Op-Amps

…and why they are useful to us

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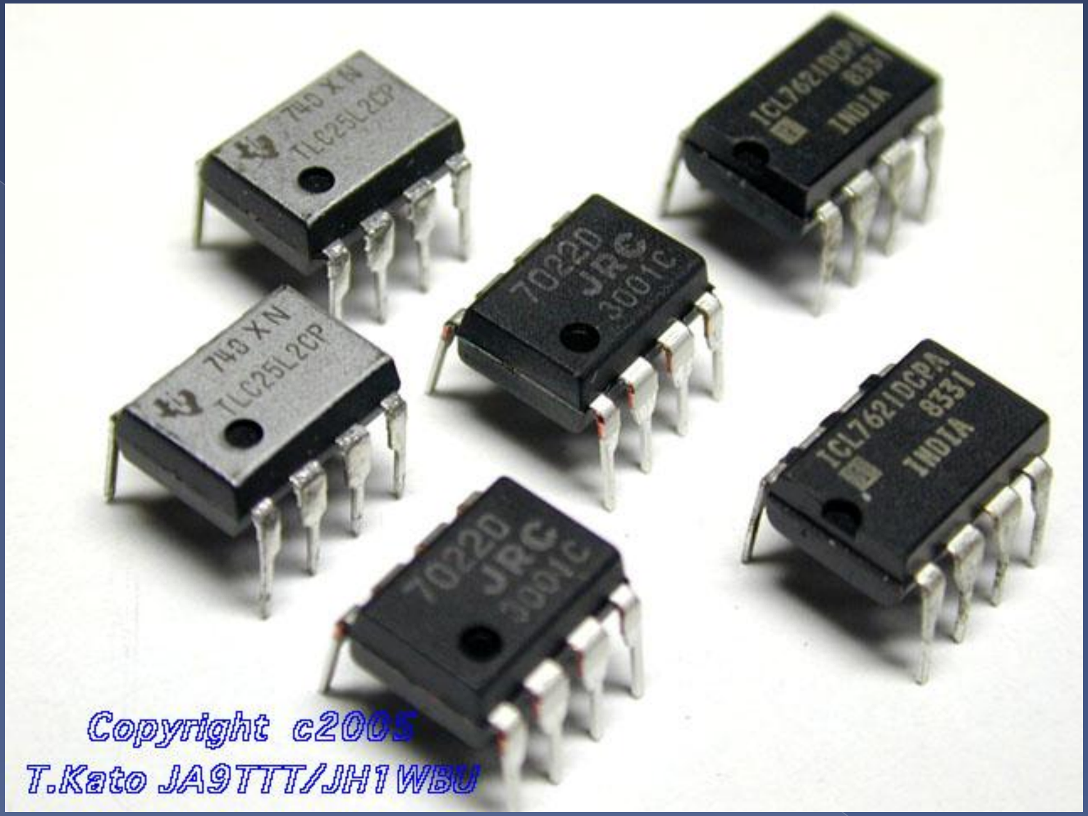


Operational Amplifiers

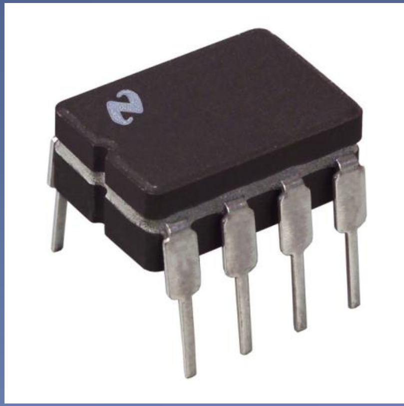
- Op-amps (amplifiers/buffers in general) are drawn as a triangle in a circuit schematic
- There are two inputs
  - inverting and non-inverting
- And one **output**
- Also power connections (note no explicit ground)

Outline of Lecture

- What is an Op-Amp?
- Characteristics of Ideal and Real Op-Amps
- Common Op-Amp Circuits
- Applications of Op-Amps
- References

What is an Op-Amp?

- An *Operational Amplifier* (known as an "Op-Amp") is a device that is used to amplify a signal using an external power source
- Op-Amps are generally composed of:
  - Transistors, Resistors, Capacitors



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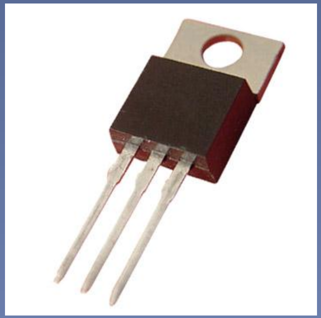

