EECS 16A

Spring 2023 - Profs. Muller & Waller

Lecture 9B – Op Amps & Negative Feedback

Toolbox

KVL: Voltage drops around a loop sum to 0

KCL: All currents coming out of a node sum to 0

$$V = IR$$

$$P = IV$$

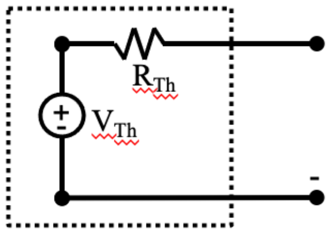
$$R = \frac{\rho L}{A}$$

V_{source}(off) → short

I_{source}(off) → open

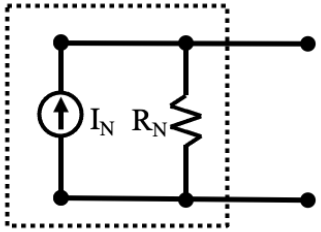
$$R_1 \parallel R_2 = \frac{R_1 R_2}{R_1 + R_2}$$

Thevenin Equivalent Circuit

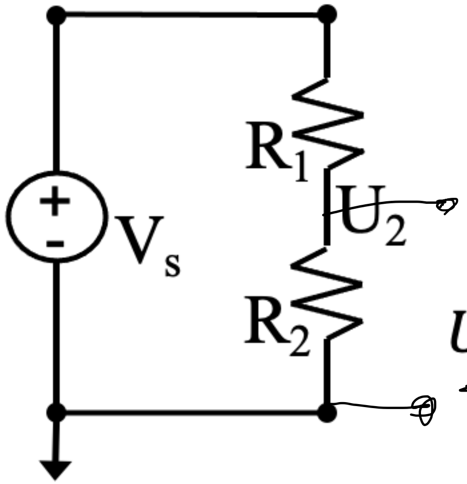


Measure V with open

Norton Equivalent Circuit



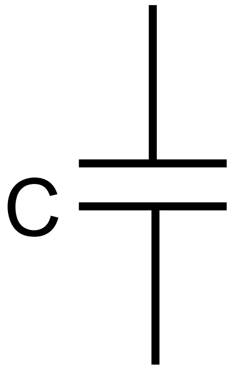
Measure I with short



$$I = \frac{V_S}{R_1 + R_2}$$

$$U_2 = \frac{V_S R_2}{R_1 + R_2}$$

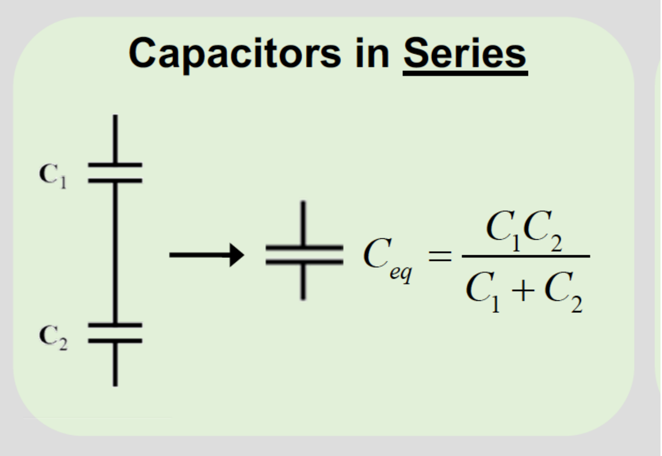
$$R_{Th} = V_{Th}/I_N$$

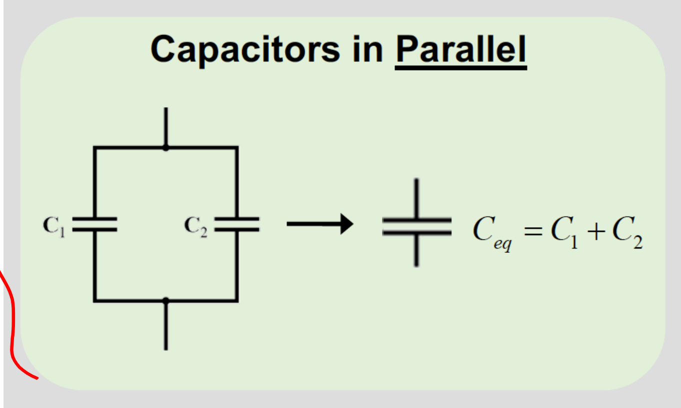


$$Q = CV$$

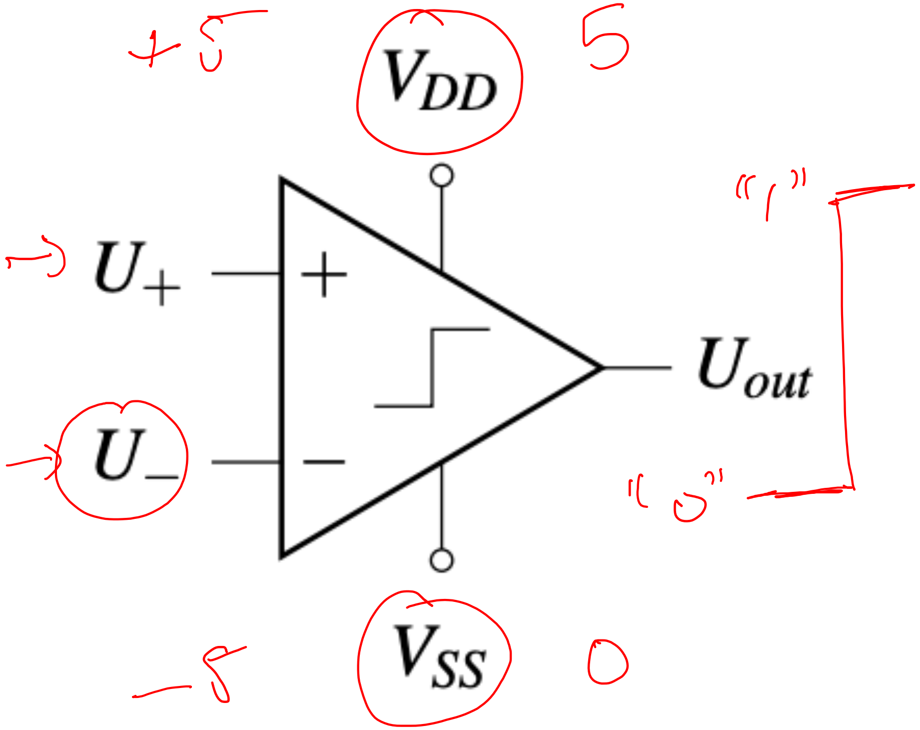
$$I = C\frac{dV}{dt}$$

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





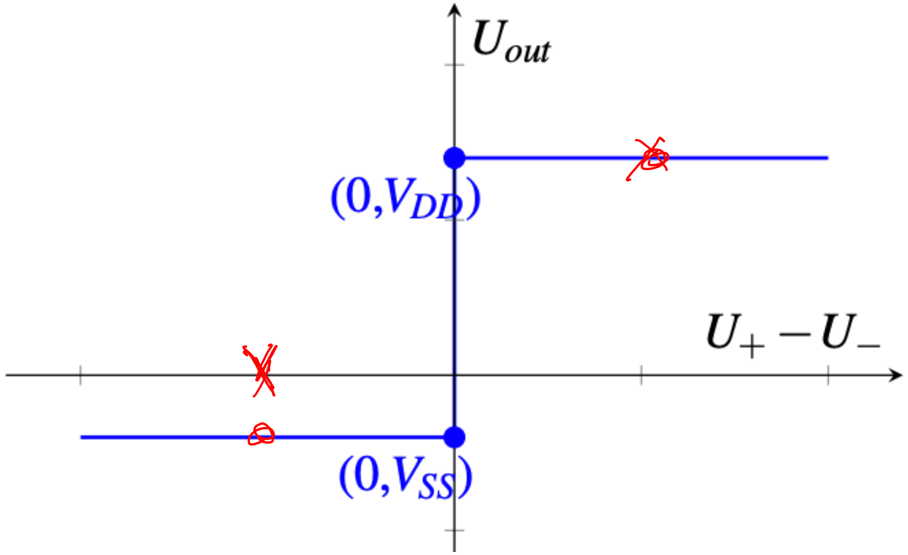
Last Time: Comparators!



