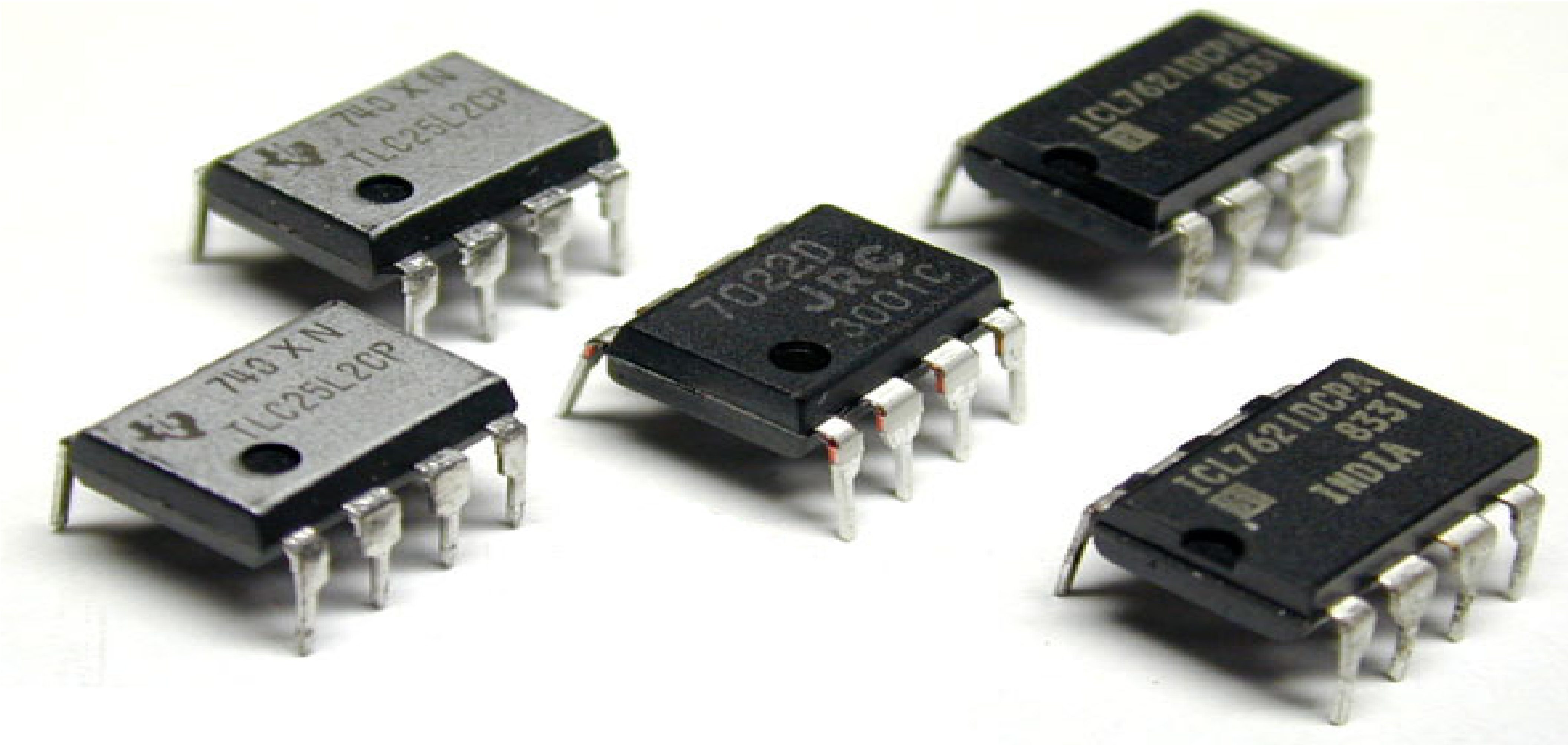
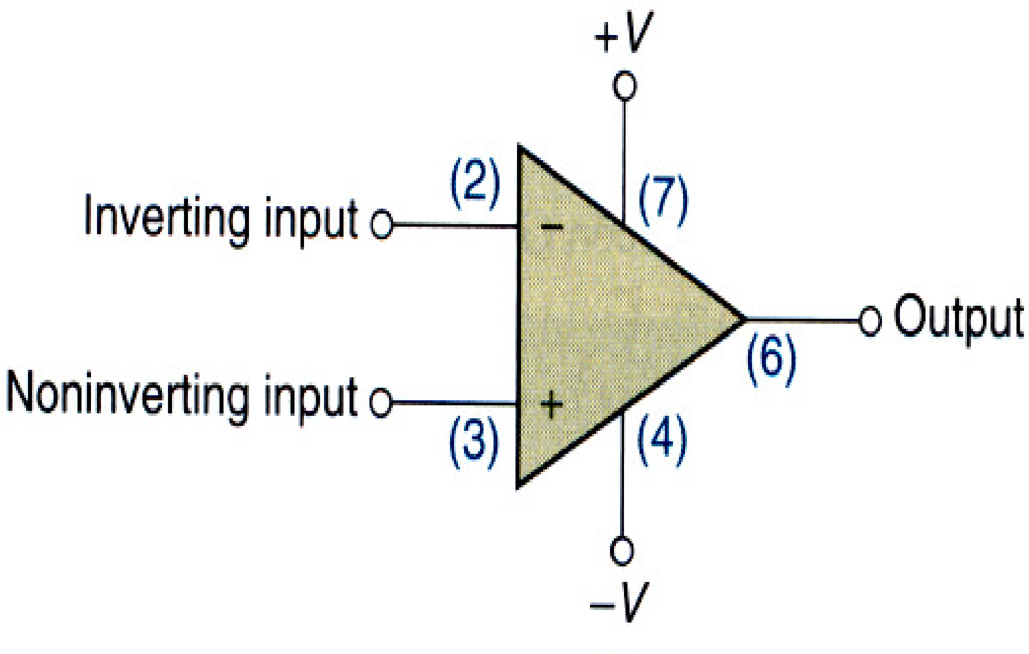
Operational Amplifier (Op – Amp)
Component Description



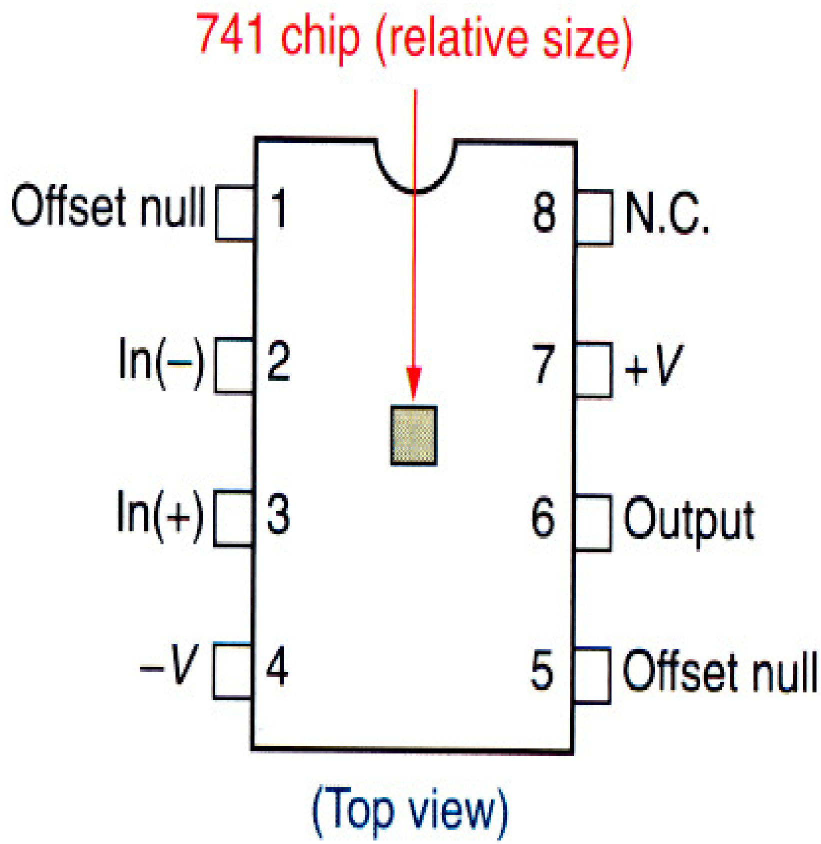
Operational Amplifier (Op – Amp)

Pin Diagram & Circuit Symbol of IC 741



(a)

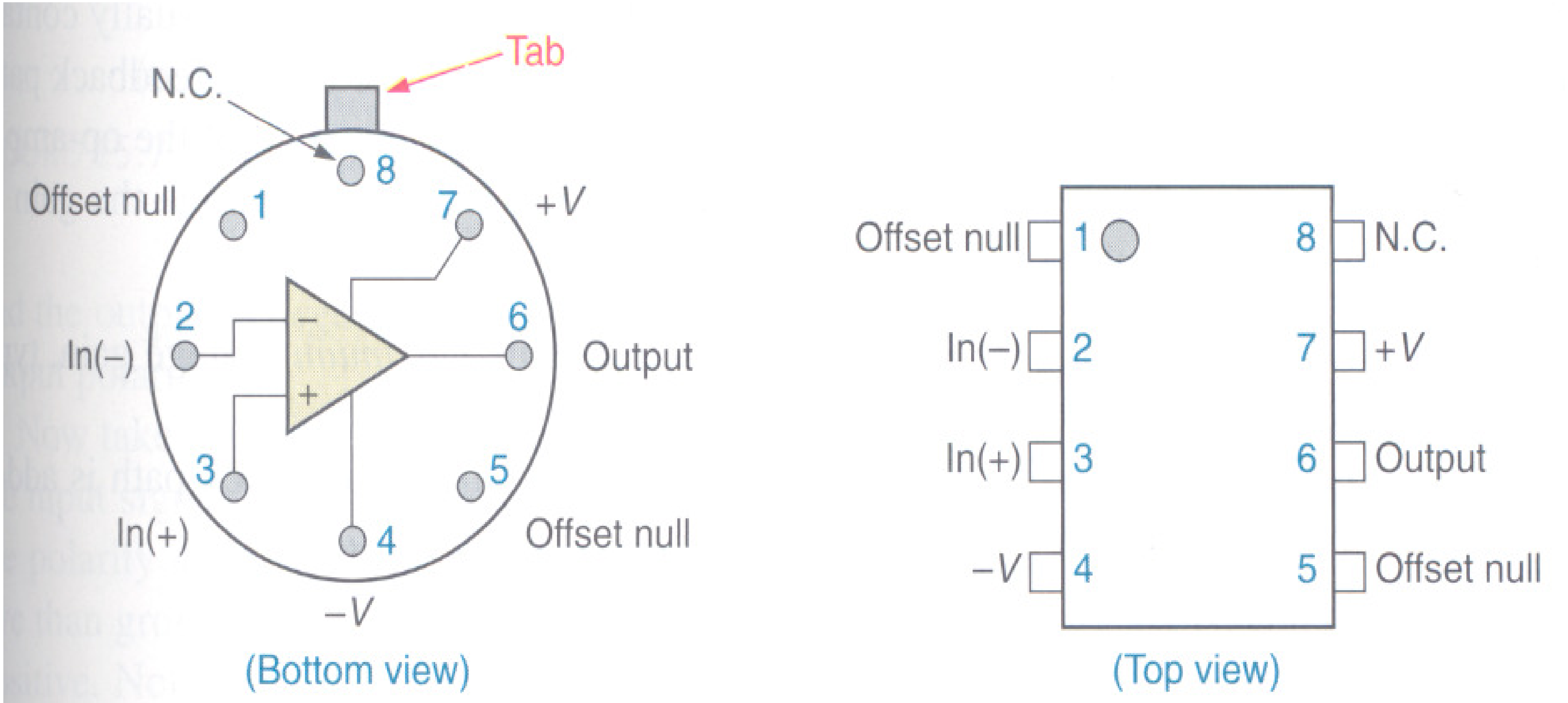
(b) The schematic symbol for an op-amp



(c) The 741 chip packaged in an 8-pin DIP (dual-in-line package)

Operational Amplifier (Op – Amp)

Types of Op – Amp Packages of IC 741



(a) Metal can (TO-5)

(b) 8-pin DIP or SMP

Operational Amplifier (Op – Amp)

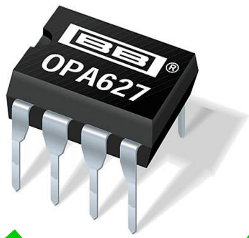
What makes it so useful & versatile ?

