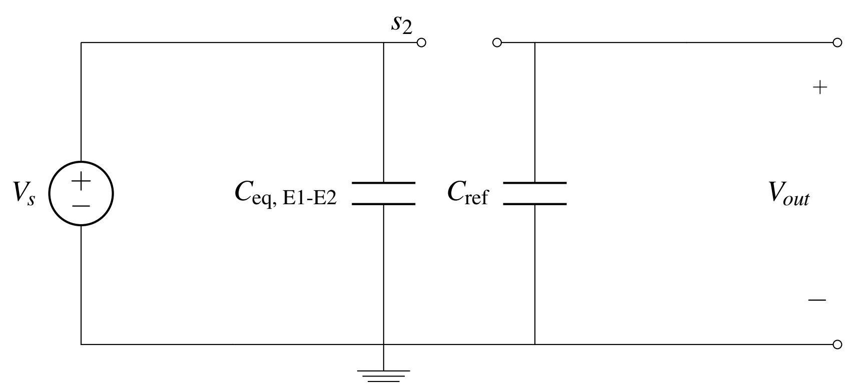


When s_1 is on, V_{out} is always the same as V_s and our second attempt fails.

- **Attempt #3** Let's now add another switch s_2 so that V_{out} no longer always equals V_s when s_1 is turned on.

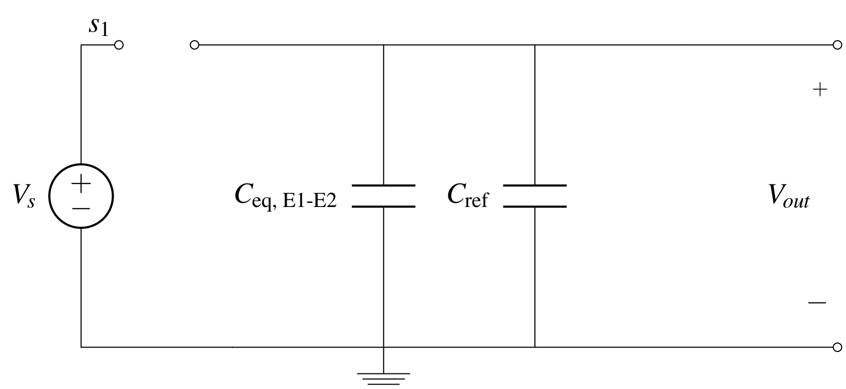


- **Phase 1:** s_1 is on and s_2 is off.



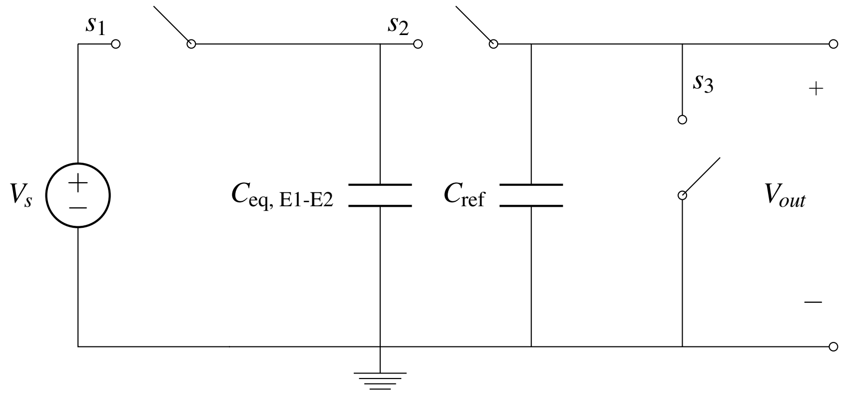
In phase 1, $C_{\text{eq, E1-E2}}$ is connected to voltage source V_s and C_{ref} is not connected to anything.

- **Phase 2:** s_1 is off and s_2 is on.