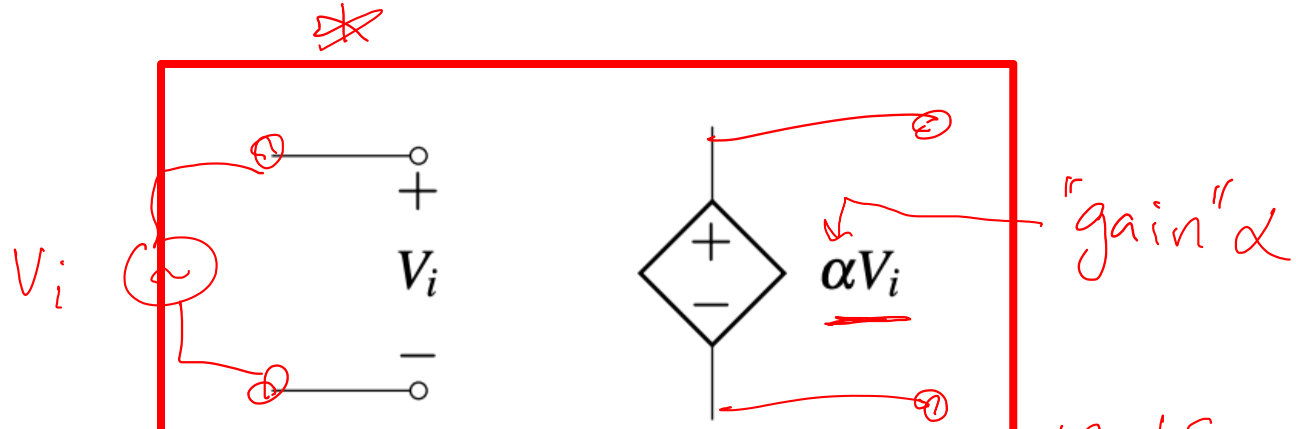
Comparators compare two values (inputs):

