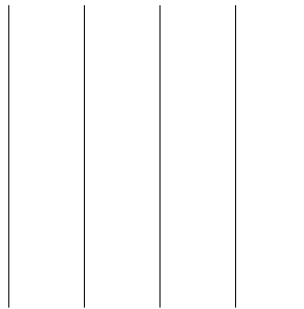
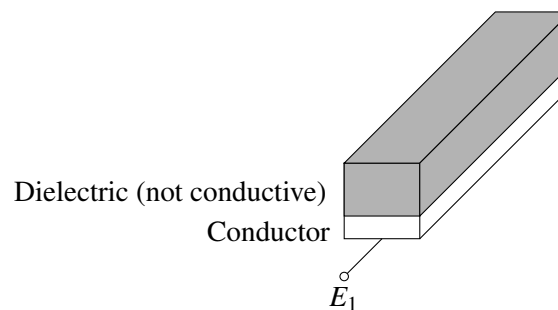


## 1D Capacitive touchscreen

Now that we've learned the basics of capacitors, let's see how a capacitive touchscreen works? Again, just like what we did for the resistive touchscreen, let's look at the "1D" version of a capacitive touchscreen first. If we look at the top view of the screen, we can think of it as having a bunch of parallel wires



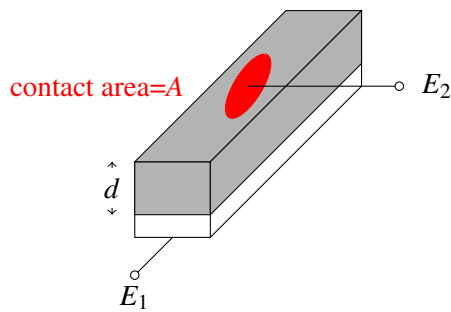
The idea is we can detect whether our finger is touching a particular wire. However, notice that we cannot distinguish the position at which we touch each wire on. Taking a closer look, each wire above can be modelled as follows



The grey layer (top layer) is made out of a dielectric material with permittivity  $\epsilon$  and the white layer (bottom layer) is a conductor. Suppose that we represent our finger (a conductor) as  $E_2$ . When our finger is not touching the wire, the capacitance between  $E_1$  and  $E_2$  is equal to zero, i.e.,

$$C_{E_1-E_2} = 0. \quad (1)$$

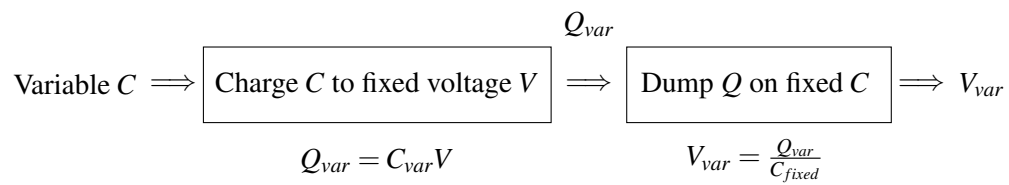
Now what happens when our finger touches the wire?



Let the red oval be the contact area of our finger and the wire. Suppose the contact area is equal to  $A$  and the thickness of the dielectric layer is equal to  $d$ . Then we know that the capacitance is equal to

$$C_{E_1-E_2} = \epsilon \frac{A}{d}. \quad (2)$$

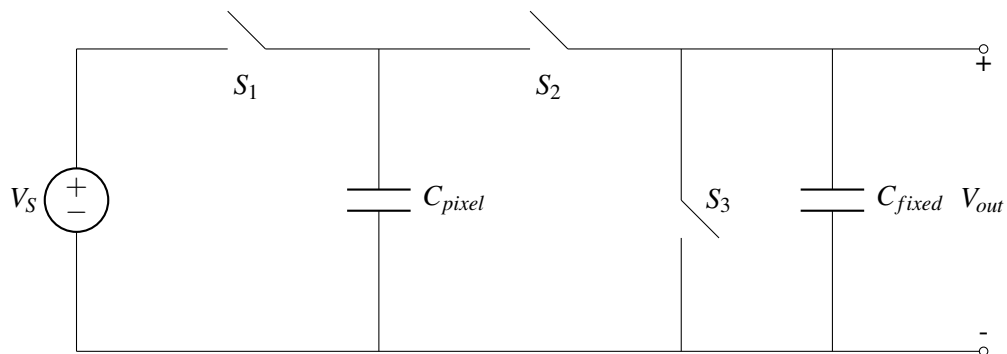
We see that the capacitance changes when your finger touches the screen. So in order to figure out whether we are touching the screen, we need a way to measure capacitance. Now let's look at how we can figure out the capacitance of a capacitor by measuring voltage. The block diagram associated with what we would like to achieve is



