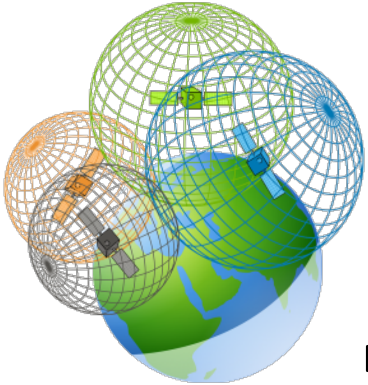
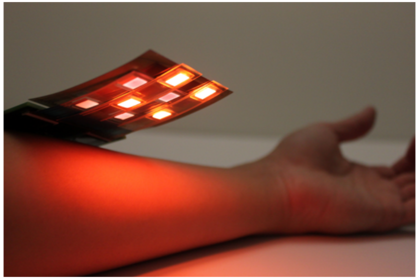




Welcome to EECS 16A!

Designing Information Devices and Systems I

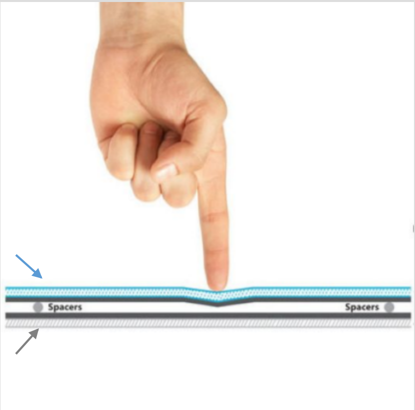
Ana Claudia Arias and Miki Lustig

Fall 2021

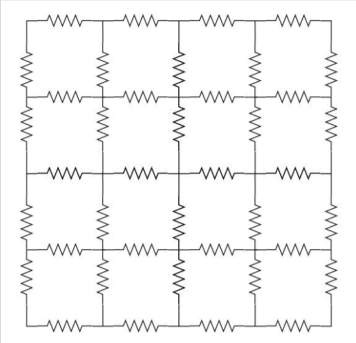
Module 2
Lecture ~~5~~ 7
Capacitors
(Note 16)

Now that we understand 2D resistive touchscreen, let's change it!

resistive sheet



resistive sheet



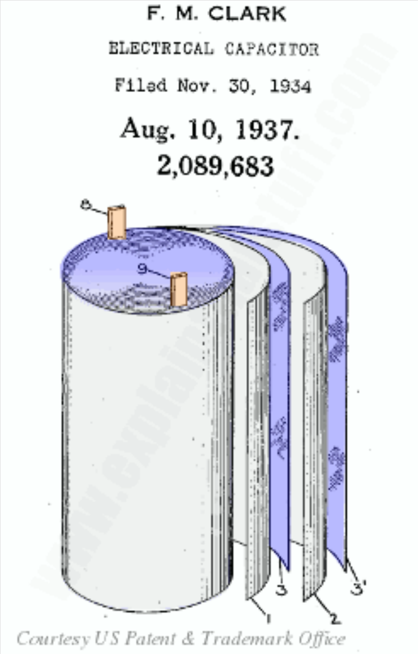
Circuit model for each resistive sheet is a grid of resistors

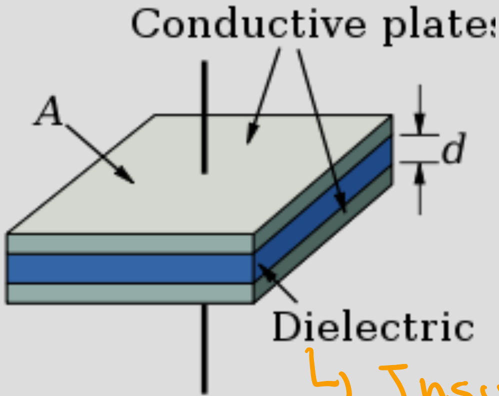
real-world touchscreens are usually capacitive, not resistive:

- **don't need to be flexible**
- **multi-touch is easier**
- **more sensitive**
- **increased contrast on screen**

Now, Capacitors!

