LECTURE 15

Lecture 14 Review:

•Dependent Sources (model for “active” devices)

•Voltage - dependent voltage source as model for amplifier

Today:

- More on The Amplifier concept: High-gain amplifiers
  - •Comparators
  - •Amplifiers with negative feedback & “Op Amps”

A Brief Diversion from our Digital Circuits
Goal - A quick look at amplifiers

•Amplifiers - needed to restore weak signals

•Amplifiers - key component in signal detection and conversion -- for example Analog to Digital Conversion

Examples of Analog/Digital conversion

•Example: at the termination of every transmission line (take a pretty lousy-looking degraded pulse and decide if it's a zero or a one).

•Example: interrogating a memory cell for its contents (again, decide if the contents represent a zero or a one)

There is an electronic component that makes is easy to manipulate analog signals and to do analog to digital or digital to analog conversion … the high-gain differential amplifier

With this component we construct two especially useful devices:

The Operational Amplifier (OP-AMP)

The Comparator (one-bit A/D converter)

DIFFERENTIAL AMPLIFIERS

Q: What <u>IS</u> in a high-gain differential amplifier?

A: A transistor circuit constructed to to have large voltage gain and be sensitive only to the voltage difference at its inputs.

Q: Where do we learn about them?

A: (1) A little in EECS 42 (CMOS logic) Stay with us!

(2) “Everything” on CMOS logic in EECS 141

(3) A lot on linear designs in EECS 105

(4) “Everything” on linear designs in EECS 140

(5) “State of art” in EECS 241 and 240

Q: What do they cost ?

A: $\underbrace{\text{.01 cents}}_{\text{BIG IC's}}$ $\underbrace{\text{to a few dollars}}_{\text{“Discretes”}}$

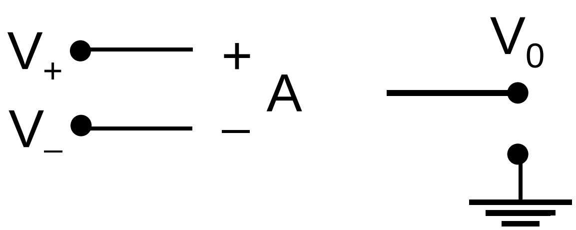
OP-AMPS AND COMPARATORS

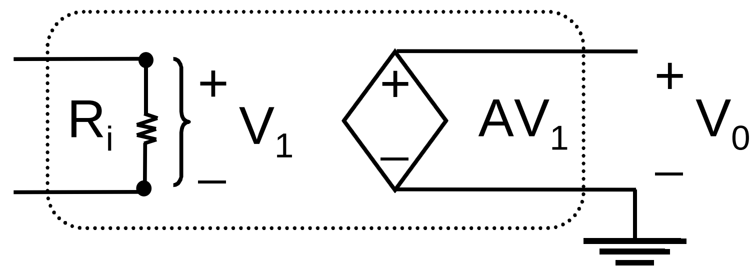
A very high-gain differential amplifier can function **either** in extremely linear fashion as an operational amplifier (by using negative feedback) **or** as a very nonlinear device – a comparator. Let's see how!

Differential Amplifier

$$V_0 = A(V_+ - V_-)$$

Circuit Model *in linear region*





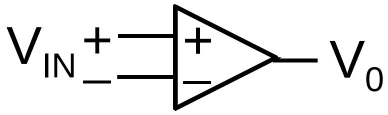
"Differential" $\Rightarrow$ V_0 depends only on difference ($V_+ - V_-$)

"Very high gain" $\Rightarrow$ $A \to \infty$

But if $A \sim \infty$, is the output infinite?