$U_+ > U_- \rightarrow U_{out} =$ "1" $= V_{DD}$

$U_+ < U_- \rightarrow U_{out} =$ "0" $= V_{SS}$

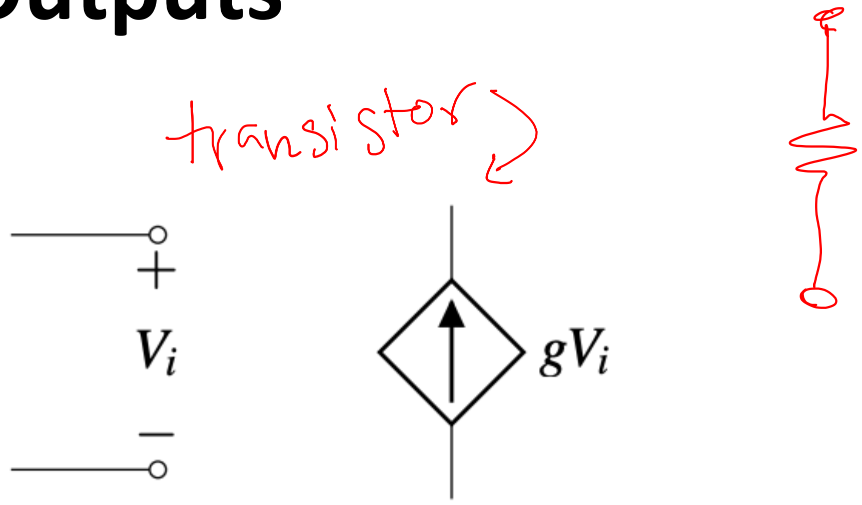


New Elements with 2 Inputs and 2 Outputs

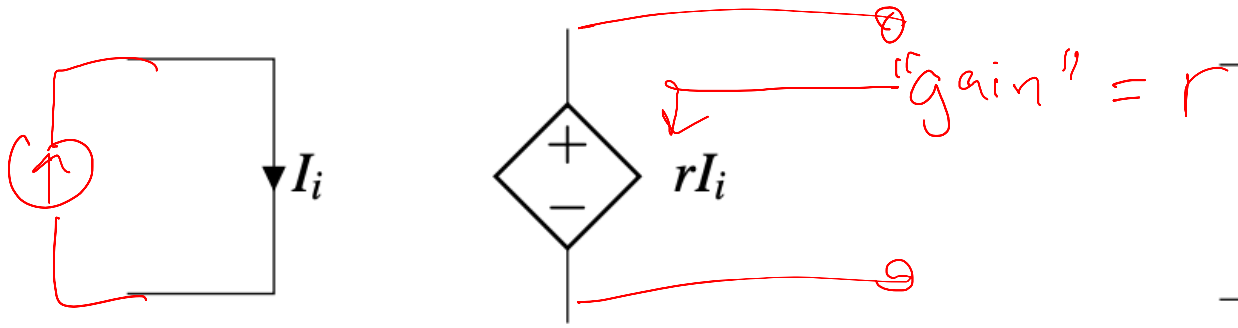


Voltage-controlled voltage source

VCVS

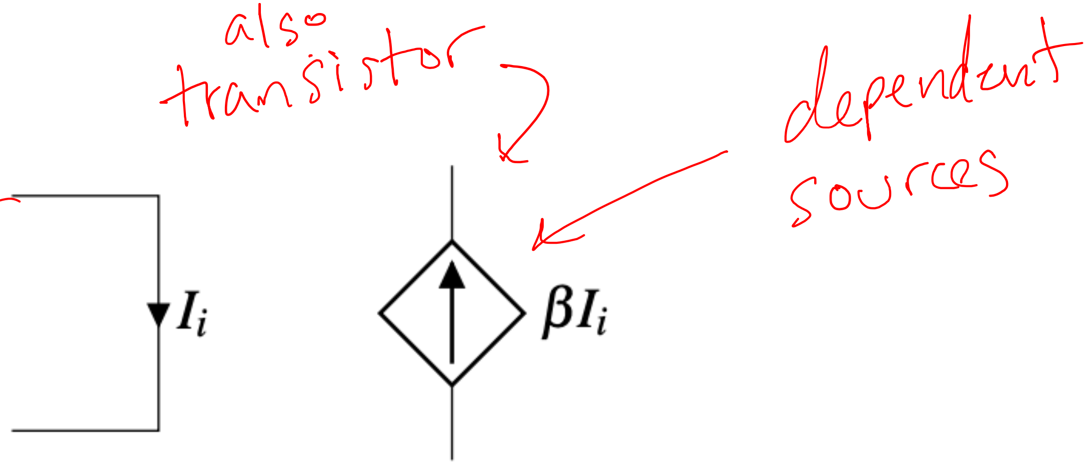


Voltage-controlled current source



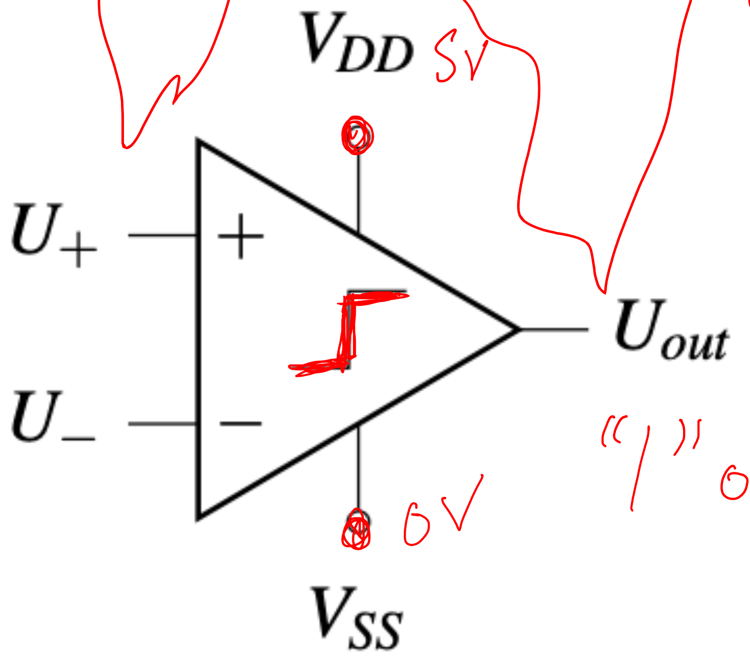
Current-controlled voltage source

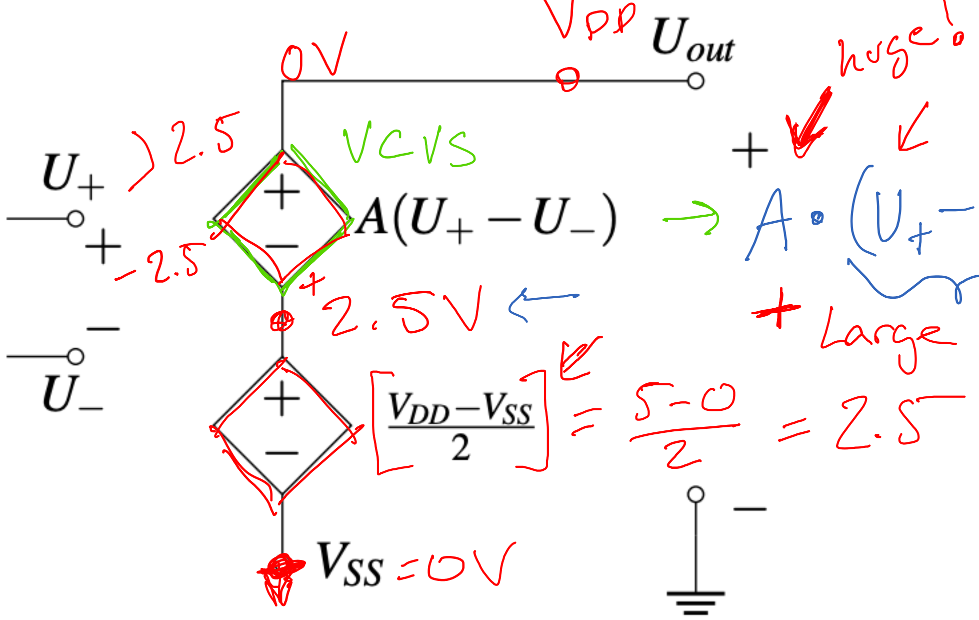
CCVS



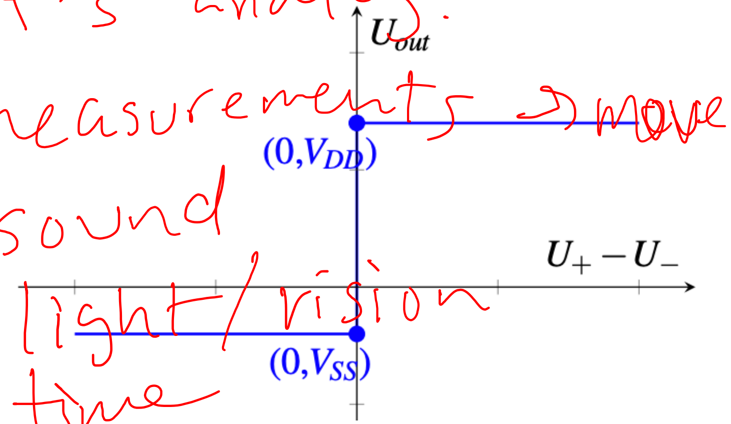
Current-controlled current source

Comparator Model – converts analog to 1-bit digital!

