Fundamentals of Microelectronics

الکترونیک ۲

فصل ۸ – تقویت کننده عملیاتی (آپ امپ)

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Chapter 8 Operational Amplifier as A Black Box

- 8.1 General Considerations
- 8.2 Op-Amp-Based Circuits
- 8.3 Nonlinear Functions
- 8.4 Op-Amp Nonidealities
- 8.5 Design Examples

Chapter Outline

General Concepts

- Op Amp Properties

Linear Op Amp Circuits

- Noninverting Amplfier
- Inverting Amplifier
- Inetgrator and Differentiator
- Voltage Added

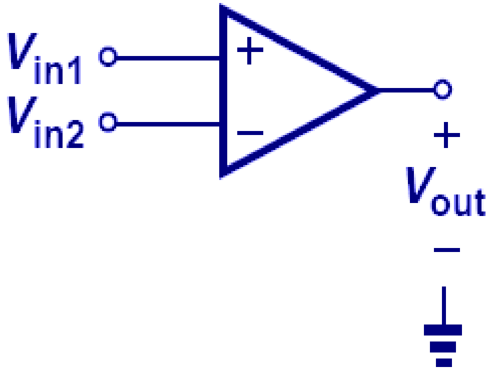
Nonlinear Op Amp Circuits

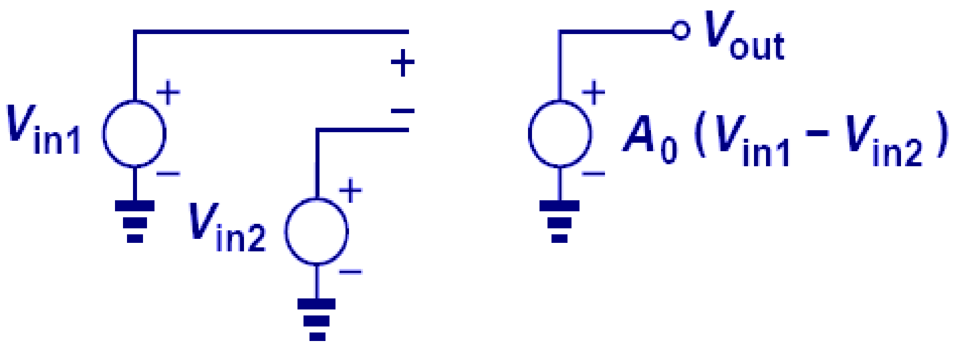
- Precision Rectifier
- Logarithmic Amplifier
- Square Root Circuit

Op Amp Nonidealities

- DC Offsets
- Input Bias Currents
- Speed Limitations
- Finite Input and Output Impedances