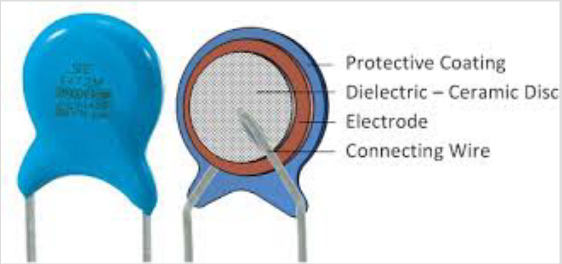
- Charge storage device (like a 'bucket' for charge)

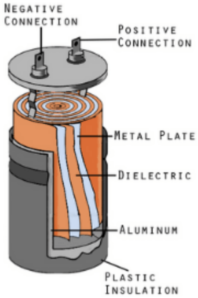


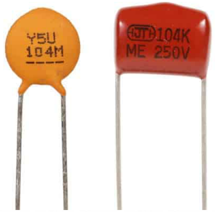


↳ Insulator

↳ Higher Energy is needed to move charge.

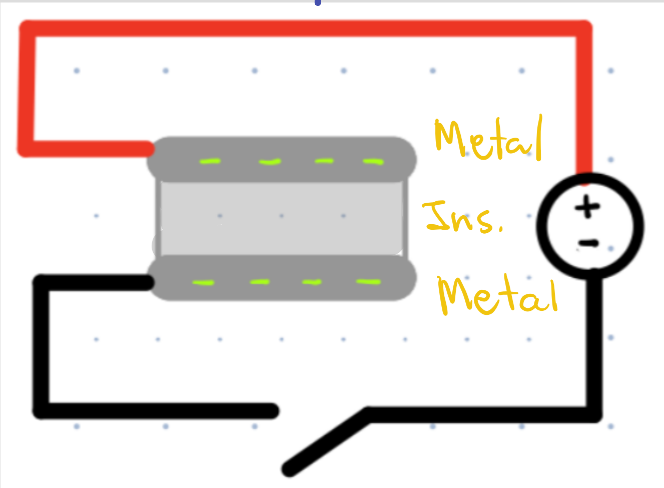






The Physics of a Capacitor

* Energy is needed to move charge.



e^-

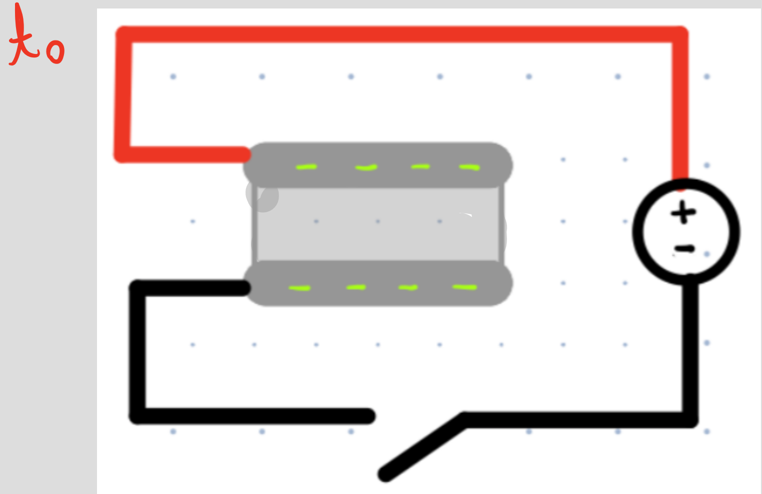
→ No current across the capacitor plates

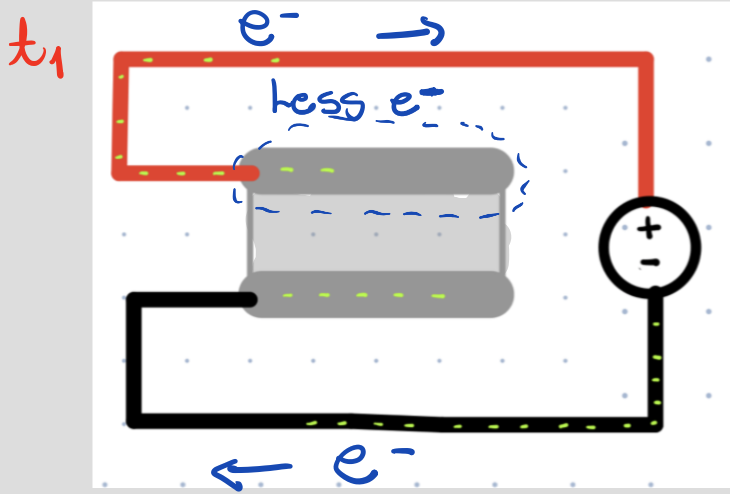
→ Voltage Source provides Energy needed for flow of charges (e^-)

https://www.youtube.com/watch?v=X4EUwTwZ110

The Physics of a Capacitor

→ Once the switch is ON e^- flow!

