Lecture 19 -- Post

Wednesday, July 19, 2023 2:47 PM

Lecture 6C: (7/26/23)

Announcements:

- Discussion - Cheating Attendance

Today's Topics:

- Feedback
- Solving Op-amp circuits

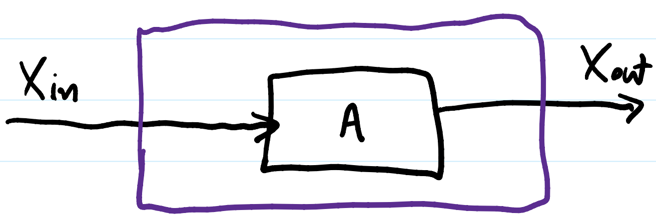
} (Note 18)

- Non-inverting op-amp circuit
- Negative Feedback Test

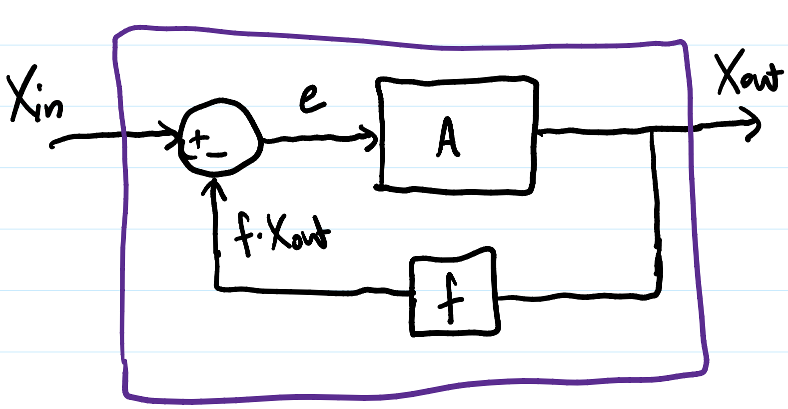
} (Note 19)

- Using an op-amp circuit (Note 18/19)
- Inverting op-amp circuit (Note 18.6)

Feedback (cont.)



Before: $\frac{X_{out}}{X_{in}} = A$



system

After (feedback):

$\frac{X_{out}}{X_{in}} = ?$

$e = X_{in} - f \cdot X_{out}$

$X_{out} = A \cdot e$

} substitute

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

system

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

$$(1+Af)\cdot X_{out} = A\cdot X_{in}$$

$$\boxed{\frac{X_{out}}{X_{in}} = \frac{A}{1+A\cdot f} \quad \text{Black's Formula}}$$

What if A is very large? ($A \gg 1$)

Ex). $A = 1000$

$$\frac{X_{out}}{X_{in}} = \frac{1000}{1+1000f} \approx \frac{1000}{1000f} = \frac{1}{f}$$

{ We changed the system gain from "A" to "$\frac{A}{1+Af}$". So what?

As $A \to \infty$

$$\lim_{A\to\infty} \frac{X_{out}}{X_{in}} = \lim_{A\to\infty} \frac{A}{1+Af} = \lim_{A\to\infty} \frac{A}{Af}$$

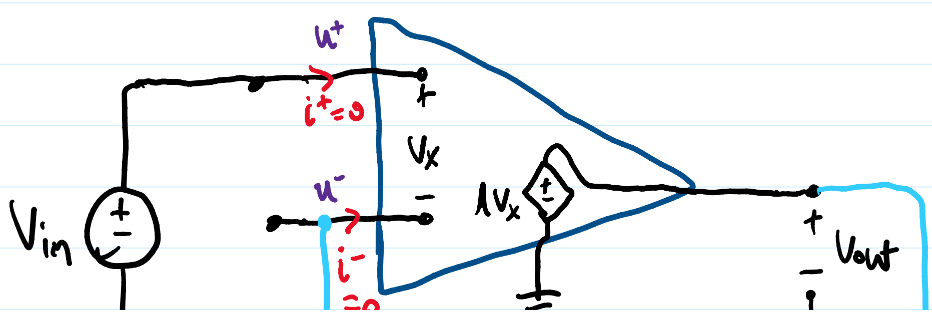
$$\boxed{\lim_{A\to\infty} \frac{X_{out}}{X_{in}} = \frac{1}{f}}$$

This is the essence of feedback. "A" is unknown, but we can control the input "X_{in}" and the feedback gain "f" to control the overall gain and set the desired "X_{out}".

