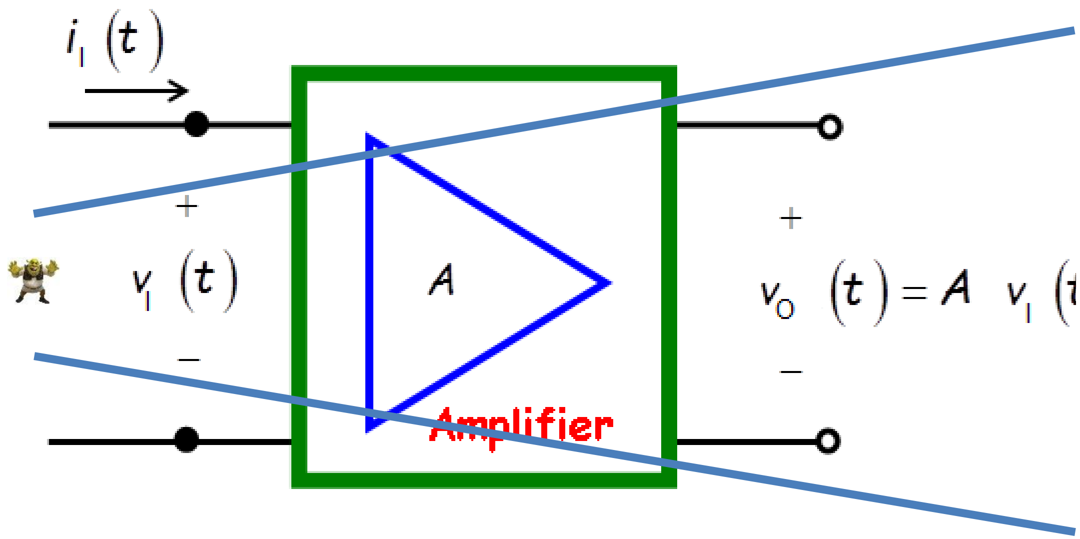
CET 141: Day 3

Dr. Noori KIM

The Operational Amplifier

Dr. Noori Kim

An amplifier?



- **An ideal amplifier**: a two-port circuit that
  - takes an input signal
  - and reproduces it exactly at its output,
  - only with a larger magnitude!
- A: **open-circuit voltage gain** of the ideal amplifier

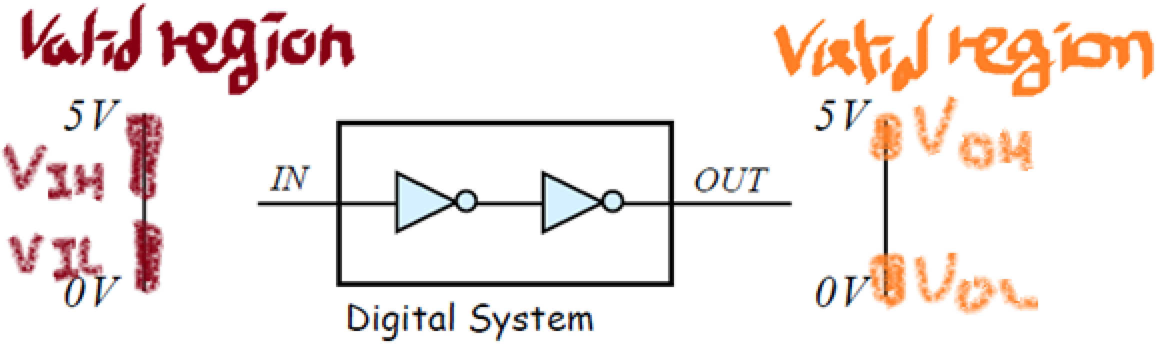
Why amplify?

- For signal amplification
  - A key to both analog and digital processing
  - to tolerate noise during communication

Why amplify? Analog

Why amplify? Digital

- Minimum amplification is needed:

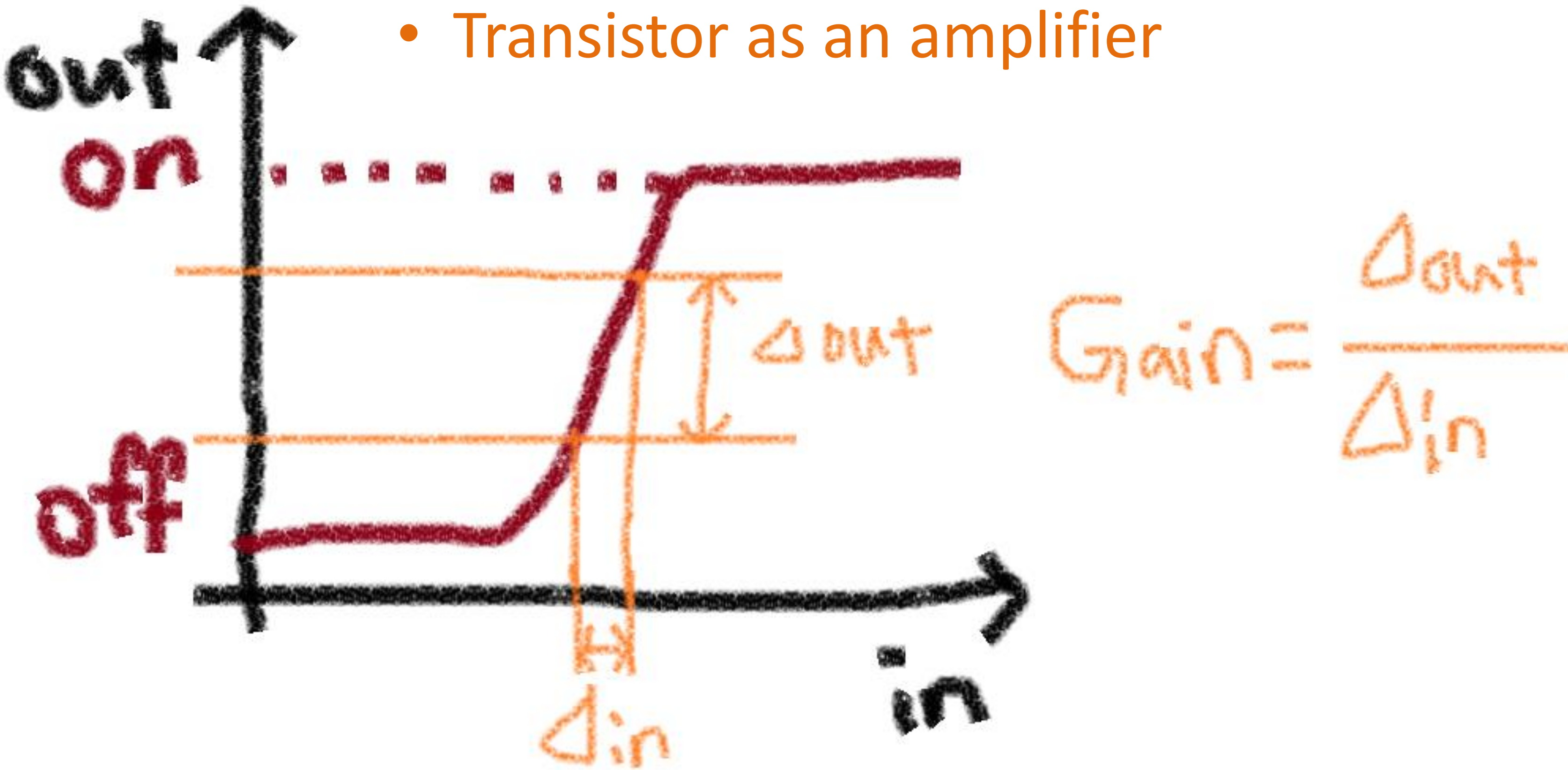


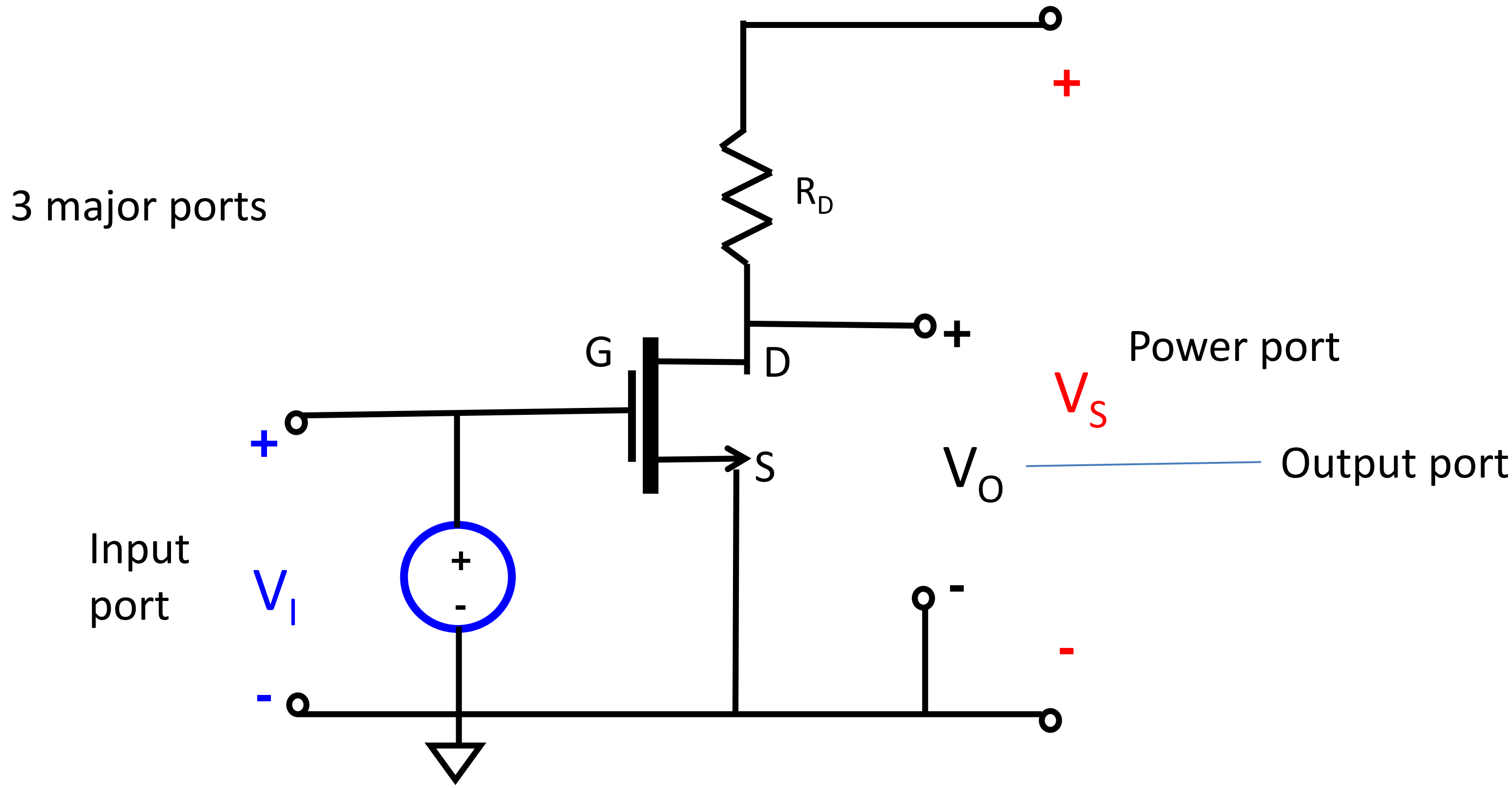
- In the **digital** domain, amplification is fundamental to **obtaining thresholds** for the static discipline
- In the **analog** domain, amplification gets **noise immunity** during communication