Basic Op Amp

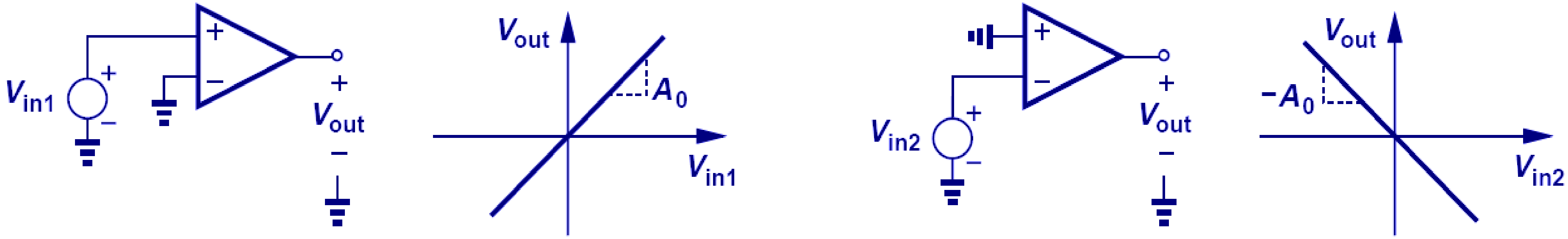


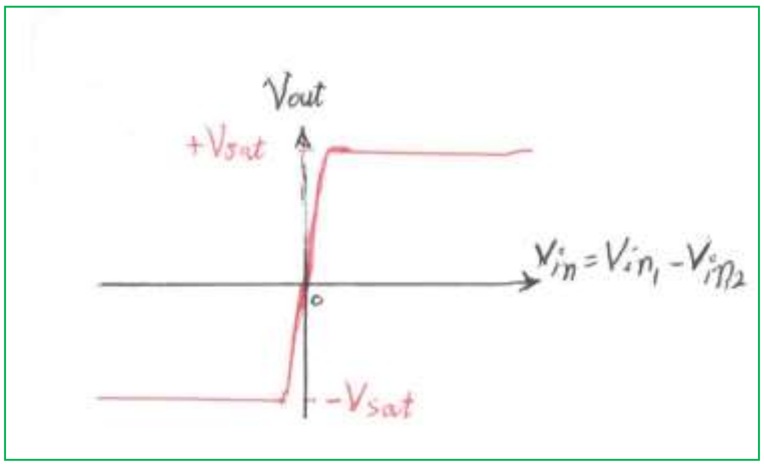


$$V_{out} = A_0 \left(V_{in1} - V_{in2} \right)$$

- Op amp is a circuit that has two inputs and one output.
- It amplifies the difference between the two inputs.

Inverting and Non-inverting Op Amp



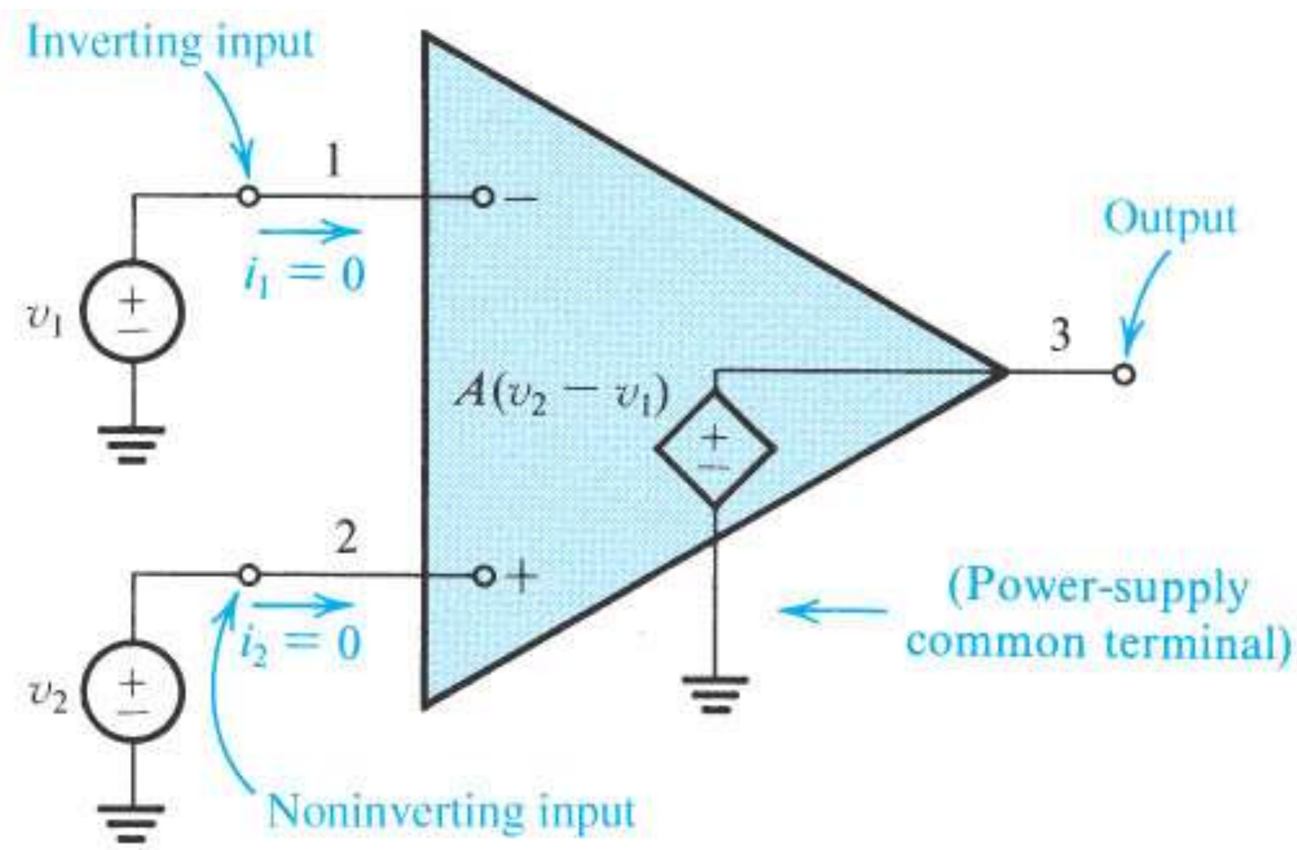


- If the negative input is grounded, the gain is positive.
- If the positive input is grounded, the gain is negative.