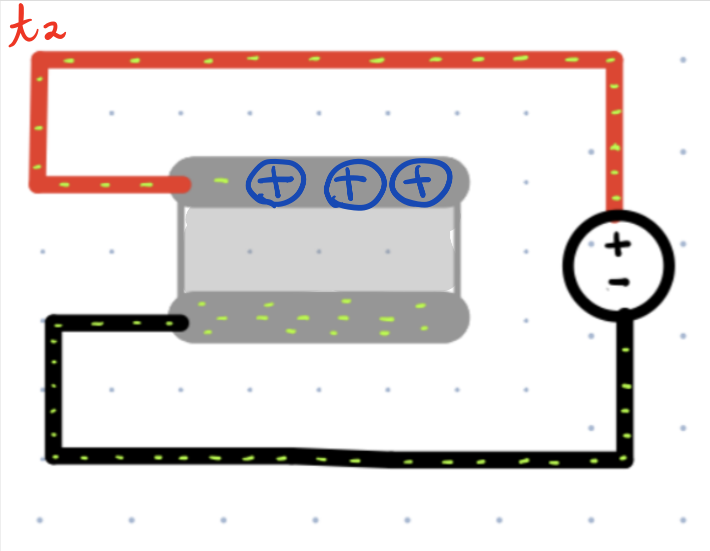


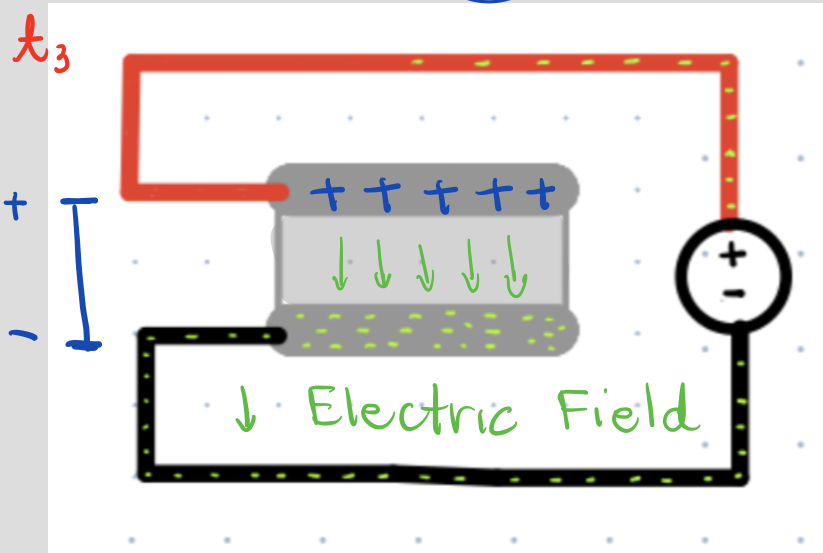


https://www.youtube.com/watch?v=X4EUwTwZ110

The Physics of a Capacitor

Lack of electrons means holes! h^+

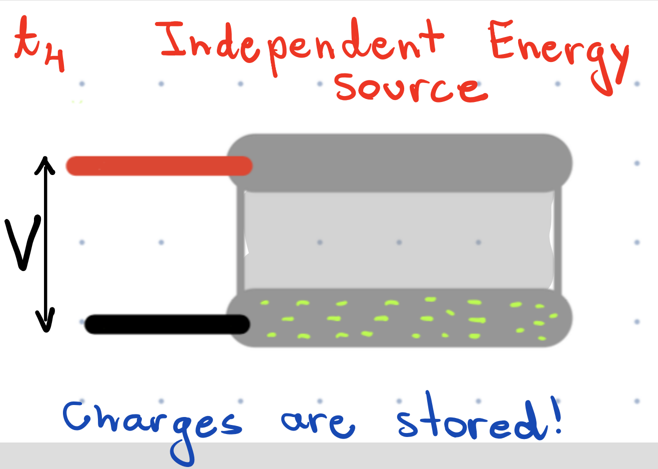




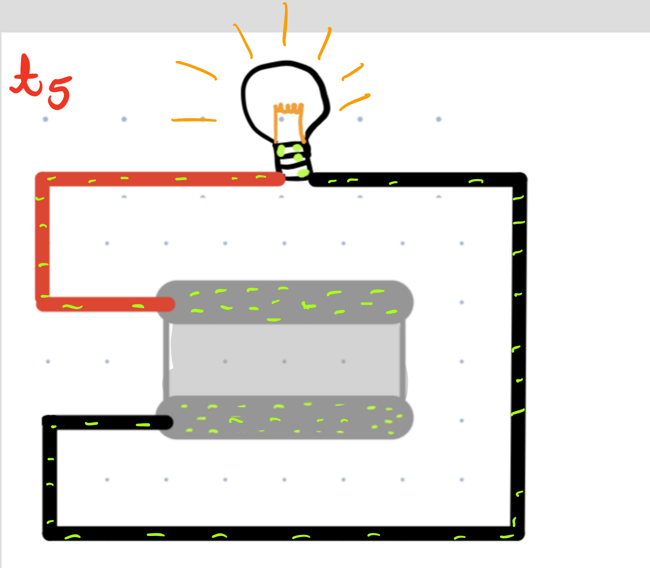
Potential difference between the two plates! $\}$ V

https://www.youtube.com/watch?v=X4EUwTwZ110

The Physics of a Capacitor



Every Capacitor can be charged up to a fixed Voltage.



The capacitor will charge a "load" until the charges on the plate are equalized. (No change in V)

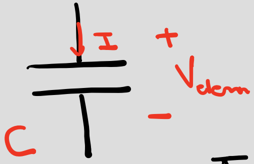
https://www.youtube.com/watch?v=X4EUwTwZ110

Charge storage device (like a ‘bucket’ for charge)