A/D & D/A converter

signal amplification

wave-shaping techniques

filtering action



precision rectification

signal generation

timing applications

voltage regulation

analog computation

mathematical operations

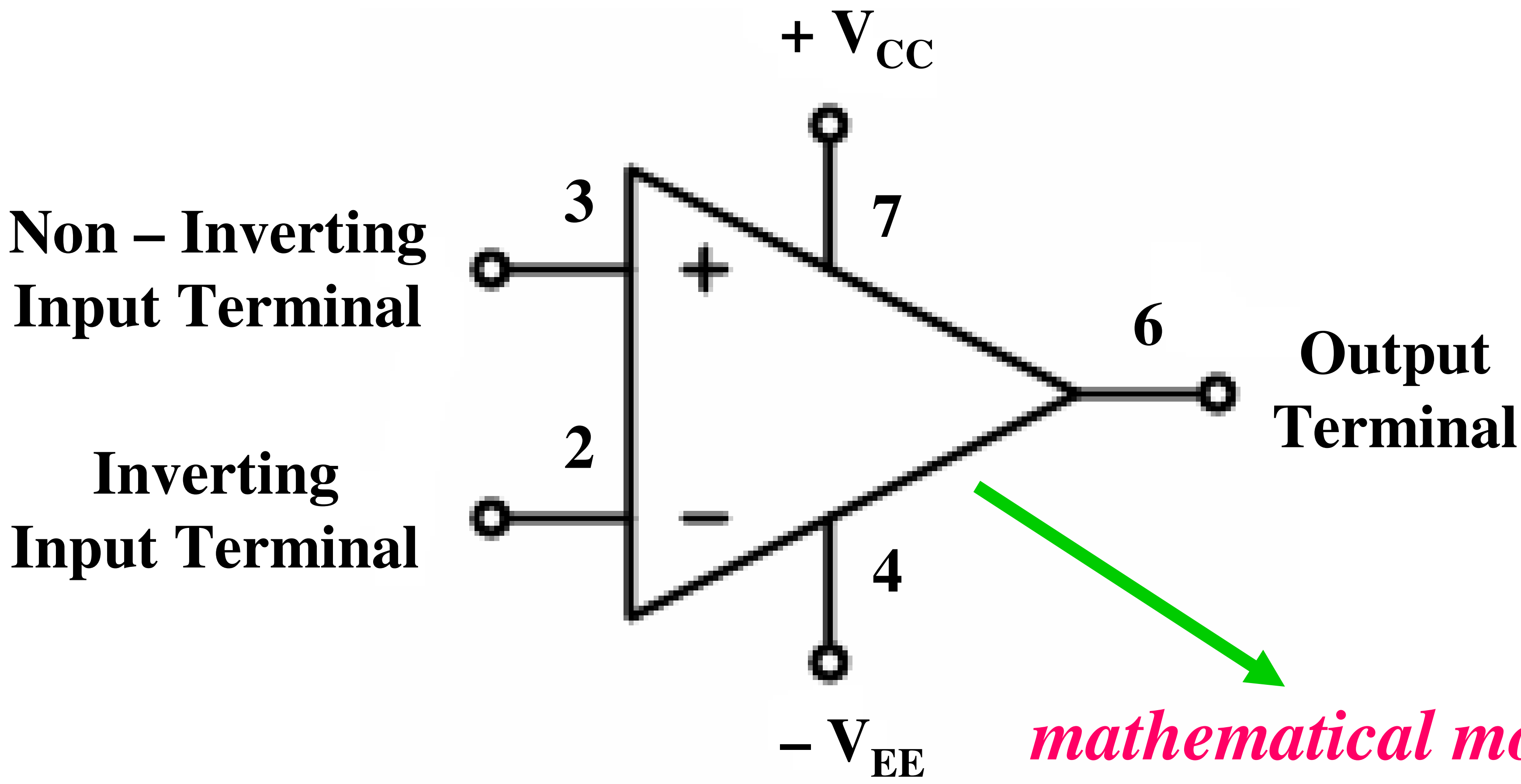
Operational Amplifier (Op – Amp)

Typical Application Areas

- Analog & Digital Communication
- Instrumentation Systems
- Analog Signal Processing
- Analog Computation Systems
- Waveform Synthesizers & Generators
- Signal Conversion Techniques
- Voltage Regulators & Power Supplies
- Timers & Timing Applications

Operational Amplifier (Op – Amp)

Circuit Symbol of IC 741C



mathematical model is required for analysis

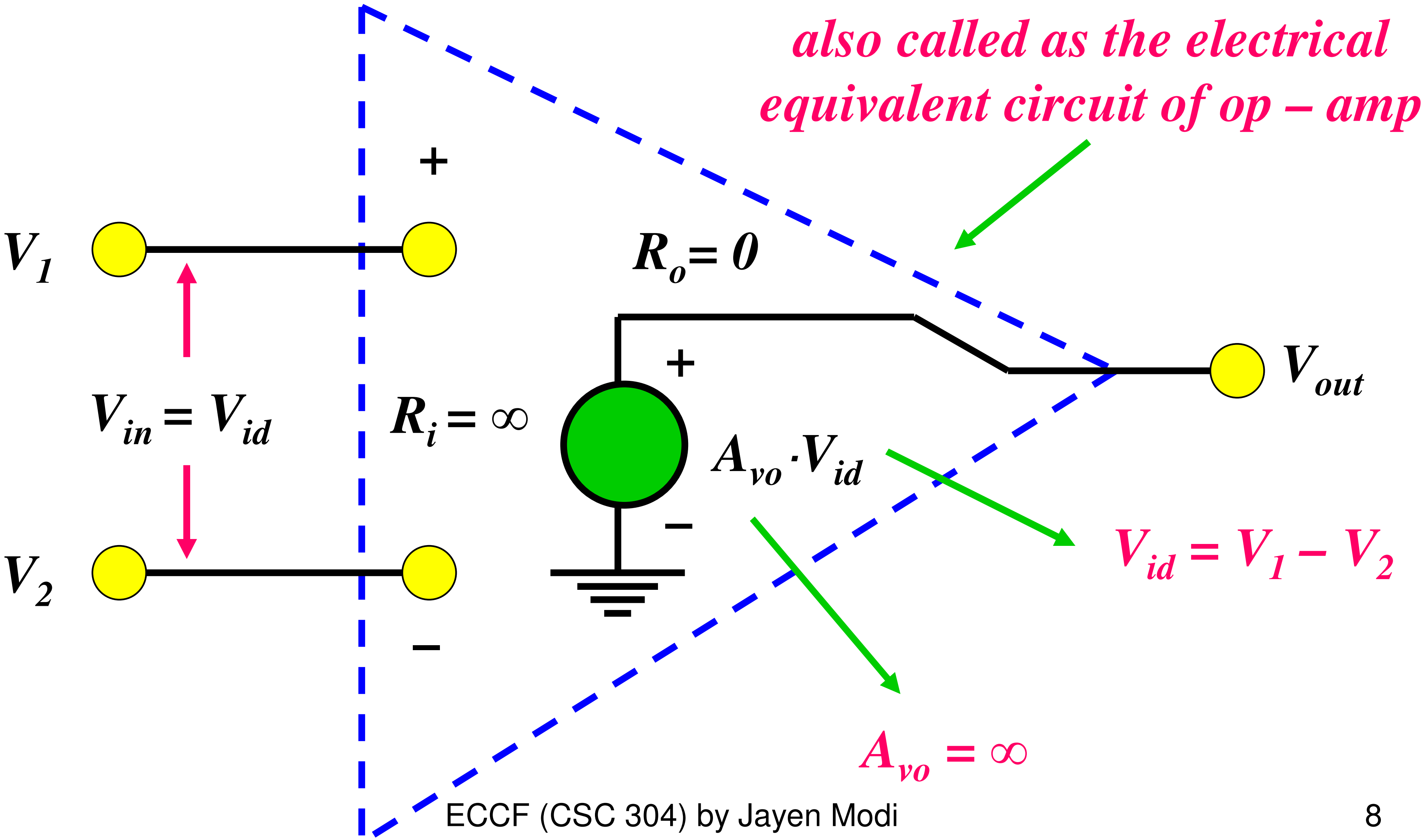
Concept of Mathematical Models

Electrical Equivalent Circuit

A mathematical model is the combination of circuit elements, properly chosen, that best approximates the actual behaviour of a semiconductor device under some certain specific operating conditions.

Remember Thevenin's Theorem ?

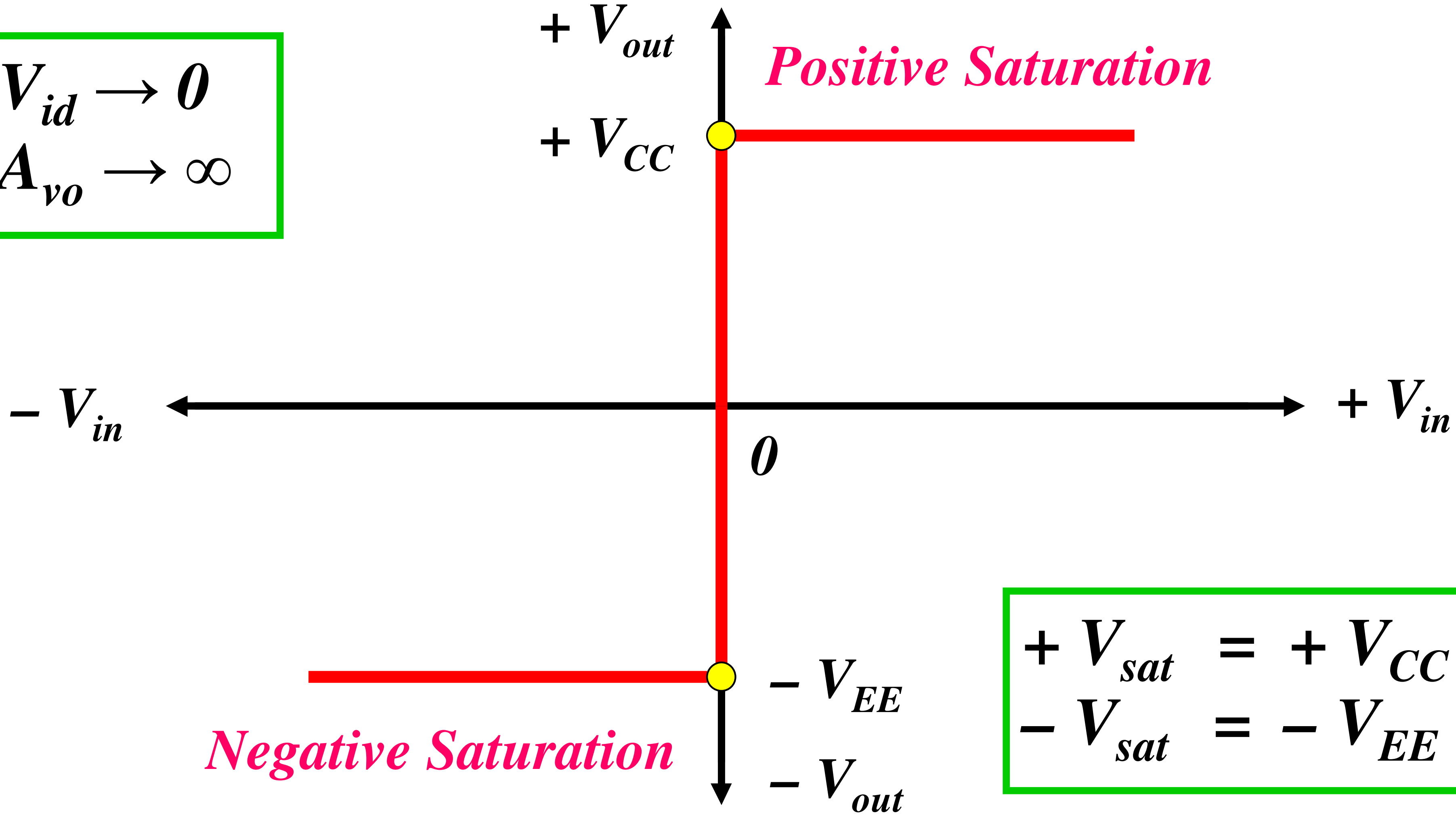
Operational Amplifier (Op – Amp)
Ideal Mathematical Model



Ideal Operational Amplifier

Open Loop Transfer Characteristics

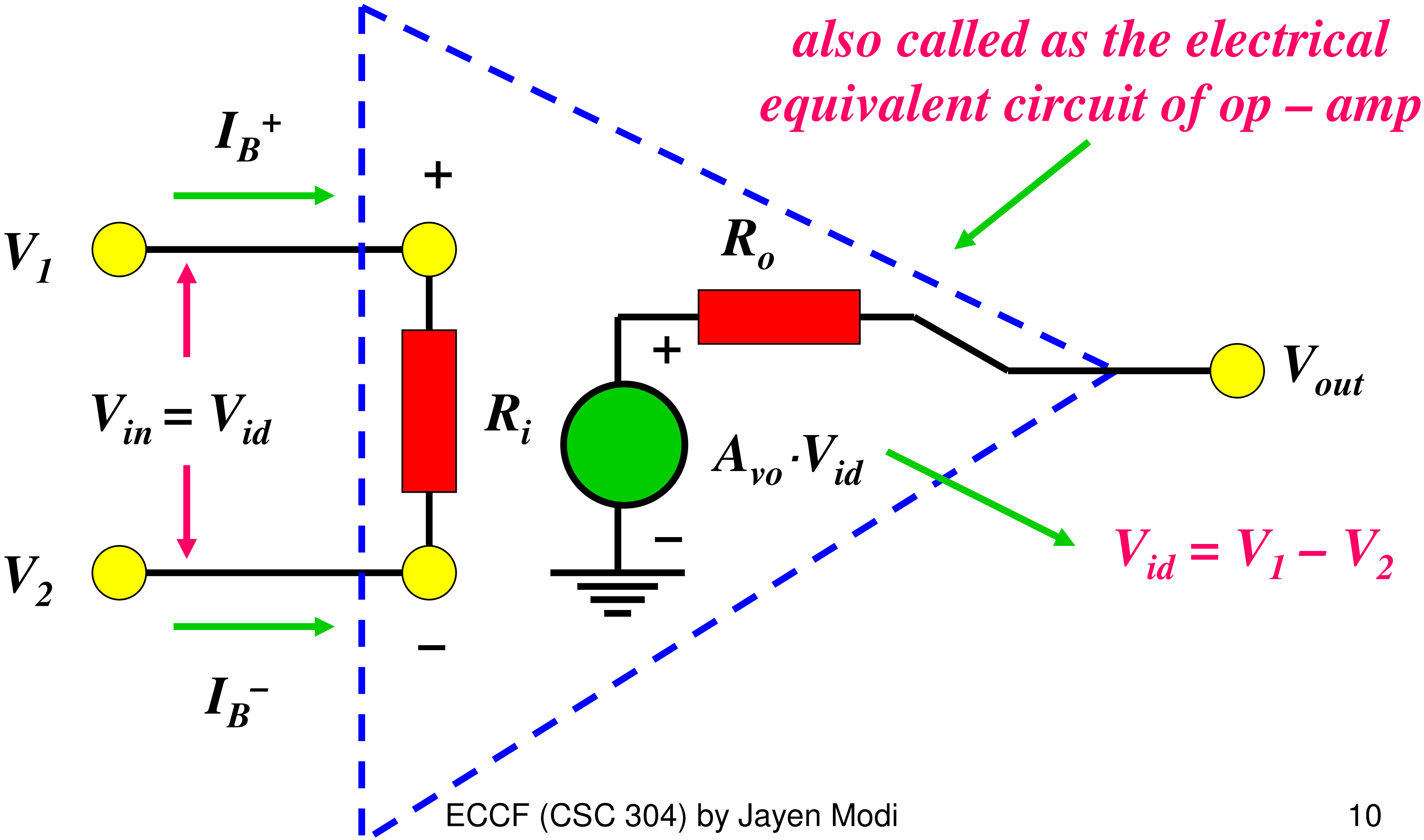
$$V_{id} \rightarrow 0$$
$$A_{vo} \rightarrow \infty$$



