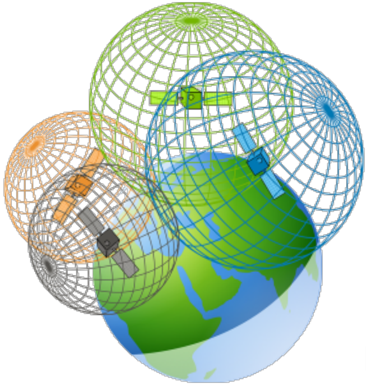
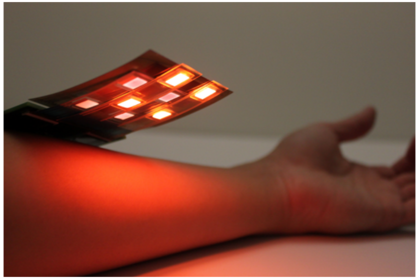




Welcome to EECS 16A!

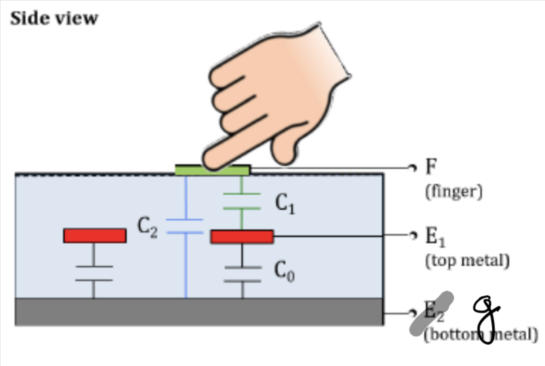
Designing Information Devices and Systems I

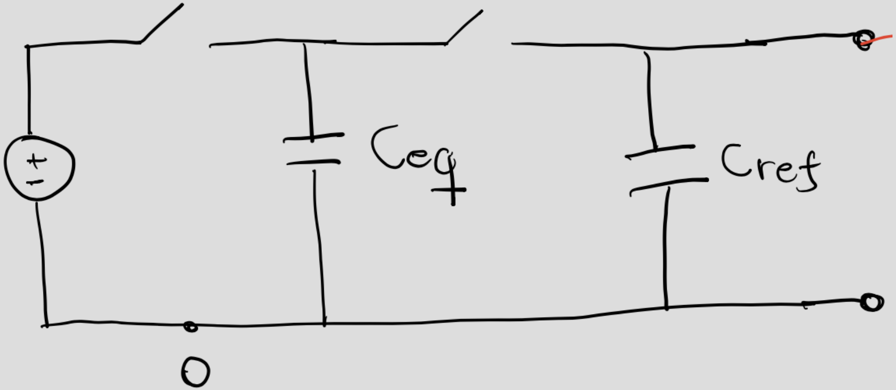
Ana Claudia Arias and Miki Lustig

Fall 2021

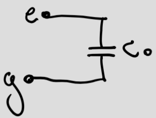
Module 2
Lecture 9
Operational Amplifier and Comparator
(Note 18)

Last Class…



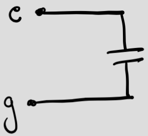


when no touch:



$$\Rightarrow \quad V_{OUT} = \frac{C_0}{C_0 + C_{ref}} \cdot V_S$$

with touch:

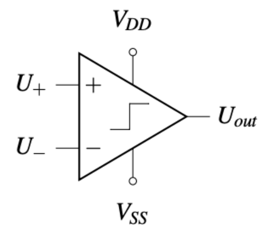


$$C_0 + \underbrace{\frac{C_1C_2}{C_1+C_2}}_{C_\Delta}$$

Extra Capacitance due to touch!

$$\Rightarrow \quad V_{OUT} = \frac{(C_0 + C_\Delta)}{C_0 + C_\Delta + C_{ref}} \cdot V_S$$

How can we go from voltage measurement to binary answer: touch or no touch?