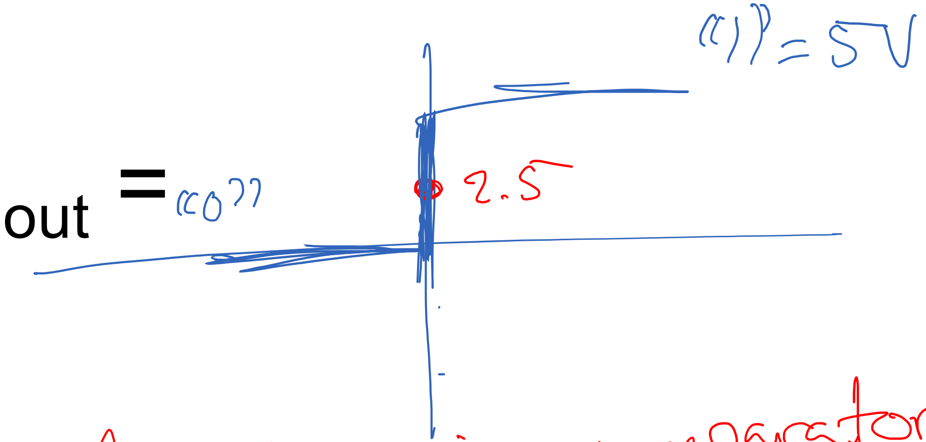




What's analog?
→ measurements → movement
→ sound
→ light/vision
→ time

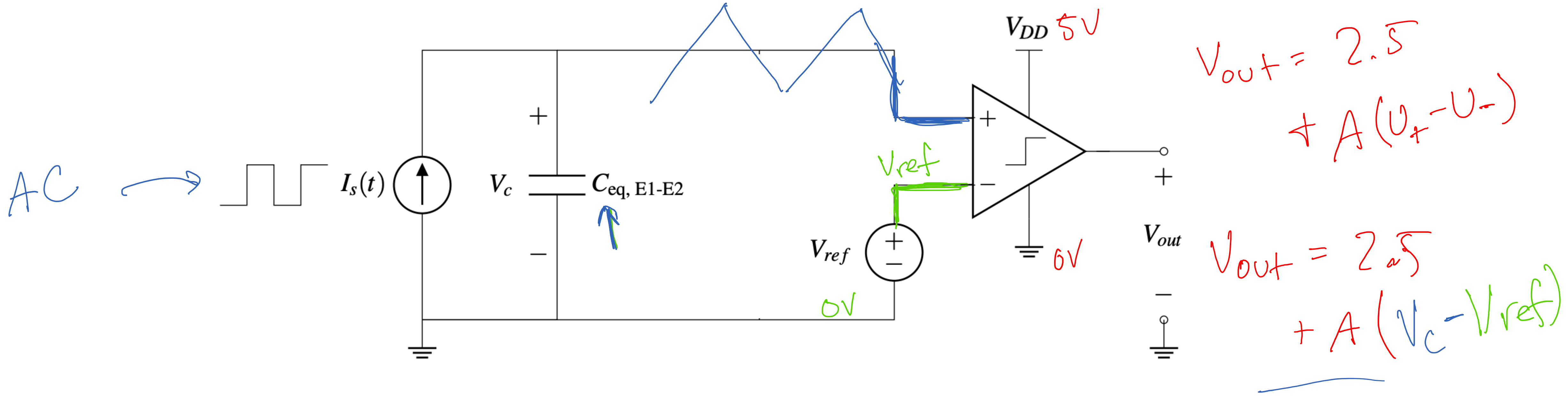


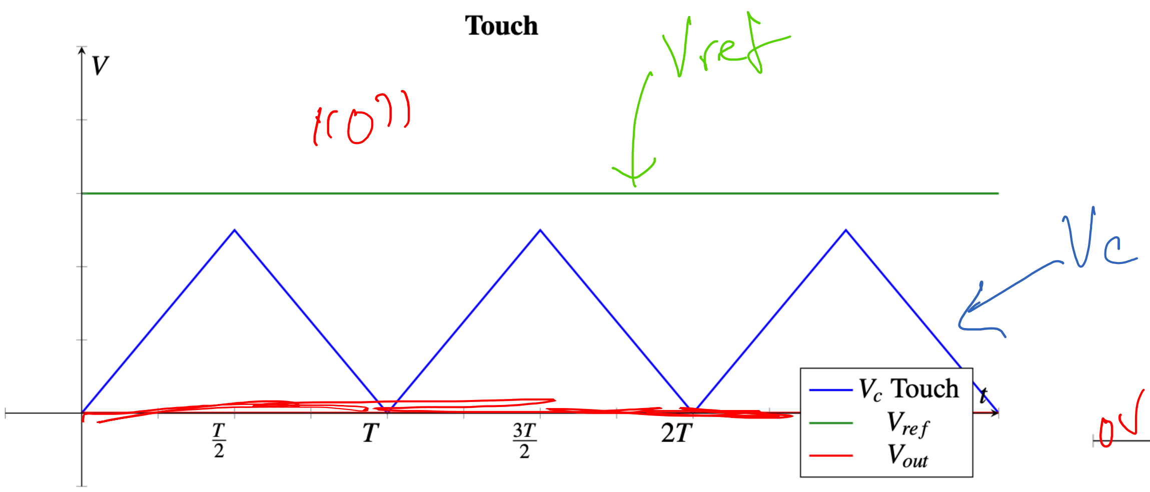
$U_{out} =$ "0"

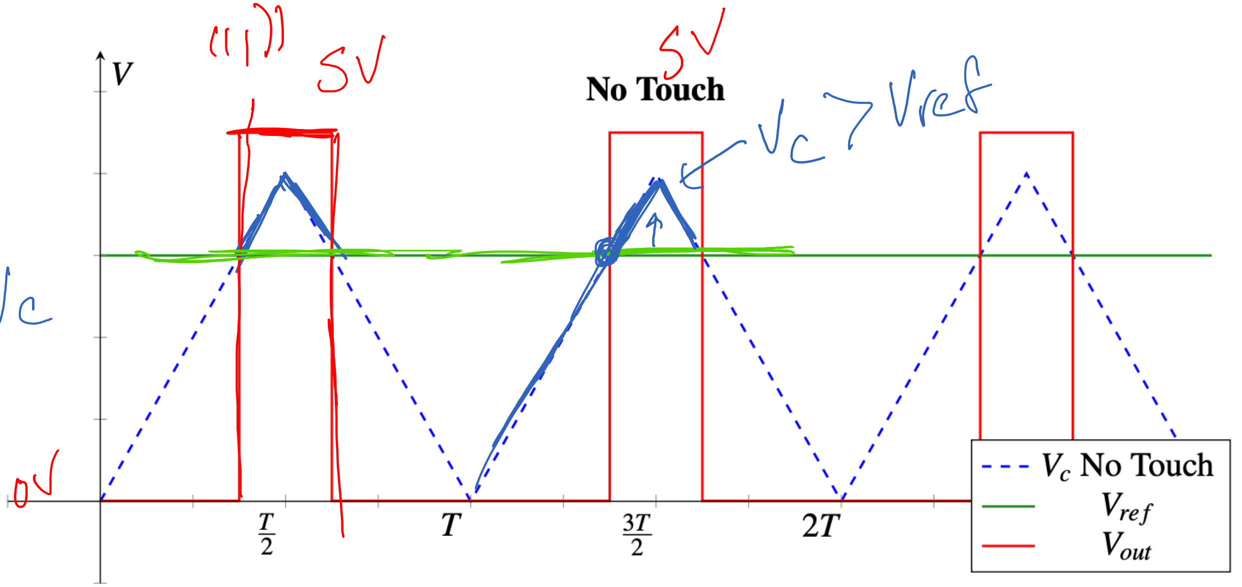


A is large in comparators!

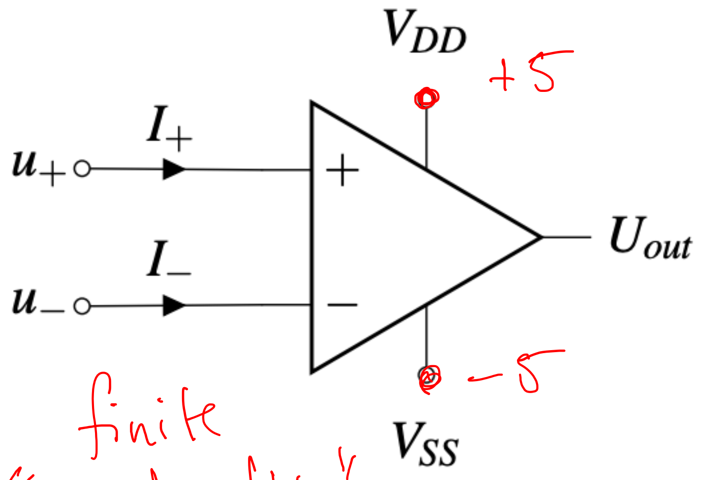
From Last Lecture: How to Read Out Touch

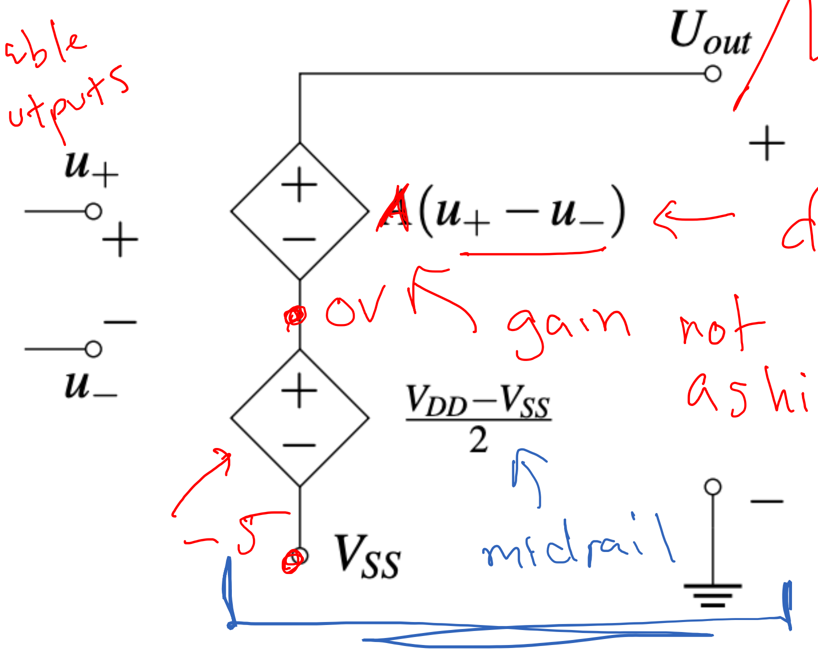




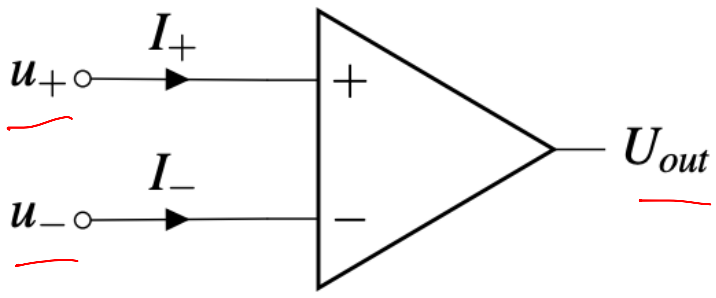


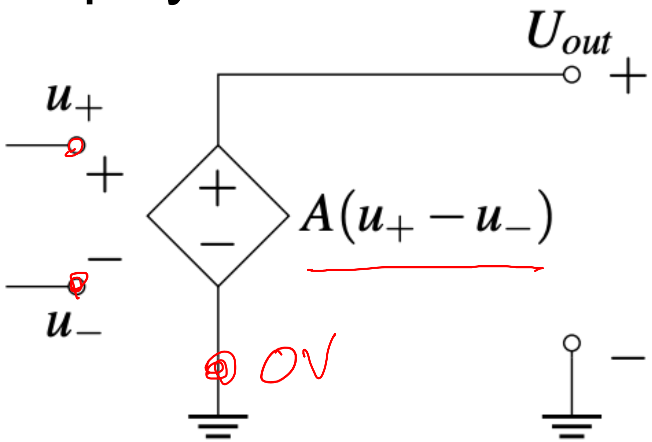
Operational Amplifier – Same Model!
(Different circuit – optimized for analog output)





If V_{DD} = V_{SS} we can simplify!