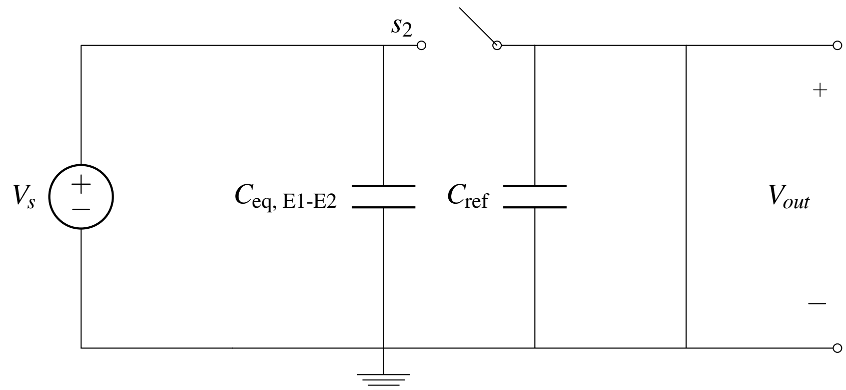


In phase 2, $C_{\text{eq, E1-E2}}$ is disconnected from V_s and C_{ref} is connected to $C_{\text{eq, E1-E2}}$. However, there is one serious problem with this circuit, since we are not sure what is the initial charge of C_{ref}, we cannot perform any circuit analysis. Our third attempt fails because the initial condition of C_{ref} is not clear.

- **Attempt #4** We learned from our third attempt that we must somehow know the initial condition of C_{ref}. How do we know the initial condition of C_{ref}? It turns out that we can acquire this missing piece of information by adding another switch s_3!

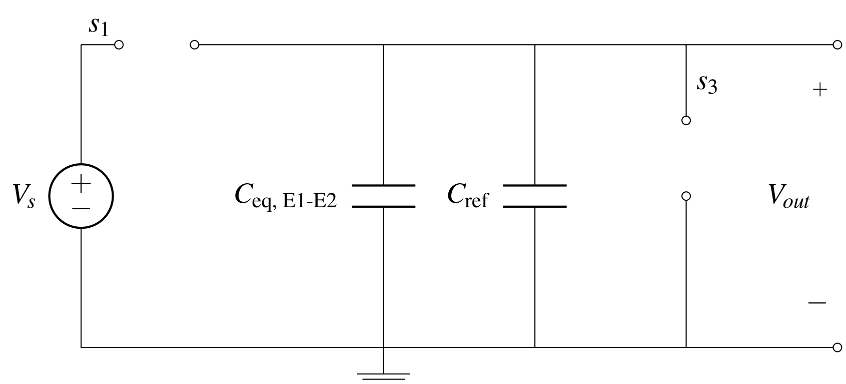


– **Phase 1:** s_1 is on, s_2 is off, s_3 is on.



In this phase, the voltage across $C_{\text{eq, E1-E2}}$ is V_s, and the voltage across C_{ref} is zero.

– **Phase 2:** s_1 is off, s_2 is on, s_3 is off.



In this phase, the voltage across $C_{\text{eq, E1-E2}}$ is the same as the voltage across C_{ref}.

How do we analyze this circuit? We know from last lecture that charge must be preserved for a capacitor, this indicates that:

$$Q_{\text{total, phase 1}} = Q_{\text{total, phase 2}}. \tag{3}$$

The total charge in each phase can be calculated by summing up $Q_{\text{eq, E1-E2}}$ and Q_{ref}.

$$Q_{\text{total, phase 1}} = Q_{\text{eq, E1 - E2}} + Q_{\text{eq, ref}} = C_{\text{eq, E1 - E2}} \times V_s + C_{\text{ref}} \times 0V. \tag{4}$$

$$Q_{\text{total, phase 2}} = Q_{\text{eq, E1 - E2}} + Q_{\text{eq, ref}} = C_{\text{eq, E1 - E2}} \times V_{out} + C_{\text{ref}} \times V_{out}. \tag{5}$$

From equations (4) and (5), we have:

$$C_{\text{eq, E1 - E2}} \times V_s + C_{\text{ref}} \times 0V = C_{\text{eq, E1 - E2}} \times V_{out} + C_{\text{ref}} \times V_{out}. \tag{6}$$