How do we implement "f"? Using circuits

Let's apply feedback to our op-amp:

Can we make $\frac{V_{out}}{V_{in}} = 1$? Connect V_{out} to u^- terminal

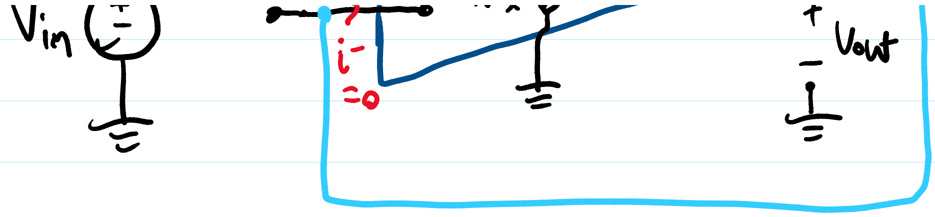


Solve the circuit:

$u^+ = V_{in}$ $\quad u^- = V_{out}$

$V_{out} = A\cdot V_x = A\cdot(u^+ - u^-)$

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



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

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

$$V_{out} = \frac{A}{1+A} V_{in}$$

We know op-amps have a large value of internal gain "A" $\longrightarrow$ $A \to \infty$

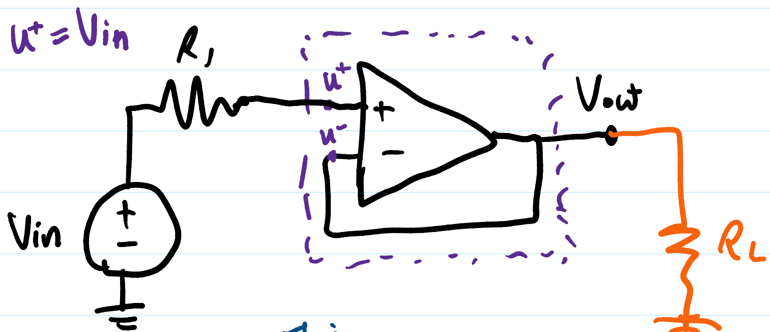
$$\boxed{V_{out} = V_{in}}$$

What does this result mean?

$u^+ = V_{in}$ $\quad u^- = V_{out} \approx V_{in}$ $\longrightarrow$ Thus, $u^+ \approx u^-$

> **Golden Rule #2:**
> If the op-amp circuit is in negative feedback, then $u^+ = u^-$

What is the point of this circuit?



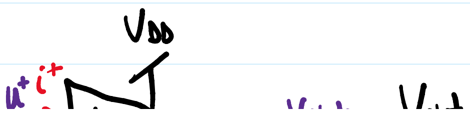
This op-amp configuration is called a <u>unity gain buffer</u>

Vout will ALWAYS be $= V_{in}$ no matter the value of resistance R_L

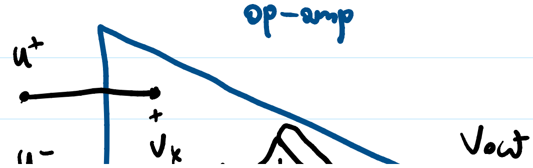
This circuit decouples Vout from Vin.