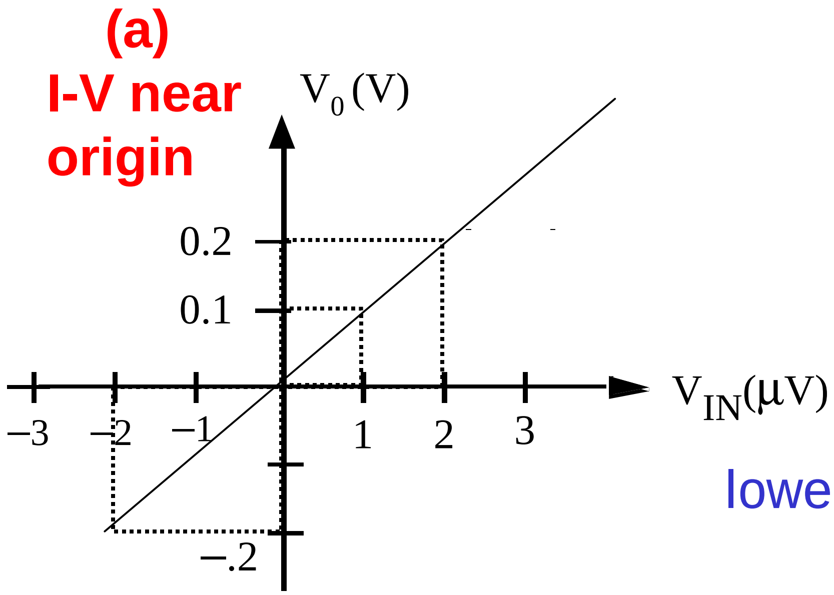
The output cannot be larger than the supply voltages. It will limit or "clip" if we attempt to go too far. We call the limits of the output the "**rails**".

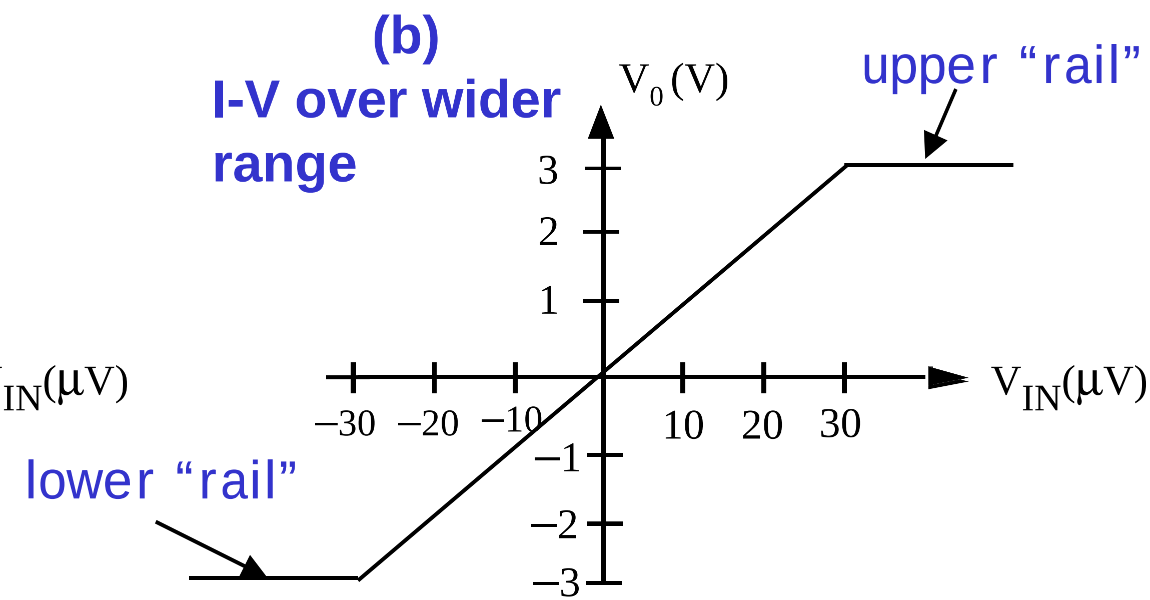
WHAT ARE I-V CHARACTERISTICS OF AN ACTUAL HIGH-GAIN DIFFERENTIAL AMPLIFIER ?



- Circuit model gives the essential linear part
- But V_0 cannot rise above some physical voltage related to the positive power supply V_{CC} (" upper rail") $\boxed{V_0 < V_{+RAIL}}$
- And V_0 cannot go below most negative power supply, V_{EE} i.e., limited by lower "rail" $\boxed{V_0 > V_{-RAIL}}$

Example: Amplifier with gain of 10^5, with max V_0 of 3V and min V_0 of –3V.