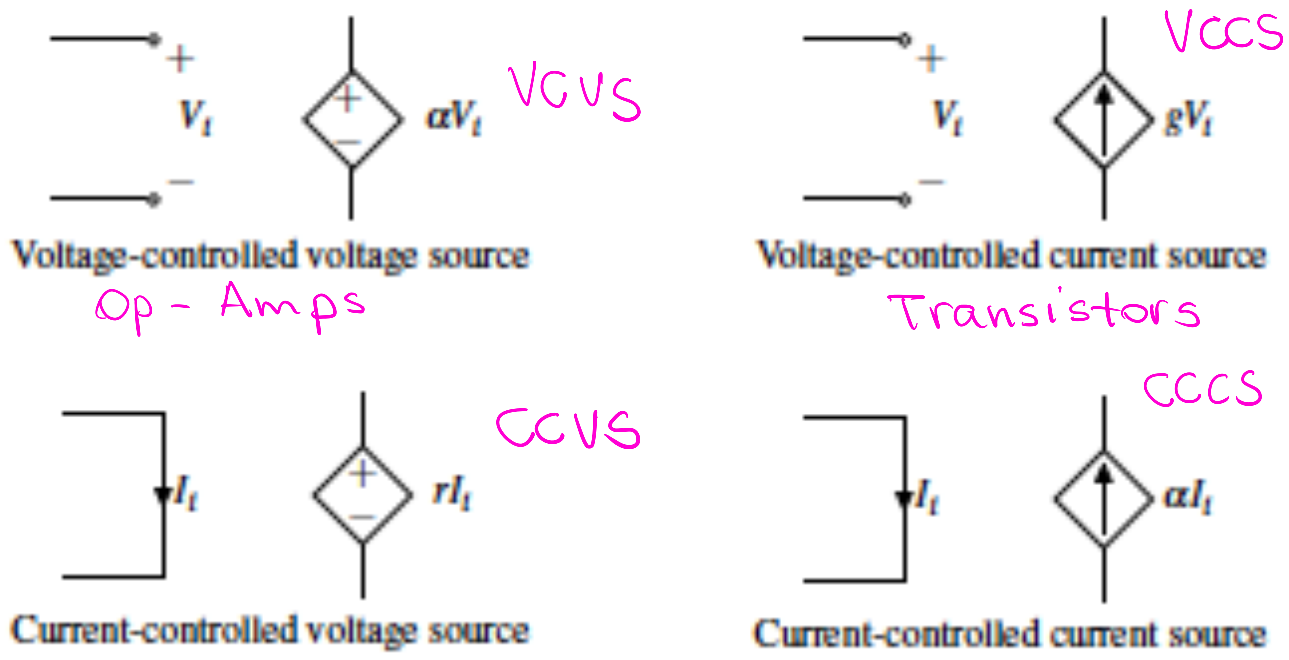
- We need to choose a Voltage that we call : Threshold Voltage (V_{th})

- Above V_{th} ∴ 1 (touch)
- Below V_{th} ∴ 0 (no- touch)

We need to compare Voltages to determine if <u>1</u> or <u>0</u>

How can we go from voltage measurement to binary answer: touch or no touch?

- New tools are needed – new circuit elements



Voltage-controlled voltage source

Op - Amps

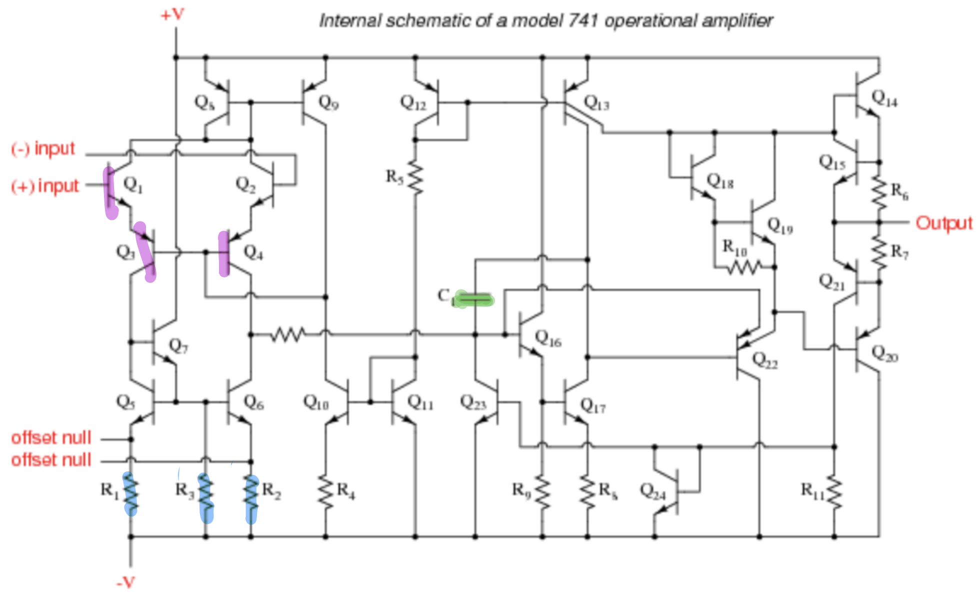
Voltage-controlled current source

Transistors

Current-controlled voltage source

Current-controlled current source

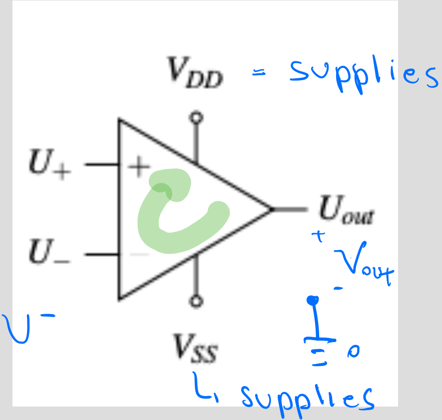
An example of an Op-amp circuit diagram



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.