Recap: Transistors

Two basic transistor disciplines

- Transistor as a switch
- Transistor as an amplifier

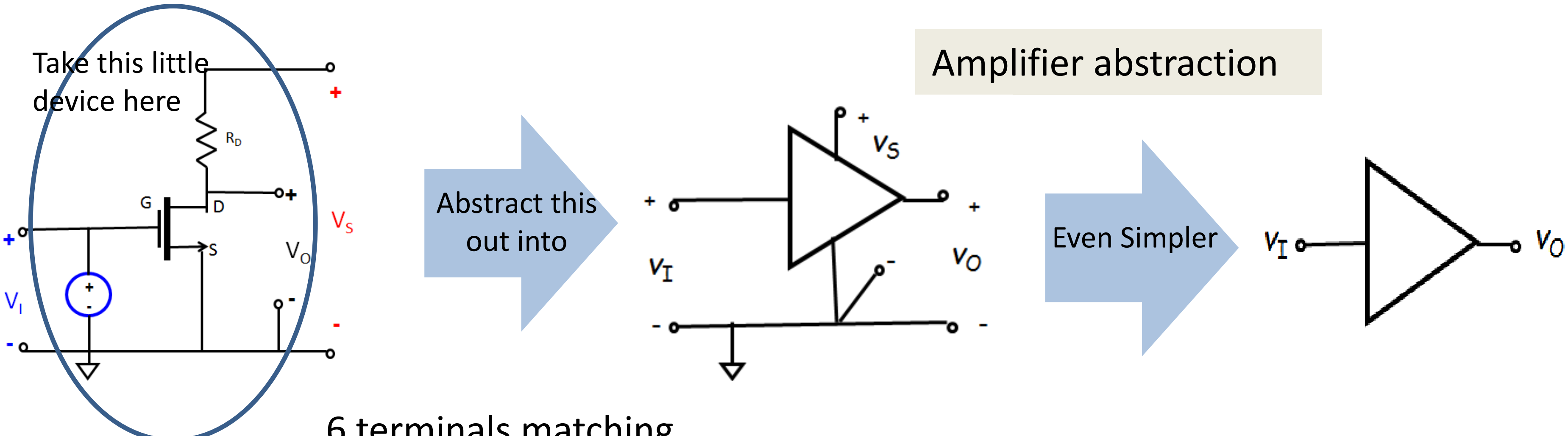




The metal–oxide–semiconductor field-effect transistor (MOSFET, MOS-FET, or MOS FET): a type of transistor used for amplifying or switching electronic signals.

Abstracting this out into some kind of building blocks

The Amplifier Abstraction



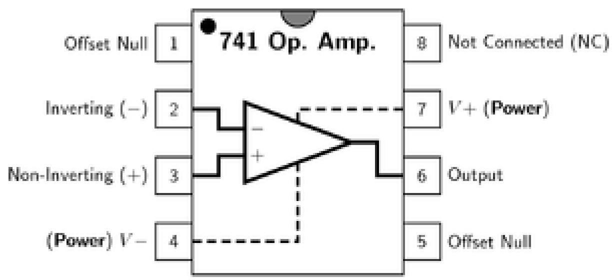
6 terminals matching

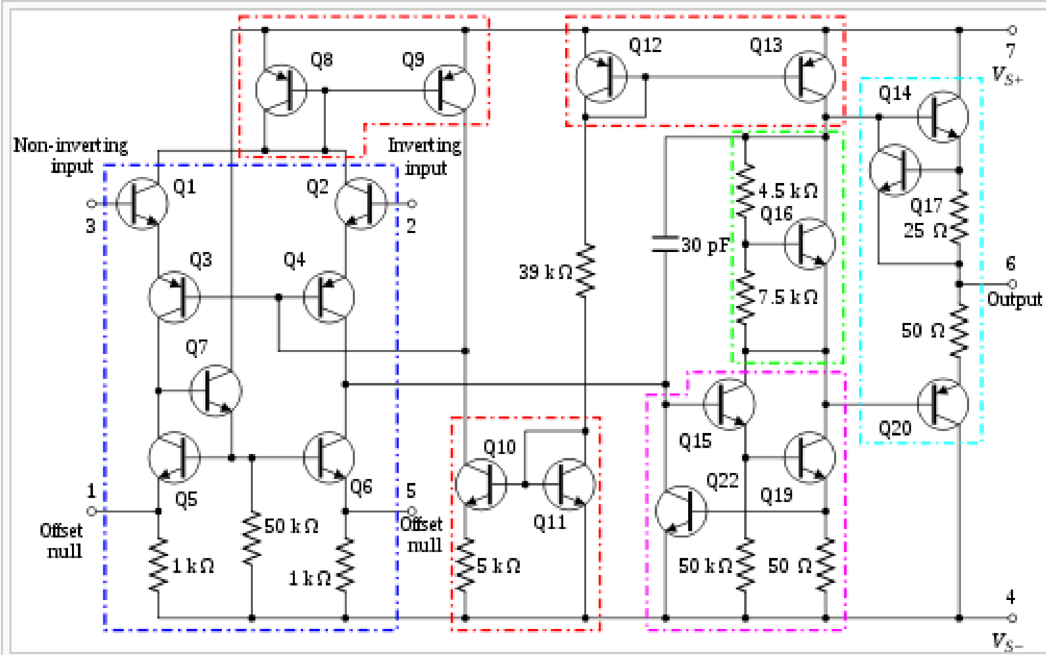
Progressively more abstracting representation of an amplifier

Ex) Internal circuitry of 741-type op-amp

- The most classical, standard structure consisting of three gain stages
- Designed in 1968 by David Fullagar at Fairchild Semiconductor

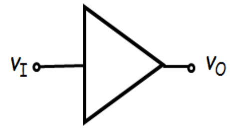
(https://en.wikipedia.org/wiki/Operational_amplifier)





A component-level diagram of the common 741 op-amp. Dotted lines outline: current mirrors (red); differential amplifier (blue); class A gain stage (magenta); voltage level shifter (green); output stage (cyan).

Abstraction?!?!

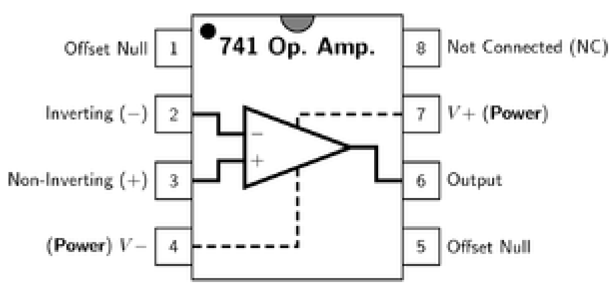
- What are inside  ?