$$+V_{sat} = +V_{CC}$$
$$-V_{sat} = -V_{EE}$$

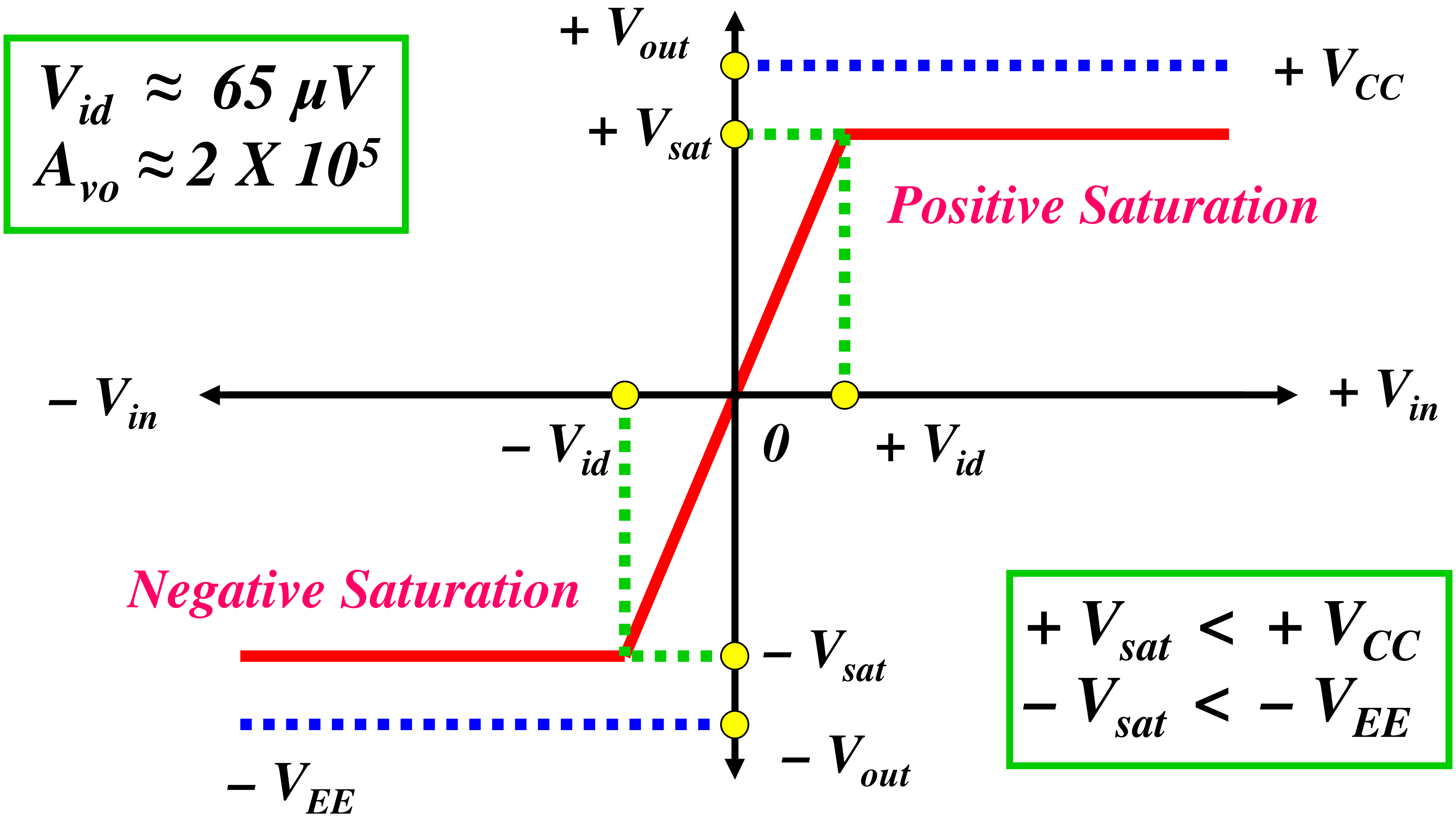
Operational Amplifier (Op – Amp)

Practical Mathematical Model



Practical Operational Amplifier

Open Loop Transfer Characteristics



Practical Operational Amplifier

Types of 'Working' Configurations

- **Open Loop Configuration**
  - → **Difference Amplifier**
  - → **Inverting Amplifier**
  - → **Non – Inverting Amplifier**

never used in actual practice for linear applications . . .
. . . but used as comparator

- **Closed Loop Configuration**
  - → **Wide variety of applications**

Inverting Amplifier
Non – Inverting Amplifier
Summing Amplifier
Averaging Amplifier
Adder & Subtractor
Integrator & Differentiator

All are linear applications but with 'reduced' gain

Practical Operational Amplifier

Applications in Open Loop Configuration

- **Difference Amplifier**
- **Inverting Amplifier**
- **Non – Inverting Amplifier**

never used in actual practice for linear applications . . .

. . . but used as comparator

That's because in open loop configuration as gain approaches infinity, a small change in the input voltage (V_{id}) will cause the output of op-amp to go either at $+V_{sat}$ or $-V_{sat}$ making it useless for linear applications