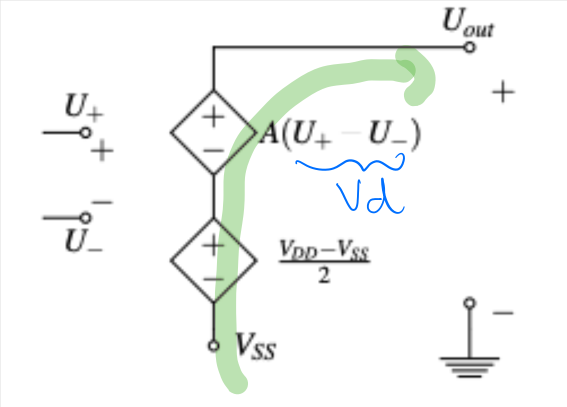


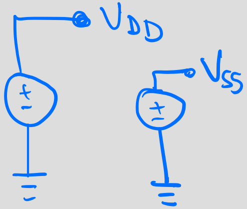
V_d

$V_d = U^+ - U^-$

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 Uout.

Model





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

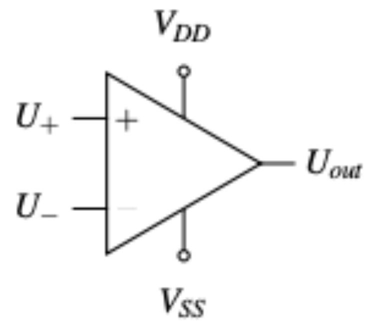
when

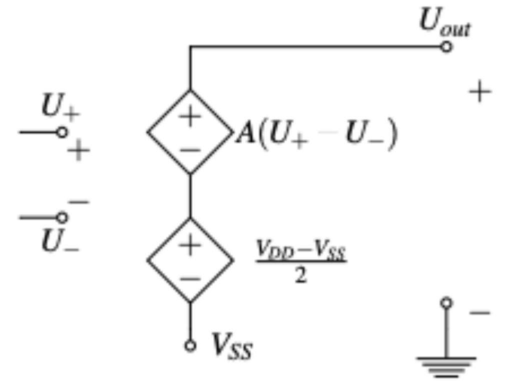
$$V_{SS} \leq \frac{V_{DD}-V_{SS}}{2} + A V_d \leq V_{DD}$$

Operational Amplifier

$\boxed{\frac{V_{DD}-V_{SS}}{2} + AV_d}$ V^*

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





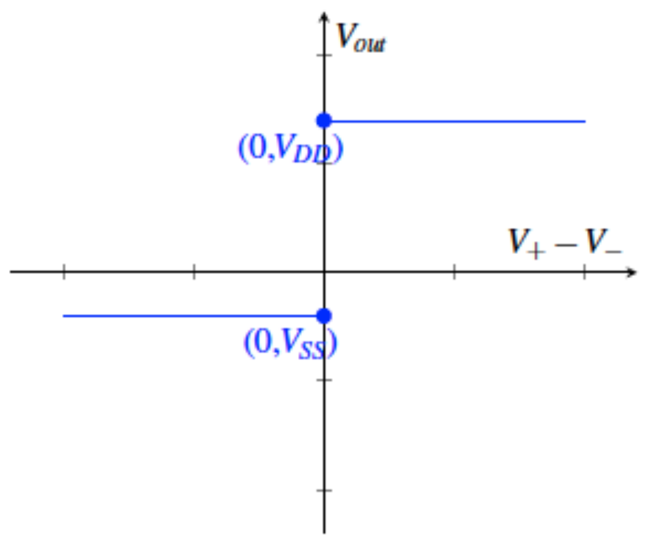
An op-amp has two input terminals marked (+) and (−) with potentials U+ and U−, two power supply terminals called VDD and VSS, and one output terminal with potential Uout.

