OPERATIONAL AMPLIFIERS: Basic Circuits and Applications

ECEN – 457 (ESS)

Outline of the course

- Introduction & Motivation OP Amp Fundamentals
- Circuits with Resistive Feedback
- Basic Operators: Differential, Integrator, Low Pass
- Filters
- Static Op Amp Limitations
- Dynamic Op Amp Limitations
- Noise
- Nonlinear Circuits
- Signal Generators
- Voltage Reference and Linear Regulators
- Operational Transconductance Amplifier
- Analog Multipliers

BRIEF OP AMP HISTORY

- The Operational Amplifier (op amp) was invented in the 40's. Bell Labs filed a patent in 1941 and many consider the first practical op amp to be the vacuum tube K2-W invented in 1952 by George Philbrick.

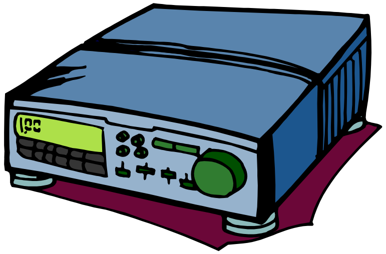
- Texas Instruments invented the integrated circuit in 1958 which paved the way for Bob Widlar at Fairchild inventing the uA702 solid state monolithic op amp in 1963.

- But it wasn't until the uA741, released in 1968, that op amps became relatively inexpensive and started on the road to ubiquity. And they didn't find their way into much consumer audio gear until the late 70's and early 80's

http://nwavguy.blogspot.com/2011/08/op-amps-myths-facts.html

WHERE DO YOU USE OP AMP?

- Audio Amplifiers
- Low Dropout Regulators
- Active Filters
- Medical Sensor Interfaces
- Baseband Receivers
- Analog to Digital Converters
- Oscillators
- Signal Generators
- Hearing Aids



- ***What is an amplifier***?

An amplifier is a device that increases its input by a certain quantity, passing through it, called gain.

- ***How many types of amplifier exist***?

— Voltage Controlled Voltage Source (VCVS)
— Voltage Controlled Current Source (VCIS)
— Current Controlled Current Source (ICIS)
— Current Controlled Voltage Source (ICVS)

- The most popular amplifiers are the Op Amp (VCVS) and the Transconductance (VCIS).

• *Are all the Op Amps connected in closed loop?*

— Majority of applications use the Op Amp in closed loops.

— Op Amps might be used in open loop as comparators.

— The transconductance amplifiers is typically used in closed loop for switched-capacitor circuits.

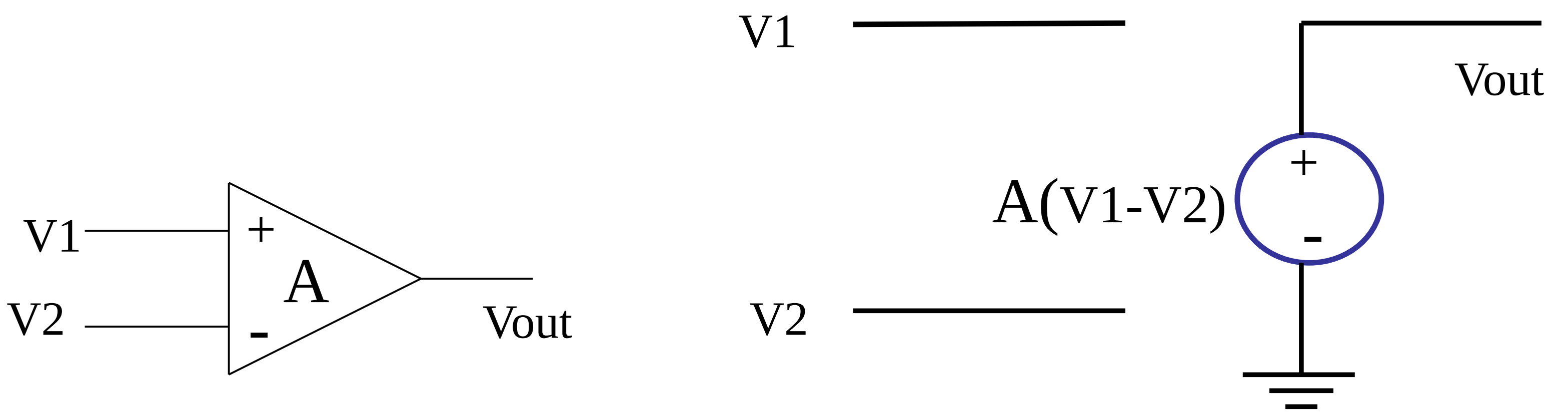
— The transconductance amplifiers are often used in open loop for continuous-time filters. (Gm-C filters)

• *Where do you use transconductance amplifier (VCIS) or current amplifier (ICIS) amplifiers?*

— In continuous-time current-mode filters.

— Sensor interface as a pre-conditioning low noise amplifiers.