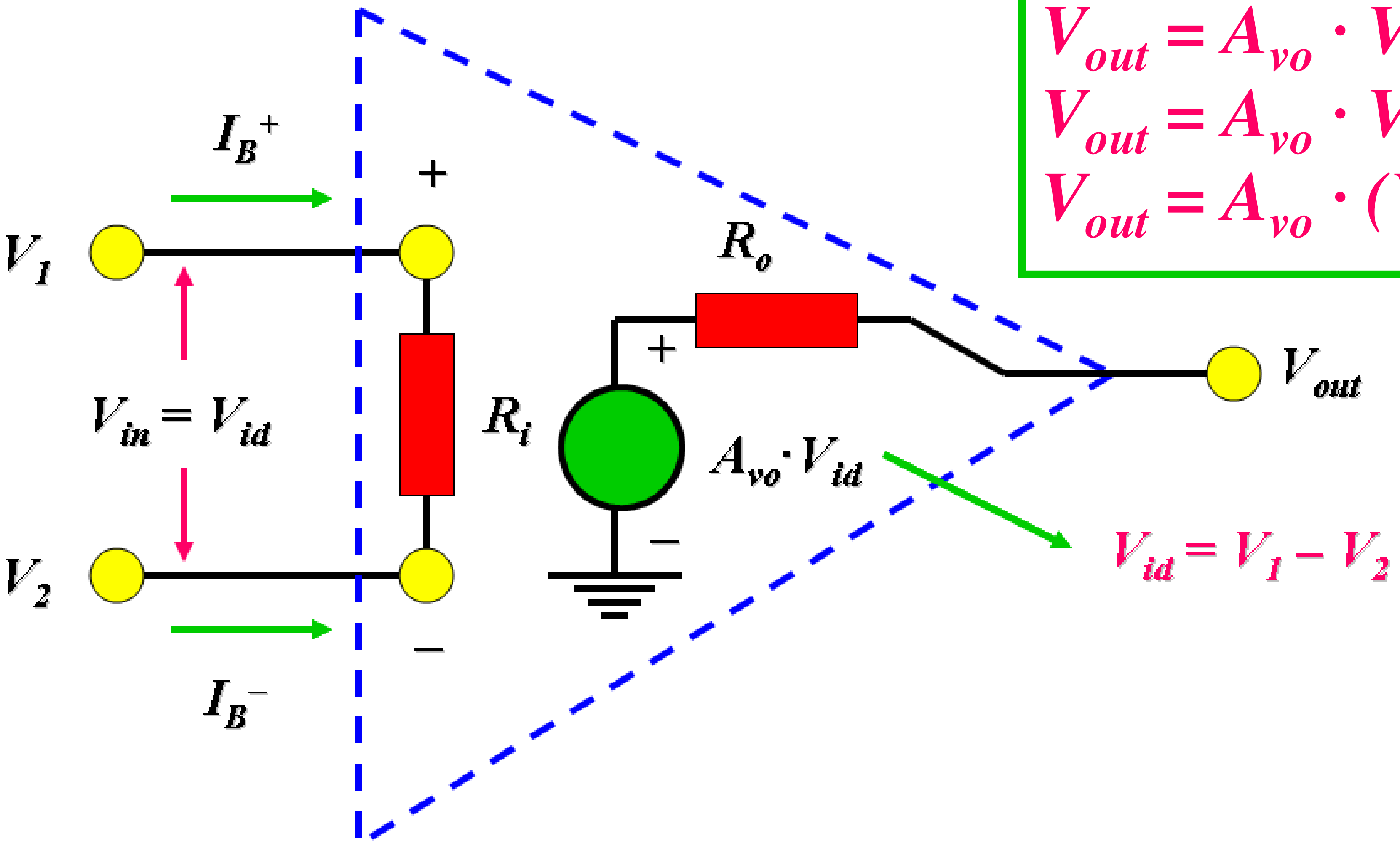
Practical Operational Amplifier

Applications in Open Loop Configuration

$$V_{out} = A_{vo} \cdot V_{id}$$

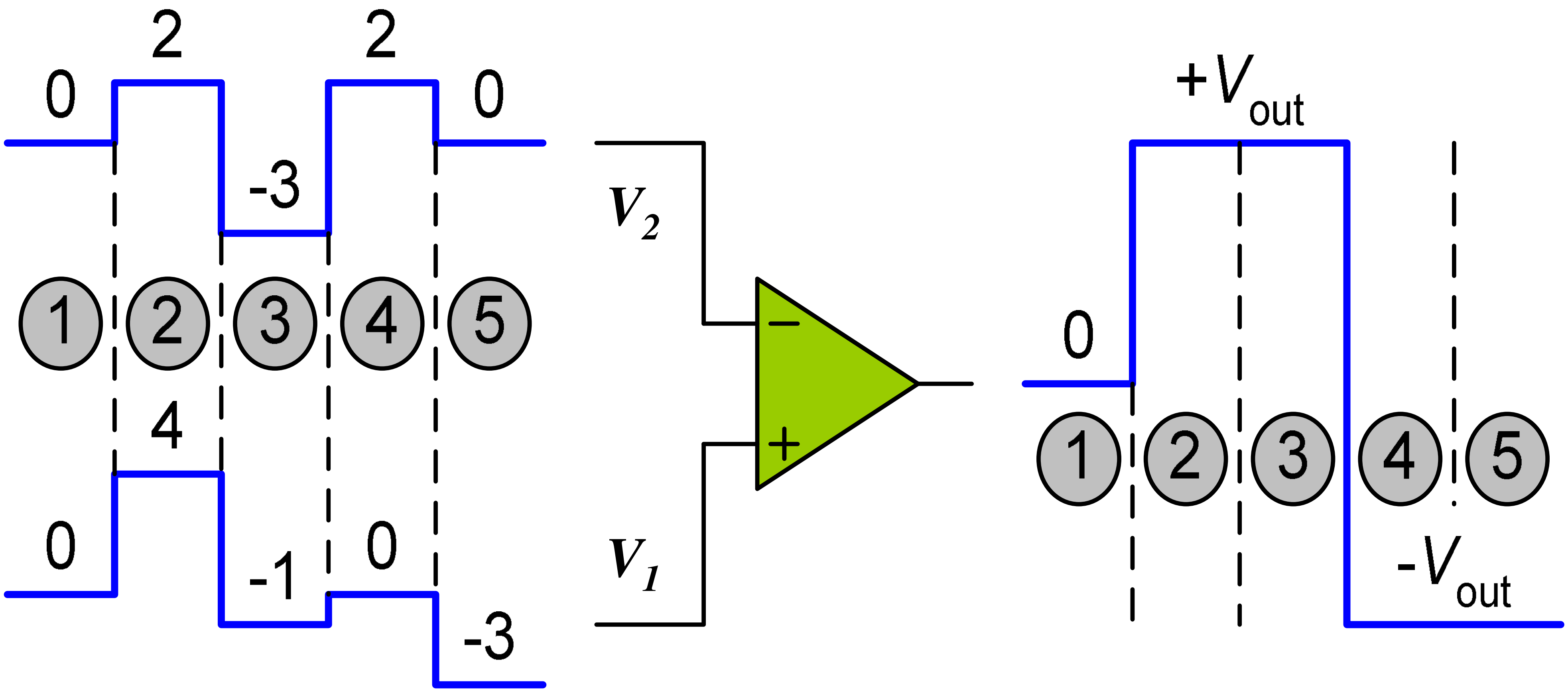
$$V_{out} = A_{vo} \cdot V_{in}$$

$$V_{out} = A_{vo} \cdot (V_1 - V_2)$$



Practical Operational Amplifier

Applications in Open Loop Configuration

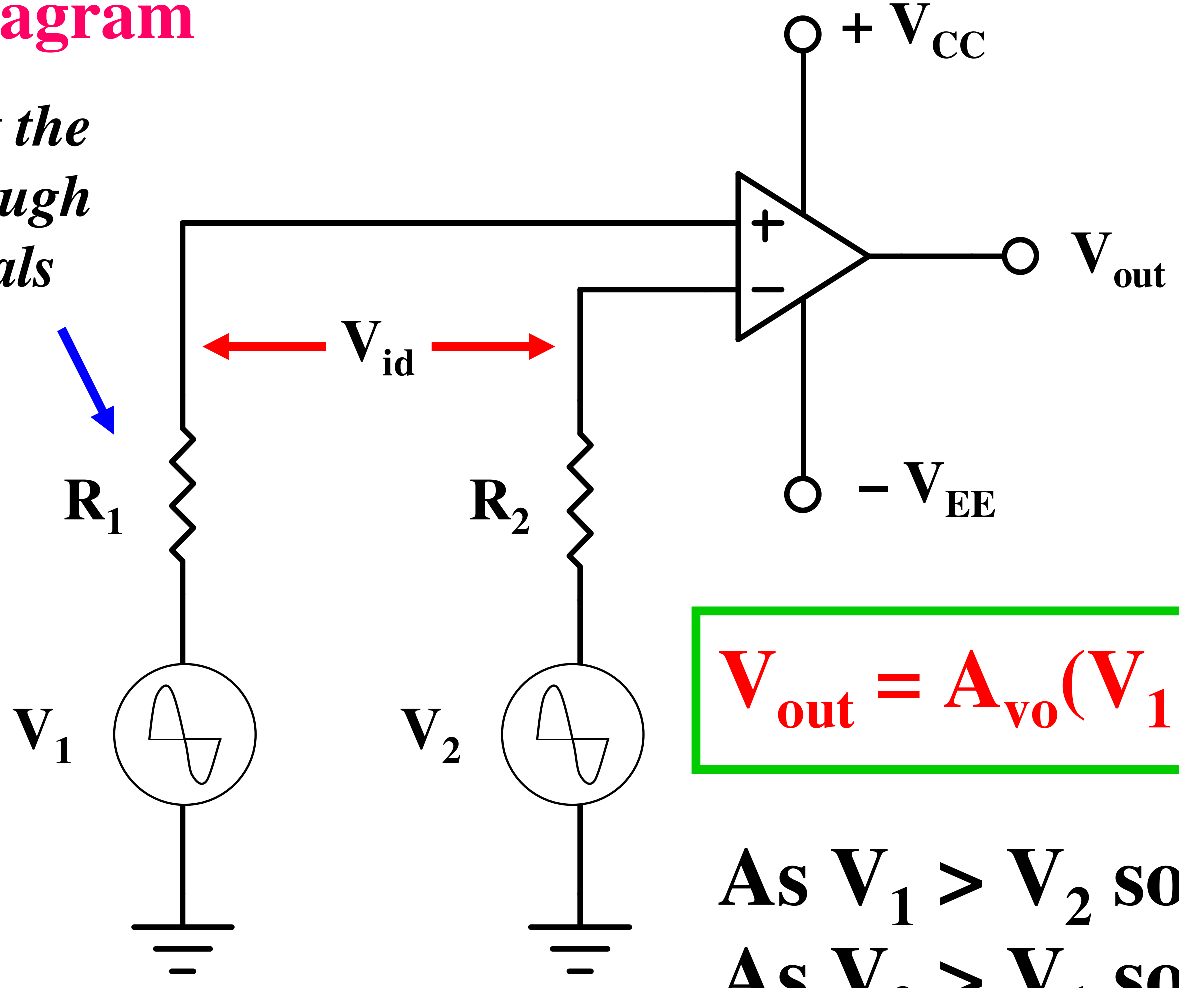


Open Loop Configuration

1. The Difference Amplifier

Circuit Diagram

used to limit the current through the terminals



$$\boxed{V_{out} = A_{vo}(V_1 - V_2)}$$

As $V_1 > V_2$ so $V_{out} = +V_{sat}$

As $V_2 > V_1$ so $V_{out} = -V_{sat}$

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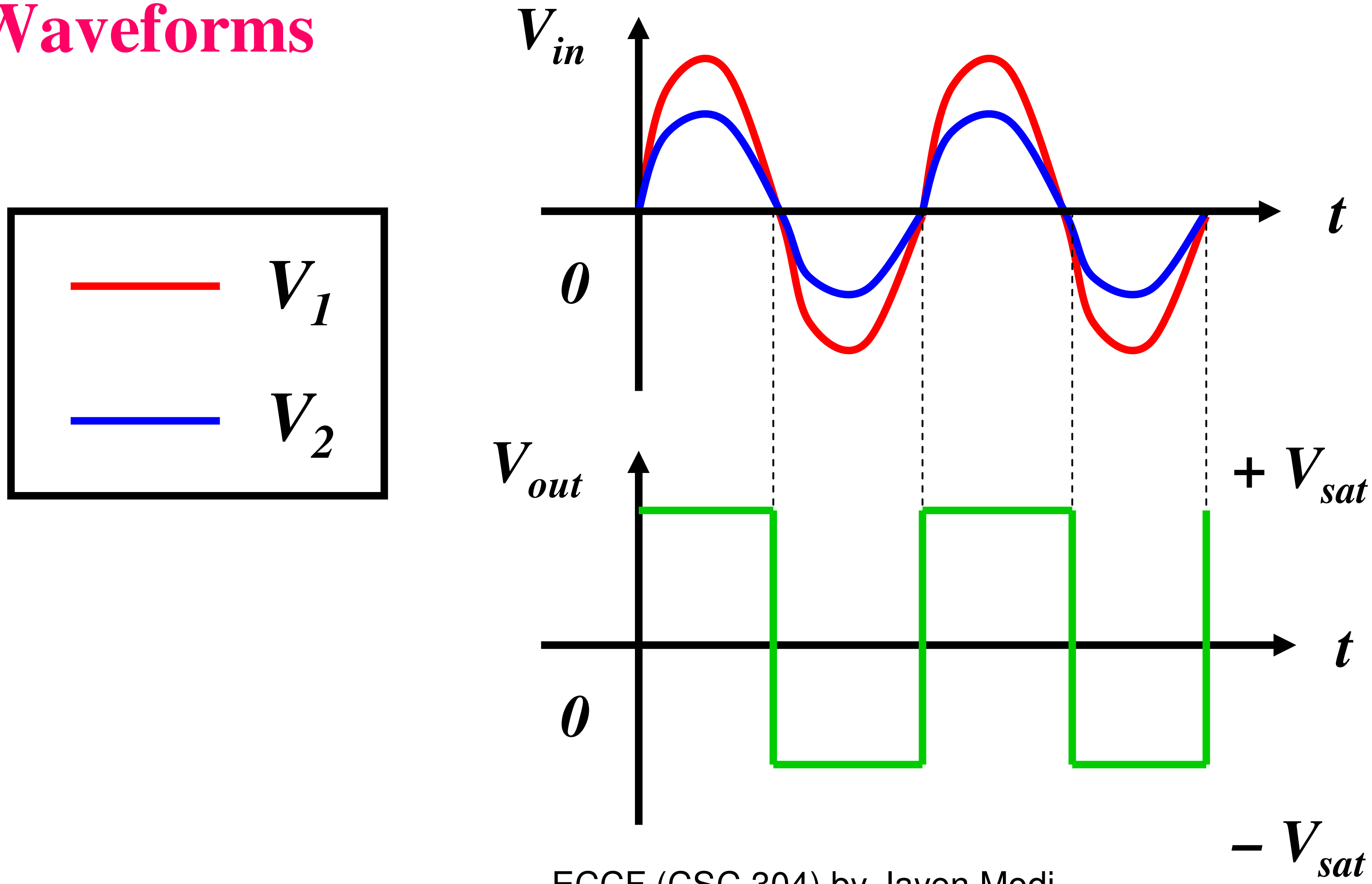
Open Loop Configuration

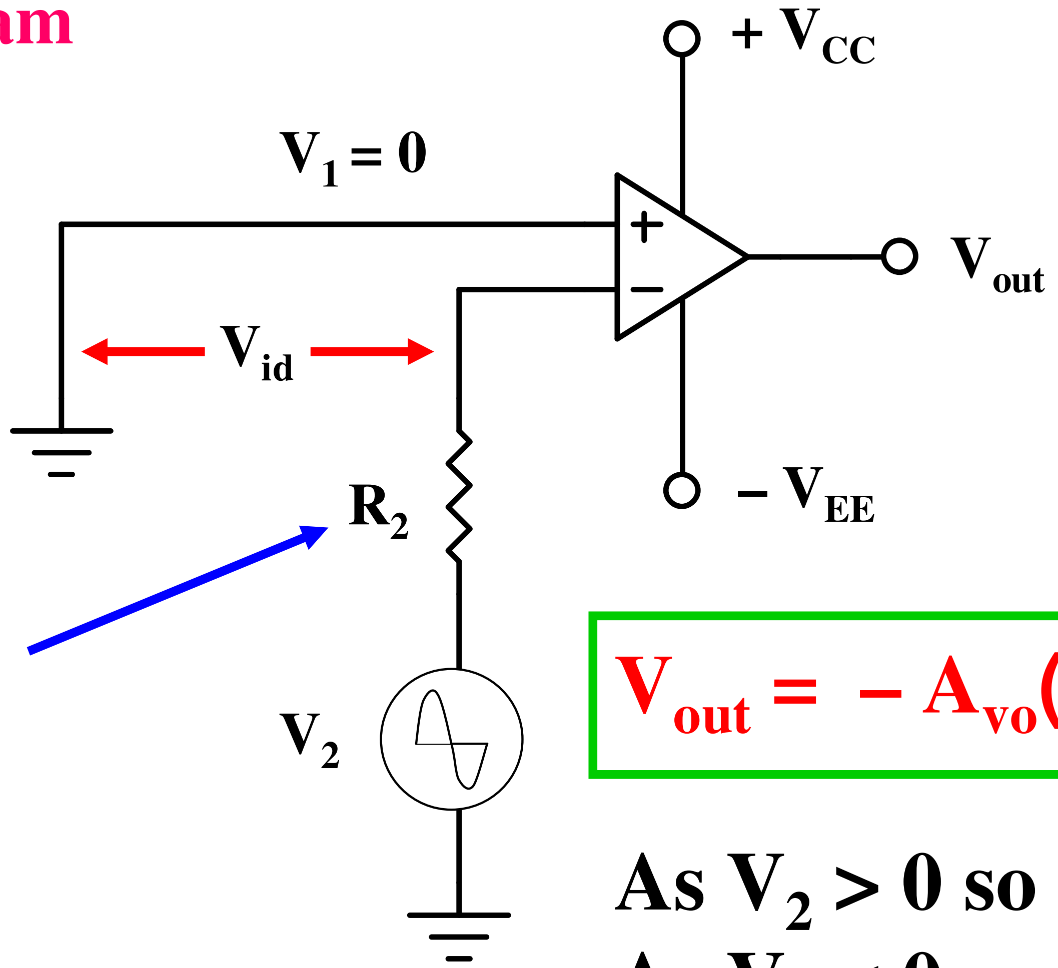
1. The Difference Amplifier

Waveforms



Open Loop Configuration
2. The Inverting Amplifier

Circuit Diagram



used to limit the current through the terminals

$$\boxed{V_{out} = -A_{vo}(V_2)}$$

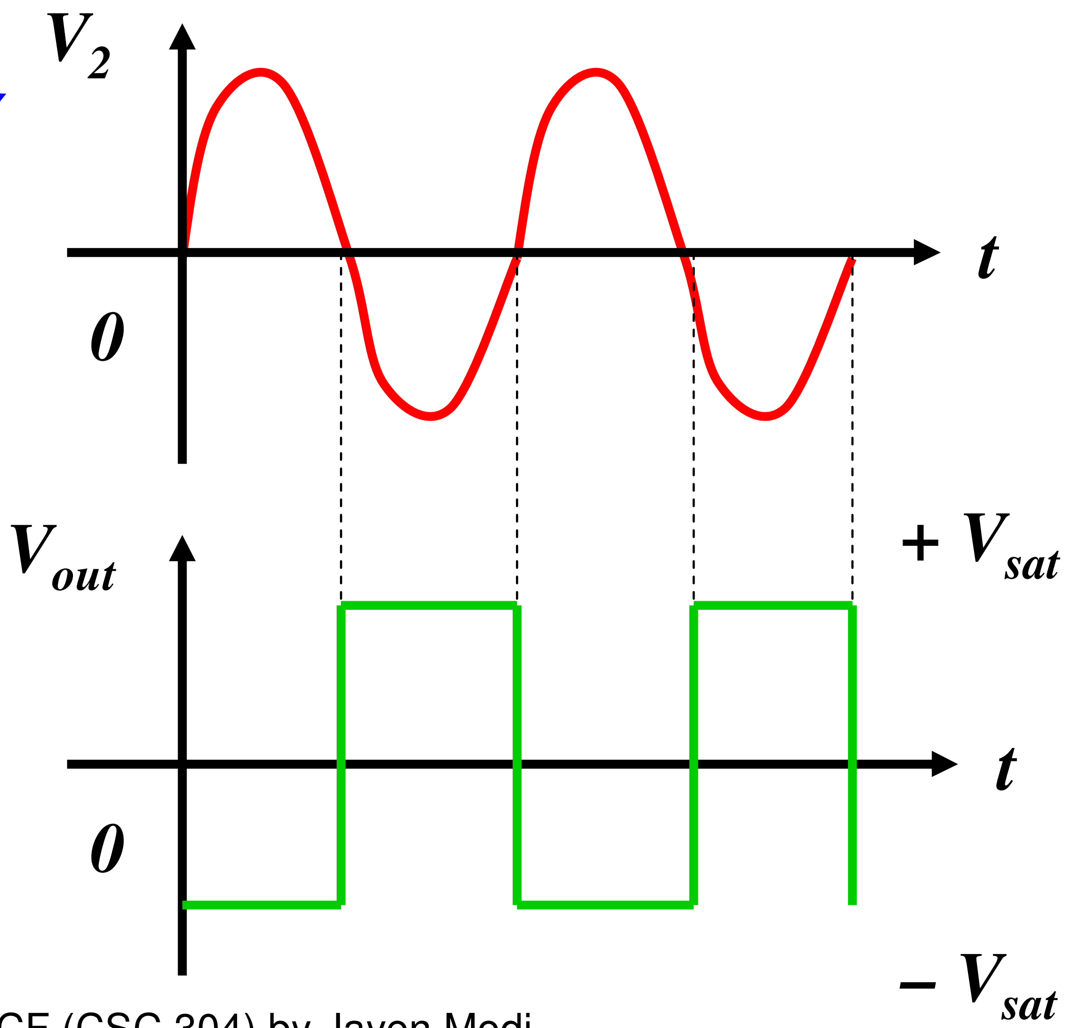
As $V_2 > 0$ so $V_{out} = -V_{sat}$

As $V_2 < 0$ so $V_{out} = +V_{sat}$

Open Loop Configuration
2. The Inverting Amplifier

Waveforms

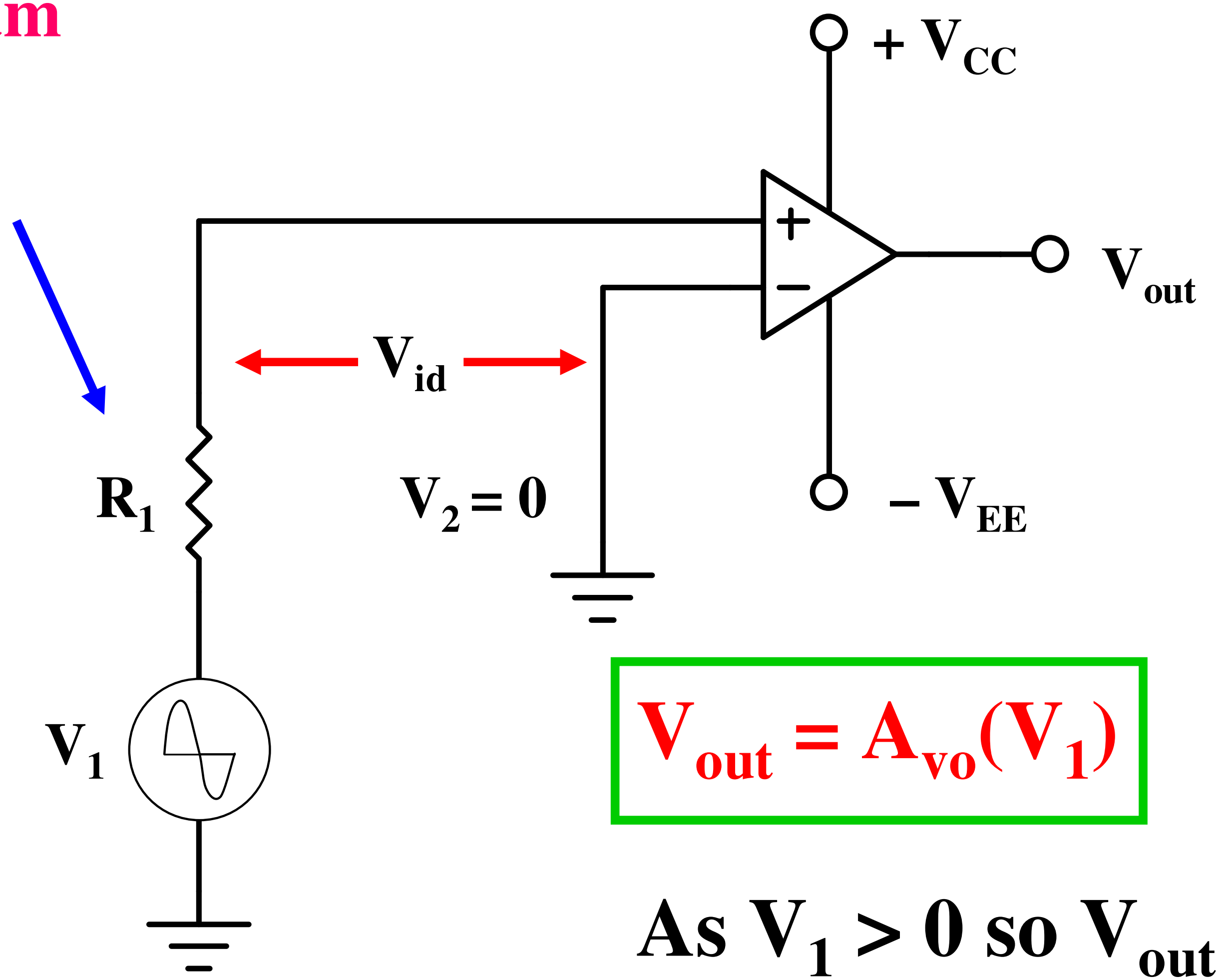
both input & output signals out of phase with each other