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

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

Can be used to compare Voltage

Comparator – optimized for binary output

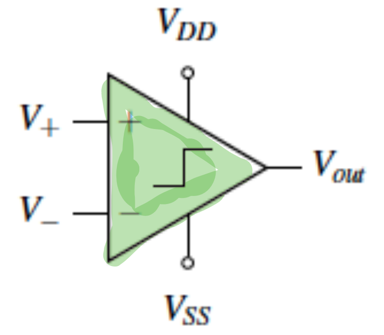


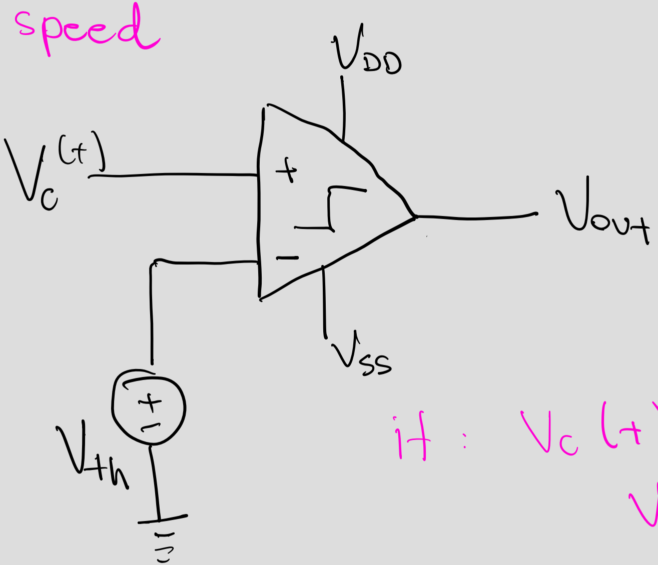
V_{DD} can be much higher than V_{ss}

$\therefore$ it amplifies the signal.