Holds electric charge when we apply a voltage across it, and gives up the stored charge to the circuit when voltage removed

Circuit Model: IV relationship

Capacitor Symbol



$$Q_{elem} = C \cdot V_{elem}$$

$[C] \quad [F] \quad [V]$

(Farad)

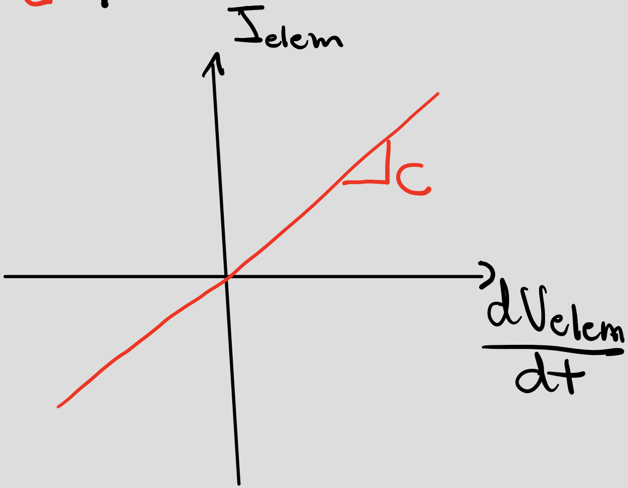
We know : $I_{elem} = \dfrac{dQ_{elem}}{dt}$

$$I_{elem} = \frac{d}{dt} C \cdot V_{elem}$$

C = constant over time

$$\boxed{I_{elem} = C \cdot \frac{dV_{elem}}{dt}}$$

↳ Can use the same 7-step analysis.



Capacitance

$$C = \varepsilon \frac{A}{d}$$

$$[F] = \left[\frac{F}{m}\right]\left[\frac{m^2}{m}\right]$$

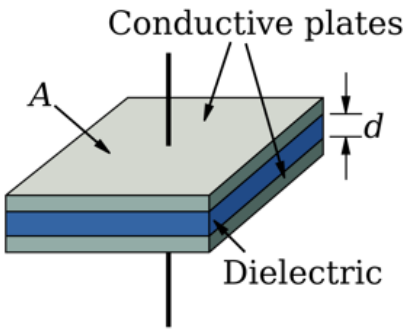
Depends on:

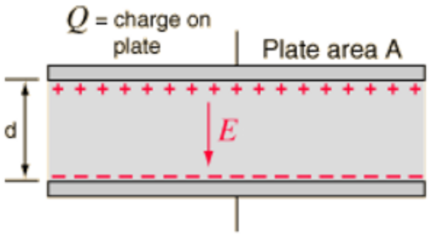
- Materials : ε permitivity

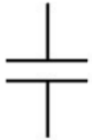
  $\varepsilon_0 = 8.85 \cdot 10^{-12}\ F/m$