- A workhorse and a building block in the analog industry
  - It's like 'printf' in the analog world
- The concept of Abstraction is very important in ECE
- A very powerful mechanism **<u>to deal with complexity</u>**

- Kinds of amplifiers

(https://en.wikipedia.org/wiki/Amplifier#Operational_amplifiers_.28op-amps.29)

Recall,



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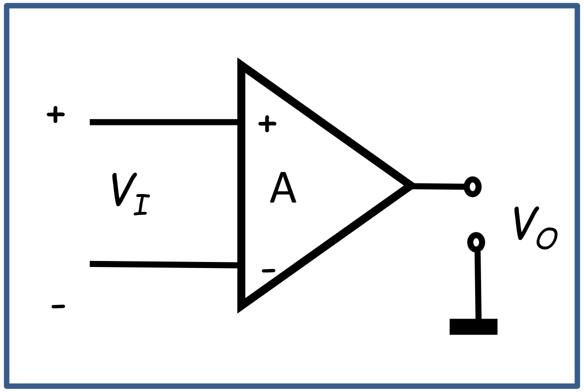
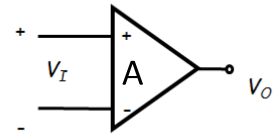
Operational amplifier (Op-amp) Abstraction

Abstraction of the op-amp

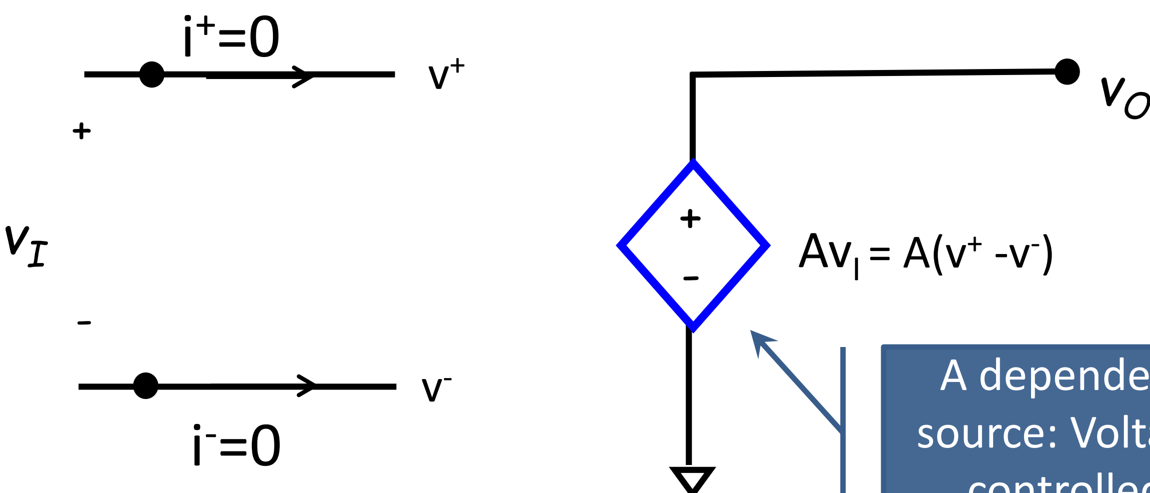


- **Recall that, an ideal amplifier**
    - takes an input signal
    - and reproduces it exactly at its output,
    - only with a larger magnitude!
- A: **open-circuit voltage gain** of the ideal amplifier

Key properties

- To use this building block  abstractly

- **A circuit model** of the **ideal** op-amp: to analyze how does this behave

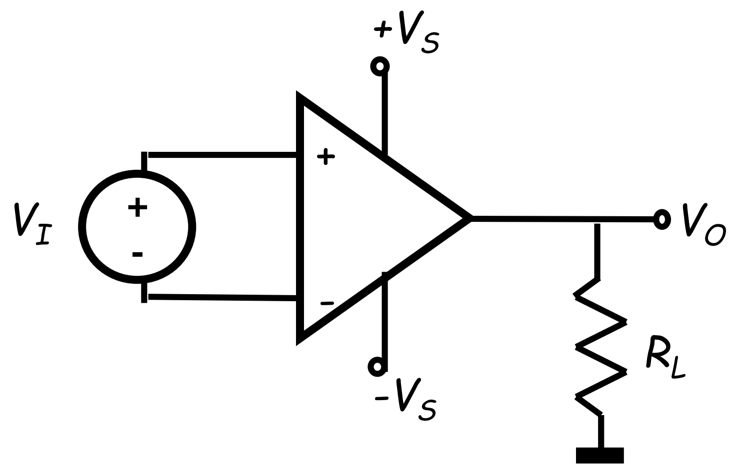


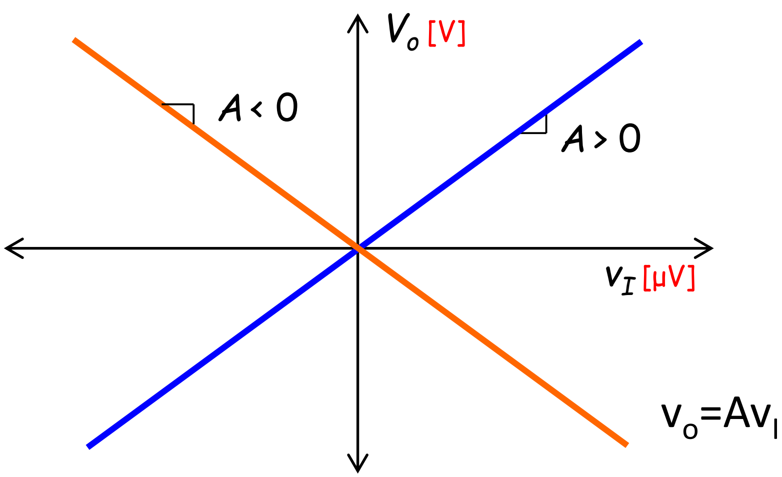
A dependent source: Voltage controlled voltage source

1. A is huge, $A \to \infty$, 10^5
   - Big=A*Small
2. The input resistance ∞
   - Looking in -> OC
3. The output resistance 0
   - Regardless of loads at the output, it keeps holding the voltage consistent

The Behavior

- Measure and Plot (output and input)