Comparator – optimized for binary output

Also optimized for speed





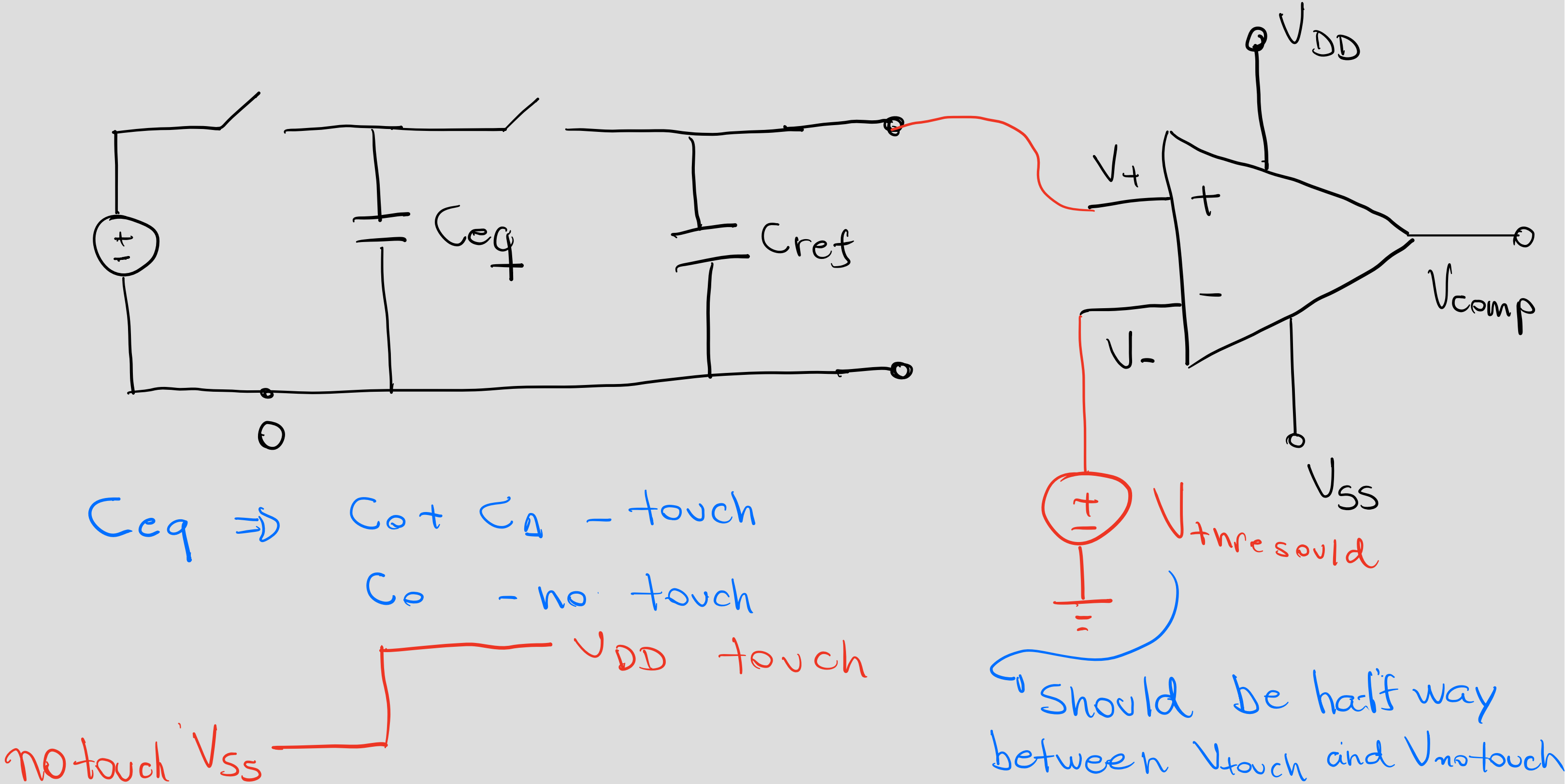
if : $V_c(t) > V_{th}$

$V_{out} = V_{DD}$

if : $V_c(t) \leq V_{Th}$

$V_{out} = V_{SS}$

Back to our Capacitive Touchscreen



Ceq ⇒ Co + CΔ – touch

Co – no touch

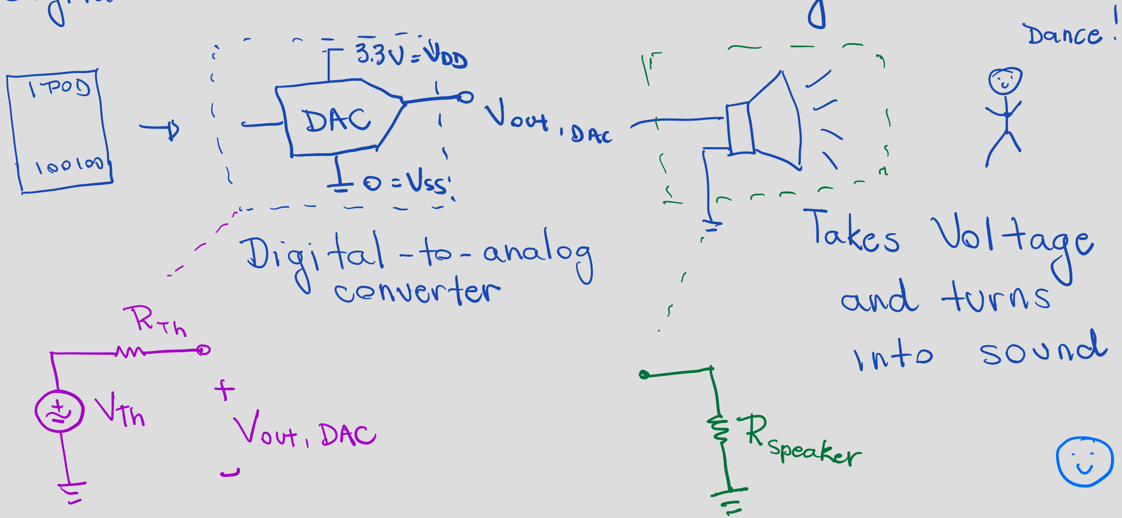
Should be half way between Vtouch and Vnotouch

New Design – Let’s play music

* Want to play music LOUD

↳ Music is stored as digital signal

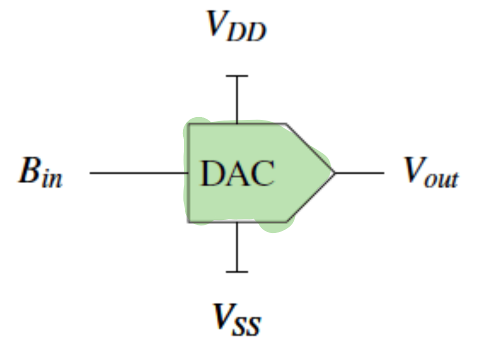
Digital ——> Analog

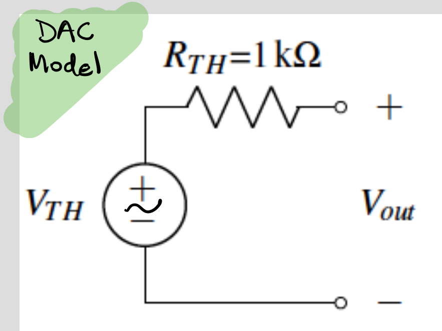


Digital-to-analog converter

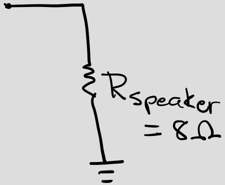
Takes Voltage and turns into sound

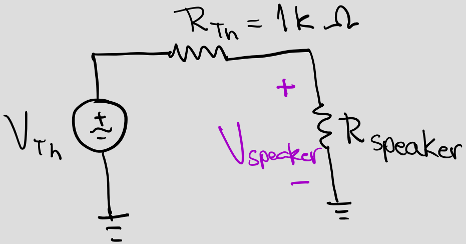
Digital to Analog Converter - DAC





Speaker





Voltage Divider

$$V_{speaker} = \frac{\overset{8\,\Omega}{\cancel{R_{speaker}}}}{\overset{1000\,\Omega}{\cancel{R_{Th}}} + \overset{8\,\Omega}{\cancel{R_{speaker}}}} \cdot V_{Th}$$