The idea is that we take the capacitor with variable capacitance (which in this case is our 1D touchscreen setup above) and connect it to a fixed voltage  $V$ . Now there will be  $Q_{var} = C_{var}V$  charge on this capacitor. Then we dump this charge on another capacitor with fixed capacitance  $C_{fixed}$ . The voltage across this capacitor with fixed capacitor will then be  $V_{var} = \frac{Q_{var}}{C_{fixed}}$ . So we can measure the final output voltage  $V_{var}$  and figure out what the variable capacitance  $C_{var}$  is!

## Charge sharing

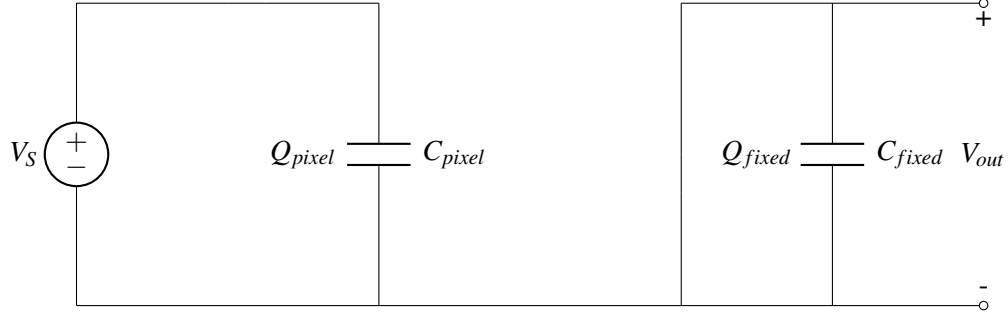
Let's see how to convert the above conceptual measurement procedure into an actual circuit.



Note that  $V_S$  is the fixed voltage source,  $C_{pixel}$  represents the variable capacitance at each pixel on the touchscreen,  $C_{fixed}$  represents the fixed capacitance, and  $V_{out}$  is the output voltage that we will measure. The way to go about analyzing circuits with switches is to redraw the circuit in each of the relevant phases.

**Phase 1:**

In the first phase of operation, we close switches  $S_1$  and  $S_3$ , and leave switch  $S_2$  open.



On the left, the fixed voltage source  $V_S$  charges up the capacitor  $C_{pixel}$ . Thus, the charge on  $C_{pixel}$  is

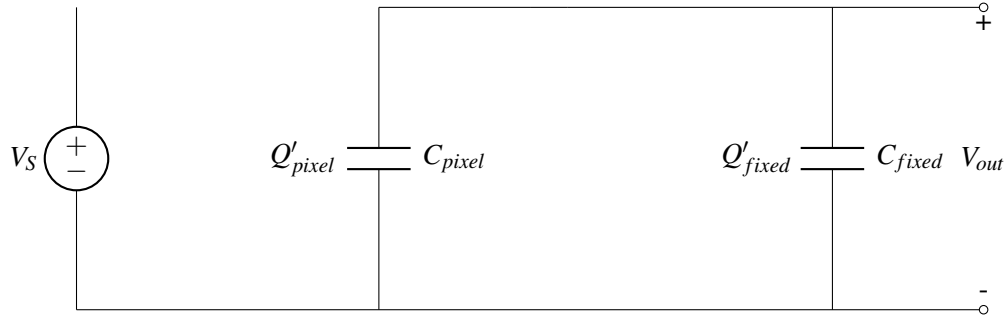
$$Q_{pixel} = C_{pixel}V_S. \quad (3)$$

Now let's ask the question: why do we need to close  $S_3$  as well? This is because we would like to initialize the voltage across capacitor  $C_{fixed}$  to be zero in order to make sure that there is no charge on  $C_{fixed}$ . Hence,

$$Q_{fixed} = 0. \quad (4)$$

**Phase 2:**

During phase 2, we open switches  $S_1$  and  $S_3$  and close switch  $S_2$ .