1) Op Amp fundamentals and ideal macromodel

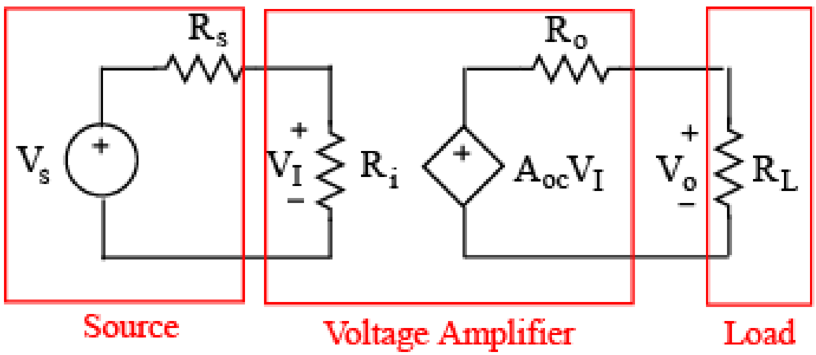


Op Amp macromodel with ideal parameters except finite voltage gain A

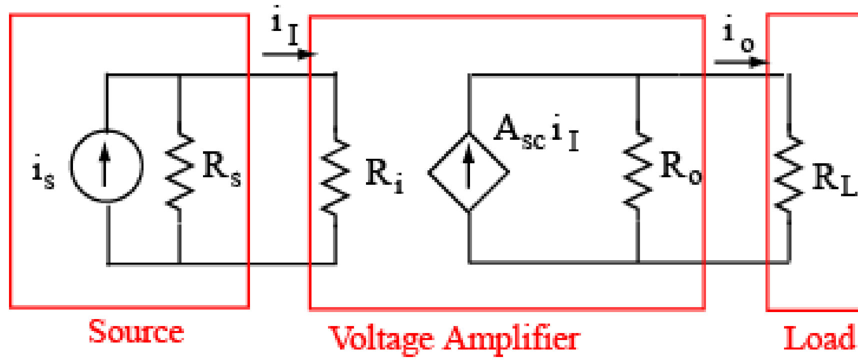
Op Amp Fundamentals

Different Amplifier Types :

1. Voltage Amplifier



2. Current Amplifier



3. Trans-conductance Amplifier

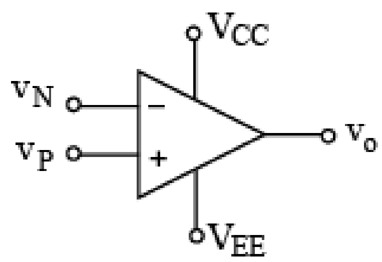
4. Trans-resistance Amplifier

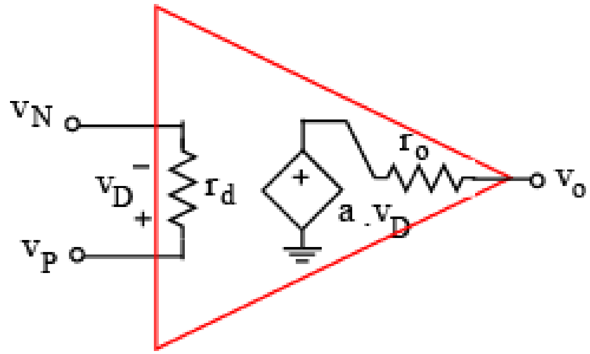
Input	Output	Amplifier Type	Gain	R_i	R_o
V_I	V_o	Voltage	V/V	∞	0
i_I	i_o	Current	A/A	0	∞
V_I	I_o	Transconductance	A/V	∞	∞
I_I	V_o	Transresistance	V/A	0	0

Op Amp Fundamentals

The Operational Amplifier :

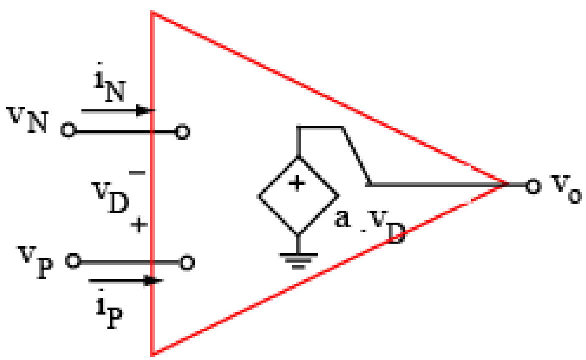
• **Op Amp is a voltage amplifier with extremely high gain (741, Gain: 200,000 (V/V), Op-77, Gain: 12 (V/uV)**





- **r_d, a, r_o are open-loop parameters**
- **v_P : Non-inverting**
  v_N: Inverting
- **v_0 = a. v_D = a (v_P – v_N)**