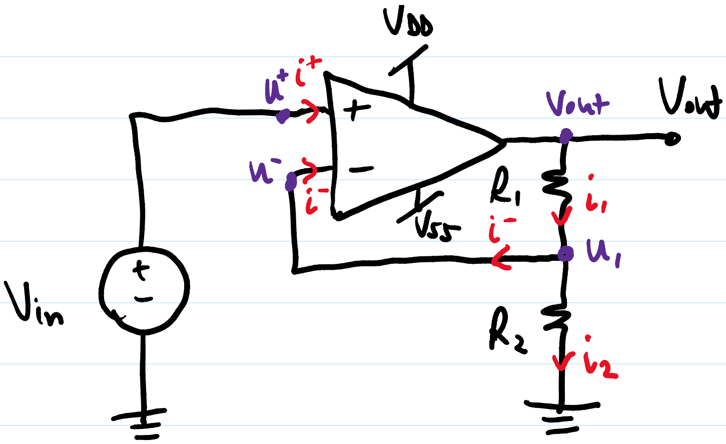
$$P_{R_L} = \frac{V_{out}^2}{R_L}$$

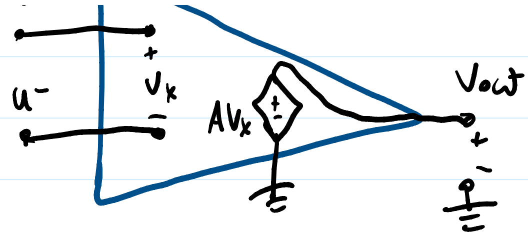
<u>Non-inverting op-amp circuit:</u>



Inside of the op-amp







$$V_{out} = A \cdot V_x = A \cdot \underbrace{(u^+ - u^-)}_{\text{difference of inputs}}$$

large gain

Method #1:

The complete way using only Golden Rule #1: $i^+ = i^- = 0$

Using NVA: Label unknown nodes: u^+, u^-, u_1, V_{out}

$= V_{in}$ $\qquad u^- = u_1$

KCL @ node $u_1 = u^-$:

$$i_1 - i^- - i_2 = 0$$

$$\frac{V_{out} - u_1}{R_1} - \cancel{i^-}^{\,0} - \frac{u_1 - 0}{R_2} = 0$$

From GR #1: $i^- = 0$

$$\frac{V_{out}}{R_1} = \left(\frac{1}{R_1} + \frac{1}{R_2}\right) u_1$$

$u_1 = u^-$

$$V_{out} = \left(1 + \frac{R_1}{R_2}\right) u^-$$

$V_{out} = A \cdot (u^+ - u^-) \rightarrow u^- = u^+ - \frac{1}{A} V_{out}$

$u^+ = V_{in} \longrightarrow \qquad = V_{in} - \frac{1}{A} V_{out}$

$$V_{out} = \left(1 + \frac{R_1}{R_2}\right) \cdot \left(V_{in} - \cancel{\frac{1}{A}}^{\,0} V_{out}\right)$$

$A \rightarrow \infty$

$$\boxed{V_{out} = \left(1 + \frac{R_1}{R_2}\right) \cdot V_{in}}$$

Gain of the non-inverting op-amp: $\frac{V_{out}}{V_{in}} = \underbrace{\left(1 + \frac{R_1}{R_2}\right)}_{G \geq 1} = G$

$G \geq 1 \leftarrow$ can "boost" input voltage

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Pick $R_1 = 2\Omega$, $R_2 = 1\Omega$

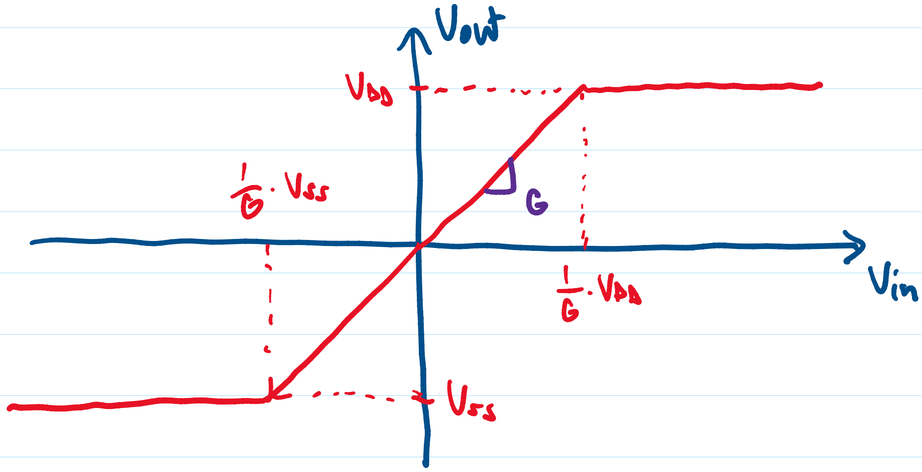
$$V_{out} = \left(1 + \frac{2\Omega}{1\Omega}\right) \cdot V_{in} = 3 \cdot V_{in}$$

Pick $R_1 = 10\Omega$, $R_2 = 5\Omega$

$$V_{out} = \left(1 + \frac{10\Omega}{5\Omega}\right) \cdot V_{in} = 3 \cdot V_{in}$$