Ideal Op Amp

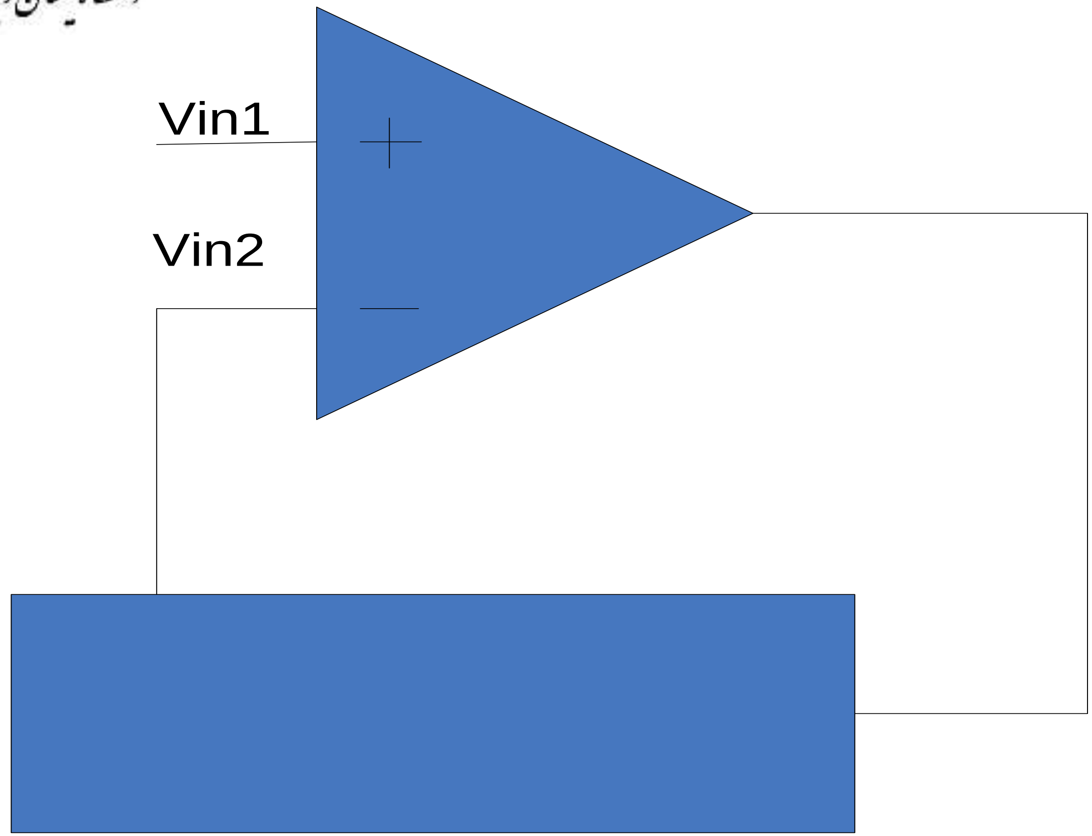
- **Infinite gain**
- **Infinite input impedance**
- **Zero output impedance**
- **Infinite speed**

Ideal Op Amp



Inverting input
1
$i_1 = 0$
v_1
Output
3
$A(v_2 - v_1)$
2
$i_2 = 0$
v_2
(Power-supply
common terminal)
Noninverting input