I got an internship at Bose this summer!

*First assignment: Design a circuit to play music – LOUD!

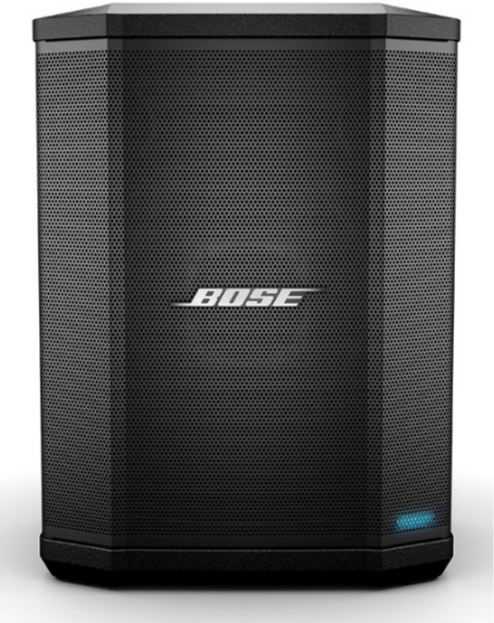
Music is analog!

Music is stored as digital

Music is analog!

digital

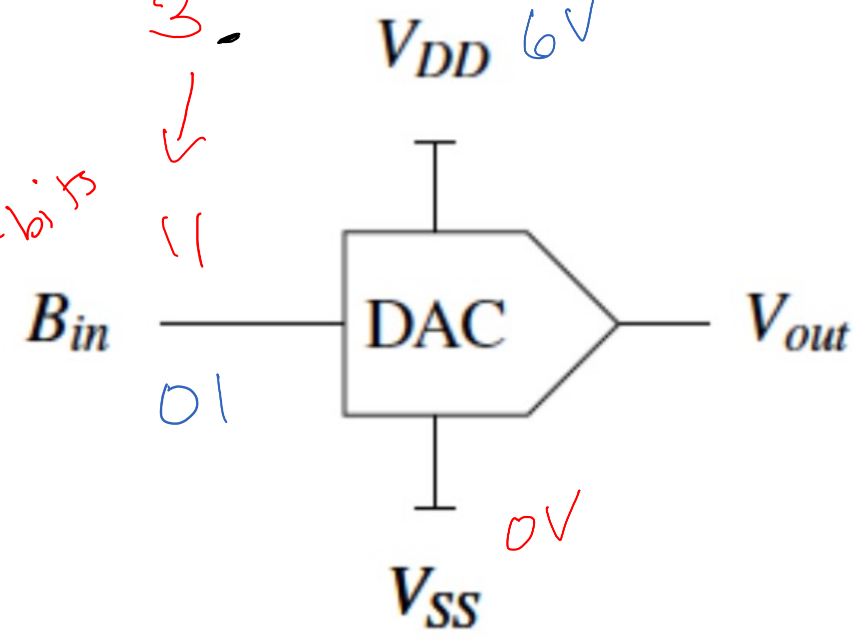
analog

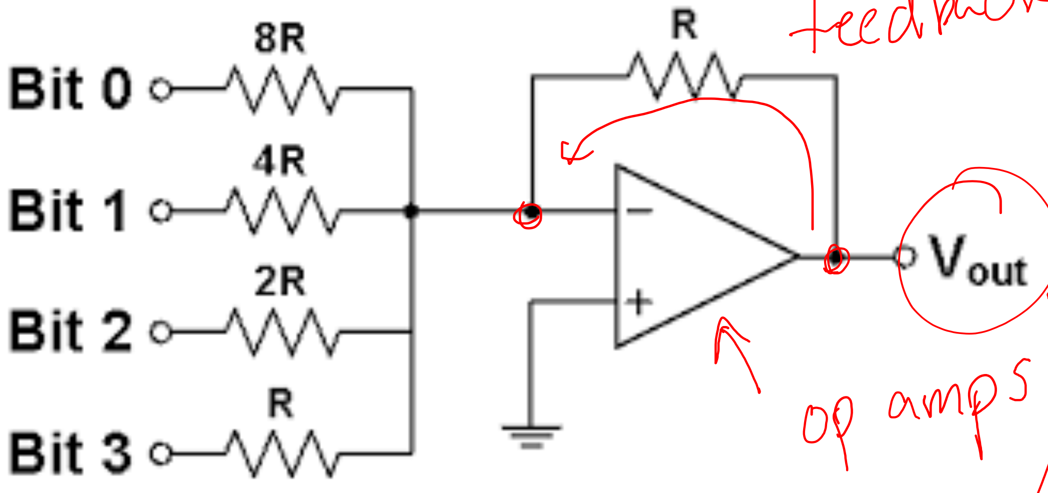


Need to convert digital to analog?