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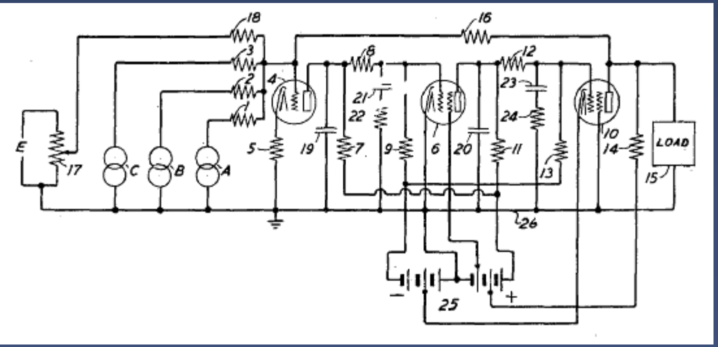
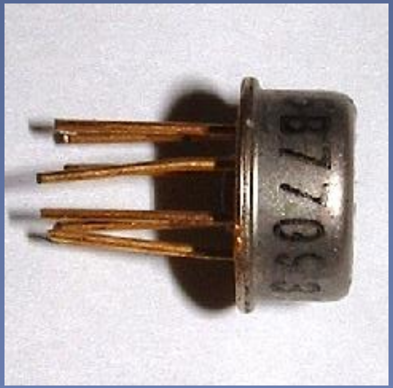
Brief History

- First patent for Vacuum Tube Op-Amp (1946)



- First Commercial Op-Amp available (1953)

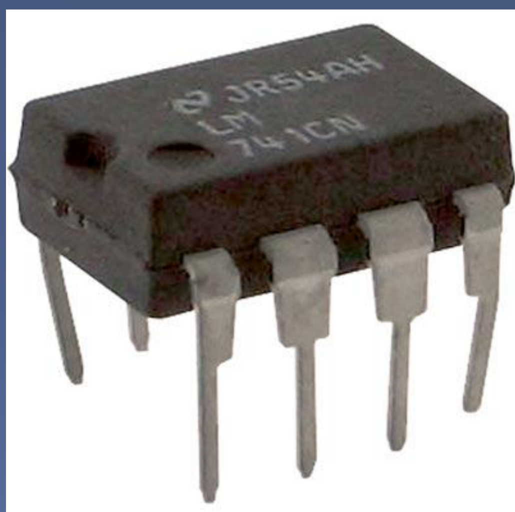
- First discrete IC Op-Amps (1961)



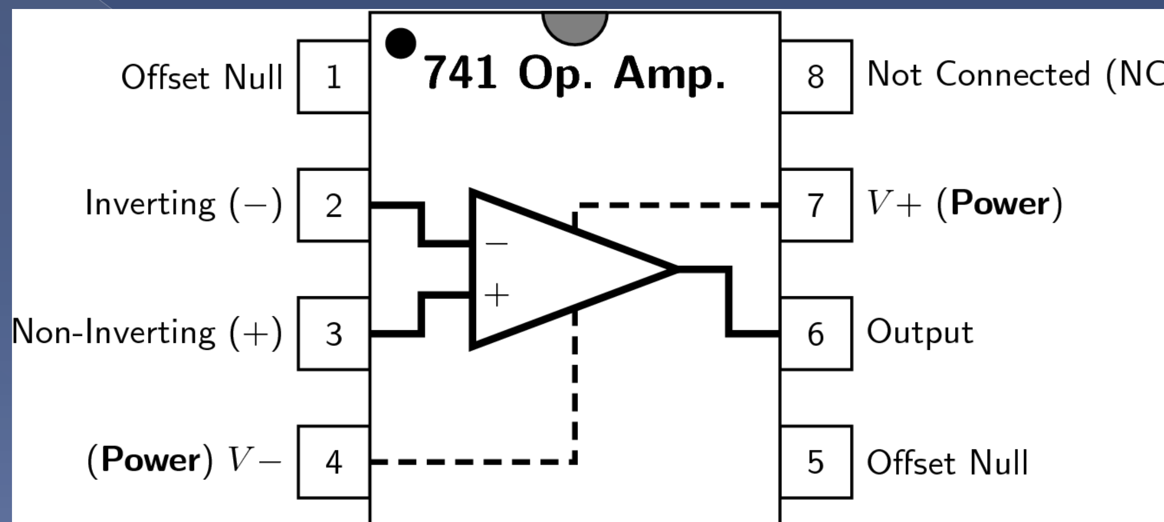
- First commercially successful Monolithic Op-Amps (1965)

History Continued…

- Leading to the advent of the modern IC which is still used even today (1967 – present)