Open Loop Configuration
3. The Non – Inverting Amplifier

Circuit Diagram

used to limit the current through the terminals



$$V_{out} = A_{vo}(V_1)$$

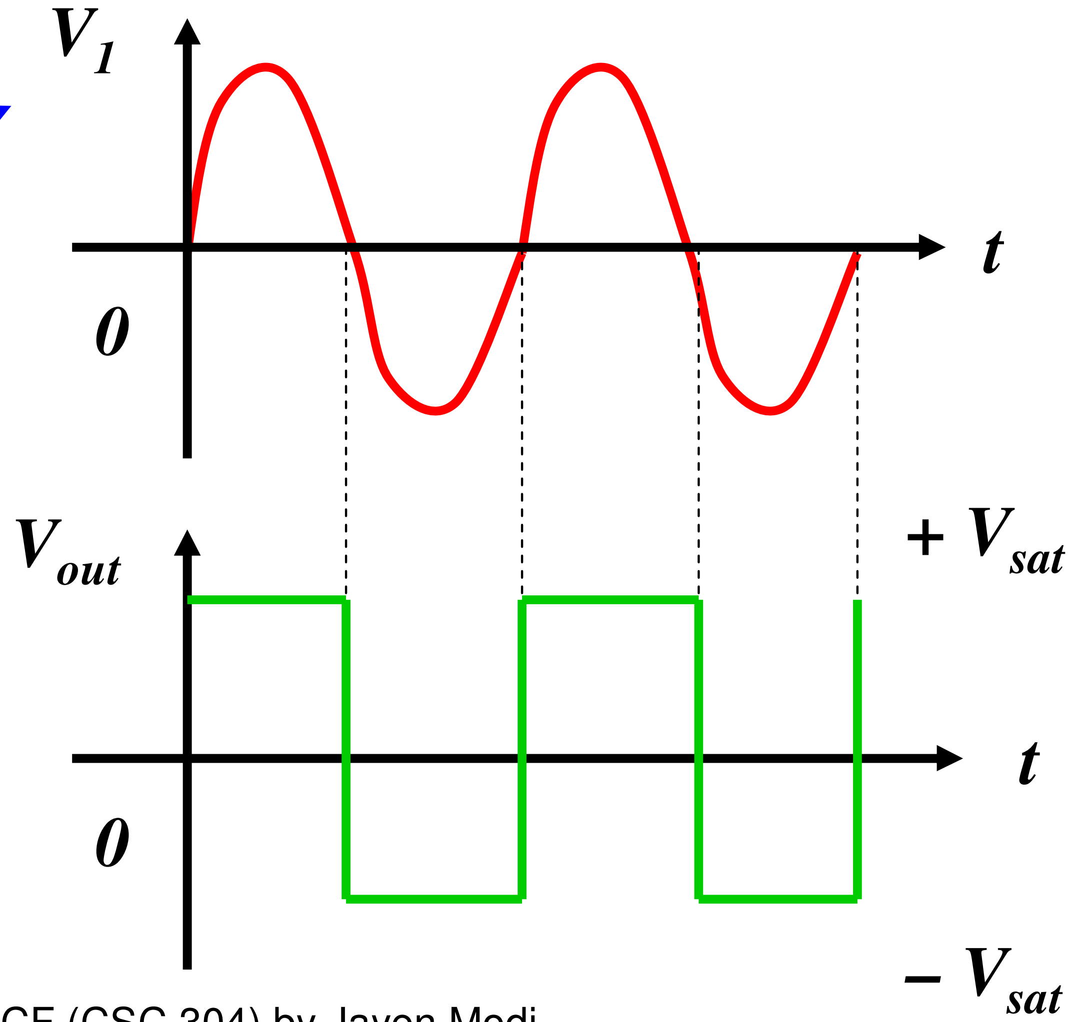
As $V_1 > 0$ so $V_{out} = + V_{sat}$

As $V_1 < 0$ so $V_{out} = - V_{sat}$

Open Loop Configuration
3. The Non – Inverting Amplifier

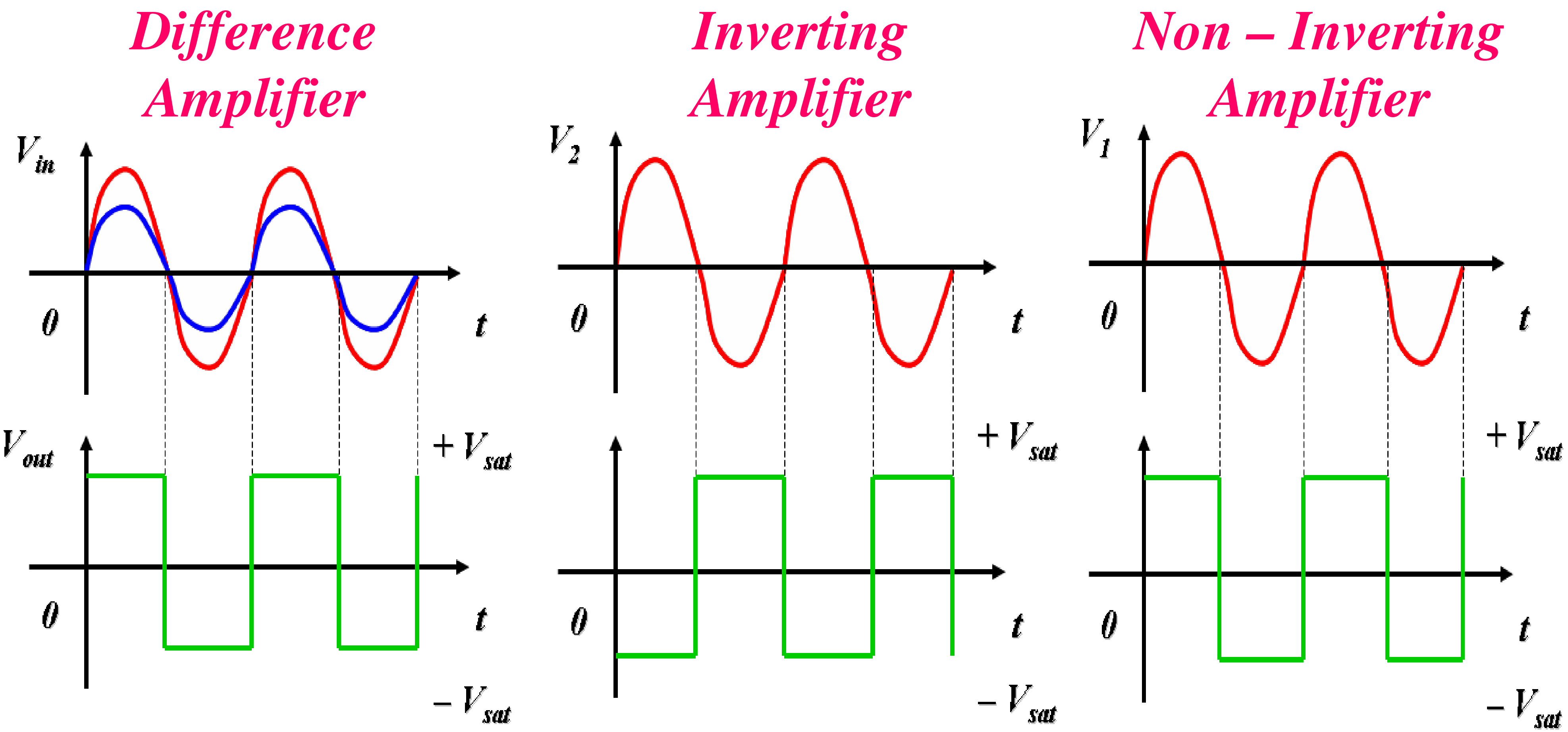
Waveforms

both input & output signals are in phase with each other



Open Loop Configuration

Input Waveforms & Output Waveforms

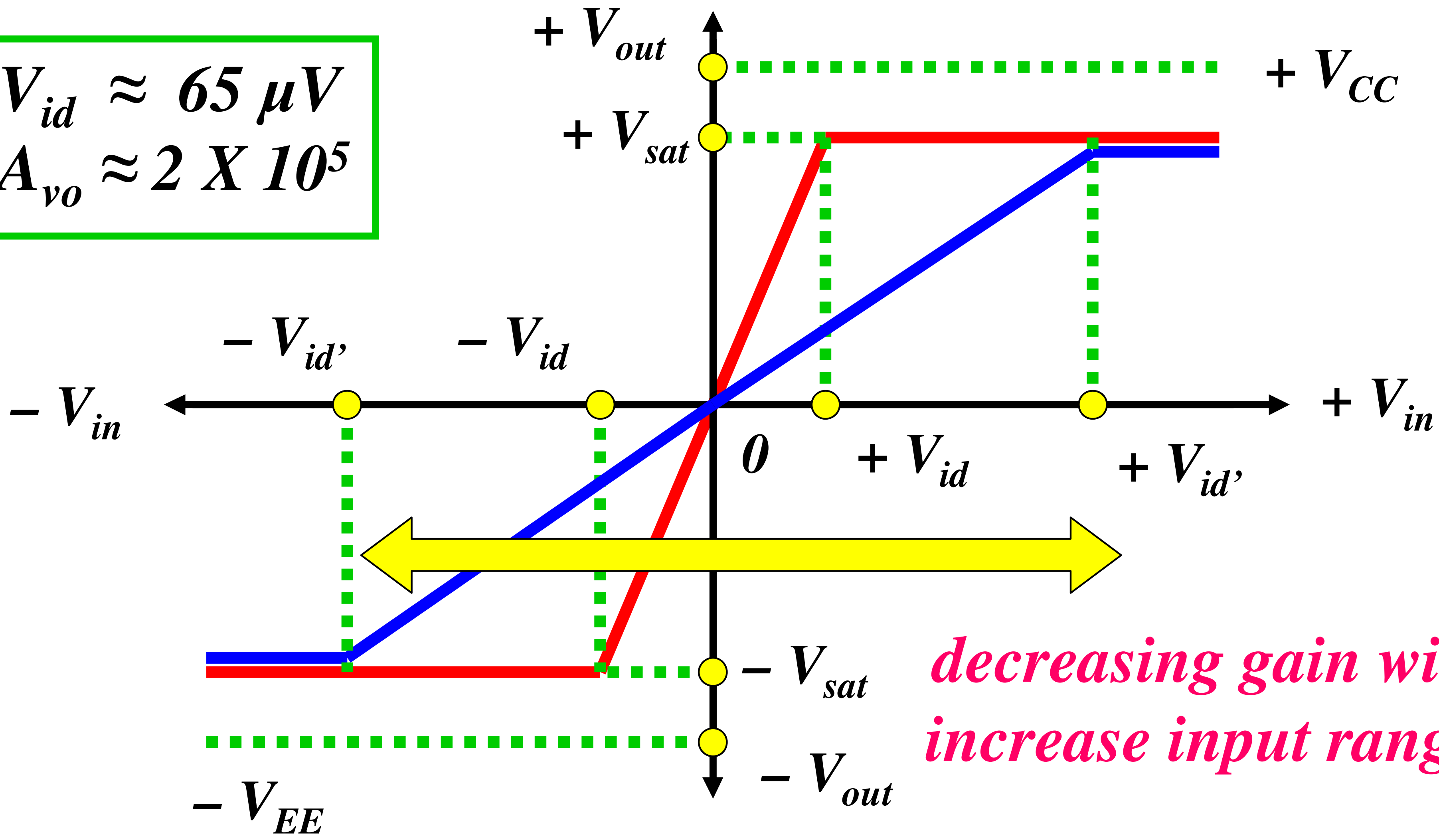


WHERE'S THE AMPLIFICATION ???