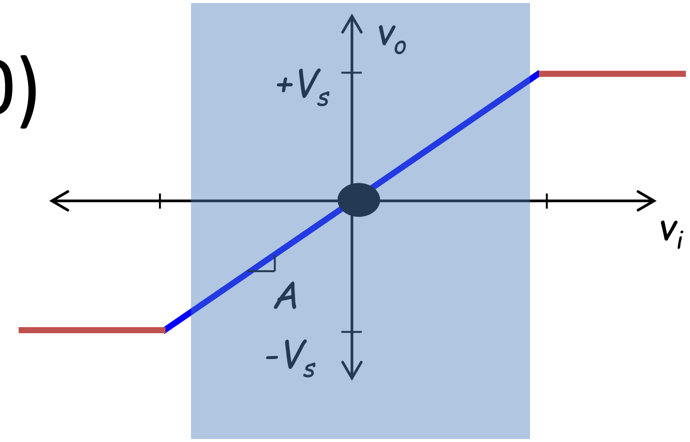




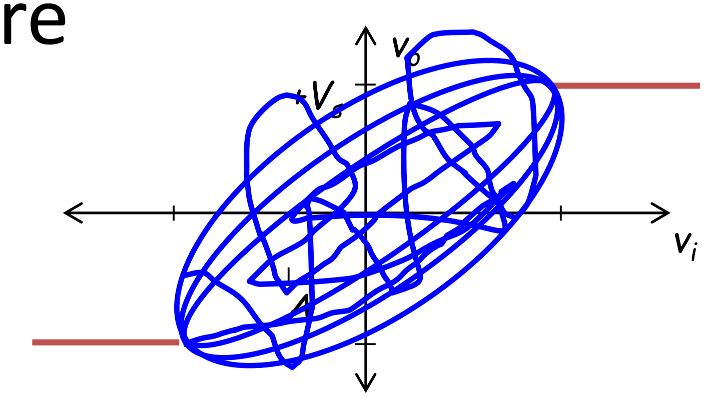
Remember, A is huge, 10^5, the slope
Small change in v_i will massively change in v_o

<u>But what we are missing here is V_s</u>

- Assuming ideal case (V_o=0,V_i=0)
  - Active region
  - Saturation: hit the rail!



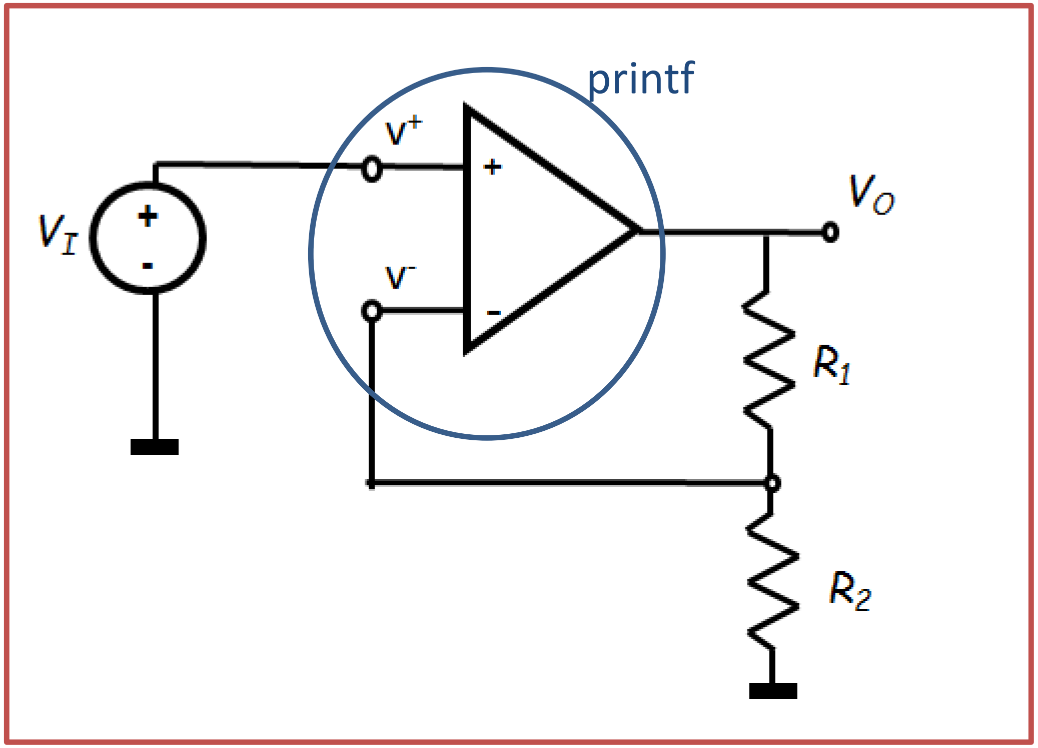
- A, the gain, the slope: very sensitive, unstable:
  - Temperature, time of a day, mood-swing…
  - It is still big, but we can't rely on it.
- If I heat the op-amp, the active line will fluctuate, will be everywhere



How can we resolve this problem??? ….
Later… but to make long story short , we can use "feedback"

Building a circuit
(Our “Hello World” program using an op-amp)