  $\varepsilon = \varepsilon_0 \varepsilon_r$

- Geometry of Conductors



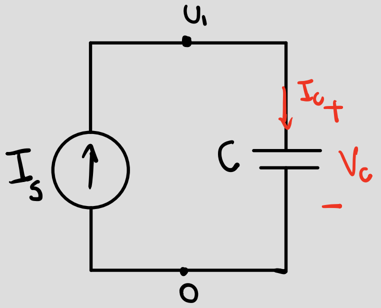


Symbol: 

Capacitance: C Units: Farads [F]

IV equation: $I = C \cdot \frac{dV}{dt}$

Simple Circuit 1



KCL : $I_s = I_c$

Element Def.:

$$I_c = C \cdot \frac{dV_c}{dt}$$

Voltage Def:

$$U_1 - 0 = V_c$$

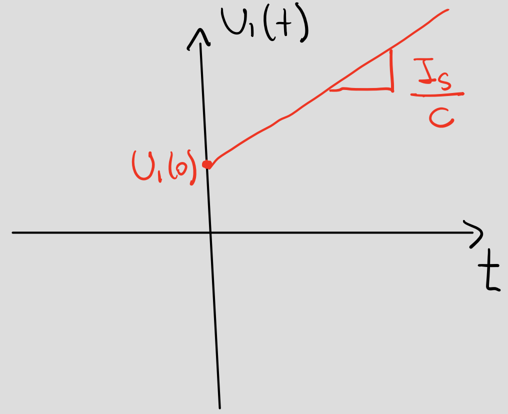
$$\boxed{I_s = C\,\frac{dU_1}{dt}} \times dt$$

$$I_s \cdot dt = C\, dU_1$$

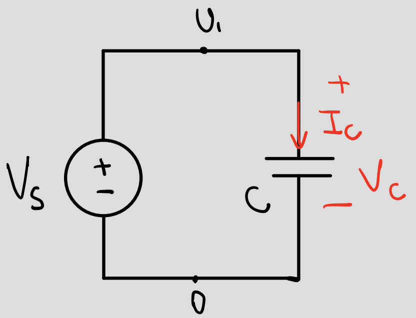
$$\int_0^t I_s\, dt = \int_{U_1(0)}^{U_1(t)} C \cdot dU_1$$

$$I_s t = C \cdot \big(U_1(t) - U_1(0)\big)$$

$$U_1(t) = \frac{I_s}{C} \cdot t + U_1(0)$$



Simple Circuit 2



$$U_1 - 0 = V_s$$
$$U_1 - 0 = V_c$$
} Voltage Def.

$$V_s = V_c$$

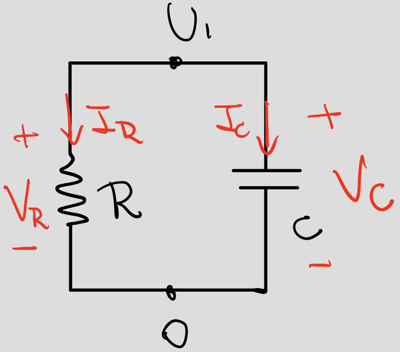
$$I_c = C \frac{dV_c}{dt} \quad \text{(capacitor Def.)}$$

$$I_c = C \frac{dV_c}{dt} = C \cdot \cancel{\frac{dV_s}{dt}}^{\,0} = 0$$

Current in a capacitor is zero when a constant Voltage source is across it.

Hint: We like zeros ... they make our lives easier!

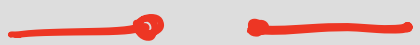
Simple Circuit 3



$U_1 = ?$

Steady State:
means the Voltages settled.

If current is zero $\Rightarrow$



looking for U_1 value when

$V_c = \text{const.}$ (steady-state)