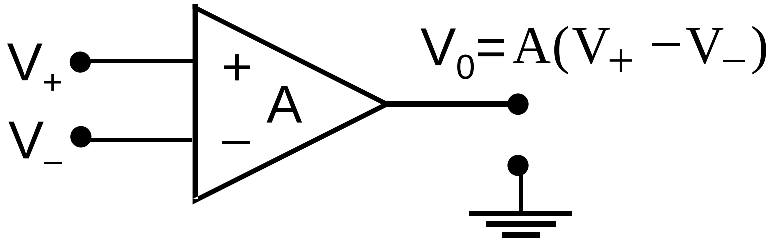


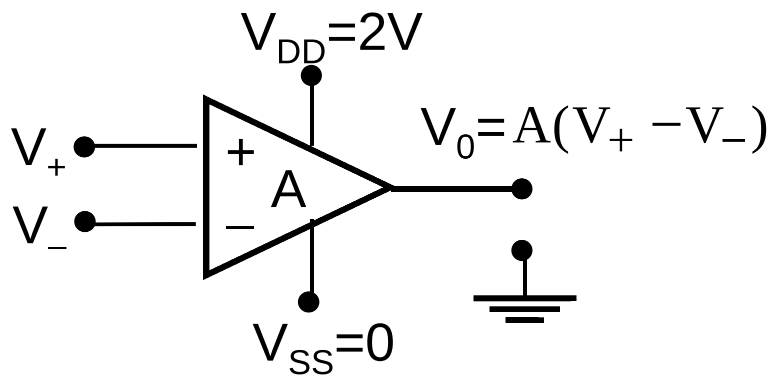


THE RAILS

The output voltage of an amplifier is of course limited by whatever voltages are supplied (the "power supplies"). Sometimes we show them explicitly on the amplifier diagram, but often they are left off.

Differential Amplifier





If the supplies are 2V and 0V, the output cannot swing beyond these values. (You should try this experiment in the lab.) So in this case we have upper rail = 2V, lower rail = 0V.

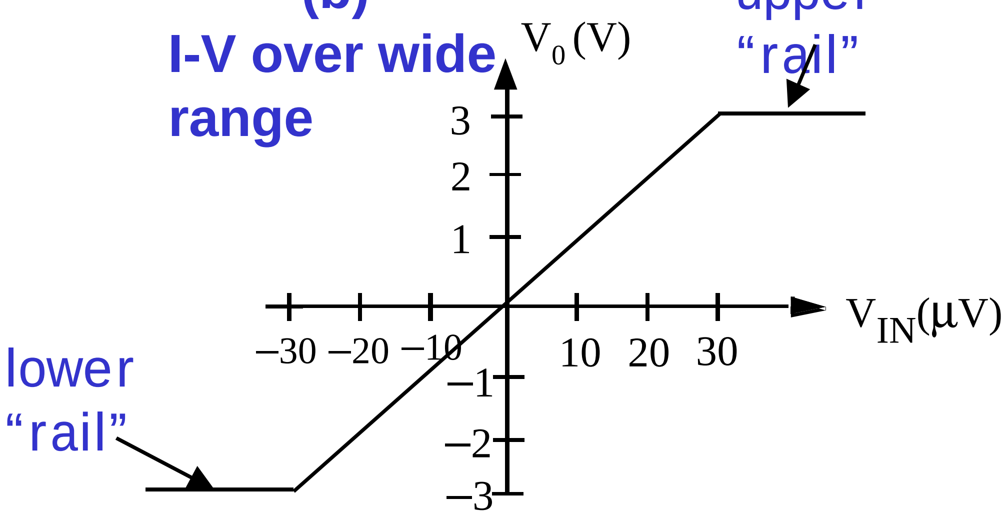
The rails cannot be larger than the supply voltages. For simplicity we will use the supply voltages as the rails.

I-V CHARACTERISTICS OF AN ACTUAL HIGH-GAIN DIFFERENTIAL AMPLIFIER (cont.)

Example: Amplifier with gain of 10^5, with upper rail of 3V and lower rail of -3V. We plot the V_0 vs V_{IN} characteristics on two different scales