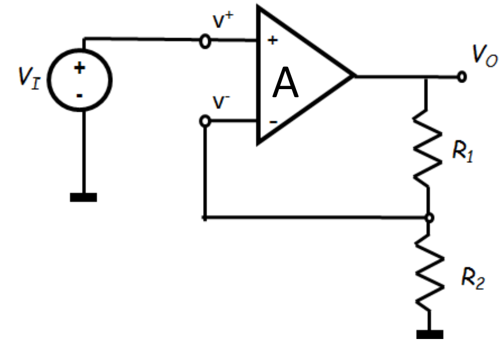
- A non-inverting amplifier

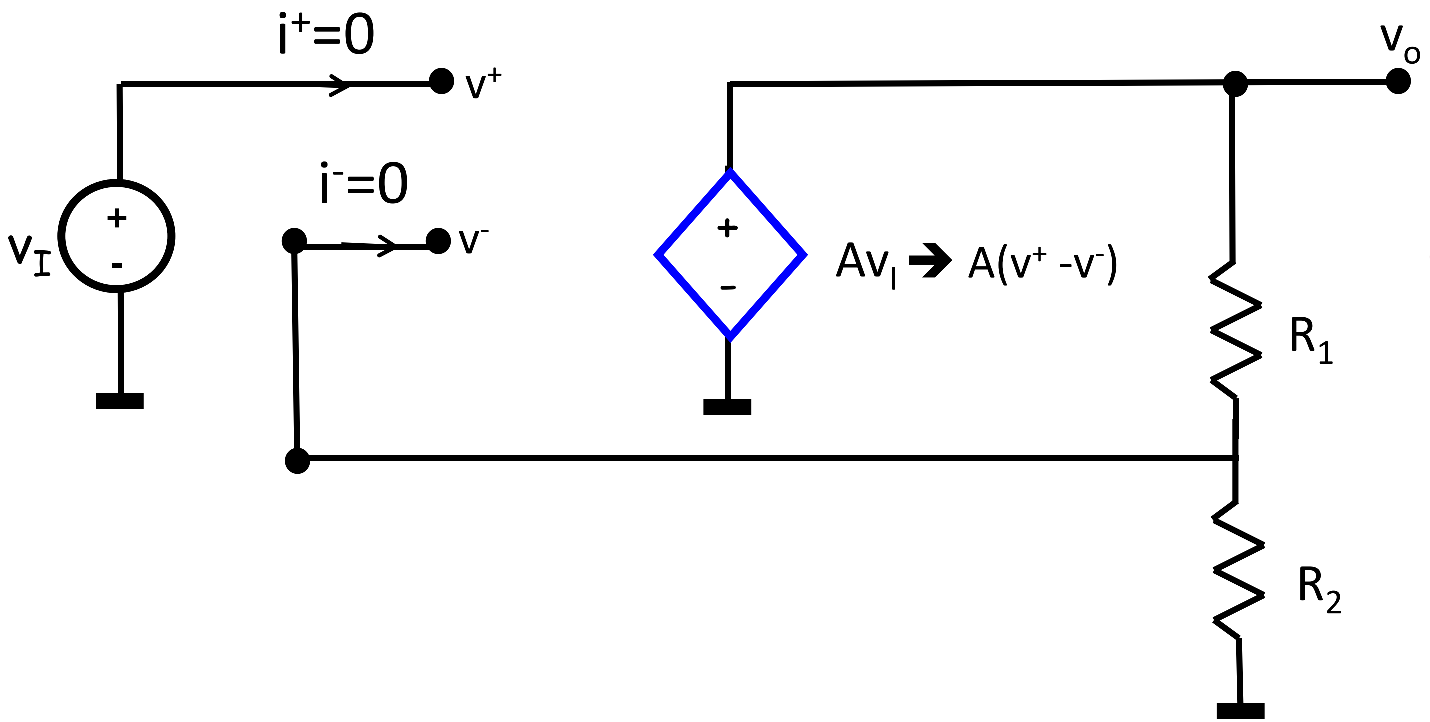



```
/* Hello World program */
#include<stdio.h>
main()
{
printf("Hello World");
}
```

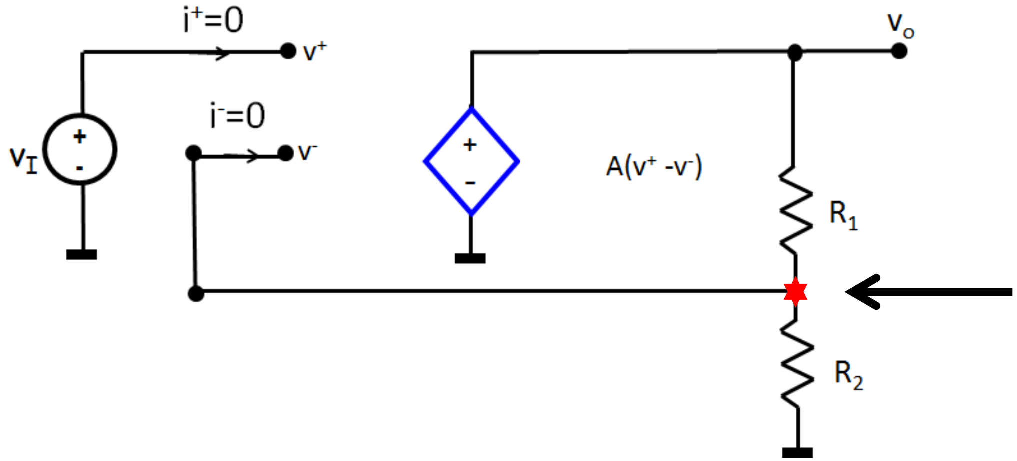
Analyzing the circuit

- We need a circuit model for





Our mission!!
Finding V_o
in terms of V_I



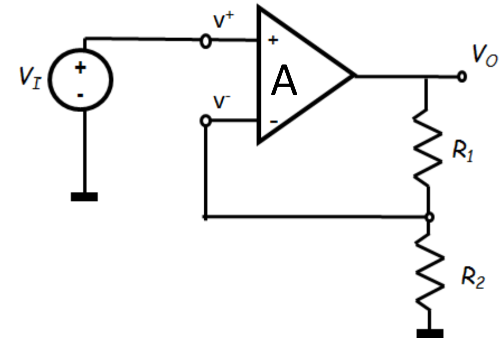
$V^{-} = \frac{v_o R_2}{R_1 + R_2}$

- Applying <u>**the node method**</u>
  - – Checking unknowns: v^- (voltage between v^- and two resistors) and v_o

$$v_o = A(v^+ - v^-)$$
$$= A\left(v_I - \frac{v_o R_2}{R_1 + R_2}\right)$$

$$v_o\left(1 + \frac{AR_2}{R_1 + R_2}\right) = Av_I$$

$$v_o = Av_I / \left(1 + \frac{AR_2}{R_1 + R_2}\right)$$



- A is huge, therefore

$$v_o = \frac{Av_I}{\left(1+\frac{AR_2}{R_1+R_2}\right)} \approx \frac{Av_I}{\frac{AR_2}{R_1+R_2}}$$

$$v_o \approx \boxed{\frac{v_I(R_1+R_2)}{R_2}}$$

No A is in here!!!