An op-amp cannot output a $V_{out} > V_{DD}$ or $V_{out} < V_{SS}$
Beyond those limits, the output saturates

$$V_{out} = \begin{cases} V_{DD} & \text{if } V_{out} > V_{DD} \\ G \cdot V_{in} & \text{if } V_{SS} < V_{out} < V_{DD} \\ V_{SS} & \text{if } V_{out} < V_{SS} \end{cases}$$



Method #2:

The faster way using both Golden Rules #1 and #2

- Requires test for negative feedback $i^+ = i^- = 0$ $u^+ = u^-$

Using NVA: Label unknown nodes: u^+, u^-, u_1, V_{out}

KCL @ node $u_1 = u^-$: $V_{in} = \underbrace{u^+ = u^-}_{GR\ \#2} = u_1$

$i_1 - i^- - i_2 = 0$

$i_1 - i - i_2 = 0$

GR #2

$$\frac{V_{out} - u_1}{R_1} - 0 - \frac{u_1 - 0}{R_2} = 0$$

GR #1: $i^- = 0$

$$V_{out} = \left(1 + \frac{R_1}{R_2}\right) u_1$$

$u_1 = u^- = u^+ = V_{in}$

$$\boxed{V_{out} = \left(1 + \frac{R_1}{R_2}\right) \cdot V_{in}}$$

How do we determine if a circuit is in negative feedback?

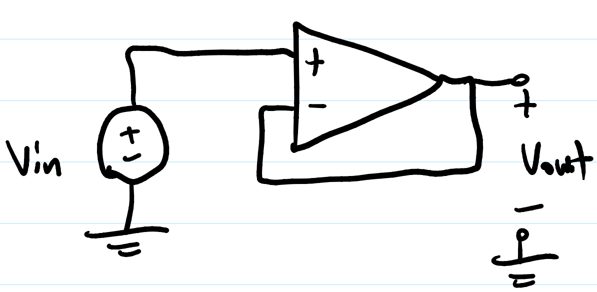
Negative Feedback Test

We can test any circuit for negative feedback by using a "perturb and observe" or "wiggle" or "dink" method

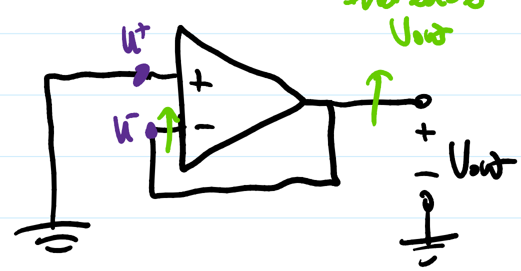
Step 1: Null independent sources
Voltage sources → short circuits
current sources → open circuits

Step 2: Perturb the output and observe how it propagates through the loop back to the output

Ex). Unity gain buffer



Step 1 ⟹



Remember that $V_{out} = A(u^+ - u^-)$

Remember that $V_{out} = A(u^+ - u^-)$

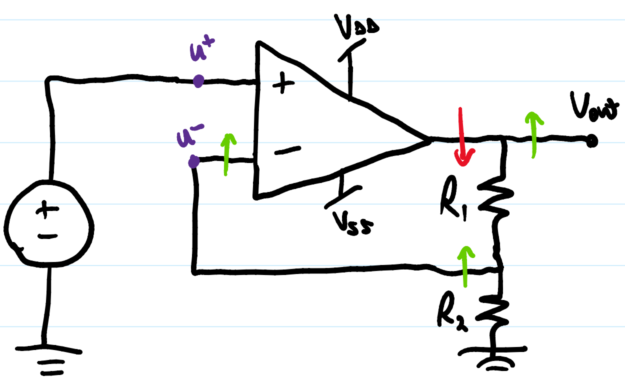
Increase V_{out} → Increases u^- → Decreases $u^+ - u^-$ → Decreases V_{out}

An increase in V_{out} causes a decrease in V_{out}

→ self-correcting ← <u>negative feedback</u>

Back to the non-inverting op-amp:

Negative Feedback Test:



Passes negative feedback test

Increase V_{out} → Increase u^- (voltage divider) → Decrease $u^+ - u^-$ → Decrease V_{out}