Now we see that  $C_{pixel}$  and  $C_{fixed}$  form a closed loop. We know that in the previous phase, the voltage across  $C_{pixel}$  was  $V_S$  and the voltage across  $C_{fixed}$  was zero. Hence, charges will have to flow from  $C_{pixel}$  to  $C_{fixed}$  until the voltage across both capacitors is the same. This process is called **charge sharing**. Assume that the switching happens instantaneously. Then the charges that were originally on  $C_{pixel}$  before stage 2 are confined in the closed loop. Let the final amount of charge on  $C_{pixel}$  and  $C_{fixed}$  be  $Q'_{pixel}$  and  $Q'_{fixed}$  respectively. We also know that at steady state the voltage across both capacitors would be the same and is just equal to  $V_{out}$ . By conservation of charge, we therefore have

$$Q_{\text{before}} = Q_{pixel} + Q_{fixed} = Q'_{pixel} + Q'_{fixed} = Q_{\text{after}} \quad (5)$$

$$C_{pixel}V_S + 0 = C_{pixel}V_{out} + C_{fixed}V_{out} \quad (6)$$

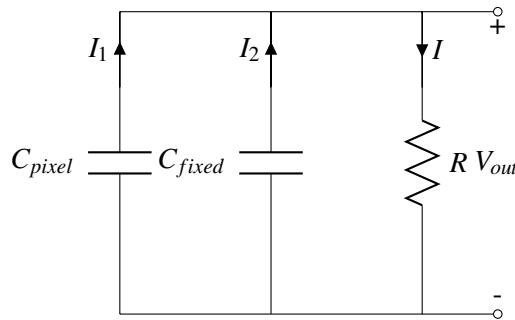
Hence we have

$$V_{out} = \frac{C_{pixel}}{C_{pixel} + C_{fixed}} V_S. \quad (7)$$

So if we measure  $V_{out}$ , we can uniquely solve for  $C_{pixel}$  to determine the capacitance, and hence whether or not a touch occurred.

## Comparators

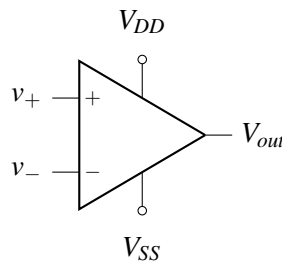
We've seen that we can get a voltage that depends on  $C_{pixel}$  from the above. However, in practice, in order to measure  $V_{out}$ , there may be some finite resistance that is connected to the circuit.



During phase 2 when the capacitor charge sharing is complete and there should be a voltage at  $V_{out}$ , current will have flowed through the resistor. Why is this a problem? Initially, we have some amount of energy stored in  $C_{pixel}$ . When current flows through the resistor, energy will be dissipated. Eventually, all the energy will be dissipated. Recalling that  $E = \frac{1}{2}CV^2$  in a capacitor, the  $V_{out}$  we measure would eventually have to be equal to zero. This would not be ideal. We want to somehow measure  $V_{out}$  without potential resistance interacting with the capacitors. It turns out that **op-amps (operational amplifiers)** can help us achieve this.

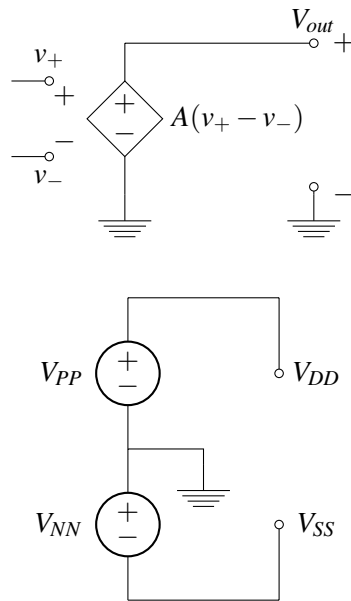
This is only one of the motivations for op amps – the other way is to get the **comparator** terminology.

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  $V_{out}$ .