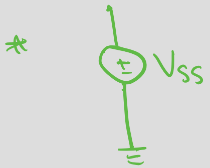
$$V_{speaker} = \frac{V_{th}}{126}$$

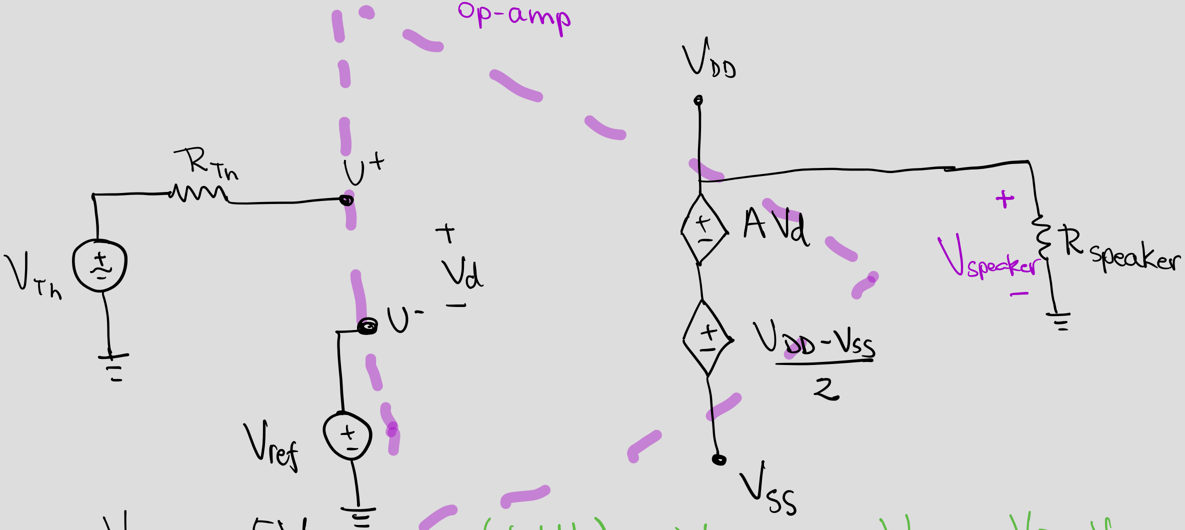
Not loud!

Too quiet!

Need to isolate DAC.

Digital to Analog Converter - DAC





$V_{DD} = -V_{SS} = 5V$

10V output

(Input)

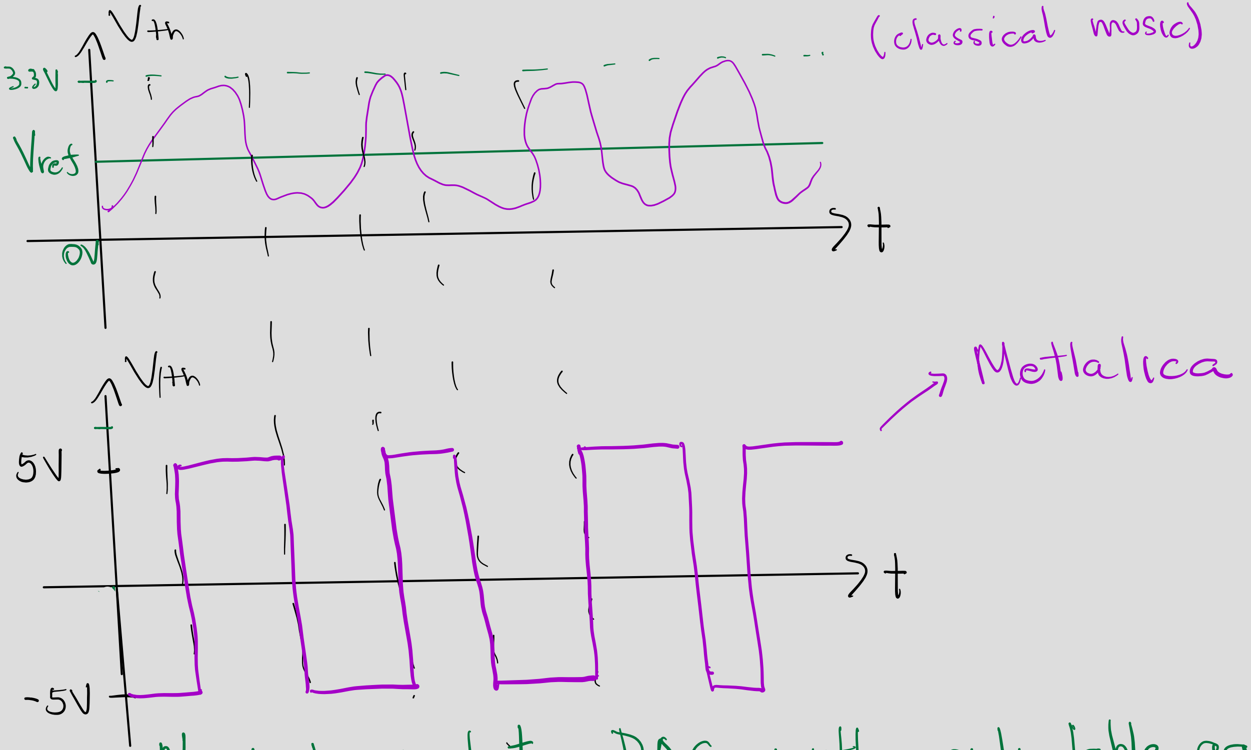
$$V_d = U^+ - U^- = V_{th} - V_{ref}$$

(KVL) $$V_{speaker} = \underbrace{V_{SS} + \frac{V_{DD}-V_{SS}}{2}}_{\cancel{\frac{V_{DD}+V_{SS}}{2}}\ 0} + AV_d = AV_d$$

