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

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Module 2
Lecture 9
Operational Amplifier and Comparator
(Note 18)
when no touch:

\[ V_{OUT} = \frac{C_0}{C_0 + C_{eq}} \cdot V_S \]

with touch:

\[ V_{OUT} = \frac{(C_0 + C_\Delta)}{C_0 + C_\Delta + C_{eq}} \cdot V_S \]
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 ($V_{th}$)
- Above $V_{th}$ : 1 (touch)
- Below $V_{th}$ : 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 $V_{DD}$ and $V_{SS}$, and one output terminal with potential $U_{out}$.

$V_d = U_+ - U_-$

$V_{out} = V_{SS} + \frac{V_{DD} - V_{SS}}{2} + AV_d$

when

$V_{SS} \leq \frac{V_{DD} - V_{SS} + AV_d}{2} \leq V_{DD}$
An op-amp (operational amplifier) is a device that transforms a small voltage difference into a very large voltage difference.

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$$\frac{V_{DD} - V_{SS}}{2} + AV_a = V^*$$

$$V_{out} = V_{DD} \text{ if } V^* > V_{DD}$$

$$V_{out} = V_{SS} \text{ if } V^* < V_{SS}$$

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

\[ V_{out} = \begin{cases} 
V_{DD} & \text{if } V_{C}^{(+)} > V_{TH} \\
V_{SS} & \text{if } V_{C}^{(+)} \leq V_{TH} 
\end{cases} \]
Back to our Capacitive Touchscreen

\[ C_{eq} \Rightarrow C_{o} + C_{f} - \text{touch} \]
\[ C_{o} - \text{no touch} \]

\[ \text{no touch} \rightarrow V_{ss} \]

\[ \text{UDD touch} \]

\[ \text{Should be halfway between } V_{touch} \text{ and } V_{no-touch} \]
New Design – Let’s play music

* Want to play music LOUD

- Music is stored as digital signal

Digital → Analog

DAC

3.3V = V_{DD}

0 = V_{SS}

Digital-to-analog converter

V_{OUT, DAC}

Takes voltage and turns into sound

Dance!

R_{TH}

V_{TH} + V_{OUT, DAC}

R_{Speaker}
Digital to Analog Converter - DAC

**Voltage Divider**

\[ V_{\text{TH}} = 1 \, \text{kΩ} \]

\[ V_{\text{Speaker}} = \frac{R_{\text{Speaker}}}{R_{\text{TH}} + R_{\text{Speaker}}} \cdot V_{\text{TH}} \]

\[ V_{\text{Speaker}} = \frac{V_{\text{TH}}}{126} \]

- Not loud!
- Too quiet!

Need to isolate DAC.
Digital to Analog Converter - DAC

\[ V_{DD} = -V_{SS} = 5V \]

10V output (Input)

\[ V_d = U^+ - U^- = V_{th} - V_{ref} \]

(KUL) \[ V_{speaker} = V_{ss} + \frac{V_{DD} - V_{SS}}{2} + A_{Vd} = A_{Vd} \]

when:

\[ V_{ss} < A_{Vd} < V_{DD} \]
Digital to Analog Converter - DAC

Need to isolate DAC with controllable gain!
Negative Feedback

\[ S_{err} = S_{in} - S_{fb} \]
\[ S_{out} = A \cdot S_{err} \]
\[ S_{fb} = f \cdot S_{out} \]
\[ \frac{S_{out}}{A} = S_{in} - S_{fb} \]
\[ S_{out} \left( \frac{1}{A} + f \right) = S_{in} \]
\[ S_{out} = \frac{1}{A + f} = \frac{A}{1 + Af} \]

- Making small adjustments to correct output on the fly
- Basis of control theory
- Many examples in daily life:
  - Biology
  - Self-driving car
  - Human driving car
  - Hand-eye coordination
Negative Feedback

\[ \frac{S_{out}}{S_{in}} = \frac{A}{1 + A \delta} \]

- Describes the behaviour of the system - transfer function.
- How \( S_{out} \) depends on \( S_{in} \)

\[ \frac{S_{out}}{S_{in}} \rightarrow \infty f \]

\( \uparrow \) We control the output via block \( \square \)!

So \( V_{out} = \frac{1}{f} V_{in} \) for very large gain.

\( \downarrow \) we can set \( f \) to get any output.

(Beautiful result) \( \smile \)
Need to isolate the DAC from speaker — OP-Amp with NFB

We want to measure $V_{out}$, take a portion of the signal and feedback as $V_{-}$.

$U^{+} = S \sin$
$V_{out} = S_{out}$
$U^{-} = S_{fb}$
$U^{+} - U^{-} = S_{err}$
Op-Amp in negative feedback

Model:

\[ V_{out} = AV_d \]

only for

\[ V_{ss} < V_{out} < V_{dd} \]

Simpler model as the second source is not needed.

(1) \[ V_d = U^+ - U^- = V_{in} - V_{fb} \]

(2) \[ V_{out} = AV_d \]

(3) \[ V_{fb} = \frac{R_2}{R_1 + R_2} \cdot V_{out} \]

"BUFFER circuit"
Golden Rules of Op-Amps

For our design we want $A = 3$

\[ V_d = \frac{V_{out}}{A} \quad \text{if } A \to \infty \]

\[ V_d = \frac{1}{A} \cdot A \frac{V_{in}}{1 + A_f} \]

\[ V_{in} = \frac{V_{in}}{1 + A_f} = 0 \]

In NFB: $U^+ = U^-$ and $A \to \infty$

Rules: (Golden Rules)

1. $I^+ = I^- = 0$ (always true)
2. $U^+ = U^-$ (only in NFB & $A \to \infty$)

[Diagram showing Op-Amp circuit with no current going in and $I^+ = I^- = 0$.]
Let's go back to playing music

DAC

Non-Inverting Amplifier
(feedback gain = 3)

Speaker

Party time!
Yay!