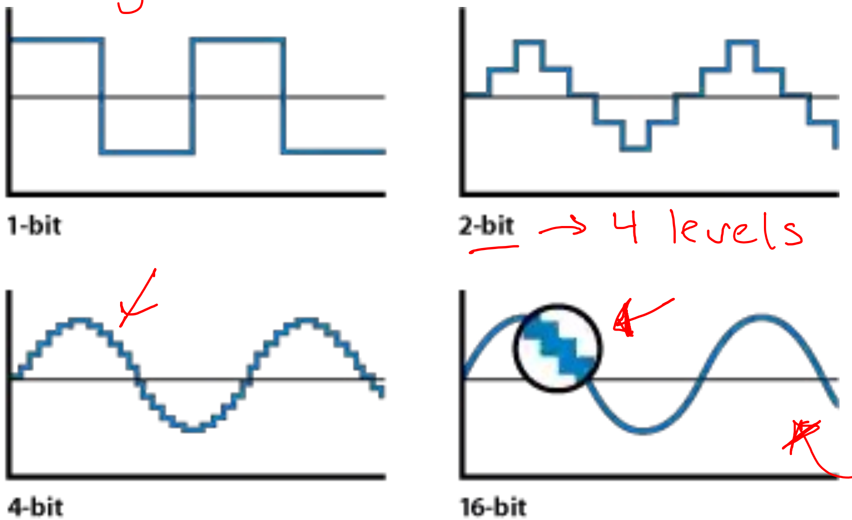
Speaker takes 0 – 10 V

DAC: Digital to Analog Converter



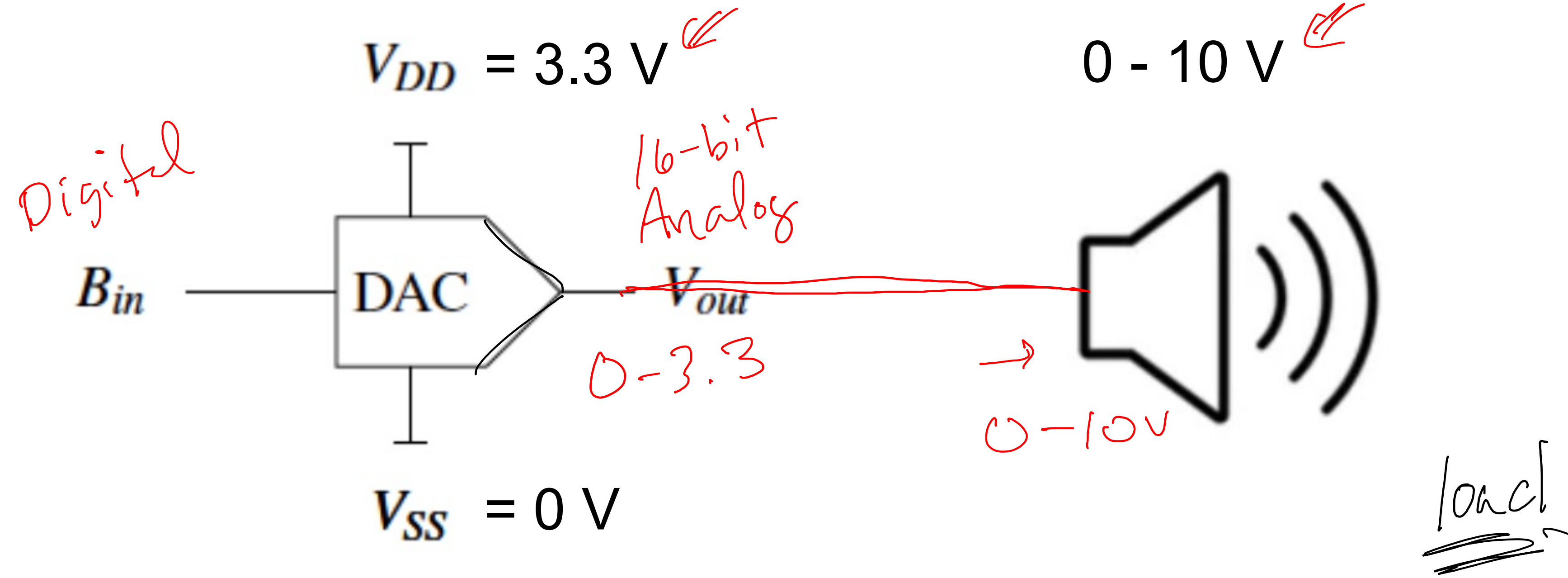


Decimal Number	Equivalent Binary Number	Decimal Number	Equivalent Binary Number
0	0000	8	1000
1	0001	9	1001
2	0010	10	1010
3	0011	11	1011
4	0100	12	1100
5	0101	13	1101
6	0110	14	1110
7	0111	15	1111



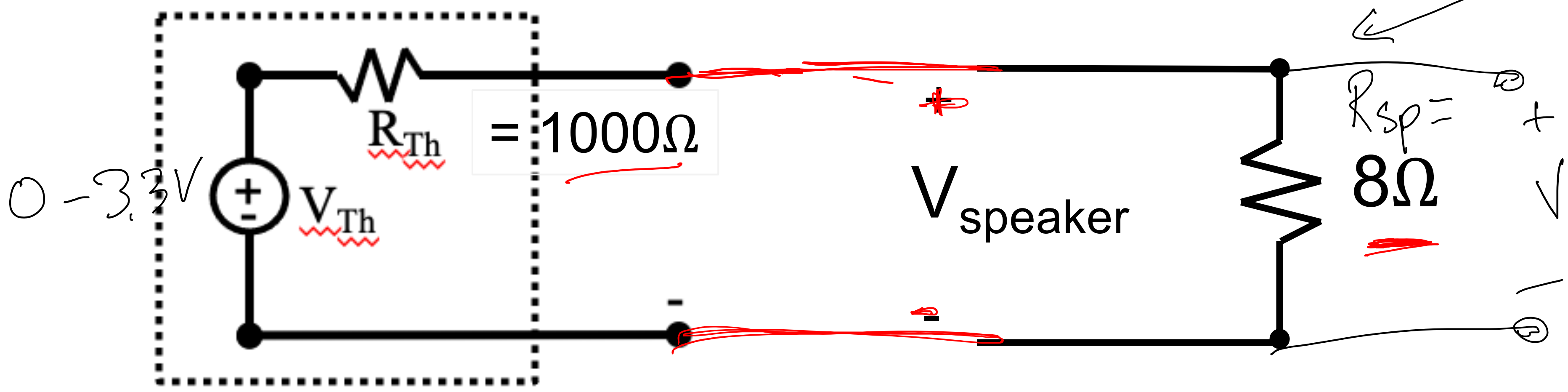

Edit: All the Sample Rates
SHUFFLE SPOT
SLIP GRID
00:00:00:00
Start
End
Length
Cursor
Grid
Nudge
Timecode
Tempo
Markers
194
16bit44.1kHz
12 bit
8 bit
7 bit
SnglLd1601
waveform
dyn
read
16 Bit/44.1 kHz

Can We Connect the DAC Directly to a Speaker?



$$V_{speaker} = \frac{V_{th} \cdot R_{sp}}{R_{sp} + R_{th}} = \frac{V_{th} \cdot 8}{8 + 1000} = V_{th} \cdot \frac{8}{1008}$$

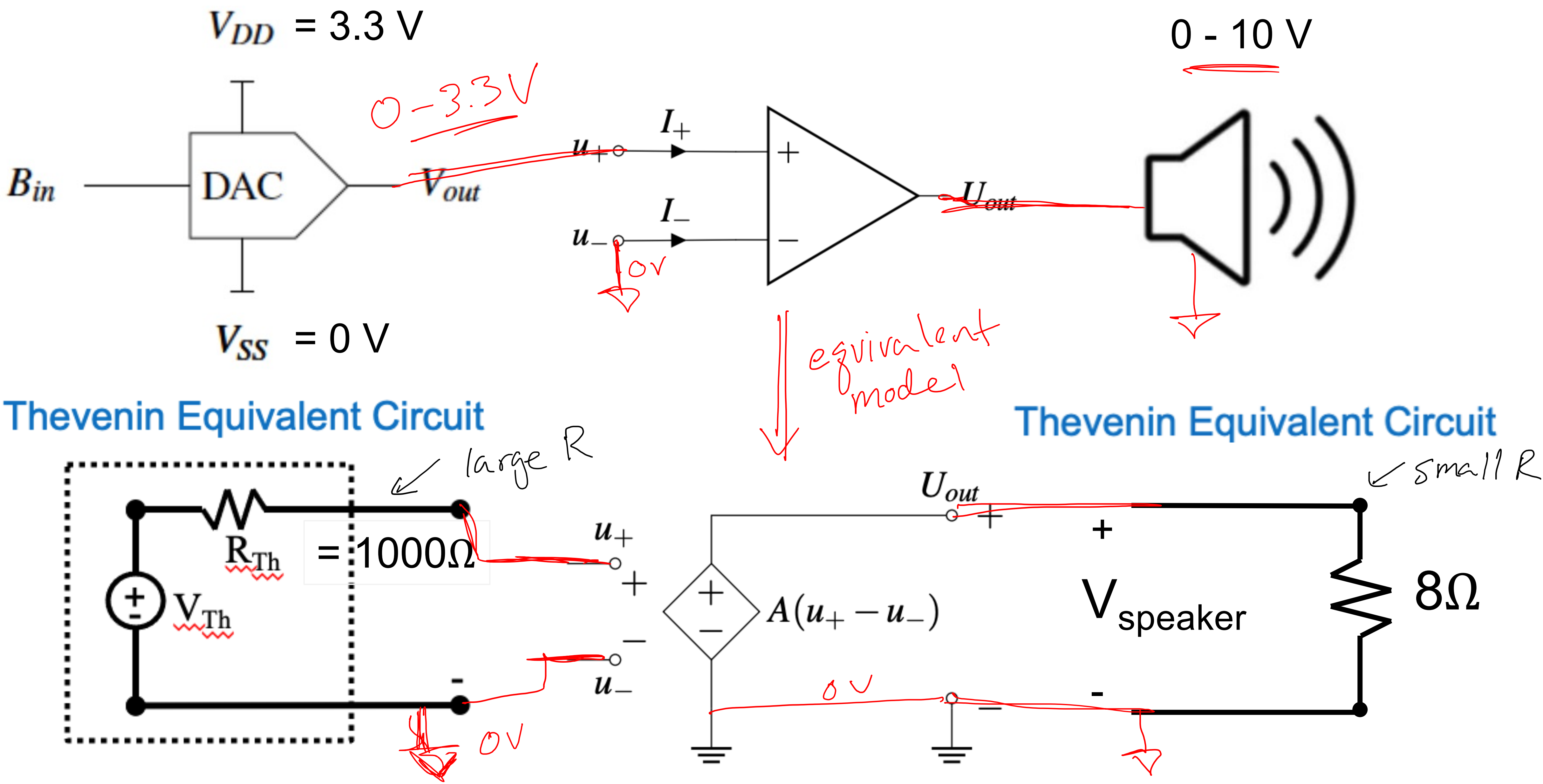
Thevenin Equivalent Circuit   Thevenin Equivalent Circuit