when:

$$V_{SS} < AV_d < V_{DD}$$

Digital to Analog Converter - DAC



Need to isolate DAC with controlable gain!

e.. 3x

Negative Feedback

$$S_{err} = S_{in} - S_{fb}$$

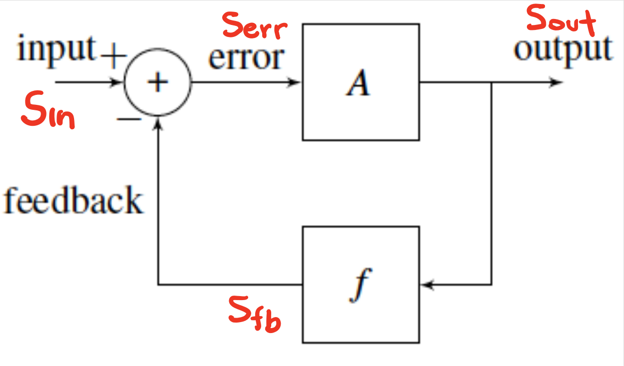
$$S_{out} = A \cdot S_{err}$$

$$S_{fb} = f \cdot S_{out}$$

$$\frac{S_{out}}{A} = S_{in} - S_{fb}$$

$$S_{out}\left(\frac{1}{A} + f\right) = S_{in}$$

$$\frac{S_{out}}{S_{in}} = \frac{1}{\frac{1}{A} + f} = \frac{A}{1 + Af}$$



- 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

$$\boxed{\frac{S_{out}}{S_{in}} = \frac{A}{1+Af}}$$

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

$$\frac{S_{out}}{S_{in}} \underset{A\to\infty}{=} \frac{1}{f}$$

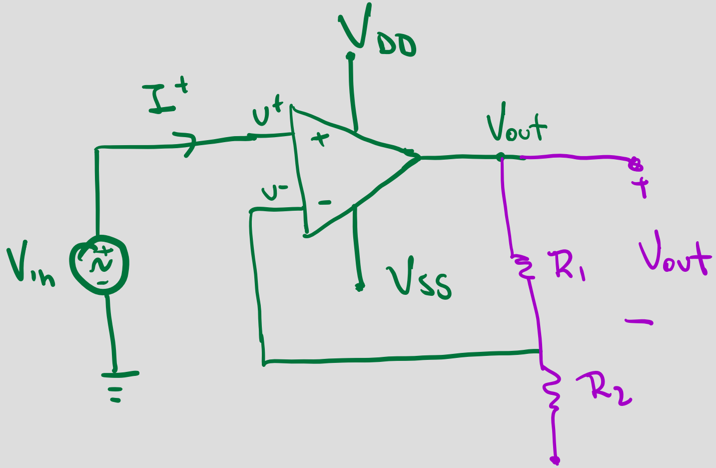
↳ We control the output via block $\boxed{f}$!

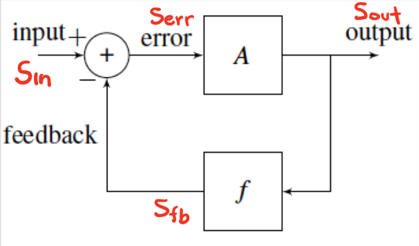
So $\boxed{V_{out} = \frac{1}{f} V_{in}}$ for very large gain.

↳ we can set f to get any output.

(Beautiful result). ☺

Need to isolate the DAC from speaker – OP-Amp with NFB





$$U^+ = S_{in}$$

$$V_{out} = S_{out}$$

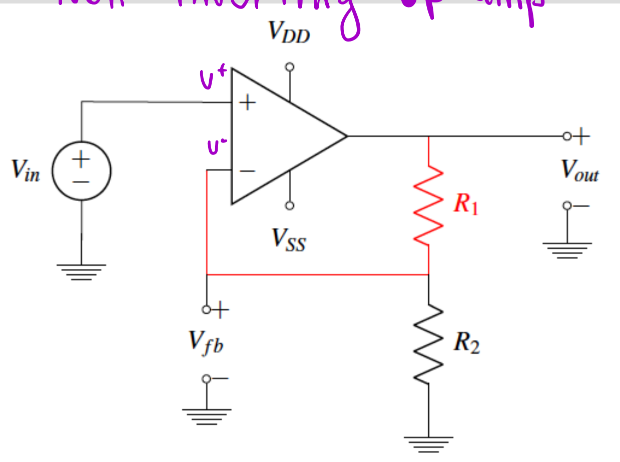
$$U^- = S_{fb}$$

$$U^+ - U^- = S_{err}$$

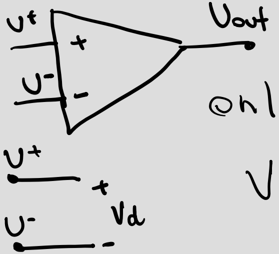
- We want to measure V_{out}, take a portion of the signal and feedback as U^-