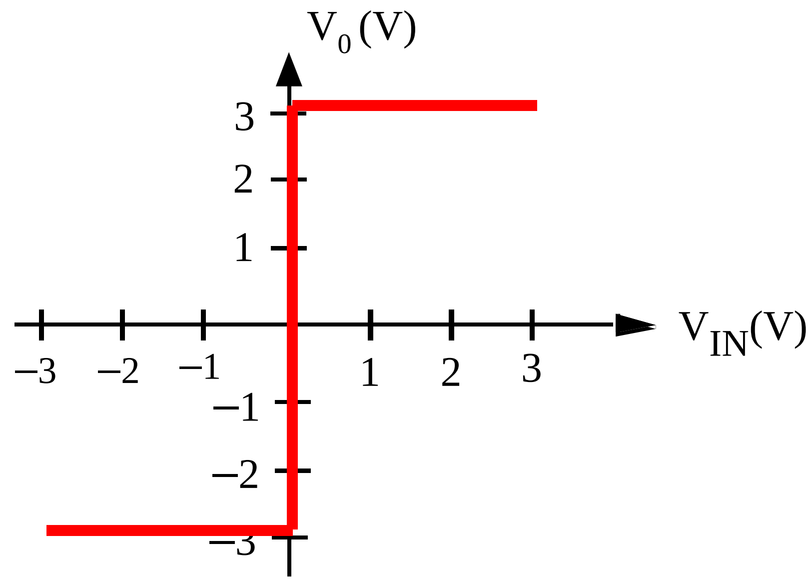
(b)

I-V over wide range



(c)

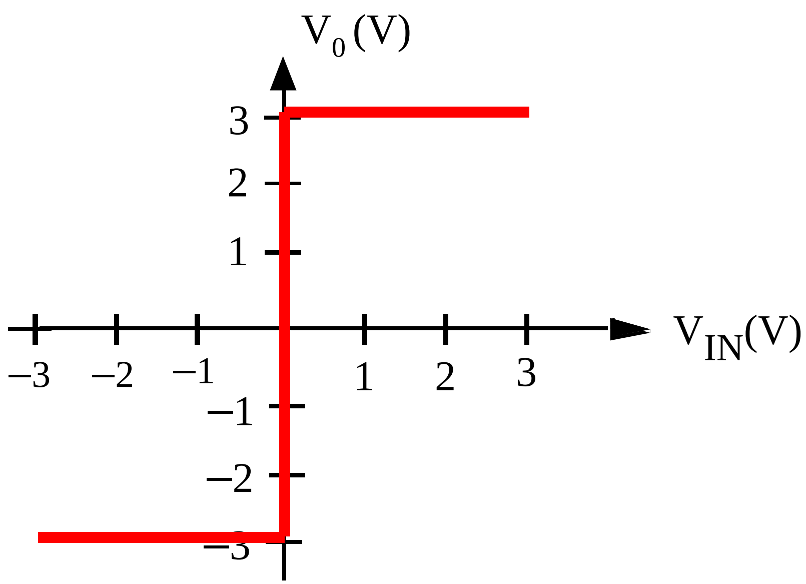
Same V_0 vs V_{IN} over even wider range



I-V CHARACTERISTICS OF AN ACTUAL HIGH-GAIN DIFFERENTIAL AMPLIFIER (cont.)

Now plot same thing but with equal horizontal and vertical scales (volts versus volts)

(c)
I-V with equal X and Y axes

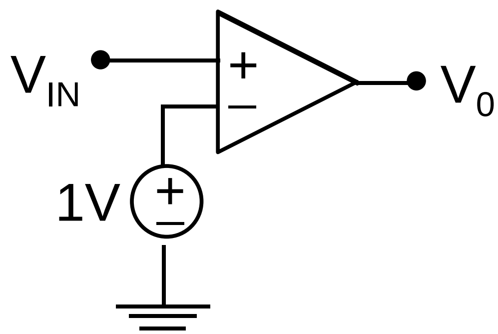


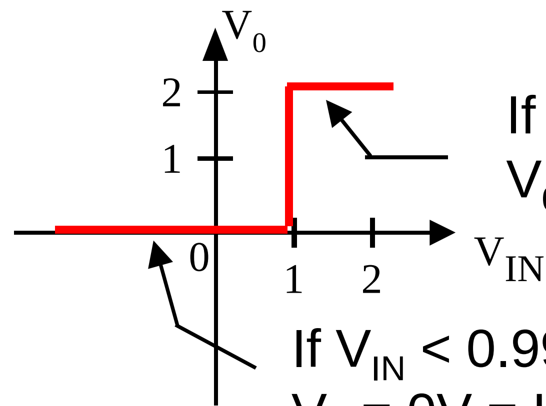
Note:

- (a) displays linear amplifier behavior
- (b) shows limit of linear region – ($|V_{IN}| < 30\ \mu V$)
- (c) shows comparator function (1 bit A/D converter centered at $V_{IN} = 0$) where lower rail = logic "0" and upper rail = logic "1"