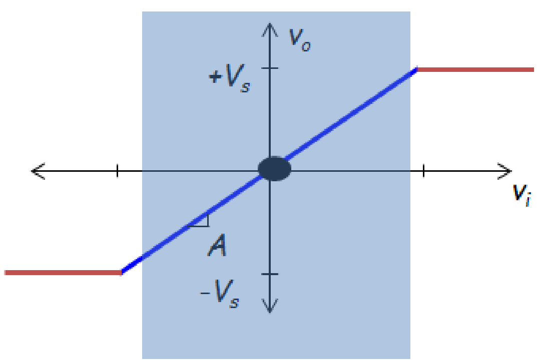
Suppose,

A=10^6 R_1=9R, R_2=R

$$v_o = \frac{Av_I}{\left(1+\frac{AR_2}{R_1+R_2}\right)} = \frac{10^6 v_I}{\left(1+\frac{10^6 R}{9R+R}\right)} = 10v_I$$

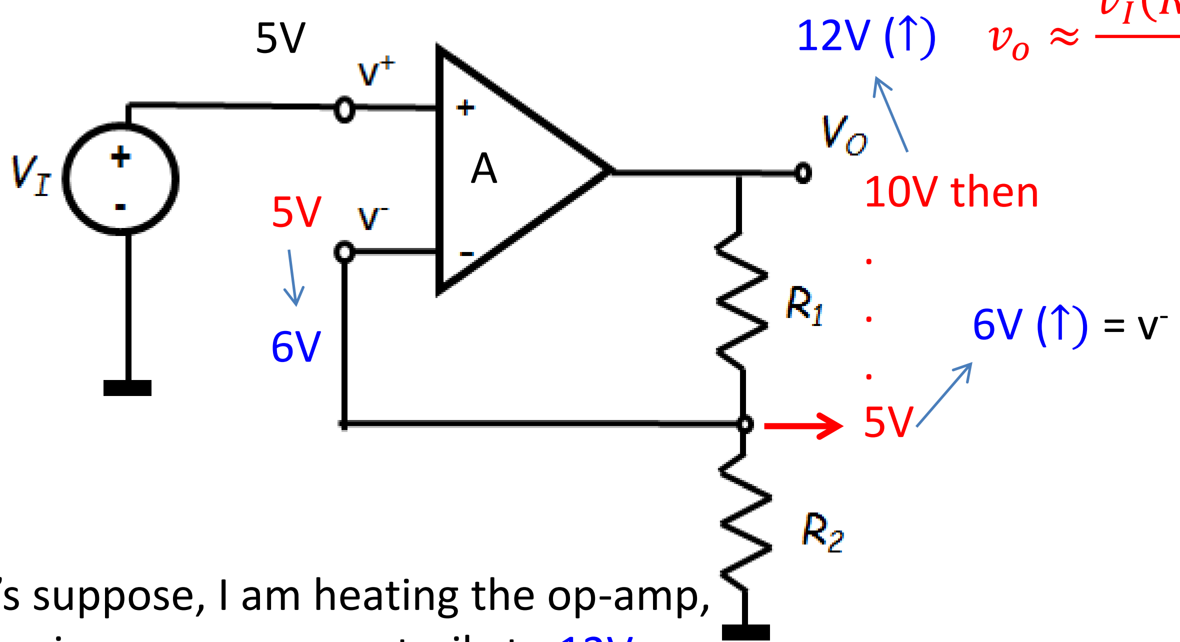
- I have a nice amplifier whose output is simply 10 times of the input.
- The gain is determined solely by some resistor values

If A does not matter in this case, if I heat the amp again. But why?



Given, v_I=5V and R1=R2=R

$$v_o \approx \frac{v_I(R_1+R_2)}{R_2} = 2v_I = 10V$$



Let's suppose, I am heating the op-amp,

1. v_o increases momentarily to 12V.
2. Then v^- becomes 6V
3. Now the input voltage becomes NEGATIVE
   - v^+=5V and v^-=6V
   - Therefore the output should go DOWN!! Pull it down! Think $v_o=A(v^+-v^-)$
4. Let's assume that now the v_o becomes 9V
5. In the same manner, v^- becomes 4.5V which will make v_o goes back up!!

A big battle is going on in the op-amp!!

feed back, push back, a portion of the output to the negative input

Negative "feedback": a big word!!!

Ideal Op-Amp *Analysis*

Two ideal Op-Amp Properties:

(1) Input impedance = ∞ : The current into both V^+ and V^- terminals are zero

(2) Therefore $V^+ = V^-$

For ideal Op-Amp circuit:

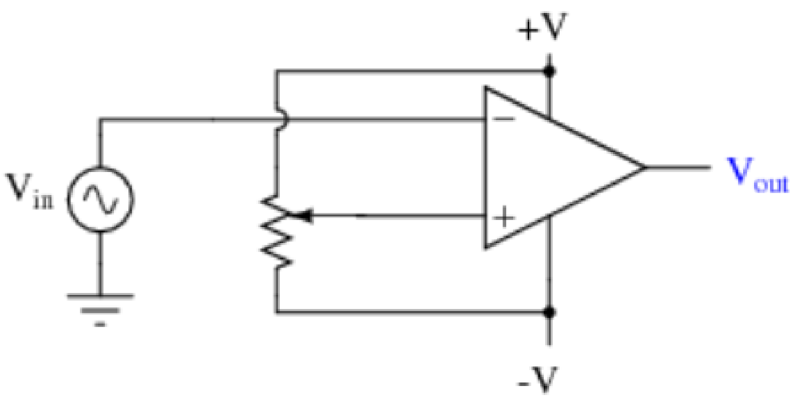
(1) Write the Kirchhoff's node equation at the noninverting terminal V^+

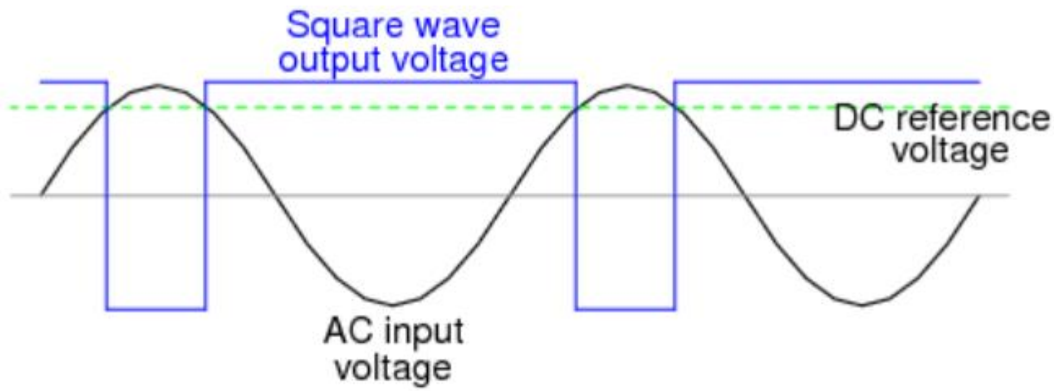
(2) Write the Kirchhoff's node equation at the inverting terminal V^-