The Ideal Op Amp:



$$a \longrightarrow \infty$$

$$r_d \longrightarrow \infty$$

$$r_o \longrightarrow 0$$

$$v_D = \frac{v_o}{a} \longrightarrow 0$$

$$v_P = v_N$$

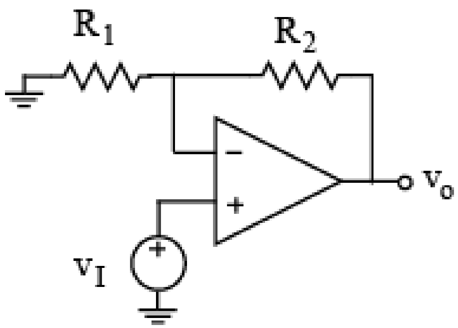
$$i_P = i_N = 0$$

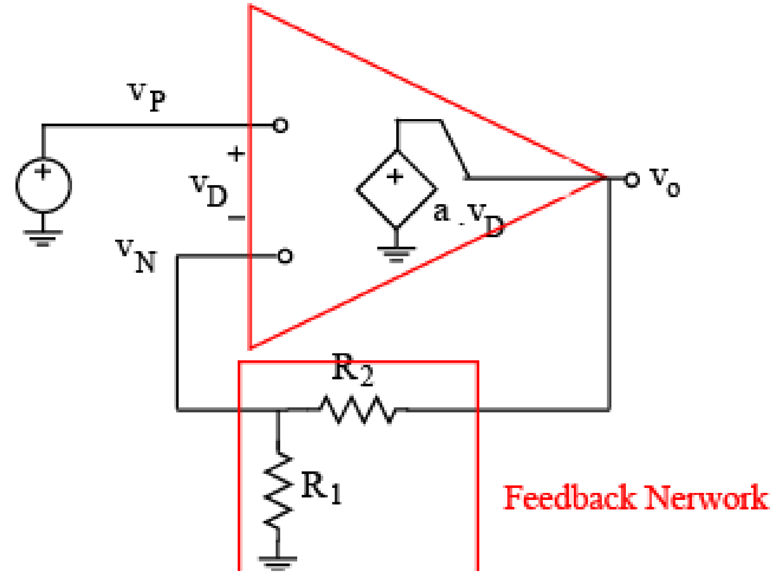
- **The virtual input short does not draw any current**
- **For voltage purposes: Input appears as a short circuit**
- **For current purposes: Input appears as an open circuit**

Op Amp Fundamentals

Basic Op Amp Configurations :

- **Non-inverting Amplifier**





$$A \text{ (Closed Loop Gain)} = \left(1 + \frac{R_2}{R_1}\right) \cdot \frac{1}{1 + \left[\left(1 + \frac{R_2}{R_1}\right) / a\right]}$$

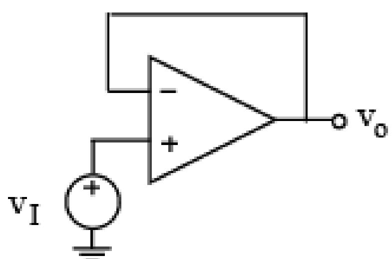
$$R_i \text{ (Closed Loop)} = \infty$$

$$R_o \text{ (Closed Loop)} = 0$$

$$A \text{ (Ideal)} = \left(1 + \frac{R_2}{R_1}\right)$$

"a" is the open loop gain of the Op Amp

- **The Voltage Follower (Unity Gain Amplifier)**



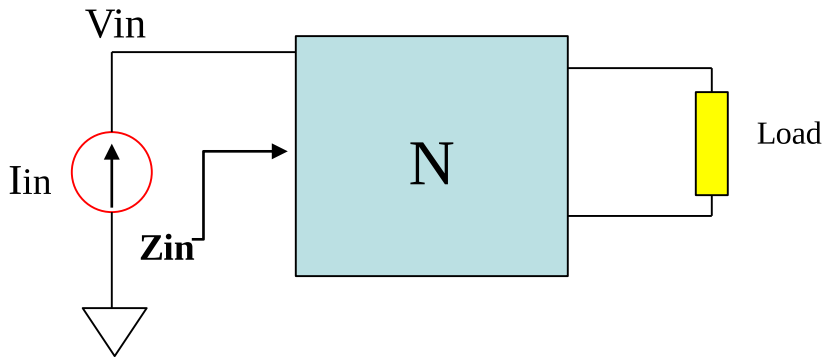
$$R_1 = \infty$$
$$R_2 = 0$$

$$A = 1$$
$$R_i = \infty$$
$$R_o = 0$$

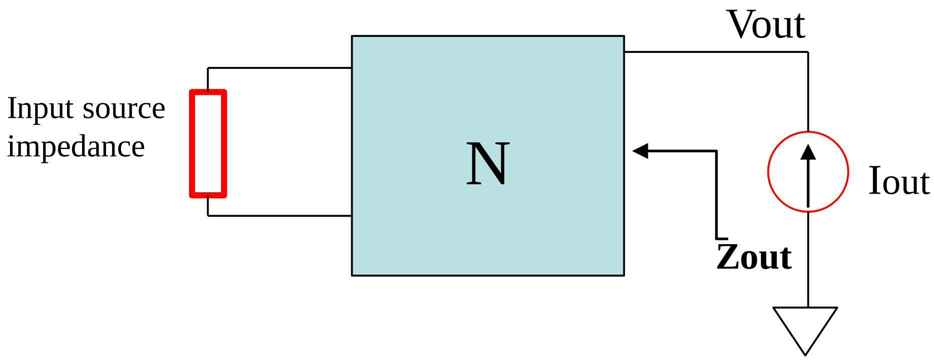
- **A resistance transformer**
- **The source does not deliver any current to load**