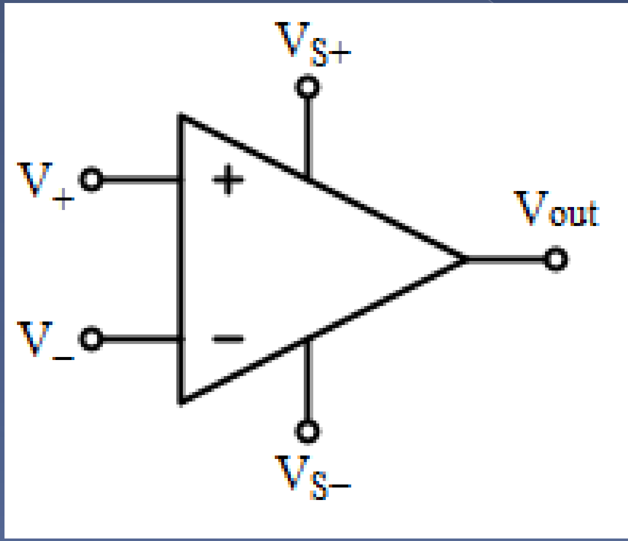
Fairchild µA741



Electrical Schematic of µA741

Op-Amps and their Math

A traditional Op-Amp:



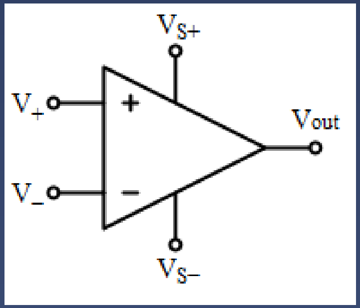
V_+ : non-inverting input
V_- : inverting input
V_{out} : output
V_{S+} : positive power supply
V_{S-} : negative power supply

$$V_{out} = K\,(V_+ - V_-)$$

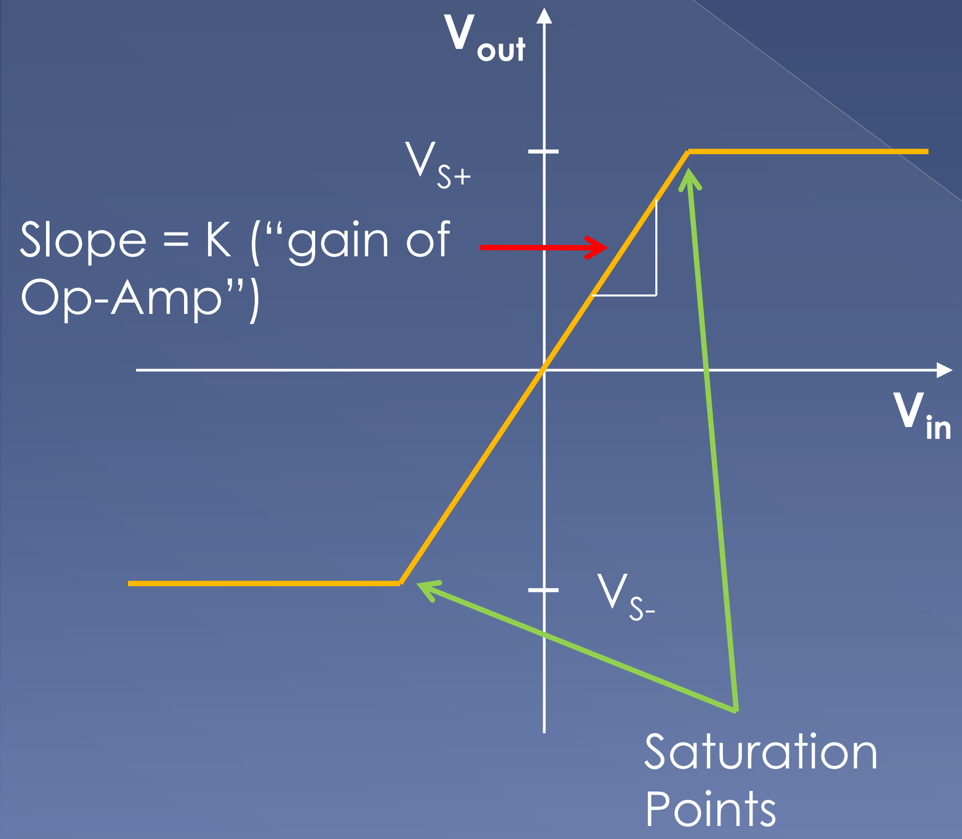
- The difference between the two inputs voltages (V_+ and V_-) multiplied by the gain (K, "amplification factor") of the Op-Amp gives you the output voltage

- The output voltage can only be as high as the difference between the power supply (V_{S+} / V_{S-})and ground (0 Volts)

Saturation



The op-amp will saturate if the input voltage is increased too much or if the gain is increased too much.



