Welcome to EECS 16A!
Designing Information Devices and Systems I

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Module 2
Lecture 9
Capacitance Modeling and Comparator
(Note 18)
We want to measure capacitance here.

\[ C_0 \]  

\[ \frac{C_1 C_2}{C_1 + C_2} = C_A \quad \text{(change)} \]

This capacitor goes away with no touch.

Problem: We don't have a capacitor!

We will try ideas to get to a final model.
Measuring Capacitance Models – Attempt #1

If there is touch: \( V_c = V_s \)
If there is no touch: \( V_c = V_s \)
\( V_{out} \) does not change!
Need a better idea...

Assume \( C_{eq} \) starts out discharged
\( V_{out}(t=0) = 0 \)
\( I_s = C_{eq} \frac{dV_{out}(t)}{dt} \rightarrow V_{out}(t) = \int \frac{I_s}{C_{eq}} dt \)

\( V_{out} = \frac{I_s \cdot t}{C_{eq}} \rightarrow C_{eq} = \frac{I_s \cdot t}{V_{out}} \)

We will learn how to design current sources in EE140.
Measuring Capacitance Models – Attempt #2 – add switches and a reference capacitor

We want to charge $C_{ref}$ and measure $V_{out}$ as $C_{ref}$ discharges.

**Phase 1**

Close $S_1$, Open $S_2$  
$C_{eq}$ charges  
$q = C_{eq} \cdot V_s$  
(charge accumulates on capacitor plates)

If $S_1$ and $S_2$ are both closed – we have attempt #1
Measuring Capacitance Models – Attempt #2 – add switches and a reference capacitor

Phase 2

1. Close S2; Open S1.
2. There is a path for charge to move.
3. $C_{eq}$ provides the energy needed for current.

Charge will be shared between $C_{eq}$ and $C_{ref}$: charge sharing.

Very close!
But... we don't know the initial value of $C_{ref}$.
Measuring Capacitance Models – Attempt #3 – known initial condition

Use $S_3$ to discharge $C_{ref}$ so we know $C_{ref} = 0$

- **Phase 1**
  - $S_1$ closed, $S_2$ open, $S_3$ closed
  - $C_{ref}$ discharges $V_{out} \rightarrow 0$
  - $q = C_{eq} \cdot V_{out} = 0$
    - $V_{out} = 0$

- **Phase 2**
  - $S_1$ open, $S_2$ closed, $S_3$ open
  - $C_{eq}$ charged
  - $C_{ref}$ discharged

$q = C_{eq} \cdot V_s$
Measuring Capacitance Models – Attempt #3 – known initial condition

Voltage across $C_{eq}$: $V_{out}$
Voltage across $C_{ref}$: $V_{out}$
Charge in $C_{eq}$: $q_1 = C_{eq} \cdot V_{out}$
Charge in $C_{ref}$: $q_2 = C_{ref} \cdot V_{out}$

Total charge is conserved!

$q_{(\text{phase1})} = q_{(\text{phase2})}$

$C_{eq} \cdot V_s = C_{eq} \cdot V_{out} + C_{ref} \cdot V_{out}$

$V_{out} = \frac{C_{eq} \cdot V_s}{C_{eq} + C_{ref}} \implies V_{out}$ changes when $C_{eq}$ changes!
Effect of touch on total capacitance

When no touch:
\[ V_{OUT} = \frac{C_0}{C_0 + C_{res}} \cdot V_S \]

With touch:
\[ V_{OUT} = \frac{(C_0 + C_\Delta)}{C_0 + C_\Delta + C_{res}} \cdot V_S \]
How can we go from voltage measurement to binary answer: touch or no touch?

- We need to choose a Voltage that we call: Threshold Voltage ($V_{\text{th}}$)
- Above $V_{\text{th}}$ : 1 (touch)
- Below $V_{\text{th}}$ : 0 (no-touch)

We need to compare Voltages to determine if 1 or 0.
How can we go from voltage measurement to binary answer: touch or no touch?

• New tools are needed – new circuit elements
An example of an Op-amp circuit diagram

Schematic diagram of a model 741 op-amp.
Operational Amplifier

An op-amp (operational amplifier) is a device that transforms a small voltage difference into a very large voltage difference.

An op-amp has two input terminals marked (+) and (−) with potentials $U_+$ and $U_-$, two power supply terminals called VDD and VSS, and one output terminal with potential $U_{out}$.

$V_d = U_+ - U_-$

The output voltage $V_{out}$ is given by:

$$V_{out} = V_{SS} + \frac{V_{DD} - V_{SS} + A \cdot V_d}{2}$$

when

$$V_{SS} \leq \frac{V_{DD} - V_{SS} + A \cdot V_d}{2} \leq V_{DD}$$
Operational Amplifier

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\[
\frac{V_{DD} - V_{SS}}{2} + AV_+ \quad V^* 
\]

\[
V_{out} = V_{DD} \quad \text{if} \quad V^* > V_{DD}
\]

\[
V_{out} = V_{SS} \quad \text{if} \quad V^* < V_{SS}
\]

Can be used to compare Voltage
Comparator – optimized for binary output

$V_{DD}$ can be much higher than $V_{SS}$, it amplifies the signal.
Comparator – optimized for binary output

Also optimized for speed

\[
\begin{align*}
\text{if} & : \ V_c(+) > V_{\text{th}} \\
V_{\text{out}} & = V_{DD} \\
\text{if} & : \ V_c(+) \leq V_{\text{th}} \\
V_{\text{out}} & = V_{SS}
\end{align*}
\]
Back to our Capacitive Touchscreen

\[ C_{eq} \Rightarrow C_0 + C_A \quad \text{touch} \]
\[ C_0 \quad \text{no touch} \]
\[ V_{touch} \quad \text{touch} \]

\[ \text{Should be halfway between } V_{touch} \text{ and } V_{no-touch} \]