Input and Output Impedances Computation

Apply a test current source at the input(output) and measure the corresponding voltage across the current source while making zero all the independent sources



$$Z_{in} = V_{in}/I_{in}$$

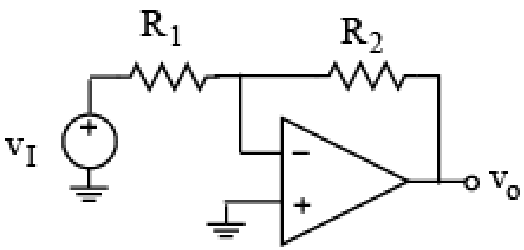


$$Z_{out} = V_{out}/I_{out}$$

Op Amp Fundamentals

Basic Op Amp Configurations :

- **Inverting Amplifier**



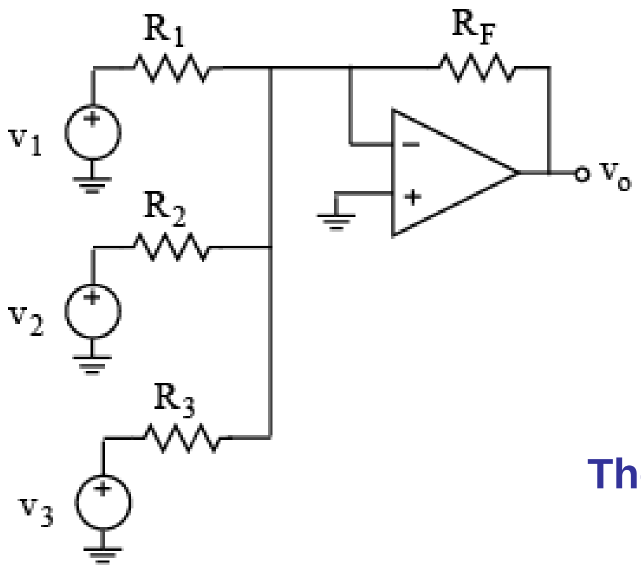
$$A\ \text{(Closed Loop Gain)} = \left(-\frac{R_2}{R_1}\right)\cdot\frac{1}{1+[(1+\frac{R_2}{R_1})/a]}$$

$$A\ \text{(Ideal)} = \left(-\frac{R_2}{R_1}\right)$$

$$R_i\ \text{(Closed Loop)} = R_1$$

$$R_o\ \text{(Closed Loop)} = 0$$

- **The Summing Amplifier (Popular Application : Audio Mixing)**



$$v_o = -\left(\frac{R_F}{R_1}v_1 + \frac{R_F}{R_2}v_2 + \frac{R_F}{R_3}v_3\right)$$

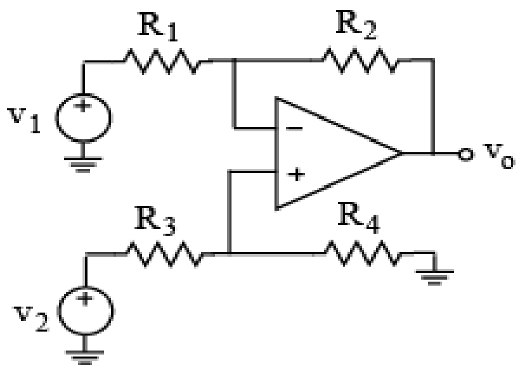
$$R_{ik} = R_k \quad , k = 1, 2, 3$$

$$R_o = 0$$

The output is the weighted sum of the inputs

Basic Op Amp Configurations :

- The Difference Amplifier (Popular Application : Instrumentation). Note that the sum of conductances at the positive and negative input terminal are equal. Verify that.

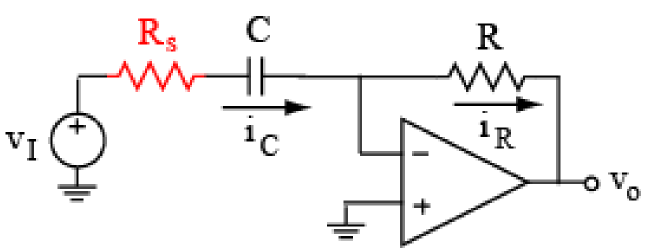


$$v_o = \left(\frac{R_2}{R_1}\right) \cdot \left[\frac{\left(1+\frac{R_1}{R_2}\right)}{\left(1+\frac{R_3}{R_4}\right)} v_2 - v_1 \right]$$

$$\frac{R_1}{R_2} = \frac{R_3}{R_4} \longrightarrow v_o = \left(\frac{R_2}{R_1}\right) \cdot [v_2 - v_1]$$

$$R_{i1} = R_1 \ , \quad R_{i2} = R_3 + R_4 \ , \quad R_o = 0$$

- The Differentiator



$$i_C = C \frac{dV_I}{dt}$$

$$i_R = -\frac{V_o}{R}$$

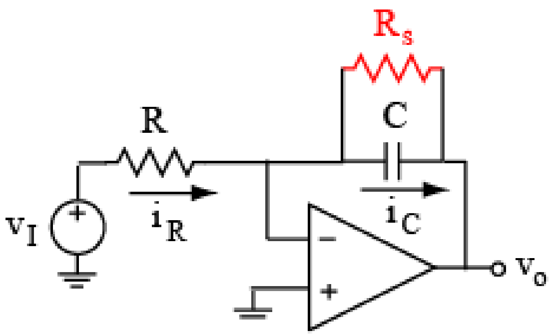
$$v_o = -RC \frac{dV_I}{dt}$$

- Without Rs the circuit tends to oscillate
- By putting the R_s in series with C, the oscillation problem is solved
- The circuit still provides differentiation function over the limited bandwidth