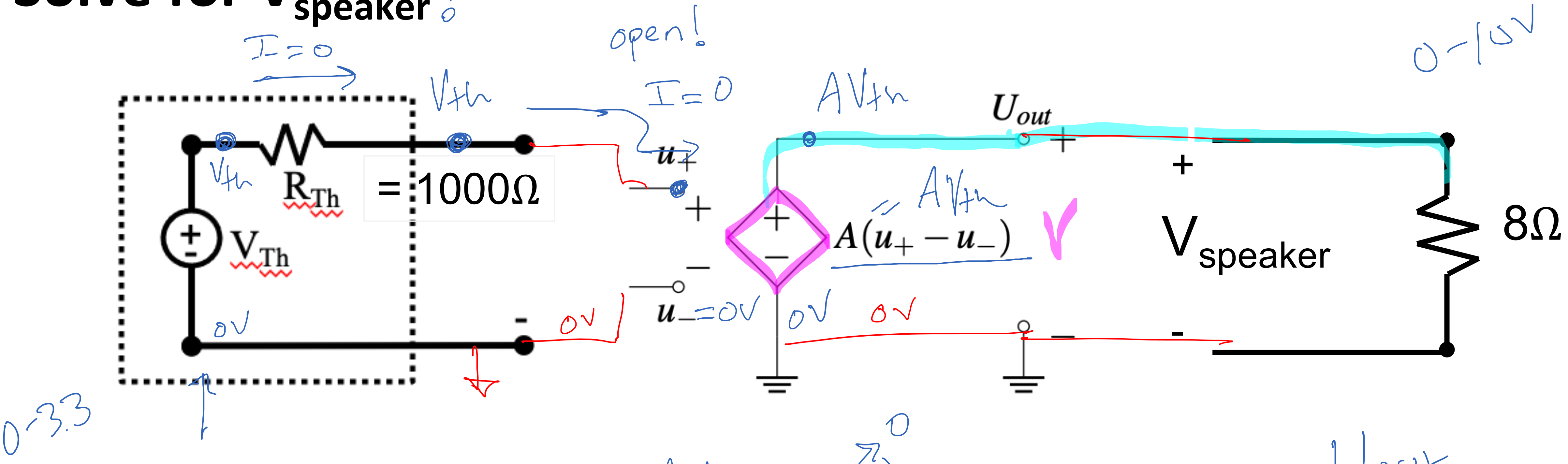
$V_{speaker} = V_{th} \times .0079$

$V_{th,max} = 3.3V$

Need to Isolate DAC and Speaker!



Solve for $V_{speaker}$!



$U_+ = V_{th}$

$A(U_+ - U_-)$ with $U_- = 0$

$= A(V_{th} - 0)$

$= AV_{th}$

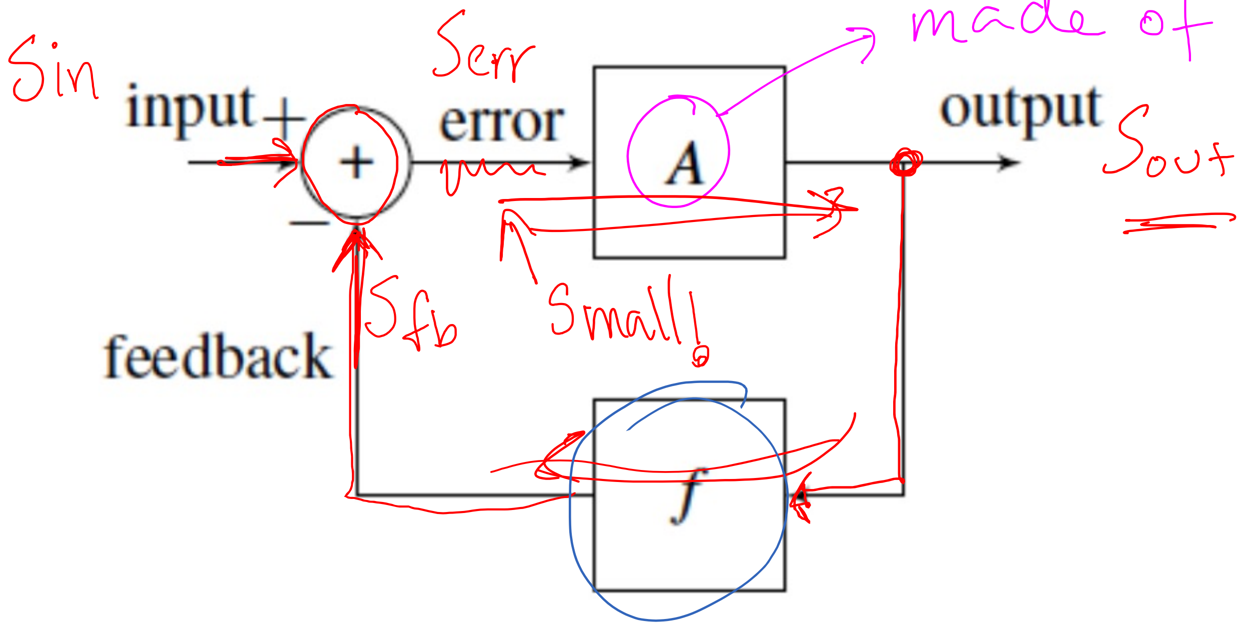
$V_{speaker} = U_{out}$

$= AV_{th}$

*Want $A = 3$! V/V

↑ unitless

Setting a Reliable Gain with Negative Feedback!



transistors are unreliable for gain

Snm

Make small adjustments to correct the output
Basis of Control Theory
Used all the time in circuits!
What are some examples from daily life?

- thermostat!
- Grades
-

solve:

$$S_{err} = S_{in} - S_{fb}$$
$$S_{out} = A\, S_{err}$$
$$S_{fb} = f\, S_{out}$$

transfer function →

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

Setting a Reliable Gain with Negative Feedback!

Black's formula

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

Describes the input-output relationship:

*The Transfer Function

$$S_{out} = \left[\frac{A}{1+Af}\right] S_{in}$$

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

A is unreliable → vary

A → really large $A \rightarrow \infty$

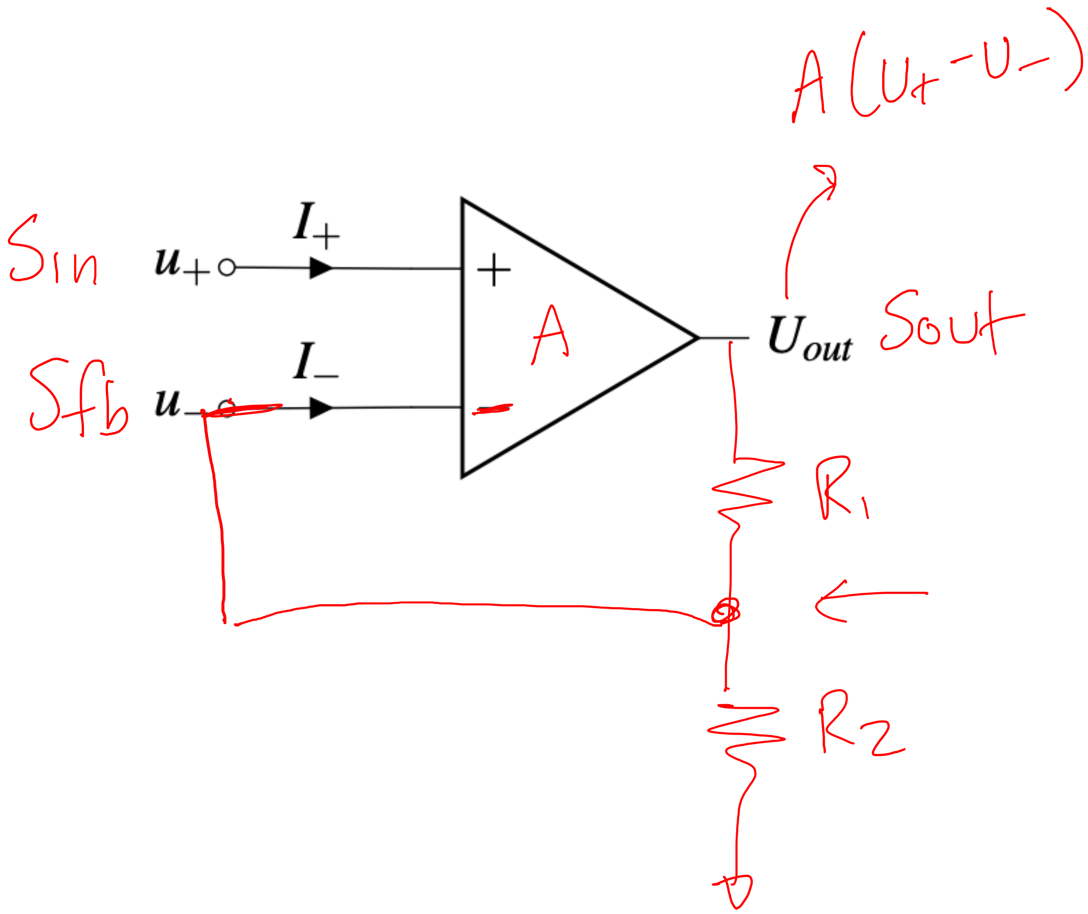
$$\frac{A}{1+Af} \approx \frac{\infty}{1+\infty f} \approx \frac{\infty}{\infty f} \approx \frac{1}{f}$$

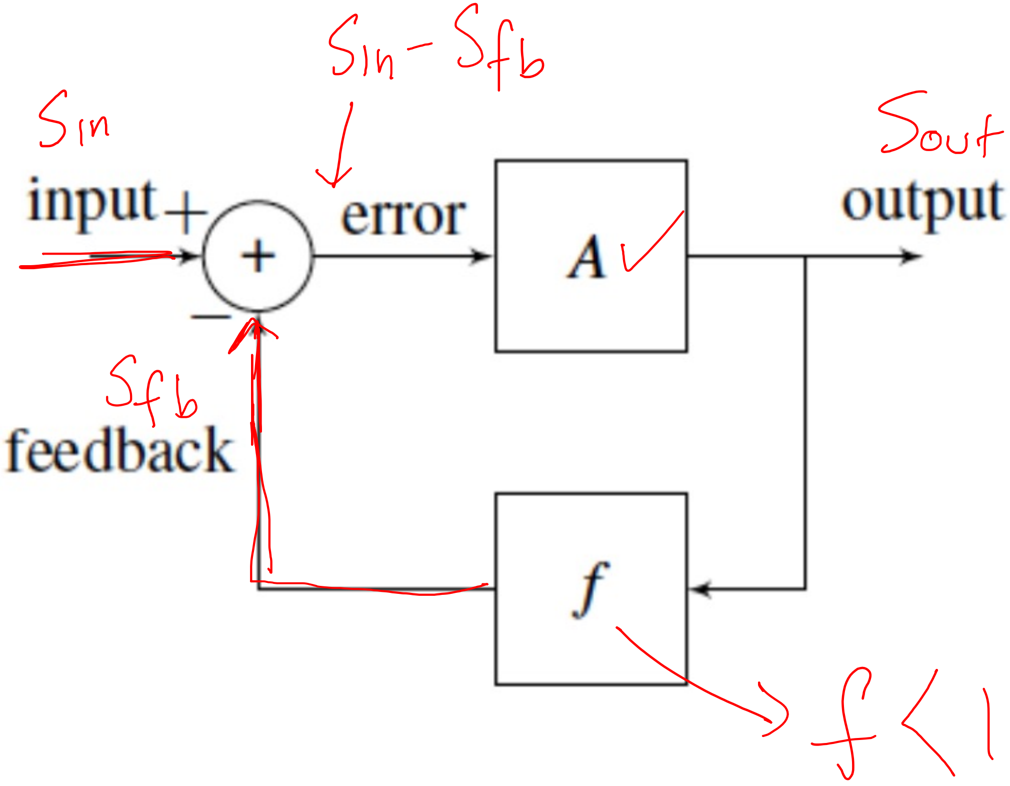
$$S_{in} \rightarrow \boxed{\frac{1}{f}} \rightarrow S_{out}$$

want high gain

gain > 1 $f < 1$

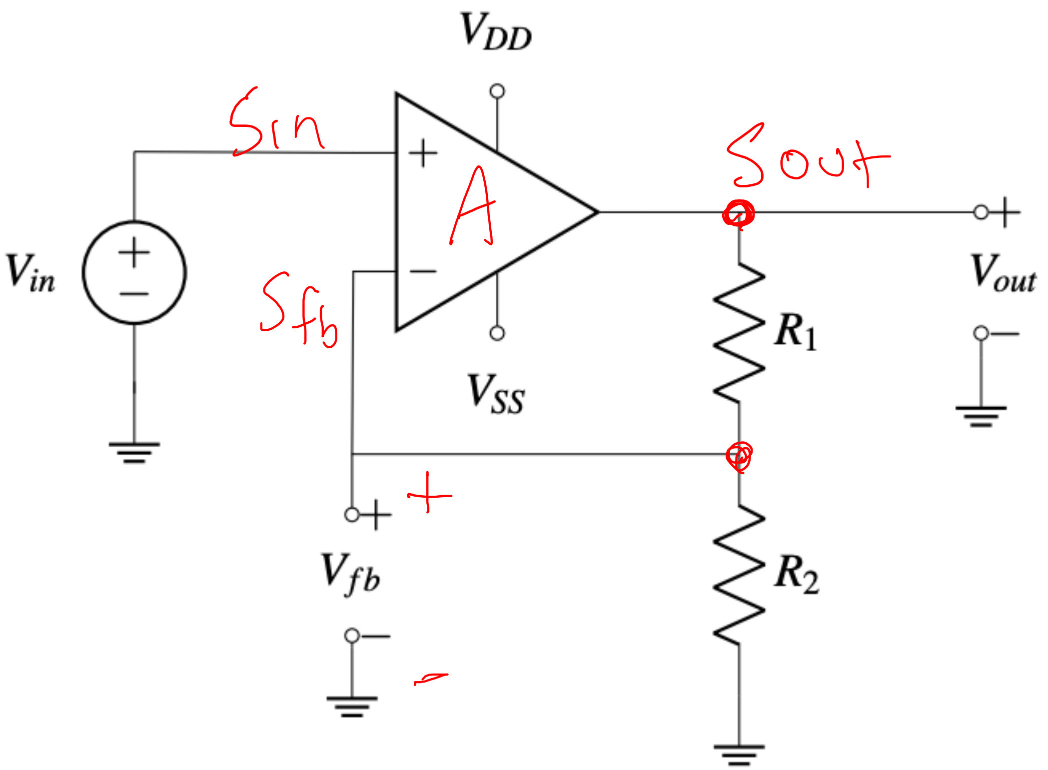
Apply Negative Feedback to an Op Amp!





An Op Amp with Negative Feedback!

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



$$V_{fb} = S_{fb} = S_{out} \cdot \frac{R_2}{R_2 + R_1}$$

$$f \cdot S_{out} = V_{fb} \qquad = \frac{R_2}{R_2 + R_1}$$

$$S_{out} = \frac{A}{1 + A\left(R_2 / (R_1 + R_2)\right)} \cdot S_{in} \qquad A \to \infty$$

$$S_{out} \approx \frac{R_1 + R_2}{R_2} \cdot S_{in} = 3!$$