The slope is normally much steeper than it is shown here. Potentially just a few milli-volts (mV) of change in the difference between V_+ and V_- could cause the op-amp to reach the saturation level

* Note that saturation level of traditional Op-Amp is 80% of supply voltage with exception of CMOS op-amp which has a saturation at the power supply's voltage

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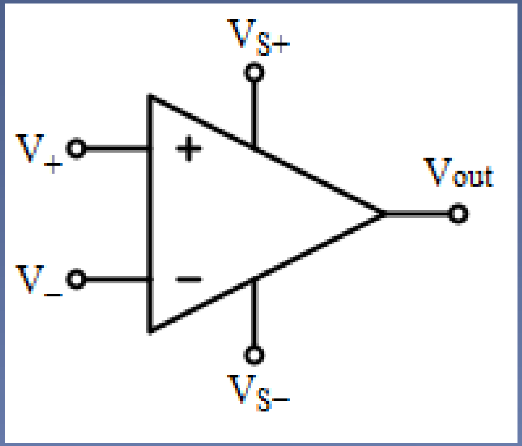
An Ideal Op-Amp

- Infinite voltage gain
- Infinite input impedance
- Zero output impedance
- Infinite bandwidth
- Zero input offset voltage (i.e., exactly zero out if zero in).

http://hyperphysics.phy-astr.gsu.edu/hbase/electronic/opamp.html#c4

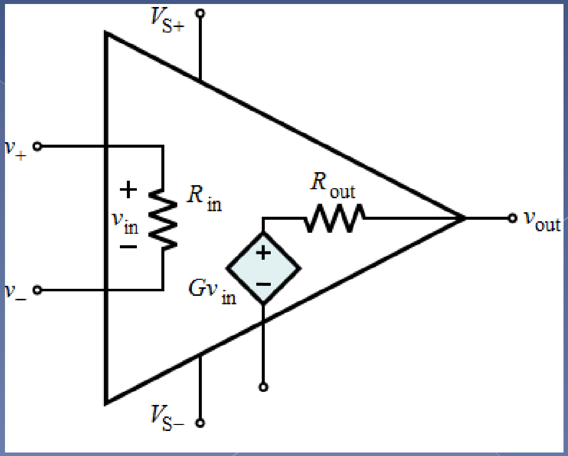
Ideal versus Real Op-Amps

Parameter	Ideal Op-Amp	Real Op-Amp
Differential Voltage Gain	∞	10^5 - 10^9
Gain Bandwidth Product (Hz)	∞	1-20 MHz
Input Resistance (R)	∞	10^6 - 10^{12} Ω
Output Resistance (R)	0	100 - 1000 Ω



Ideal

Real



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Basics of an Op-Amp Circuit

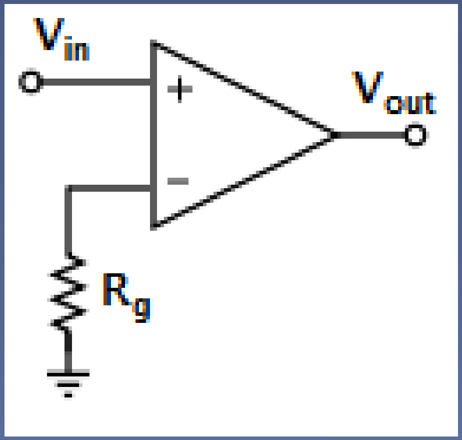
- An op-amp amplifies the difference of the inputs V_+ and V_- (known as the differential input voltage)
- This is the equation for an *open loop* gain amplifier:

$$V_{out}=K(V_+-V_-)$$

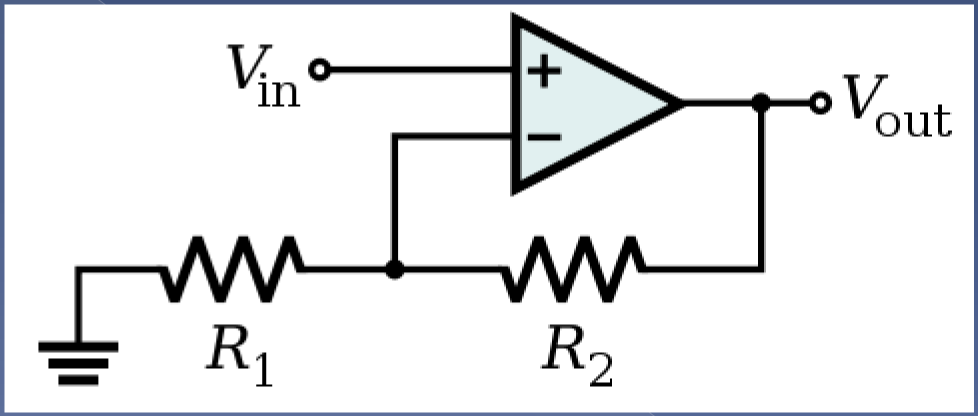
- K is typically very large – at around 10,000 or more for IC Op-Amps
- This equation is the basis for all the types of amps we will be discussing