(3) Set $V^+ = V^-$ and solve for the desired closed-loop gain

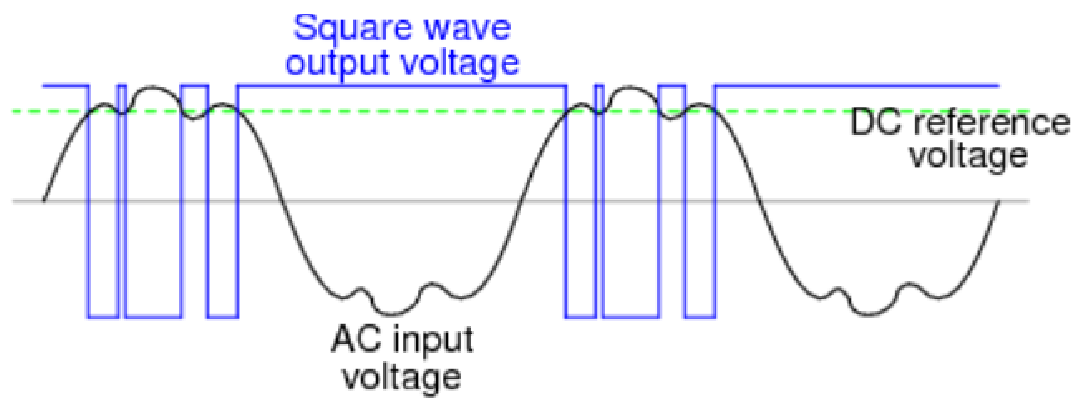
What about positive feedback?

A simple comparator: one threshold



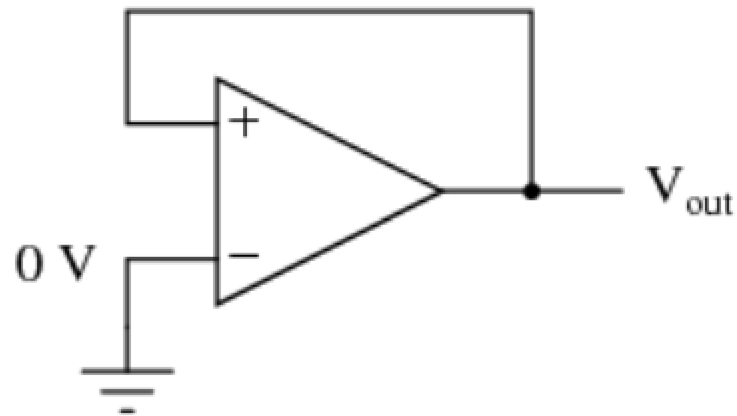


A "clean" AC input waveform produces predictable transition points on the output voltage square wave



https://www.allaboutcircuits.com/textbook/semiconductors/chpt-8/positive-feedback/

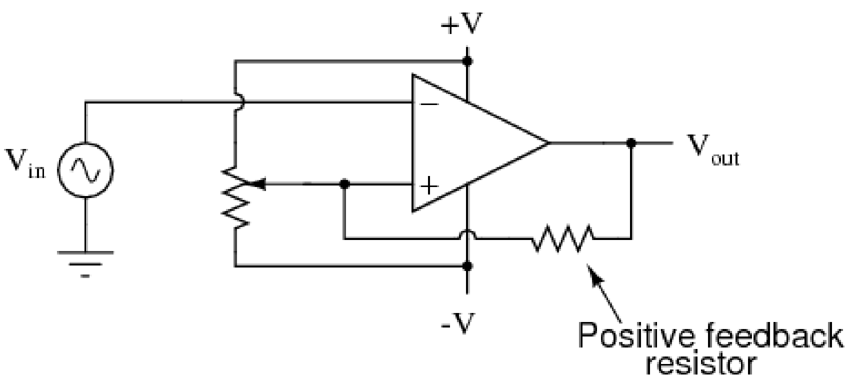
Positive feedback

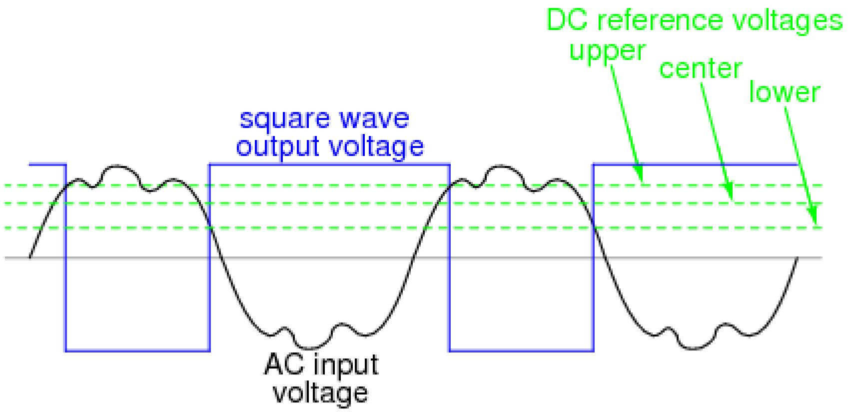


What will happen? Remember “A” is still alive

1. $(V^{+}-V^{-})A=Vout$
2. Vout feedbacks to V^{+}
    - Resulting in full positive output saturation If $(V^{+}-V^{-}) >0$
    - Resulting in full negative output saturation if $(V^{+}-V^{-})<0$

Adding a positive feedback





A positive feedback to the comparator circuit ➔ introducing hysteresis

- The output to remain in its current state unless the AC input voltage undergoes a major change in magnitude.

This is a Schmitt Inverter