Therefore, we can derive the following equation for V_{out}:

$$V_{out} = \frac{C_{\text{eq, E1 - E2}}}{C_{\text{eq, E1 - E2}} + C_{\text{ref}}} \times V_s. \tag{7}$$

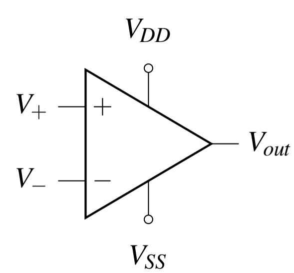
This particular circuit analysis approach we have used is called "charge sharing". "Charge sharing" refers to the sharing of charge among capacitors. Between different steady phases for a circuit, one important ground rule remains true: the total charge stored by all capacitors must always be the same. We can use the "charge sharing" approach to solve many capacitor problems.

Now we can solve for $C_{\text{eq, E1 - E2}}$ given V_{out}. Recall that we only want to figure out whether or not our finger is touching this pixel rather than $C_{\text{eq, E1 - E2}}$, we need some device that can transform the continuous $C_{\text{eq, E1 - E2}}$ value to some binary value: is there a finger pressing on top of this pixel? Or, more specifically, is $C_{\text{eq, E1 - E2}}$ greater than its default value when there is no finger touch?

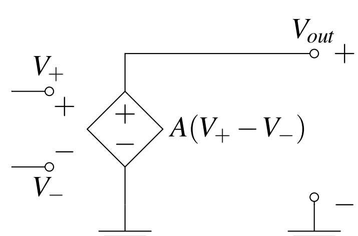
18.3 Comparator & Op-amp Basics

We want to figure out if there is a finger pressing on top of a pixel from V_{out}. In order to do so, we can use a comparator. Before explaining how a comparator works, we will first introduce the concept of op-amp.

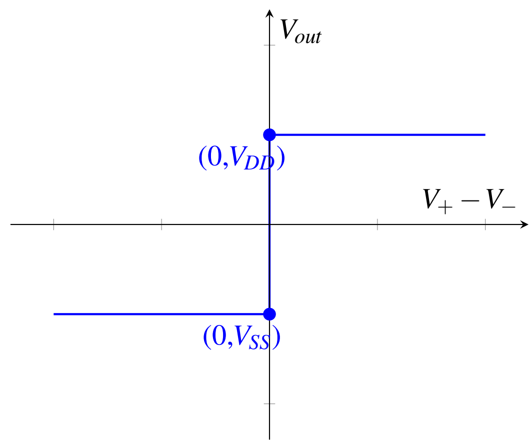
Op-amp (operational amplifier), by definition, is an amplifier that can amplify something small into something much bigger. For example, a speaker is an audio amplifier, if you connect your smart phone to a speaker, it can generate sounds much louder than your phone can do. The circuit symbol for an op amp is shown below:



We have two input terminals named V_+ and V_-, two power supply terminals named V_{DD} and V_{SS}, and one output terminal named V_{out}. The op-amp circuit can transform a voltage signal $(V_+ - V_-)$ into $(V_{out} - V_{SS})$. For the op amp to function correctly, we need to connect the two external voltage sources V_{DD}, V_{SS} to the op amp. What the symbol actually represents is the following



In the first circuit, we see a new symbol — a diamond with +/- signs inside. This represents a voltage-controlled voltage source where the voltage across it depends on the voltage(s) in other parts of the circuit. In this case, the voltage across the the voltage-controlled voltage source is $A\,(V_+ - V_-)$ where A is a constant. For any good op amps, the constant A term is very large – approaching infinity.
Equivalently, we have the following plot that describes the relationship between V_{out} and $V_+ - V_-$.



For any ideal op amp, when $V_+ < V_-$ ($V_+ - V_- < 0$), we have V_{out} equals V_{SS}; when $V_+ - V_- > 0$, we have V_{out} equals $V_{DD} - V_{SS}$. If we zoom in around $V_+ - V_- = 0$ by a million times, we will be able to see there is actually some finite slope associated with the transition region.
Now, we add an op-amp to the circuit model we built to extract $C_{\text{eq, E1-E2}}$.