Open Loop vs Closed Loop

- A closed loop op-amp has feedback from the output to the input, an open loop op-amp does not



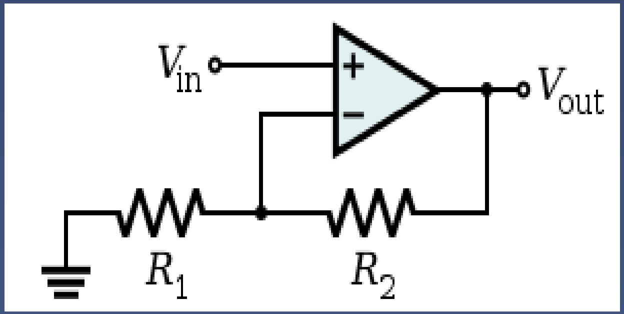
Open Loop



Closed Loop

Non-Inverting Op-Amp

- Amplifies the input voltage by a constant
- Closed loop op-amp
- Voltage input connected to non-inverting input
- Voltage output connected to inverting input through a feedback resistor
- Inverting input is also connected to ground
- Non-inverting input is only determined by voltage output



Non-Inverting Op-Amp

$V_{out}=K(V_{+}-V_{-})$

$R_1/(R_1+R_2)$ ← Voltage Divider

$V_{-}=V_{out}\ (R_1/(R_1+R_2)\ )$

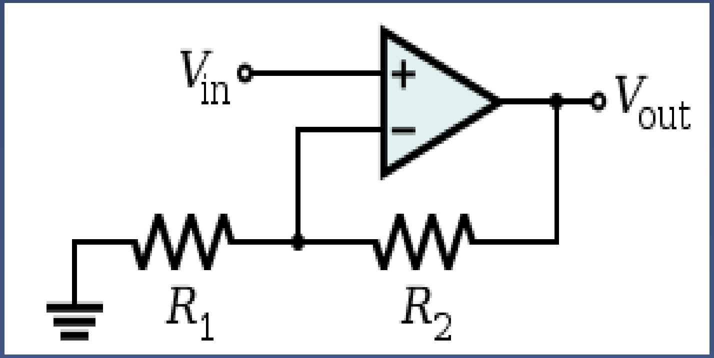
$V_{out}=[V_{in}-V_{out}\ (R_1/(R_1+R_2))]\ K$

$V_{out}=V_{in}/[(1/K)+\ (R_1/(R_1+R_2))]$

As discussed previously assuming, K is very large, we have:

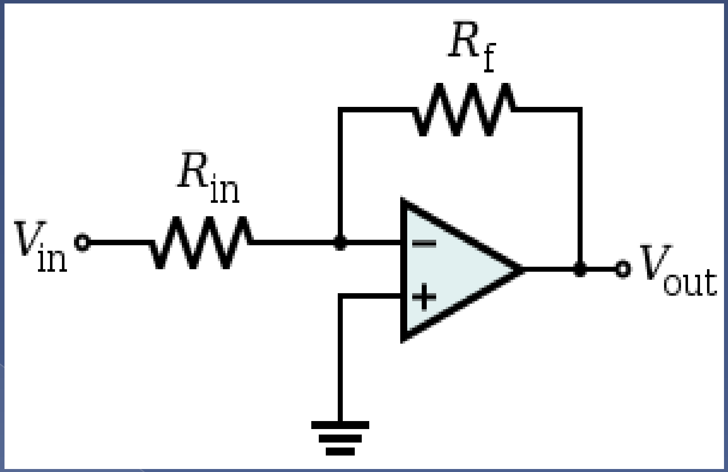
$V_{out}=V_{in}/(R_1/(R_1+R_2))$

$V_{out}=V_{in}\ (1+(R_2/R_1))$



Inverting Op-Amp

- Amplifies and inverts the input voltage
- Closed loop op-amp
- Non-inverting input is determined by *both* voltage input and output
- The polarity of the output voltage is opposite to that of the input voltage
- Voltage output is connected to inverting input through a feedback resistor
- Non-inverting input is grounded