Op Amp Fundamentals

Basic Op Amp Configurations :

- **The Integrator (Popular Applications: Function generators, Active filters, A/Ds, Analog (PID) controllers)**

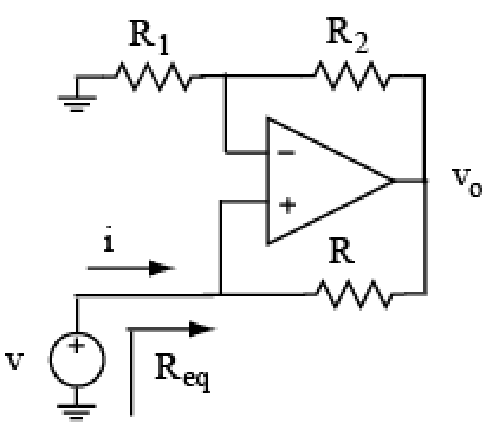


$$\frac{v_i}{R} = -C\frac{dV_o}{dt}$$

$$\frac{dV_o}{dt} = -\frac{v_I}{RC}$$

- **Due to the input offset error of the op amp the output drifts until it saturates at the value close to one of the supplies.**
- **By putting R_p in parallel with C, we can prevent saturation and have integration over a limited bandwidth.**

- **The Negative Resistance Converter (NIC)**

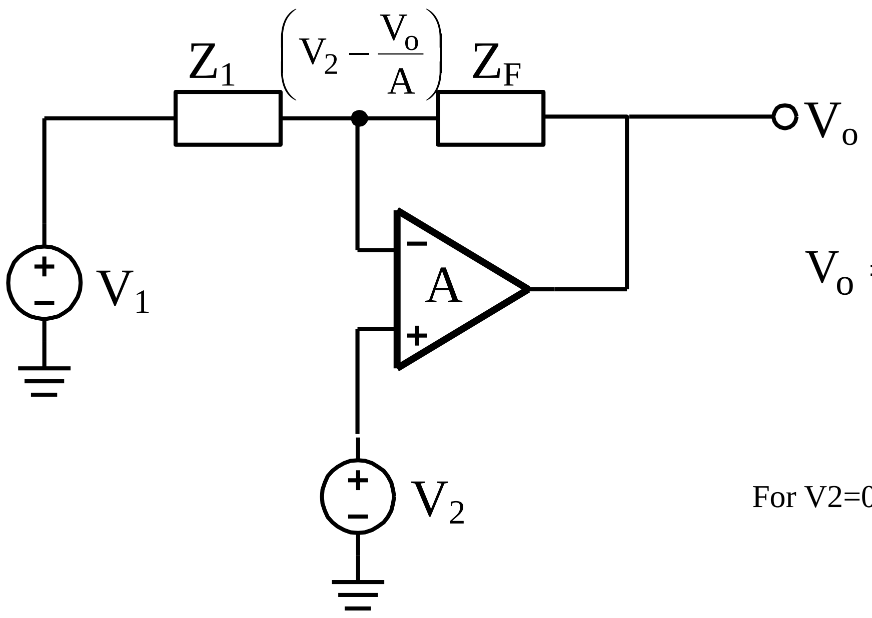


$$R_{eq} = \left(-\frac{R_2}{R_1}\right) R$$

- **Current is floating toward the source**
- **Negative resistance releases the power.**
- **Applications:**

1) Neutralization of unwanted resistances in the design of current source
2) Control pole location (Oscillators)

Remarks on inverter or non-inverting amplifier configurations



$$V_o = \frac{-\frac{Z_F}{Z_1}V_1}{1+\frac{1}{A}\left(1+\frac{Z_F}{Z_1}\right)} + \frac{\left(1+\frac{Z_F}{Z_1}\right)V_2}{1+\frac{1}{A}\left(1+\frac{Z_F}{Z_1}\right)}$$

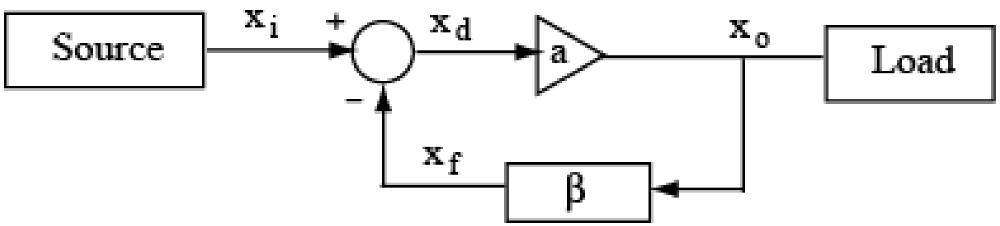
For V2=0 and ideal infinite A, then Vo/V1 becomes:

$$V_o/V_1 = -Z_F/Z_1$$

Where the impedance can be any passive component R or C or a combination of connection of these two components. Examples are the differentiator, integrator, first-order low pass, high pass among many others.