$$I_c = C \frac{\cancel{dV_c}^{\,0}}{\cancel{dt}} = 0$$

KCL: $\cancel{I_c}^{\,0} + I_R = 0$

$I_R = 0$

Ohm's Law: $V_R = \cancel{I_R}^{\,0} R = 0$

Voltage Def: $U_1 - 0 = \cancel{V_R}^{\,0}$

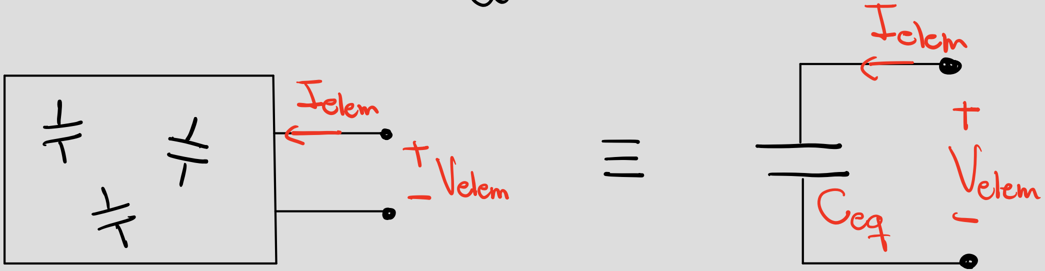
$$\boxed{U_1 = 0}$$

Equivalent Circuits with Capacitors

* Capacitor-only circuits

~~Step 1 : find V_{th} and I_{No}~~ no source

Step 2 : $C_{eq} = \dfrac{I_{elem}}{\dfrac{dV_{elem}}{dt}}$



Only if (match $\dfrac{dV_{elem}}{dt}$)

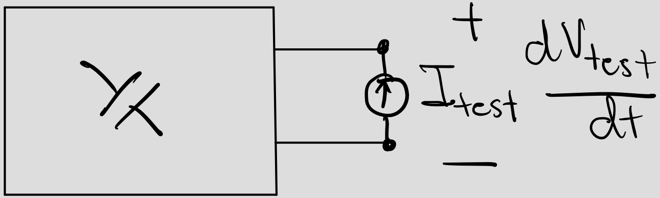
Two Methods:

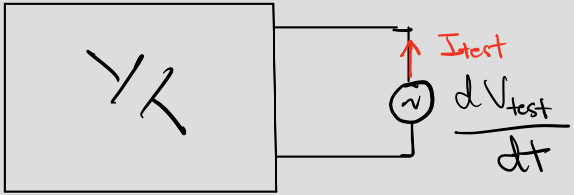
a) Apply I_{test} and measure $\frac{dV_{test}}{dt}$

b) Apply $\frac{dV_{test}}{dt}$ and measure I_{test}

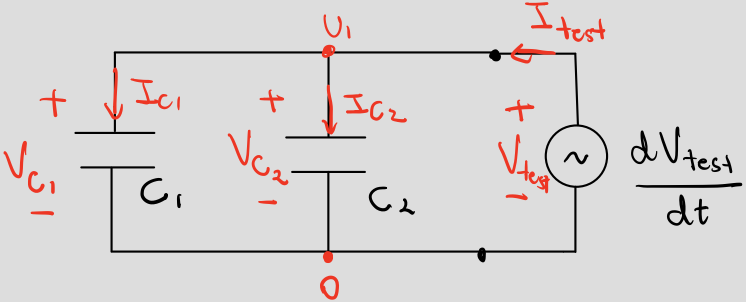
$$= C_{eq} = \frac{I_{test}}{\frac{dV_{test}}{dt}}$$

(a)





Example 1



$V_{C_1} = U_1$, $V_{C_2} = U_1$ and

$U_1 = V_{test}$

$$\frac{dU_1}{dt} = \frac{dV_{test}}{dt}$$

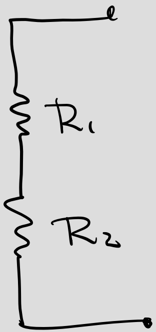
Elem def: $I_{C_1} = C_1 \frac{dV_1}{dt} = C_1 \frac{dU_1}{dt} = C_1 \frac{dV_{test}}{dt}$

Elem def: $I_{C_2} = C_2 \frac{dV_2}{dt} = C_2 \frac{dU_1}{dt} = C_1 \frac{dV_{test}}{dt}$

KCL: $I_{test} = I_{C_1} + I_{C_2} = C_1 \frac{dV_{test}}{dt} + C_2 \frac{dV_{test}}{dt}$

$$I_{test} = (C_1 + C_2)\frac{dV_{test}}{dt}$$

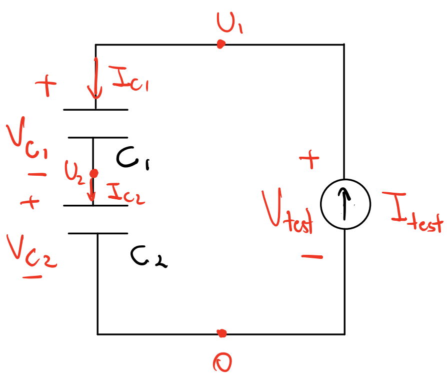
$$\boxed{C_{eq} = \frac{I_{test}}{\frac{dV_{test}}{dt}} = C_1 + C_2}$$



$$\equiv R_{eq} = R_1 + R_2$$

Series

Example 2 : "Capacitors in series"