Inverting Op-Amp

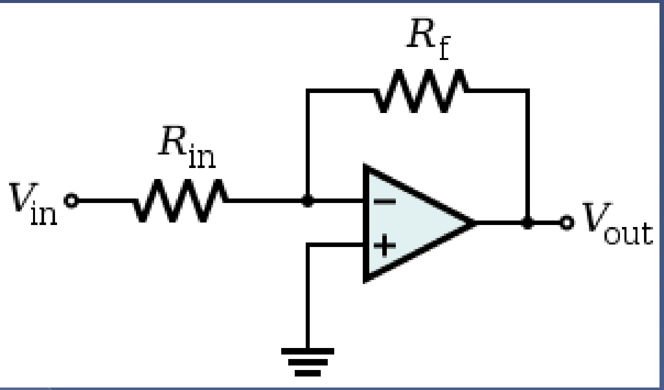
$$V_{out}=K(V_{+}-V_{-})$$

$$V_{-}=V_{out}(R_{in}/(R_{in}+R_{f}))+V_{in}(R_{f}/(R_{in}+R_{f}))$$

$$V_{-}=(V_{out}R_{in}+V_{in}R_{f})/(R_{in}+R_{f})$$

$$V_{out}=K(0-V_{-})$$

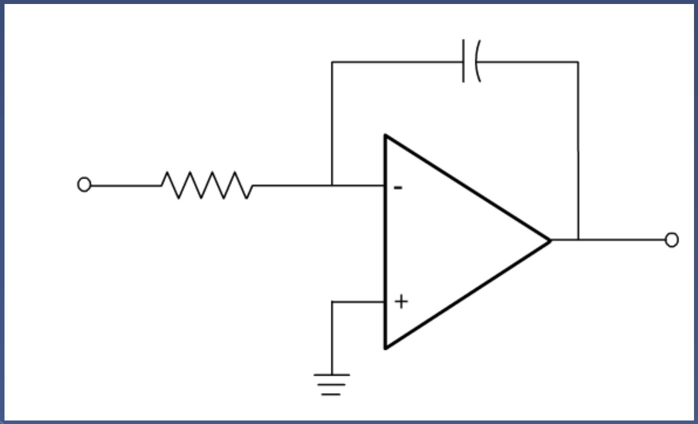
$$V_{out}=-V_{in}R_{f}/[(R_{in}+R_{f})/K+(R_{in})]$$



$$V_{out}=-V_{in}R_{f}/R_{in}$$

Integrating Op-Amp

- Integrates the inverted input signal over time
- Closed loop op-amp
- Voltage output is connected to inverting input through a *capacitor*
- The resistor and capacitor form an RC circuit
- Magnitude of the output is determined by length of time voltage is present at input
- The longer the input voltage is present, the greater the output

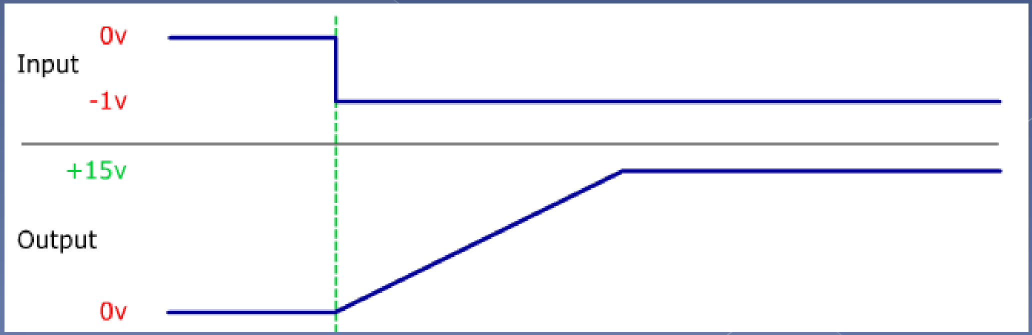


Integrating Op-Amp

- When the circuit is first connected the capacitor acts as a short. Gain is less than 1, V_{out} is 0
- As time progresses, and the capacitor charges, it's effective resistance increases. Now V_{out} is increasing as well
- When the capacitor is fully charged it acts as an open circuit with infinite resistance. Now V_{out} goes into saturation (~80% power supply voltage)
- The rate of voltage output increase depends on the RC time constant