Op Amp Fundamentals

Negative Feedback; A Systematic Approach :



Building Blocks outputs:

1) **Error Amplifier;** $x_o = a \cdot x_d$

2) **Feedback Network;** $x_f = \beta \cdot x_o$

3) **Summing Network;** $x_d = x_i - x_f$

$$A \text{ (Closed Loop Gain)} = \frac{x_o}{x_i} = \frac{a}{1+a\beta}$$

$$T \text{ (Loop Gain)} = a\beta$$

$$A = \frac{1}{\beta}\,\frac{T}{1+T} = A_{ideal} \cdot \frac{1}{1+(1/T)} = A_{ideal} \cdot [1- \frac{1}{1+T}] = A_{ideal} \cdot [1-\varepsilon]$$

$$\text{Gain Error} = \frac{A - A_{ideal}}{A_{ideal}} \sim \frac{1}{T}$$

- **Price for a tight closed loop accuracy : a >> A**
- **The smaller the closed-loop is, the smaller the percentage from deviation is.**

Op Amp parameter characterization

Feedback Properties :

1) Gain De-sensitivity

- **The negative feedback desensitizes the open loop gain**
- **Components in β should have very good quality**

$$A = \frac{a}{1 + a\beta}$$

$$\frac{dA}{da} = \frac{1}{(1 + a\beta)^2}$$

$$\frac{\Delta A}{A} \sim -\frac{\Delta \beta}{\beta}$$

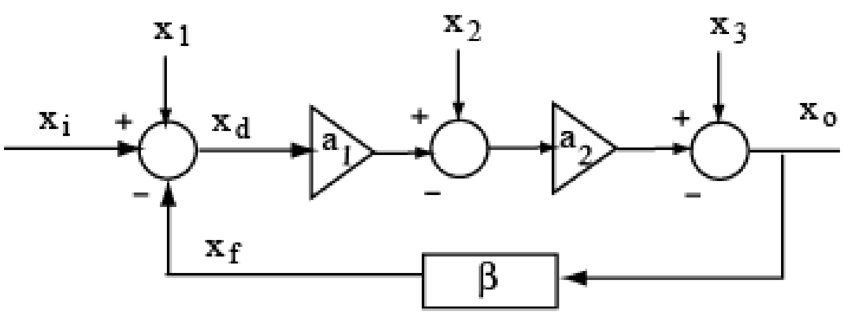
$$\frac{dA}{A} = \frac{1}{(1 + a\beta)} \frac{da}{a}$$

$$\frac{\Delta A}{A} \sim \frac{1}{(1 + T)} \frac{\Delta a}{a}$$

2) Nonlinear Distortion Reduction

- **As long as *a* is sufficiently large and to make *T >> 1* , *A* will be fairly constant and close to *1/β* in spit of the decrease of *a* away from the origin**

3) Effect on Disturbance and Noise



x_1 : Input offset errors

x_2 : Power supply hum

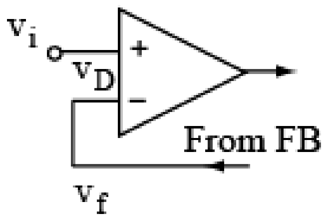
x_3 : Output load changes

$$x_o = \frac{a_1 a_2}{(1 + a_1 a_2 \beta)} \left[x_i + x_1 + \frac{x_2}{a_1} + \frac{x_3}{a_1 a_2} \right]$$

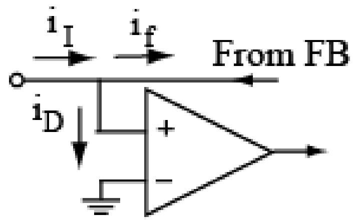
Negative Feedback Op Amp Fundamentals

Feedback in Op Amp Circuits :

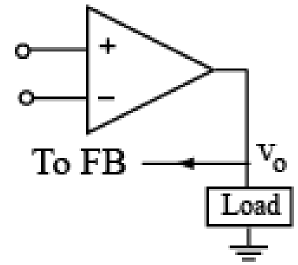
<u>Negative feedback topologies</u>



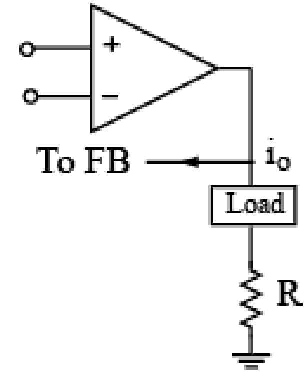
Input Series FB



Input Shunt FB



Output Shunt FB



Output Series FB

- **Input + Feedback enter the amplifier at different nodes: Input Series FB**
- **Input + Feedback enter the amplifier at the same nodes: Input Shunt FB**