What the symbol actually represents is the following



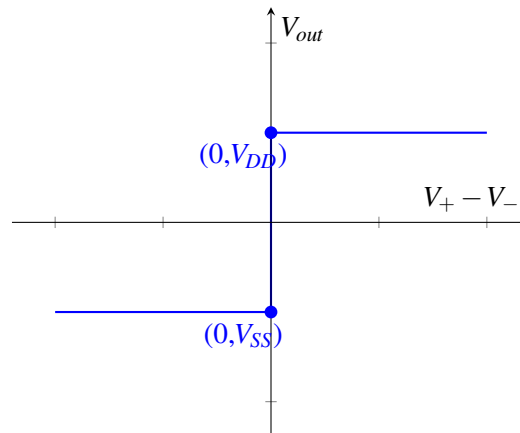
In the first circuit, we see a new symbol — a diamond with +/- signs inside. This represents a variable voltage source where the voltage across it depends on the voltage(s) in other parts of the circuit. In this case, the voltage across the variable voltage source is equal to  $A(v_+ - v_-)$  where  $A$  is a constant.

For any good op amps, the constant  $A$  term is very large – approaching infinity. Suppose there is a small difference between  $v_+$  and  $v_-$ , what would  $V_{out}$  be? We know that  $V_{out} = A(v_+ - v_-)$  so it may look like  $V_{out}$  will either be a very positive number or a very negative number. However, notice that our power supply is  $V_{PP}$  and  $V_{NN}$ ; hence our output voltage cannot possibly be larger than  $V_{DD} = V_{PP}$  or smaller than  $V_{SS} = -V_{NN}$ , i.e.,

$$-V_{NN} \leq V_{out} \leq V_{PP}. \quad (8)$$

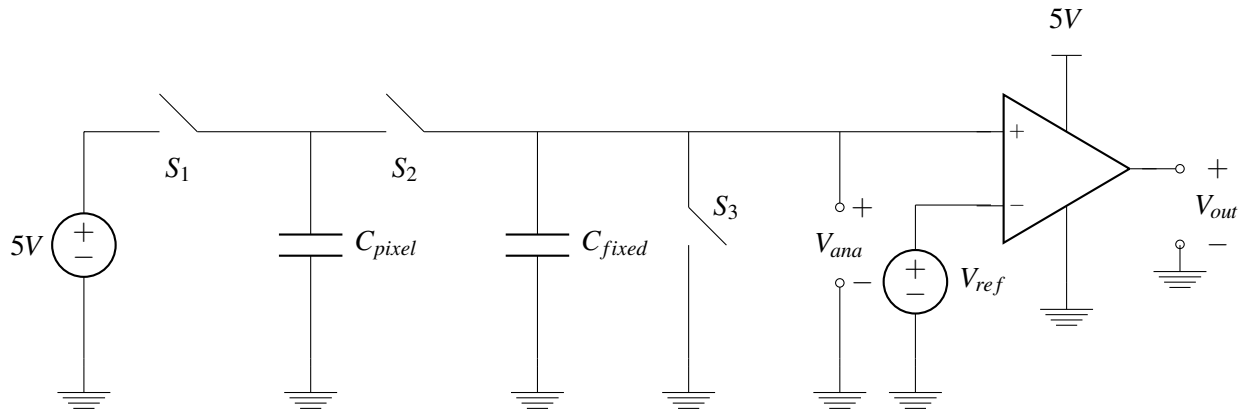
So notice that when the difference between  $v_+$  and  $v_-$ ,  $v_+ - v_-$ , is just slightly above or below zero, the output voltage would be  $V_{DD}$  or  $V_{SS}$  respectively. This essentially gives us a way to compare  $v_+$  and  $v_-$ ! When  $v_+ > v_-$ , then  $V_{out} = V_{DD}$ ; when  $v_+ < v_-$ ,  $v_{out} = V_{SS}$ .

Equivalently, we have the following plot that describes the relationship between  $V_{out}$  and  $v_+ - v_-$ .



It may seem like the output voltage jumps from  $(0, V_{SS})$  to  $(0, V_{DD})$  directly. However, in fact, there is a very steep line of slope  $A$  going from  $(-\epsilon, V_{SS})$  to  $(\epsilon, V_{DD})$  where  $\epsilon$  is very close to 0 since  $A$  is very large.