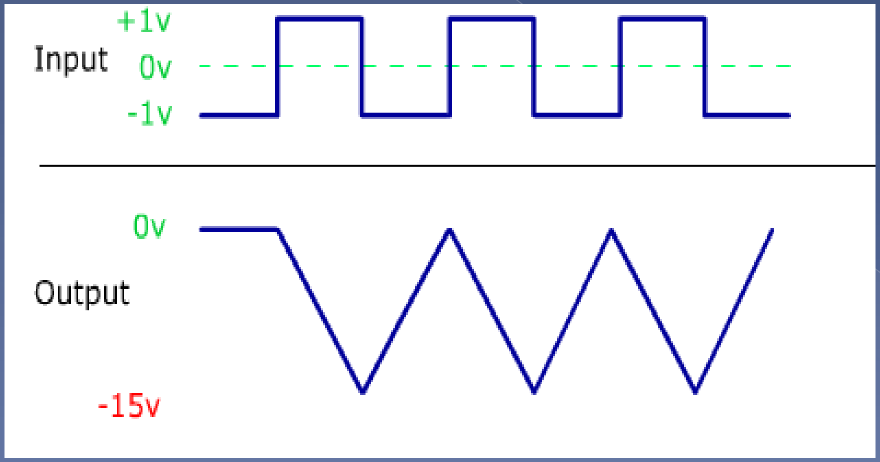
$$V_{out} = -V_{in} R_C / R_{in}$$

$$V_{out} = -\frac{1}{RC}\int_0^t V_{in}(\tau)d\tau$$

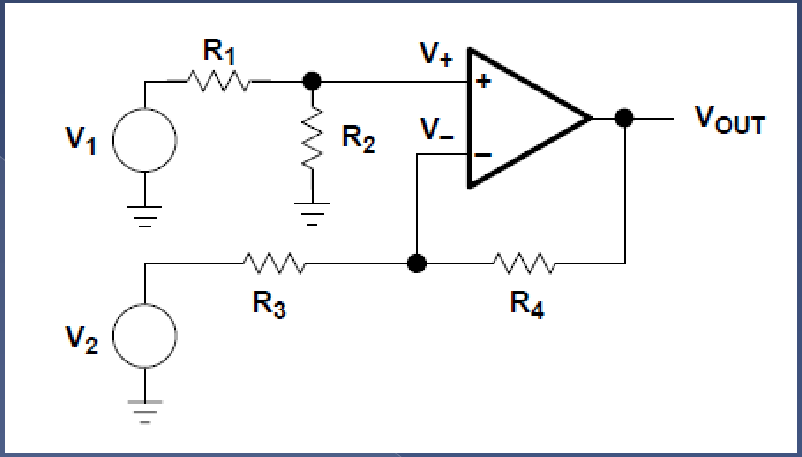


Integrating Op-Amp

- An integrating op-amp circuit can create a sawtooth signal if a square wave is applied at V_{in}



Differential Amplifier



<u>Voltage relations</u>

$$V_+ = V_1 \frac{R_2}{R_1 + R_2}$$

$$V_{OUT1} = V_+(G_+) = V_1 \frac{R_2}{R_1 + R_2}\left(\frac{R_3 + R_4}{R_3}\right)$$

- The purpose of the differential amplifier is to produce an output proportional to the difference of the input voltages
- V_+ is given by the voltage divider equation

Differential Amplifier continued

Output voltage

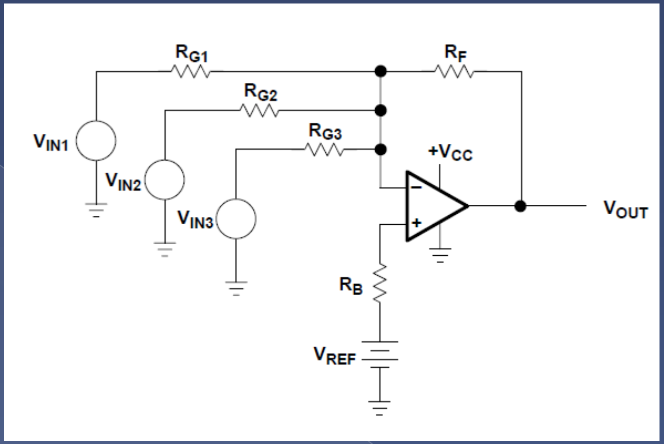
$$V_{OUT2} = V_2\left(-\frac{R_4}{R_3}\right)$$

$$V_{OUT} = V_1 \frac{R_2}{R_1 + R_2}\left(\frac{R_3 + R_4}{R_3}\right) - V_2 \frac{R_4}{R_3}$$

$$V_{OUT} = (V_1 - V_2)\frac{R_4}{R_3}$$

V_{out} as we see is the difference of voltage V1 & V2 multiplied by the resistance R4 & R3 which scales the difference