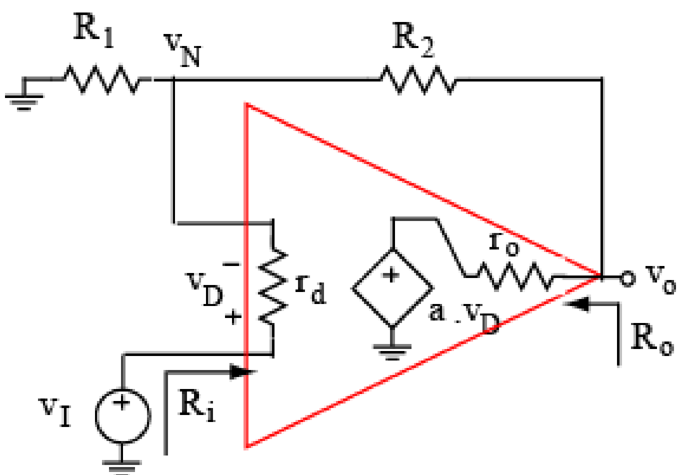
- **If we short the output load and still there is FB signal at the input: Output Series FB**
- **If we short the output load and still there is FB signal at the input: Output Series FB**

AT THE INPUT/OUTPUT PORT, A *<u>SERIES</u>* TOPOLOGY *<u>RAISES</u>* AND A *<u>SHUNT</u>* TOPOLOGY <u>LOWERS</u> THE CORRESPONDING PORT RESISTANCE

Feedback Op Amp Fundamentals

Analysis of Basic Op Amp Configurations Using Feedback Theory :

- **Non-inverting Amplifier (Input Series – Output Shunt FB)**



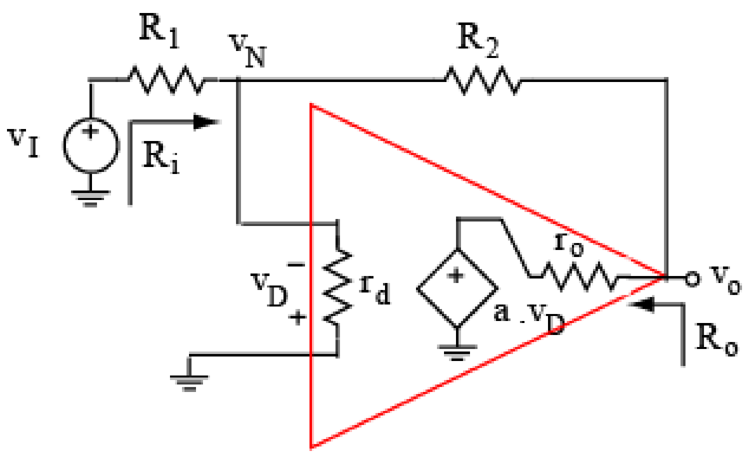
$$A \sim \left(1 + \frac{R_2}{R_1}\right) \cdot \frac{T}{1+T}$$

$$\beta = \frac{R_1}{R_2 + R_1}$$

$$R_i \sim r_d \cdot [\,1 + T\,]$$

$$R_o \sim r_o \,/\, [\,1 + T\,]$$

- **Non-inverting Amplifier (Input Shunt – Output Shunt FB)**



$$A \sim \left(-\frac{R_2}{R_1}\right) \cdot \frac{T}{1+T}$$

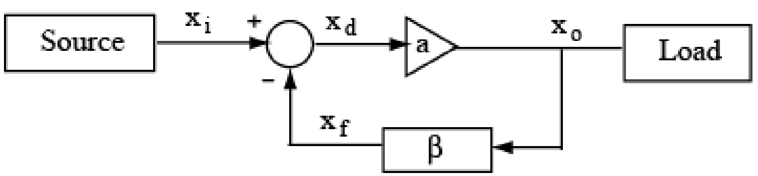
$$\beta = \frac{R_1}{R_2 + R_1}$$

$$R_i \sim R_1 + \frac{R_2}{1+a} \quad \text{(Miller Effect)}$$

$$R_o \sim r_o \,/\, [\,1 + T\,]$$

Op Amp Loop Gain Computation

Finding the Loop Gain (T) Directly:



- **Suppress all *input* sources,**
- **Break the loop at some convenient point**
- **Inject the test signal (v_T)**
- **Find the return signal (v_R) at the breaking point using the feedback path:**

$$v_R = a \cdot b \cdot (-1) \cdot v_T$$

$$T = a \cdot b = -\left.\frac{v_R}{v_T}\right|_{x_I = 0}$$

$$A = A_{ideal} \cdot \frac{1}{1 + (1/T)}$$

$$R = r \cdot (1 + T), \quad r: \text{open-loop resistnace } (a \rightarrow 0)$$

Finding the Feedback Factor (β) Directly:

By finding β, using datasheet we can find a and calculate T = a . β

- **Suppress all *input* sources,**
- **Disconnect the op amp**
- **Replace the op amp with its terminal resistances (r_d, r_o)**
- **Apply a test source v_T via r_o, find the difference voltage v_D across r_d, then:**

$$\beta = -\left.\frac{v_D}{v_T}\right|_{x_I = 0}$$

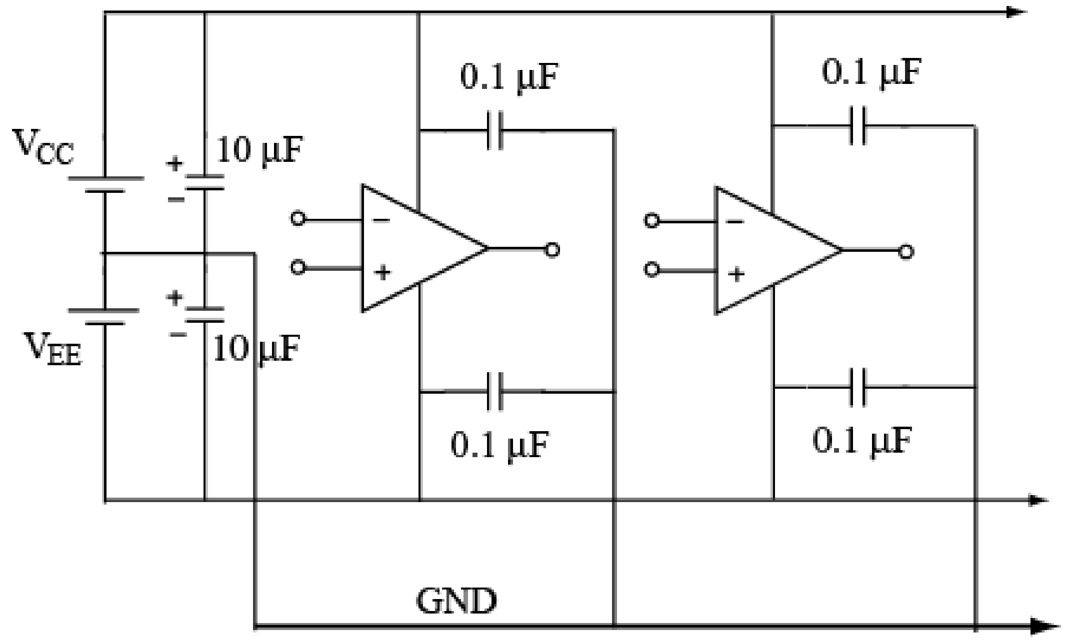
Op Amp Powering

Op Amp Powering:

- **0.1 μF capacitance:**

1) Prevents the AC noise coming from non-zero impedance between the supply and the ground.

2) Neutralizes spurious feedback loops arising from non-zero Impedance between the supply and ground.

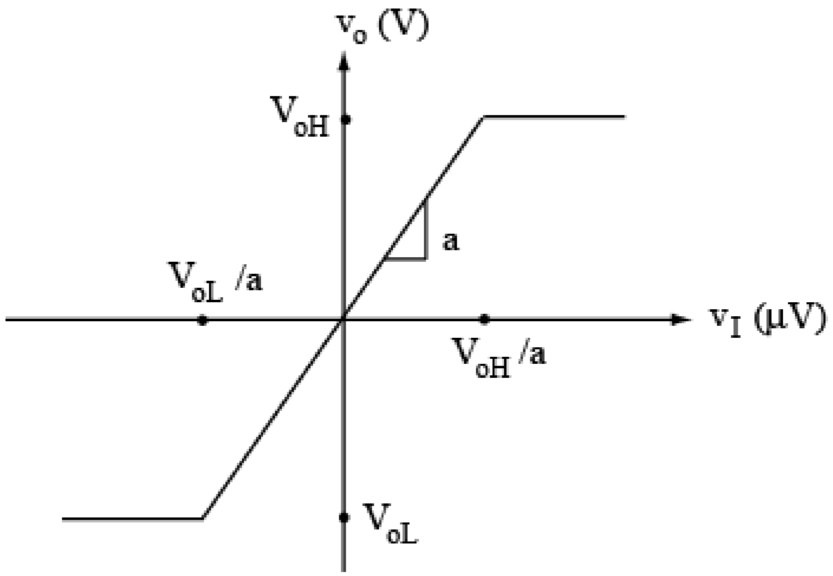


- **10 μF capacitance provides board-level by pass.**
- **Using wide ground traces is recommended.**
- **V_{CC} and V_{EE} can be dual +15V , -15V supplies (analog systems), or single 5 V and zero supply (mixed-mode applications)**

Op Amp I-O Piecewise linear approximation

Op Amp Powering:

- **V_{CC} and V_{EE} set upper and lower bounds on the output swing capacity**



1) Linear Region; a = 0.2 V/µV
Model: dependent source

2) Positive Saturation Region;
V_{oH} remains fixed.

3) Negative Saturation Region;
V_{oL} remains fixed.

- **Bipolar op amps: $V_{oH} \sim V_{CC} – 2$ V, $V_{oL} \sim V_{EE} – 2$ V**
- **CMOS op amps: $V_{oH} \sim V_{CC}$, $V_{oL} \sim V_{EE}$**

- **Common characteristic of saturating amplifier: Clipped output voltage**
- **Undesirable in many cases.**
- **Application : POP MUSIC FUZZ BOXES**