Practical Operational Amplifier

‘Manipulated’ Transfer Characteristics

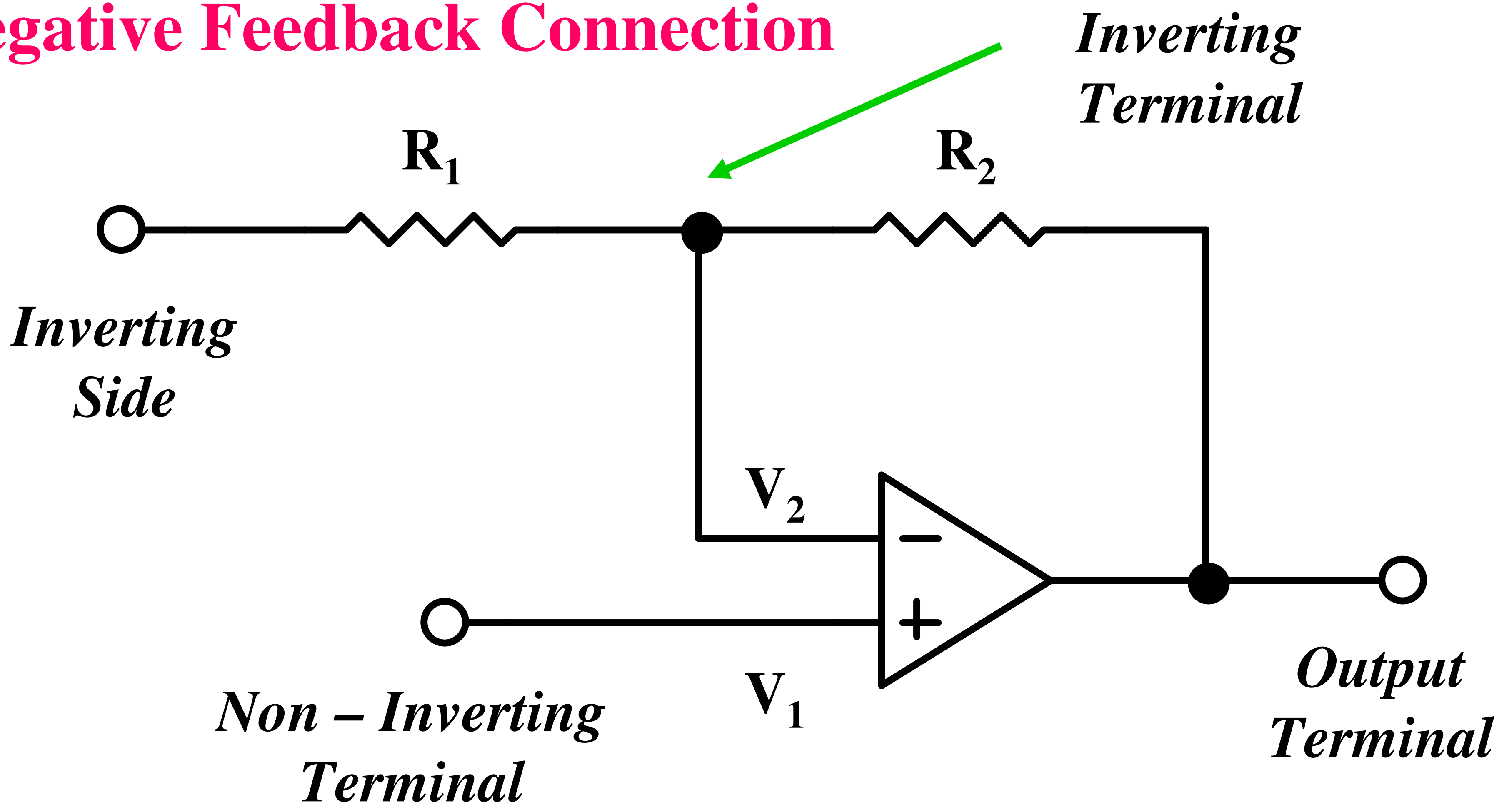
$V_{id} \approx 65\ \mu V$
$A_{vo} \approx 2\ X\ 10^5$



decreasing gain will increase input range

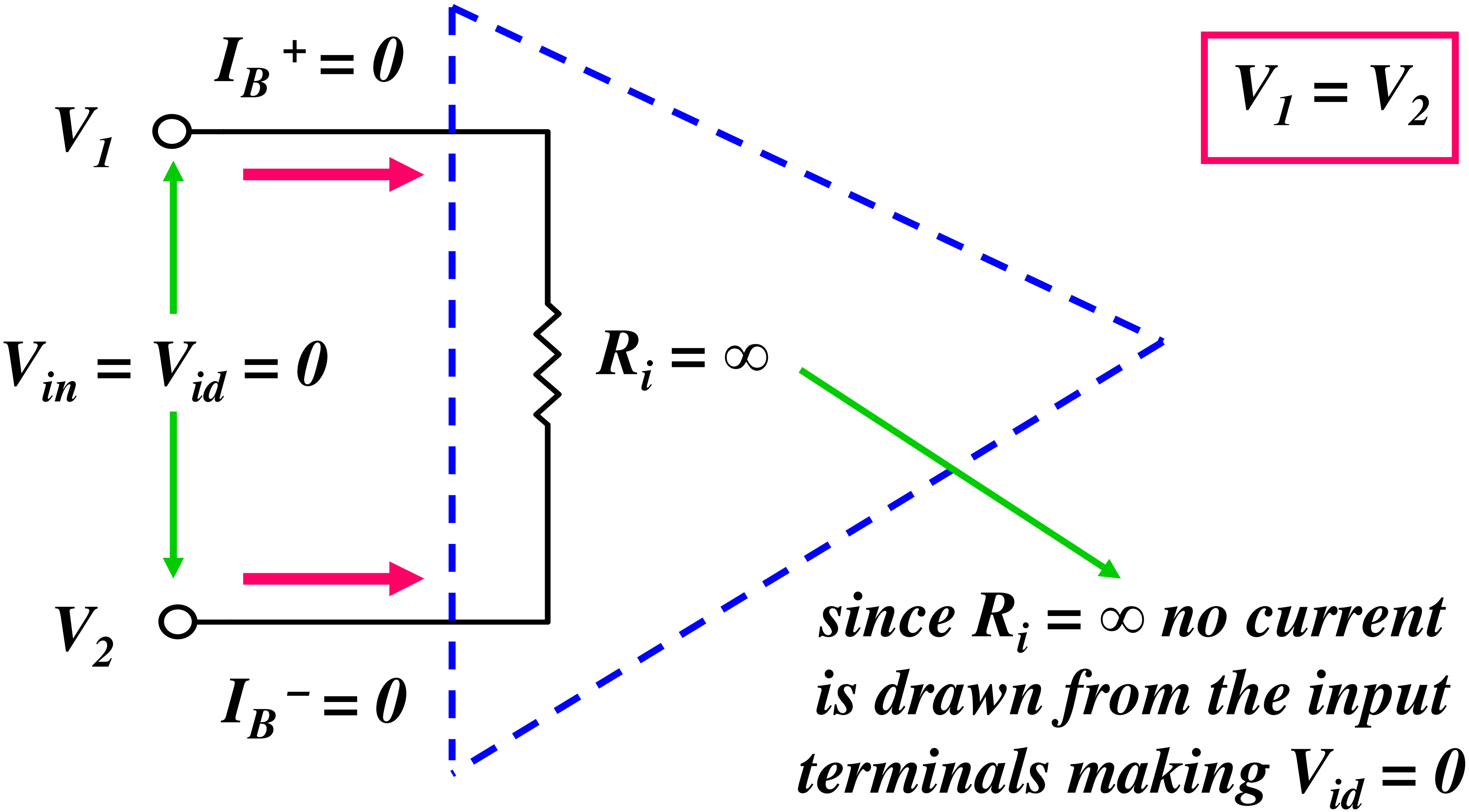
Practical Operational Amplifier
Applications in Closed Loop Configuration

Negative Feedback Connection



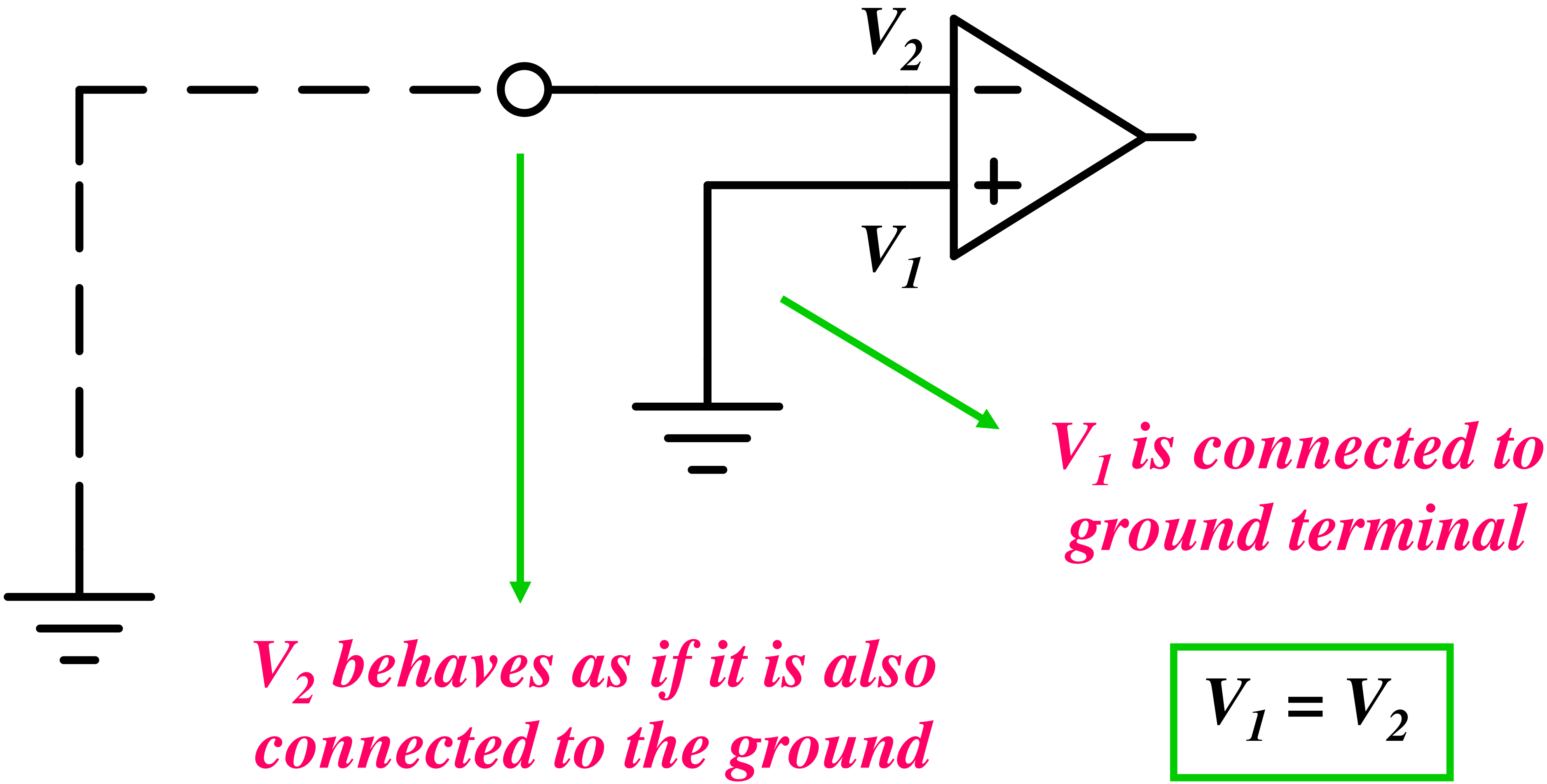
Practical Op – Amp Analysis

1. Virtual Short Concept in Op – Amp



Practical Op – Amp Analysis

2. Virtual Ground Concept in Op – Amp



$$\boxed{V_1 = V_2}$$

Ideal Operational Amplifier

Features of Ideal Operational Amplifier

- Open – loop voltage gain is infinite
- Input Impedance is infinite
- Output Impedance is zero
- Bandwidth is infinite
- CMRR is infinite
- Slew Rate is infinite
- Output Offset Voltage is zero
- Input Bias Currents are zero

not possible to achieve in actual practice

Practical Operational Amplifier

Features of Practical Operational Amplifier

- Large Open – Loop Voltage Gain (2 x 10^5)
- Very high Input Impedance (2 MΩ)
- Very low Output Impedance (75 Ω)
- Output Offset Voltage of upto ± 15 mV
- High value of CMRR (80 dB – 120 dB)
- Small Bandwidth (5 Hz)
- Finite Slew Rate (0.5 V/µs)
- Input Bias Currents of upto 500 nA

features of µA 741

D.C. Characteristics of Op – Amp

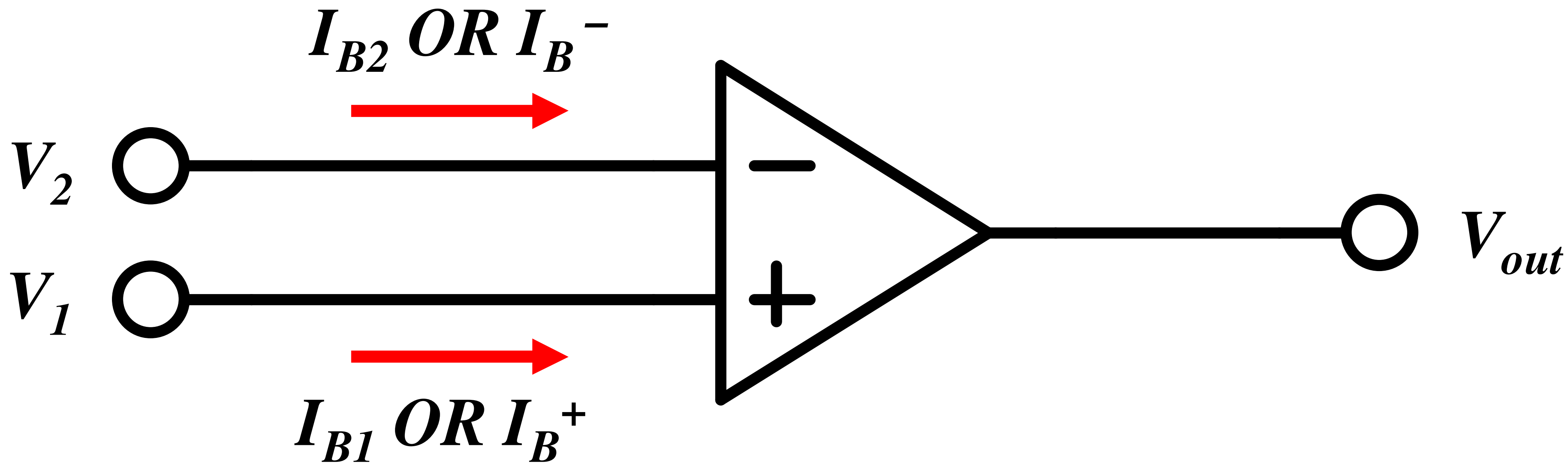
1. Input Bias Current (I_B)

- The input stage of op – amp is differential amplifier made up of either BJT or JFET
- These devices are biased in the active region of their operation by supplying some input current
- Ideally due to the extreme high input resistance of input stages, these currents are almost negligible
- Practically some of input current flows through both the op – amp input terminals