EXAMPLE OF A HIGH-GAIN DIFFERENTIAL AMPLIFIER OPERATING IN COMPARATOR (A/D) MODE

Simple comparator with threshold at 1V. Design lower rail at 0V and upper rail at 2V (logic “1”). A = large (e.g. 10^2 to10^5)

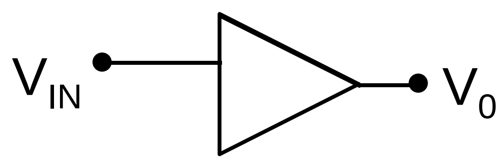




If $V_{IN} > 1.010$ V,
V_0 = 2V = Logic “1”

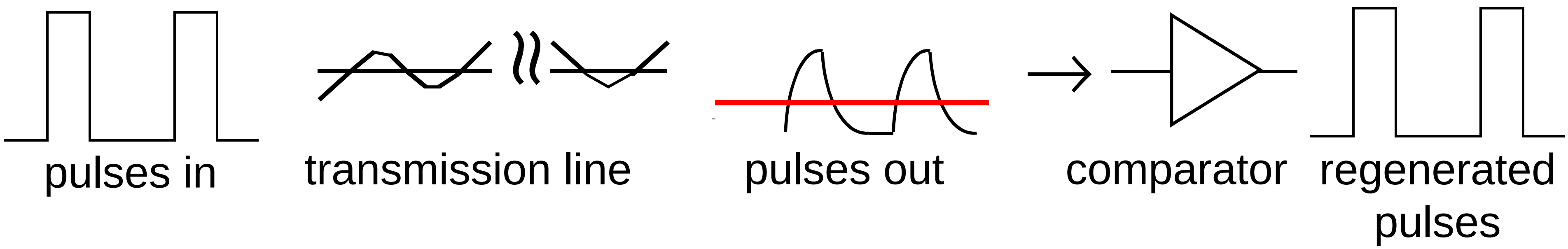
If $V_{IN} < 0.99$ V,
V_0 = 0V = Logic “0”

NOTE: The actual diagram of a comparator would not show an amplifier with “offset” power supply as above. It would be a simple triangle, perhaps with the threshold level (here 1V) specified.



Comparator

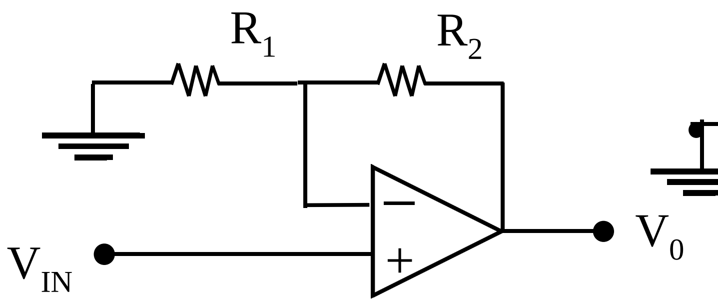
ONE-BIT A/D CONVERSION
REQUIRED IN DIGITAL SYSTEMS



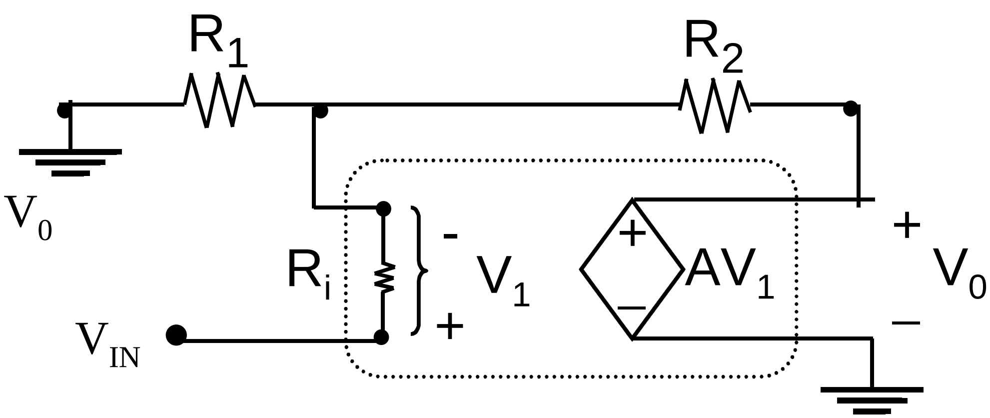
As we saw, we set comparator threshold at a suitable value (e.g., halfway between rails) and comparator output goes to +rail if $V_{IN} > V_{THRESHOLD}$ and to –rail if $V_{IN} < V_{THRESHOLD}$.