Summing Amplifier

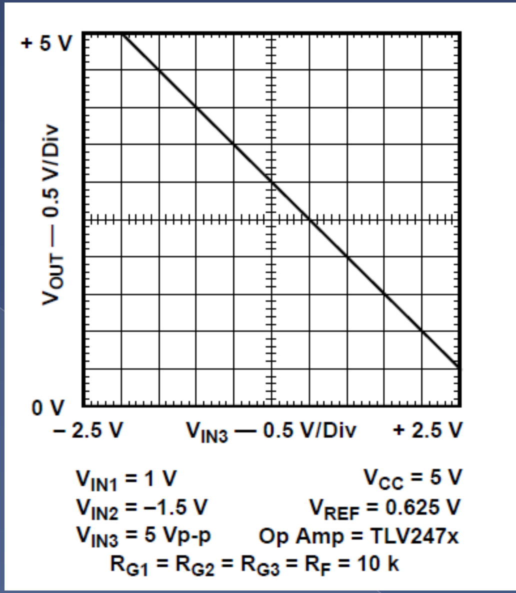


Output voltage

$$V_{OUT} = -\left(V_{IN1}\frac{R_F}{R_{G1}} + V_{IN2}\frac{R_F}{R_{G2}} + V_{IN3}\frac{R_F}{R_{G3}} + \dots\right) + V_{REF}\left(1 + \frac{R_F}{R_{G1} \parallel R_{G2} \parallel R_{G3} \dots}\right)$$

The summing amplifier does exactly as the name suggests by adding up the voltages given to it and producing an output voltage which is the sum of the input voltages scaled by the feedback resistance and input resistance

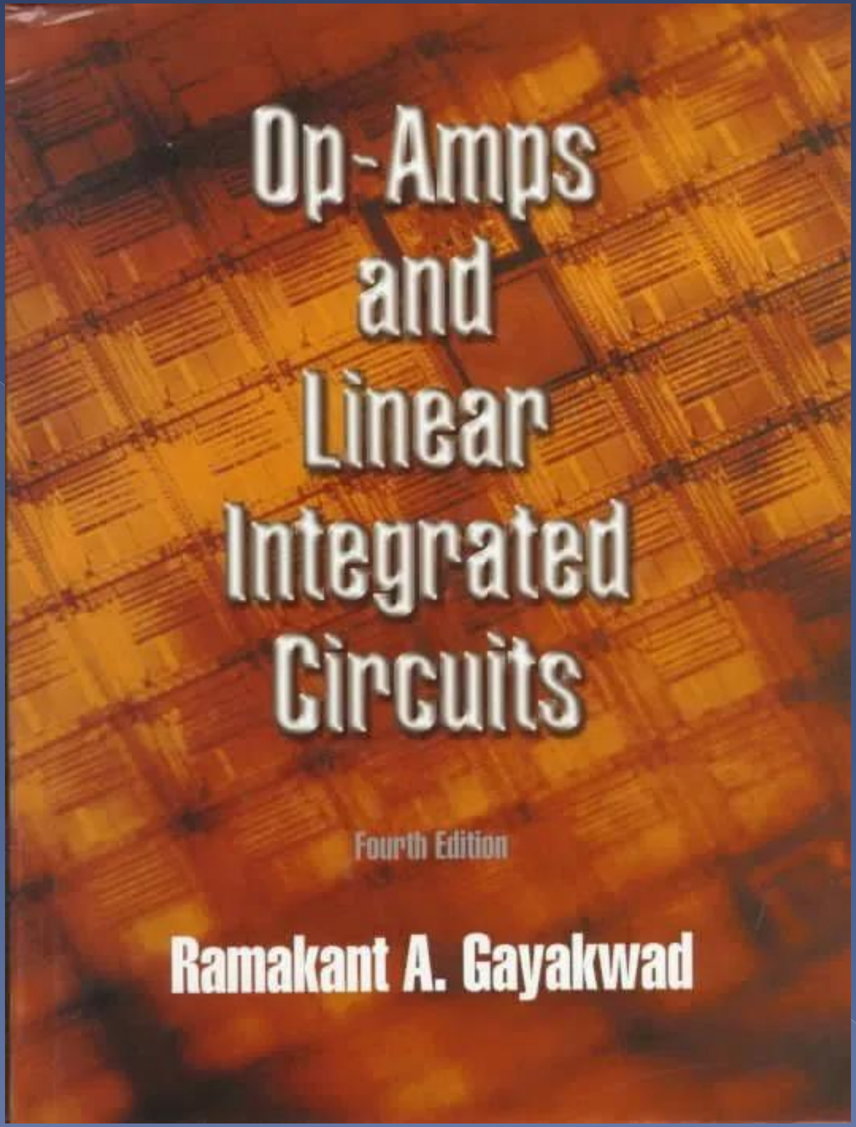
Summing Amplifier continued



$$V_{OUT} = -\left(V_{IN1}\frac{R_F}{R_{G1}} + V_{IN2}\frac{R_F}{R_{G2}} + V_{IN3}\frac{R_F}{R_{G3}} + \dots\right) + V_{REF}\left(1 + \frac{R_F}{R_{G1} \parallel R_{G2} \parallel R_{G3} \dots}\right)$$

The graph shown above is a plot of output voltage V_{out} vs input voltage V_{in} 3

REFERENCES:


Op-Amps and Linear Integrated Circuits
Fourth Edition
Ramakant A. Gayakwad