These are called as the bias currents I_{B1} & I_{B2}

D.C. Characteristics of Op – Amp

1. Input Bias Current (I_B)



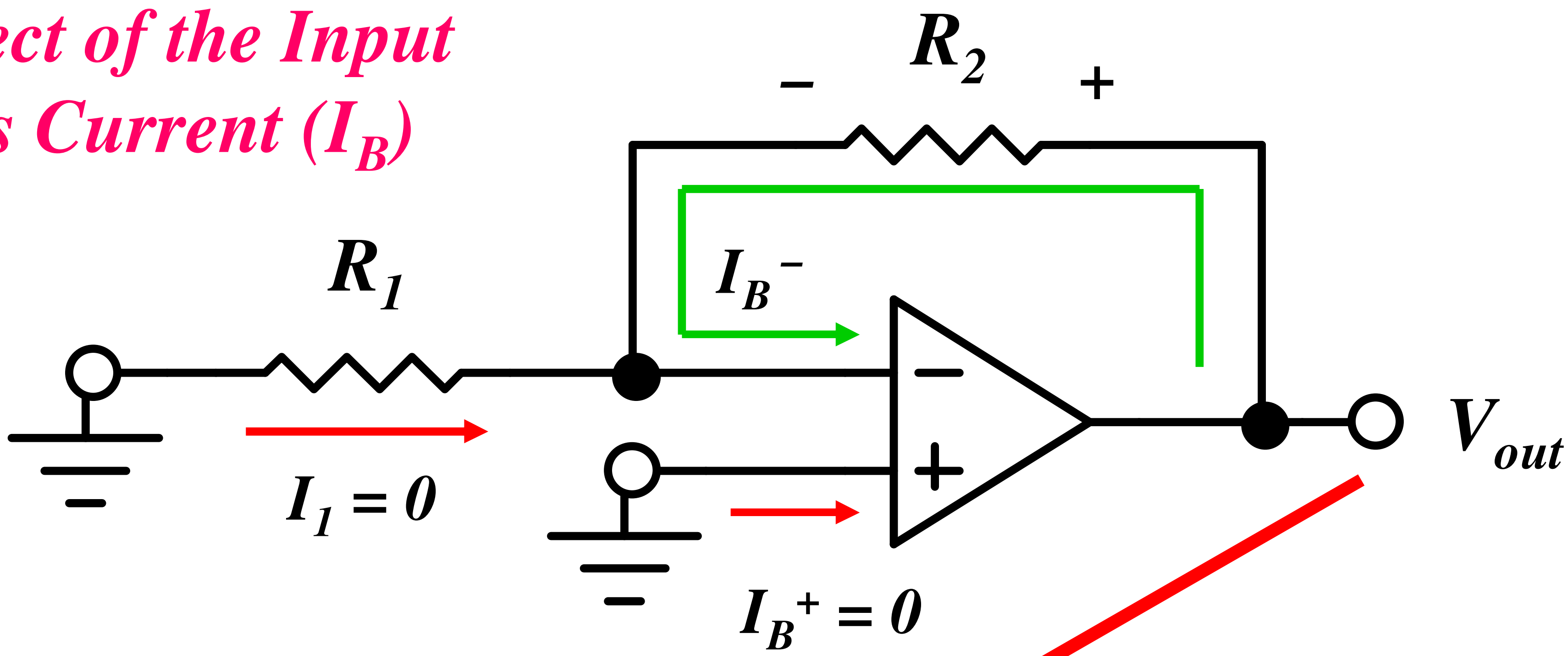
average of the two currents entering op-amp terminals is called input bias current

$$\boxed{I_B = \frac{I_B^+ + I_B^-}{2}}$$

D.C. Characteristics of Op – Amp

1. Input Bias Current (I_B)

Effect of the Input Bias Current (I_B)



$$\boxed{V_{out} = (I_B^-)R_2}$$

presence of bias current results in an output offset voltage $V_{out} = V_{oos}$

D.C. Characteristics of Op – Amp

2. Input Offest Current (I_{ios})

- **Bias current compensation will work only if both bias currents are equal (I_B^+ & I_B^-)**
- **Since input transistors can't be made identical there is some difference in the bias currents**
- **This small difference called as the input offset current (I_{ios}) & is given by :-**

$$\boxed{|I_{ios}| = I_B^+ - I_B^-}$$

D.C. Characteristics of Op – Amp

3. Input Offset Voltage (V_{ios})

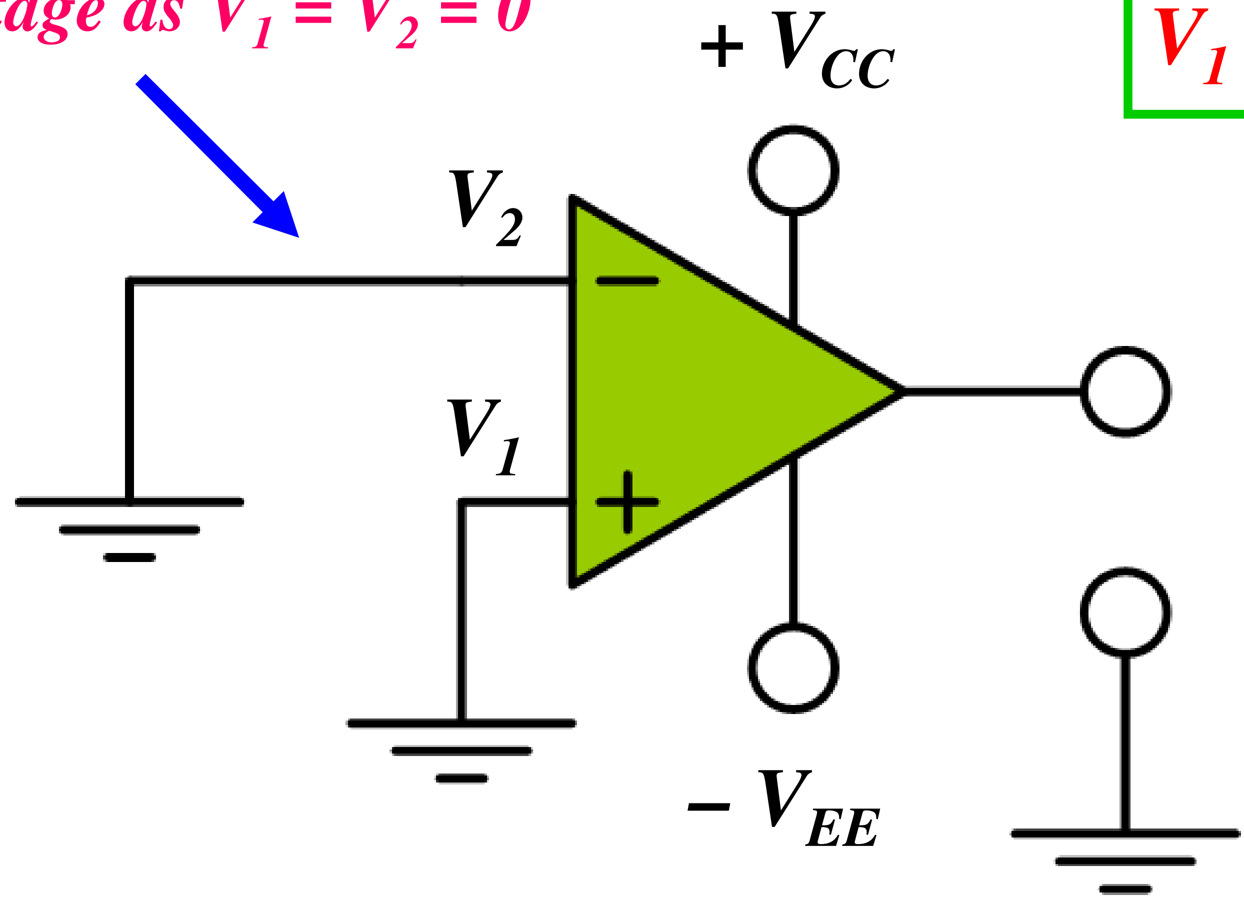
- **Shorting together the input terminals of the op – amp gives output voltage as $V_{out} = 0$ since $V_1 = V_2 = 0$**
- **Due to the mismatches between the two transistors of input stage of differential amplifier, $V_{out} \neq 0$**
- **To force the output voltage (V_{out}) to become zero, we need to apply some input voltage to the op – amp**
- **This is called as the input offset voltage (V_{ios}) defined as amount to null the output voltage**

V_{ios} is used for forcing to make $V_{out} = 0$

D.C. Characteristics of Op – Amp

3. Input Offset Voltage (V_{ios})

Op – amp producing output offset voltage as $V_1 = V_2 = 0$



$$\boxed{V_1 = V_2 = 0}$$

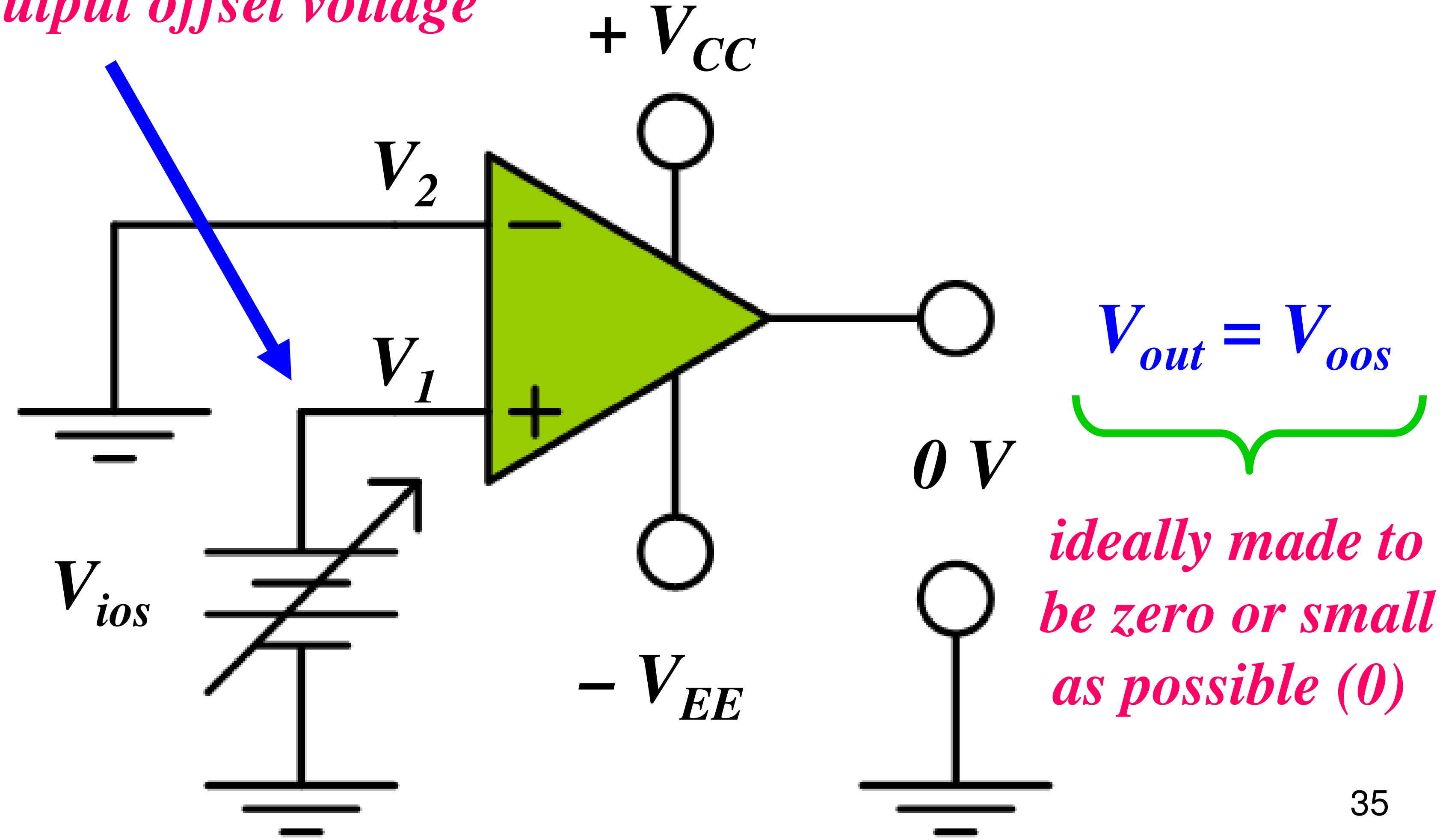
$$\underbrace{V_{out} = V_{oos}}$$

output offset voltage with $V_1 = V_2 = 0$

D.C. Characteristics of Op – Amp

3. Input Offset Voltage (V_{ios})

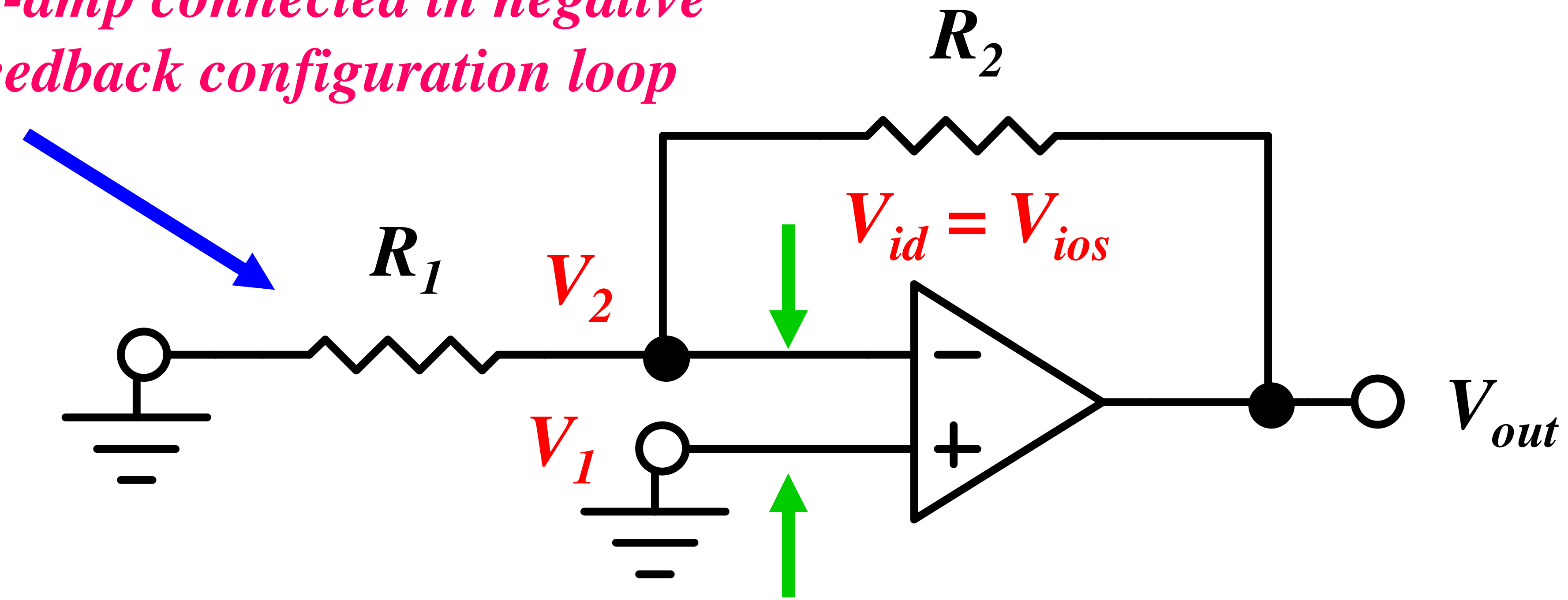
Input offset voltage applied to null the output offset voltage