KCL : $I_{C_1} = I_{C_2} = I_{test}$

Elements :

$$I_{C_2} = C_2 \frac{dV_{C_2}}{dt}$$

$$I_{C_1} = C_1 \frac{dV_{C_1}}{dt}$$

Voltage Def :

$$V_{C_2} = U_2 - 0$$

$$V_{C_1} = U_1 - U_2$$

$$V_{test} = U_1 - 0$$

For V_{C_2}:

$$I_{C_2} = C_2 \frac{dV_{C_2}}{dt}$$

$$I_{test} = C_2 \frac{dU_2}{dt} \equiv \frac{dU_2}{dt} = \frac{I_{test}}{C_2}$$

For V_{C_1}

$$I_{C_1} = C_1 \frac{dV_{C_1}}{dt}$$

$$\frac{dV_1}{dt} = \frac{I_C}{C_1} = \frac{dU_1 - dU_2}{dt} = \frac{I_{test}}{C_1}$$

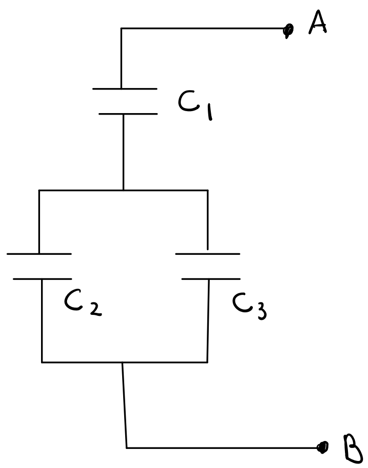
$$\frac{dU_1}{dt} = \frac{dU_2}{dt} + \frac{I_{test}}{C_1} = \frac{I_{test}}{C_2} + \frac{I_{test}}{C_1}$$

$$\frac{dU_1}{dt} = \frac{dV_{test}}{dt} = I_{test}\left(\frac{1}{C_2} + \frac{1}{C_1}\right)$$

$$C_{eq} = \frac{I_{test}}{\frac{dV_{test}}{dt}} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}} = \frac{C_1 C_2}{C_1 + C_2} = C_1 \| C_2$$

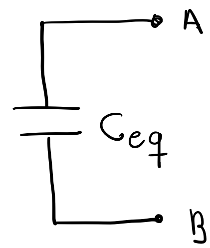
$$C_{eq} = C_1 \| C_2 \quad (\| - \text{parallel mathematical operator})$$