Op-Amp in negative feedback

Non-inverting op-amp

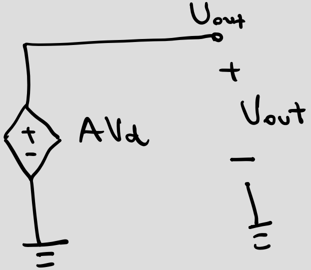


Model :



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) $V_{out} = A V_d$

(3) $V_{fb} = \underbrace{\frac{R_2}{R_1+R_2}}_{\hookrightarrow f} \cdot V_{out}$

"BUFFER CIRCUIT"

$$V_{out} = A\,(V_{in} - f \cdot V_{out})$$

$$V_{out}\,(1 + Af) = A\,V_{in}$$

$$A_v = \text{Gain} = \frac{V_{out}}{V_{in}} = \frac{A}{1+Af}$$

$$A_v \underset{A \to \infty}{=} \frac{1}{f} \hookrightarrow \frac{R_1+R_2}{R_2} = 1 + \frac{R_1}{R_2}$$

Golden Rules of Op-Amps

For our design we want $A = 3$

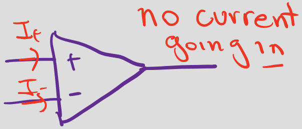
$$V_d = \frac{V_{out}}{A} \quad \text{if} \quad A \to \infty$$

$$V_d = \frac{1}{A} \cdot \frac{A}{1+Af} V_{in} = \frac{V_{in}}{1+Af} = 0$$

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

Rules: (Golden Rules)

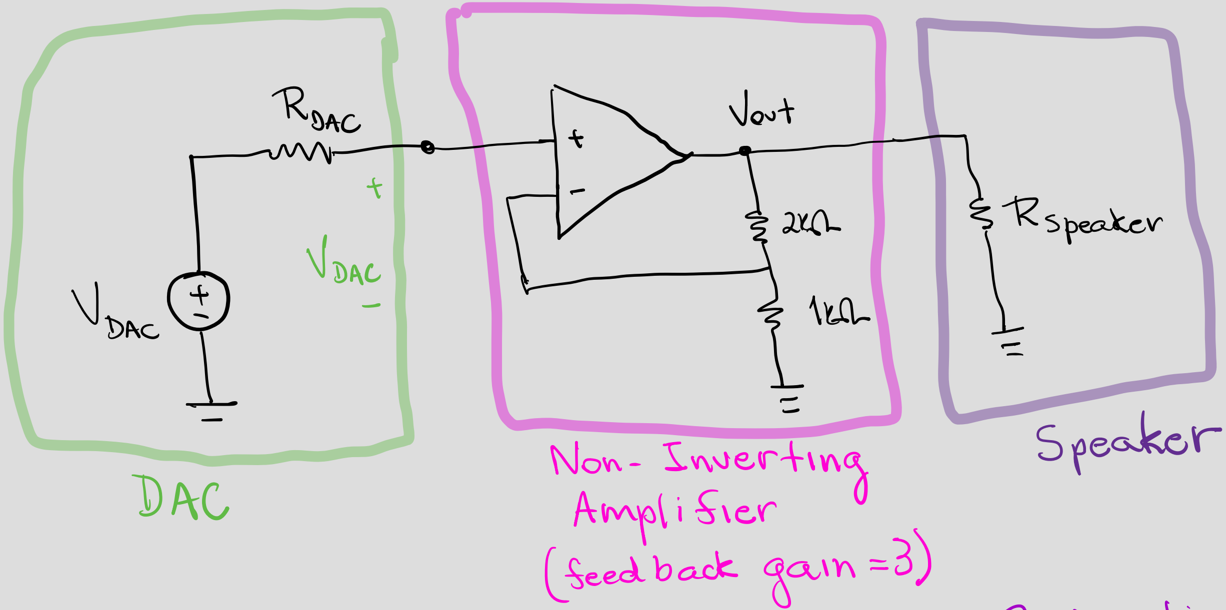
(1) $I^+ = I^- = 0$ (always true)



$I^+ = I^- = 0$

(2) $V^+ = V^-$ (only in NFB & $A \to \infty$)

Let's go back to playing music



Party time!

Yay!