D.C. Characteristics of Op – Amp

3. Input Offset Voltage (V_{ios})

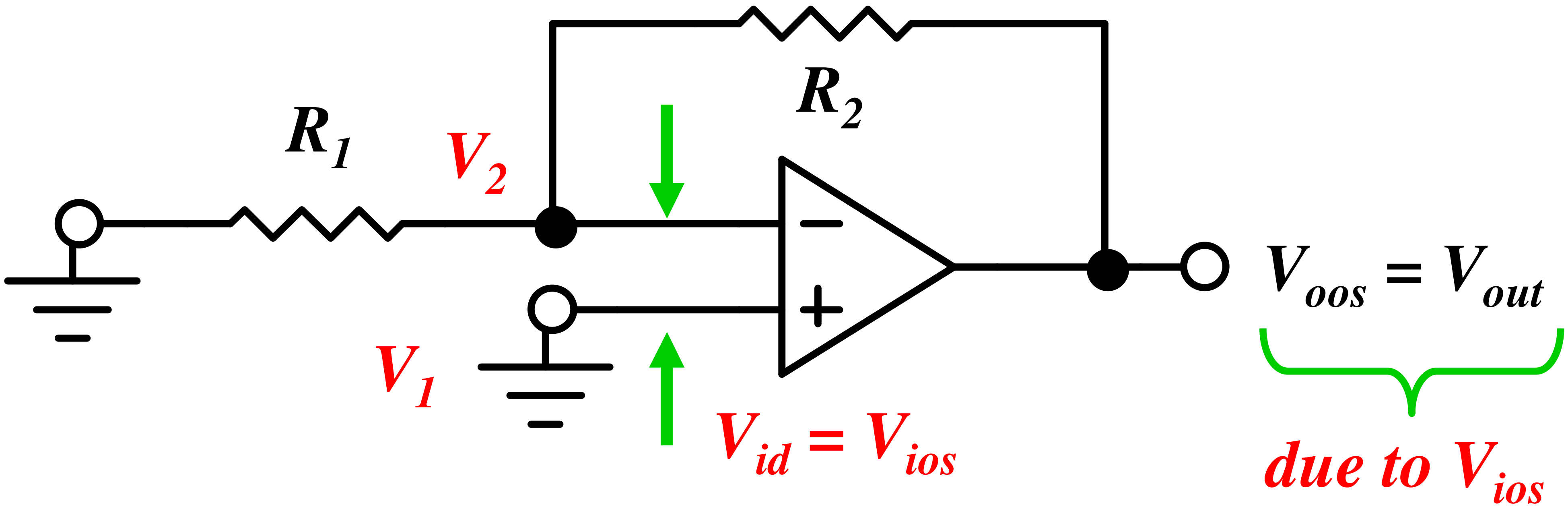
Op-amp connected in negative feedback configuration loop



due to unequal bias currents as $I_{B1} \neq I_{B2}$ there exists voltages hence potential difference between V_1 & V_2

D.C. Characteristics of Op – Amp

3. Input Offset Voltage (V_{ios})



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

measuring the V_{oos} helps to calculate the input offset V_{ios}

D.C. Characteristics of Op – Amp

4. Output Offset Voltage (V_{oos})

- Output offset voltage is the voltage at output terminal of the op – amp without any input applied to it
- Output offset voltage results due to the effect of input bias current current (I_{B2}) which can be minimized
- By compensating resistor (R_{comp}) it can be minimized but effect remains due to input offset current (I_{ios})
- It is due to the input offset voltage (V_{ios}) resulting at the op-amp input terminals without any input

$$\boxed{V_{oos} = f\,(I_{B2}, I_{ios}\ \&\ V_{ios})}$$

Input Offset Voltage Compensation

(a) Op – Amp with offset null terminals

- **Many op-amps, including the IC 741C have a pair of external offset null pins as shown in the figure**
- **10 kΩ potentiometer is connected between the offset null pins 1 & 5 with wiper connected to – V_{EE}**
- **The potentiometer is gradually adjusted around the voltage of – V_{EE} for zero output voltage (minimum)**
- **This procedure has to be repeated many times using an op-amp for practical applications**

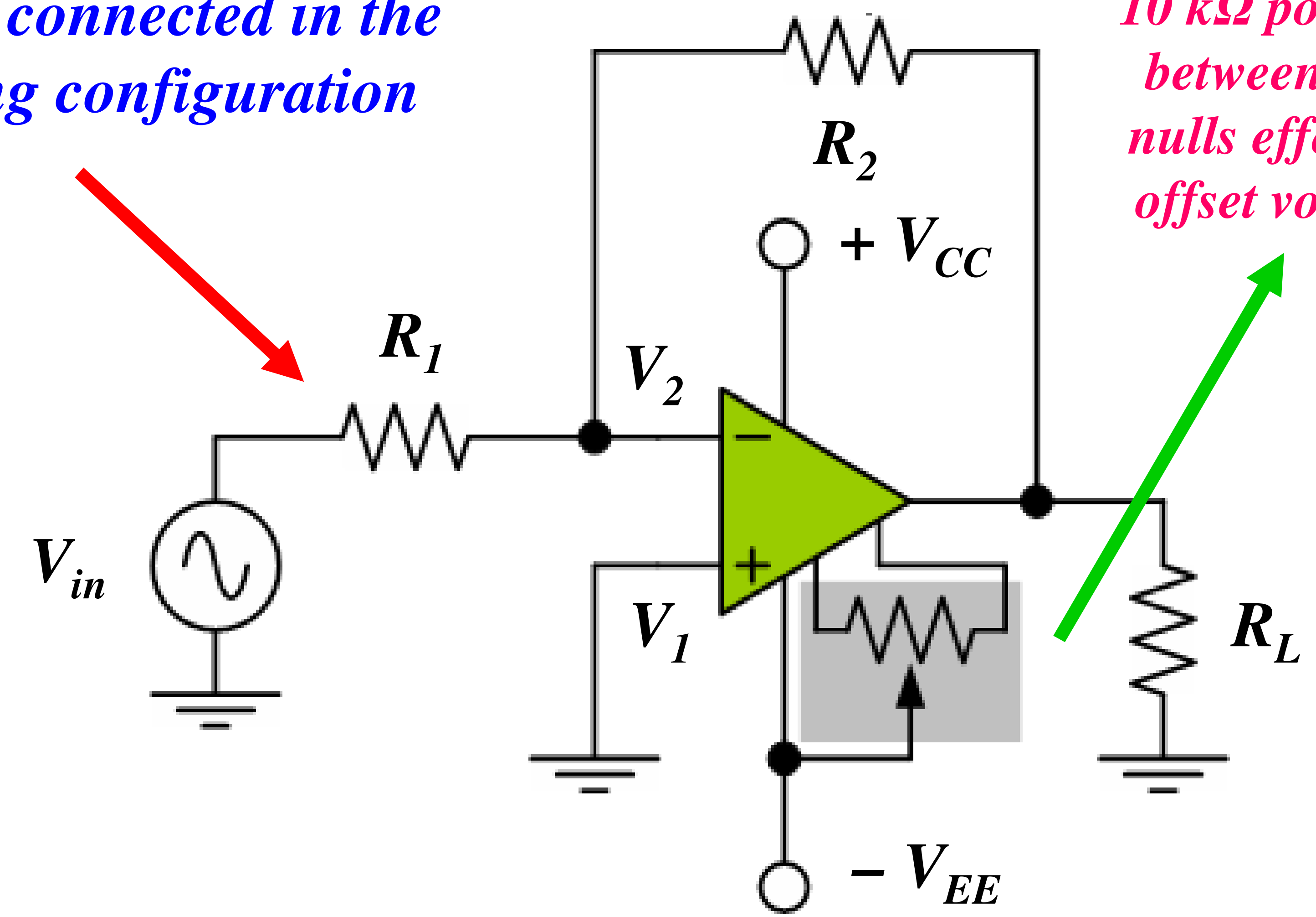
Refer class note book for circuit diagram

Input Offset Voltage Compensation

(a) Op – Amp with offset null terminals

Op-amp connected in the inverting configuration

10 kΩ potentiometer between pin 1 & 5 nulls effect of input offset voltage (V_{ios})



Op – Amp Transient Analysis
(b) Slew Rate (SR) Characteristics

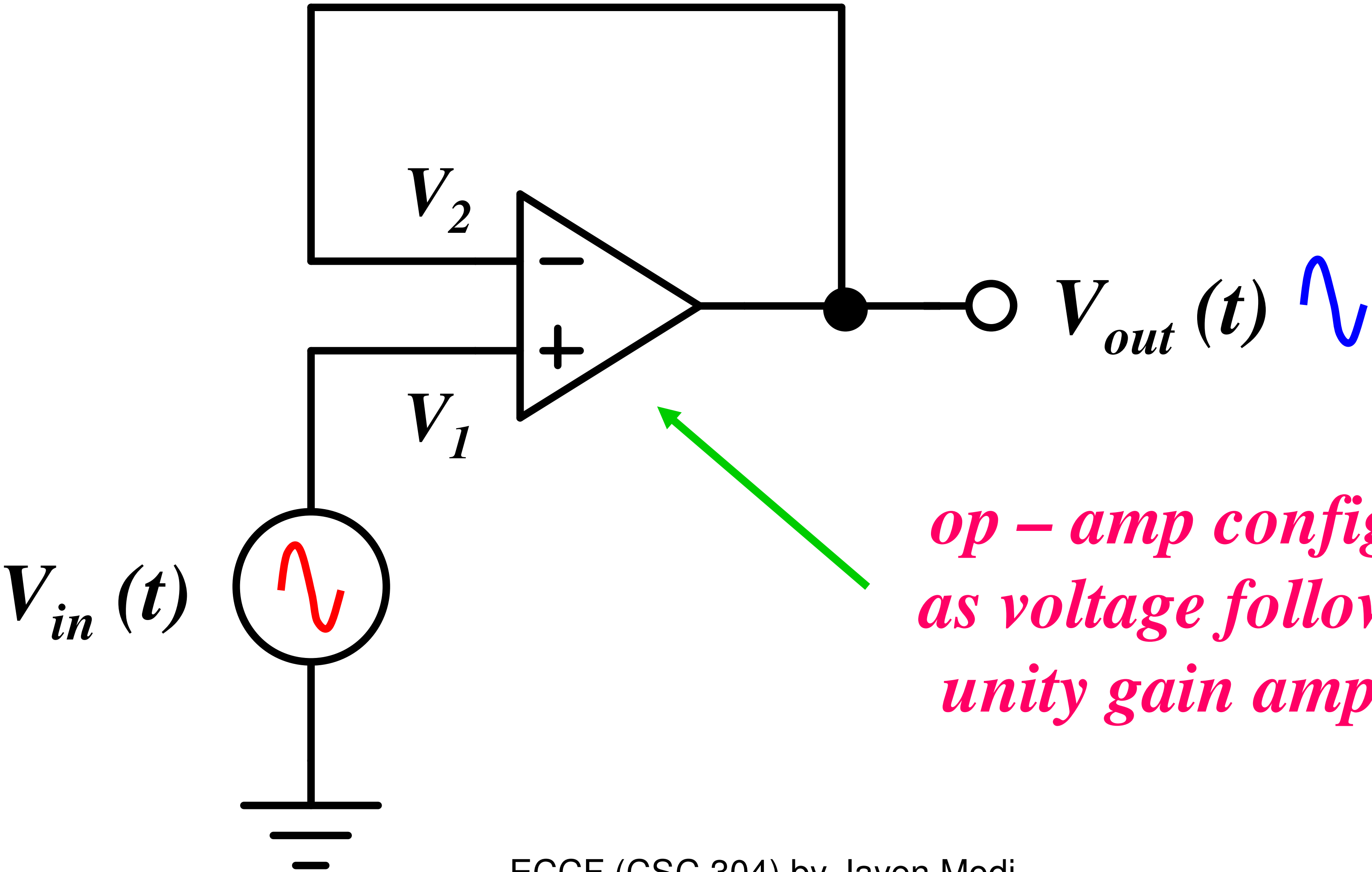
- **Slew Rate (SR) is defined as maximum rate of change of op – amp output voltage with time**

- **Higher the value of the slew rate, better is the op – amp since V_{out} can change as fast as V_{in}**

$$\boxed{SR = \left.\frac{dV_{out}}{dt}\right|_{max}}$$

Slew Rate (SR) Characteristics

Circuit Diagram of Unity Gain Amplifier



op – amp configured as voltage follower or unity gain amplifier

Slew Rate (SR) Characteristics

Mathematical Analysis & Derivations

$$\left.\begin{array}{l} Given\ V_{in}(t) = V_m \sin \omega_m t \\ hence\ V_{out}(t) = V_m \sin \omega_m t \end{array}\right\}$$

since op – amp configured as voltage follower (buffer)

Differentiate $V_{out}(t)$ with respect to time :-

$$\frac{dV_{out}}{dt} = V_m \cdot \omega_m \cdot \cos \omega_m t$$

now maximize dV_{out}/dt by putting term $\cos \omega_m t = 1$

$$\left.\frac{dV_{out}}{dt}\right|_{max} = V_m \cdot \omega_m \Rightarrow SR = \left.\frac{dV_{out}}{dt}\right|_{max}$$

$$\boxed{hence\ SR = V_m \cdot 2\pi f_m \ where\ \omega_m = 2\pi f_m}$$

Slew Rate (SR) Characteristics

Limits on Voltage (V_m) & Frequency (f_m)

$$\boxed{\textit{Slew Rate (SR)} = 2\pi f_m V_m}$$

please refer your class notebook for equation

$$f_m(max) = \frac{SR}{2\pi V_m}$$

$$V_m(max) = \frac{SR}{2\pi f_m}$$

maximum values of the amplitude & frequency for the given slew rate