OP-AMPS AND COMPARATORS

A very high-gain differential amplifier can function in extremely linear fashion as an operational amplifier by using negative feedback.



EXAMPLE



Circuit Model

Negative feedback $\Rightarrow$ **Stabilizes** the output

We can show that that for $A \to \infty$ and $R_i \to 0$,

$$V_0 \cong V_{IN} \cdot \frac{R_1 + R_2}{R_1}$$

Stable, finite, and independent of the properties of the OP AMP !

NEGATIVE FEEDBACK

Familiar examples of negative feedback:

Thermostat controlling room temperature

Driver controlling direction of automobile

Photochromic lenses in eyeglasses

Fundamentally pushes toward stability

Familiar examples of positive feedback:

Microphone "squawk" in room sound system

Mechanical bi-stability in light switches

Thermonuclear reaction in H-bomb

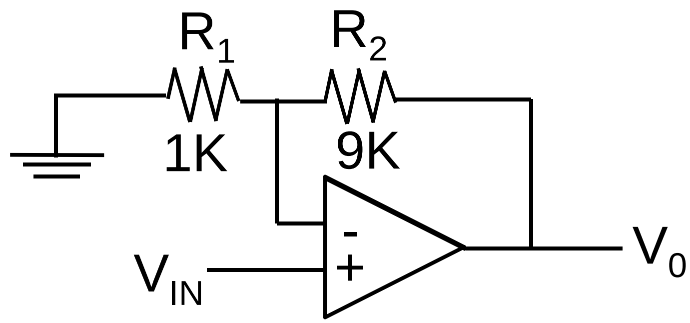
Fundamentally pushes toward instability or bi-stability

  W. G. Oldham

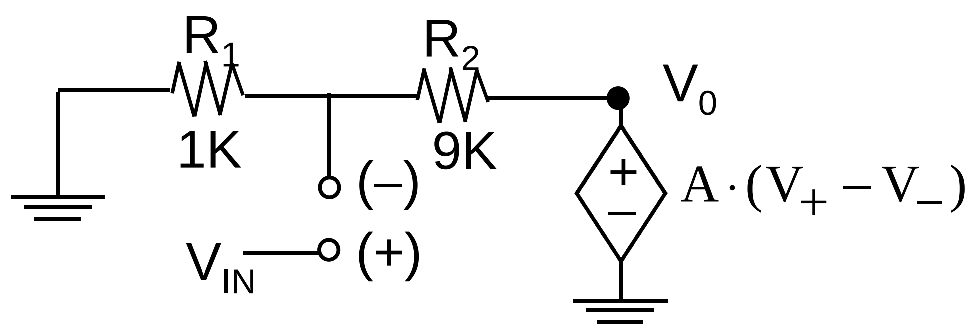
OP-AMPS – "TAMING" THE WILD HIGH-GAIN AMPLIFIER

KEY CONCEPT: **Negative feedback**

Example:



Circuit (assume $R_{IN} \cong \infty$)



Analysis:

$$\left.\begin{aligned} V_{(-)} &= \frac{R_1}{R_1+R_2} \cdot A(V_+ - V_-) \\ V_+ &= V_{IN} \end{aligned}\right\}$$

$$V_{(-)}\left(1+\frac{R_1 A}{R_1+R_2}\right) = AV_{IN}\left(\frac{R_1}{R_1+R_2}\right)$$

$$V_{(-)} = \frac{AR_1}{(A+1)R_1+R_2} V_{IN}$$

Lets solve for V_-
then find V_O from
$V_O = A\ (V_+ - V_-)$

$$\Rightarrow V_0 = A(V_+ - V_-) = AV_{IN}\left(1-\frac{AR_1}{(A+1)R_1+R_2}\right)$$

$$V_0 = V_{IN}\frac{A(R_1+R_2)}{(A+1)R_1+R_2} \cong V_{IN}\frac{R_1+R_2}{R_1} = 10V_{IN}$$

$$\text{if } A \to \infty$$