Now let's go back to touchscreen circuit design example and see how using comparators could avoid the problems mentioned earlier.



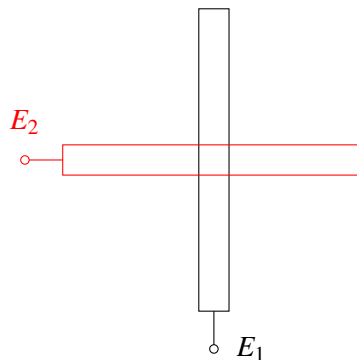
We know that as described earlier,

$$V_{ana} = \frac{C_{pixel}}{C_{pixel} + C_{fixed}} \times 5V. \quad (9)$$

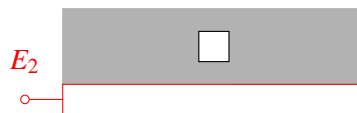
Then we can choose  $C_{fixed}$  and  $V_{ref}$  such that  $V_{ana} > V_{ref}$  when there was a touch (in this case  $V_{out} = 5V$ ), and  $V_{ana} < V_{ref}$  when there is not a touch (in this case  $V_{out} = 0V$ ).

## 2D capacitive touchscreen

Now let's look at how a 2D capacitive touchscreen could work. Here's the top view of our arrangement



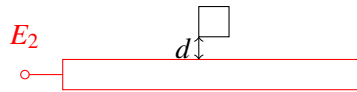
And here's the side view of our arrangement



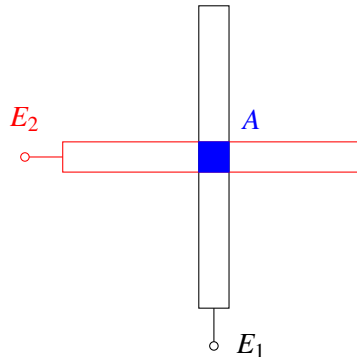
The shaded area is the dielectric. Now let's look at what happens when there is no touch.

**No touch:**

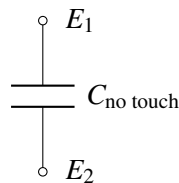
Let the distance between the vertical and horizontal bar be  $d$ .



And let the cross-sectional area be  $A$ .

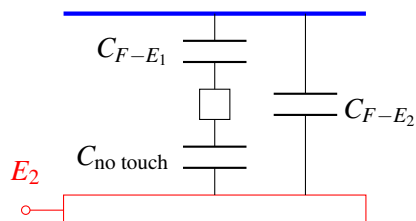


Thus, the capacitance when there is no touch is:

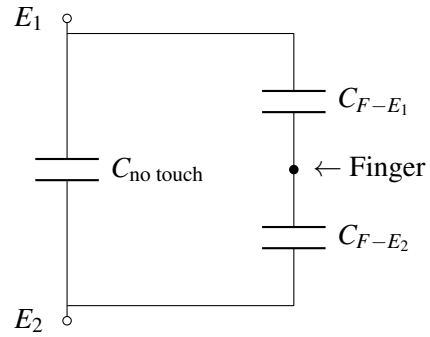


$$C_{E_1-E_2} = C_{\text{no touch}} = \epsilon \frac{A}{d}. \quad (10)$$

**With touch:** Let's see what happens when there is a touch. Let the blue line represent our finger, which is essentially touching the dielectric.



$C_{F-E_1}$  is the capacitance between our finger and electrode  $E_1$  and  $C_{F-E_2}$  is the capacitance between our finger and electrode  $E_2$ . Equivalently, in circuit form, we have the following



So when there is a touch, the capacitance is equal to

$$C_{E_1-E_2} = C_{\text{no touch}} + C_{F-E_1} \parallel C_{F-E_2} \quad (11)$$

$$= C_{\text{no touch}} + \frac{C_{F-E_1} C_{F-E_2}}{C_{F-E_1} + C_{F-E_2}}. \quad (12)$$

Now we can use the same capacitance measurement (+comparator) circuit we developed earlier using op-amps to determine whether there is a touch or not for the 2D case.