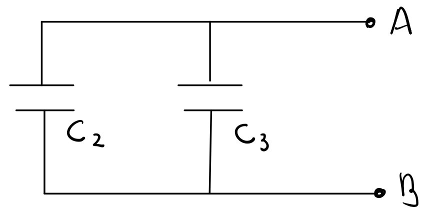
Example 3



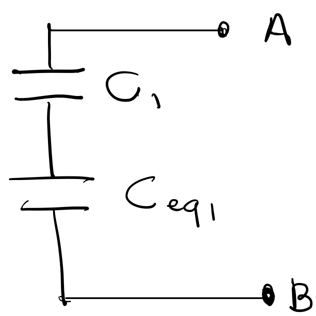
$$C_{eq} = C_1 \parallel (C_2 + C_3)$$

$\equiv$



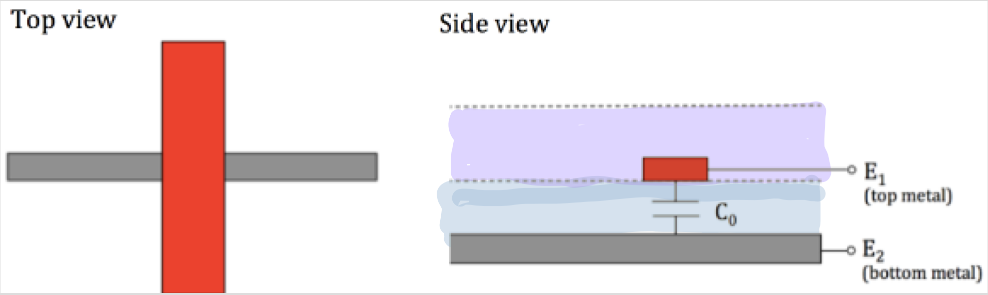


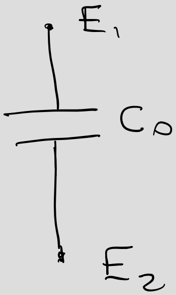
$\Rightarrow$ $C_{eq_1} = C_2 + C_3$



$$C_{eq} = C_1 \parallel C_{eq_1}$$

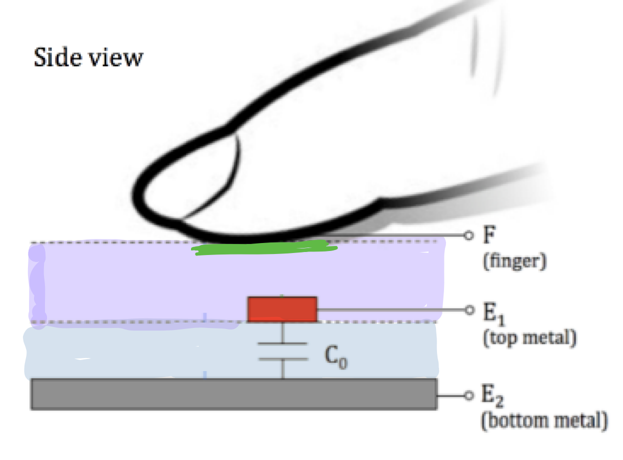
Capacitive Touchscreen – Model without touch



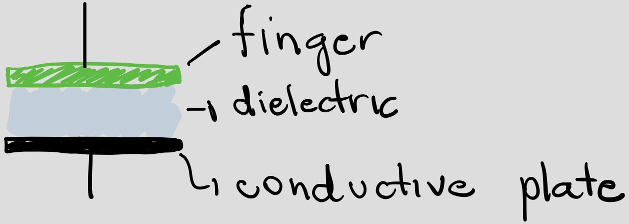


$$C_0 = \varepsilon \cdot \frac{A}{d}$$

Capacitive Touchscreen – Model with touch

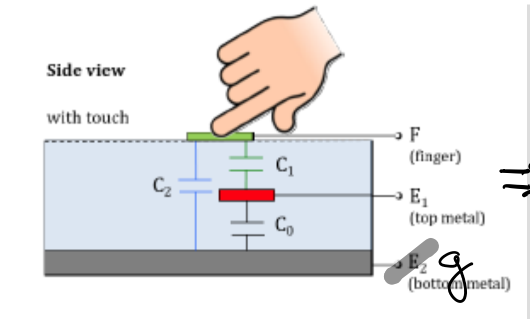


When there is a touch, it makes a capacitor!

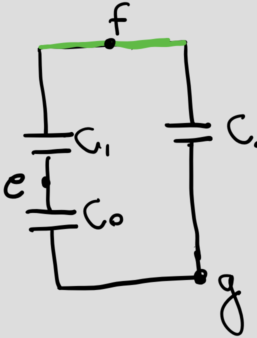


Problem: How can Voltage/Current when the finger is one of the terminals?

Solution: Models / Good architecture

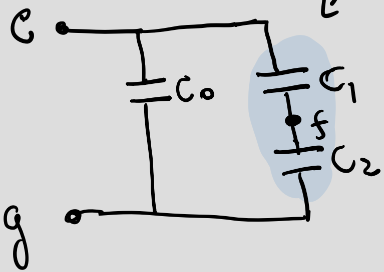


$\Rightarrow$ circuit model

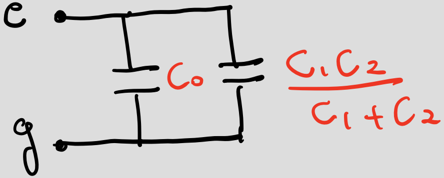


We only have acess to nodes e and g, not f

Redraw to focus on terminals (nodes) e and g

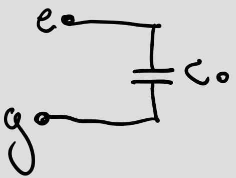


Equivalent capacitance for C_1 in series with C_2

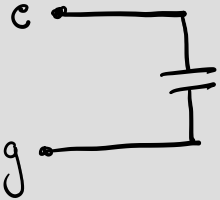


$\Rightarrow$ Equiv. Capacitance for C_0 in parallel to $\frac{C_1 C_2}{C_1 + C_2}$

when no touch:



with touch:



$C_0 + \frac{C_1 C_2}{C_1 + C_2}$

Extra Capacitance due to touch!