Virtual Short

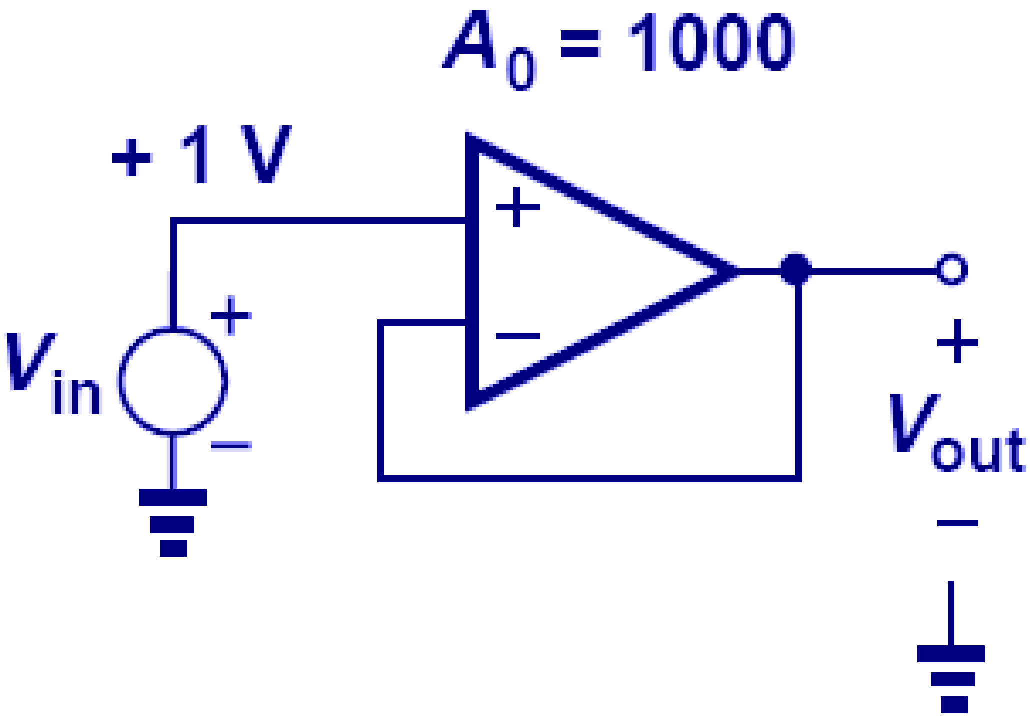


$$V^- \approx V^+$$

$$I_{in_1} = I_{in_2} \approx 0$$

- **Due to infinite gain of op amp, the circuit forces V_{in2} to be close to V_{in1}, thus creating a virtual short.**

Unity Gain Amplifier

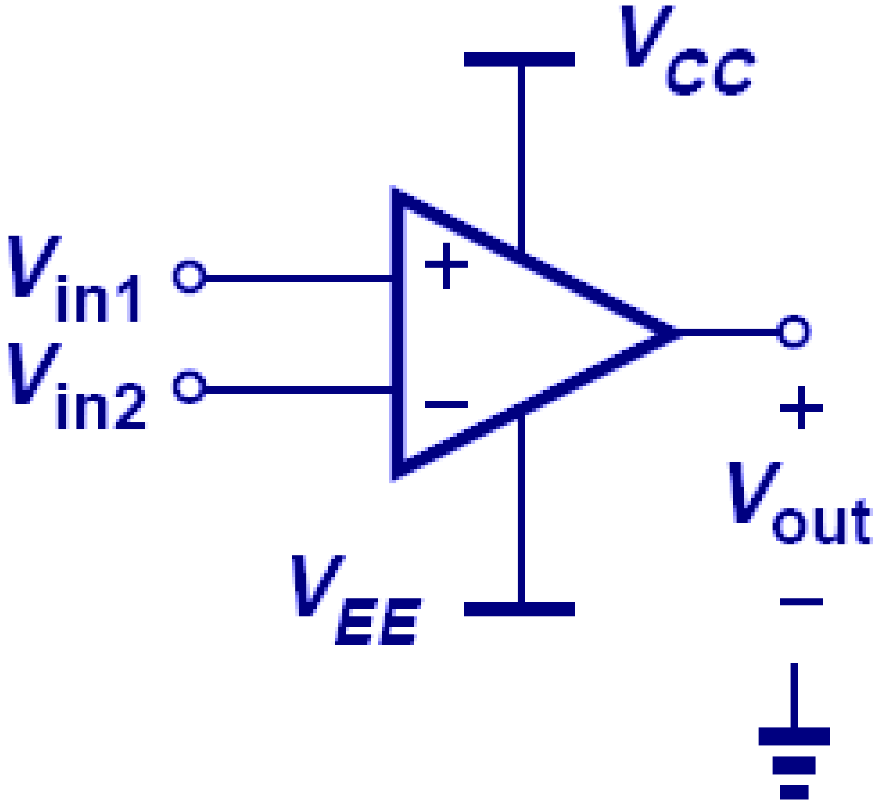


$$V_{out} = A_0(V_{in1} - V_{in2})$$
$$= A_0(V_{in} - V_{out}).$$

$$V_{out} = A_0(V_{in} - V_{out})$$
$$\frac{V_{out}}{V_{in}} = \frac{A_0}{1 + A_0}$$

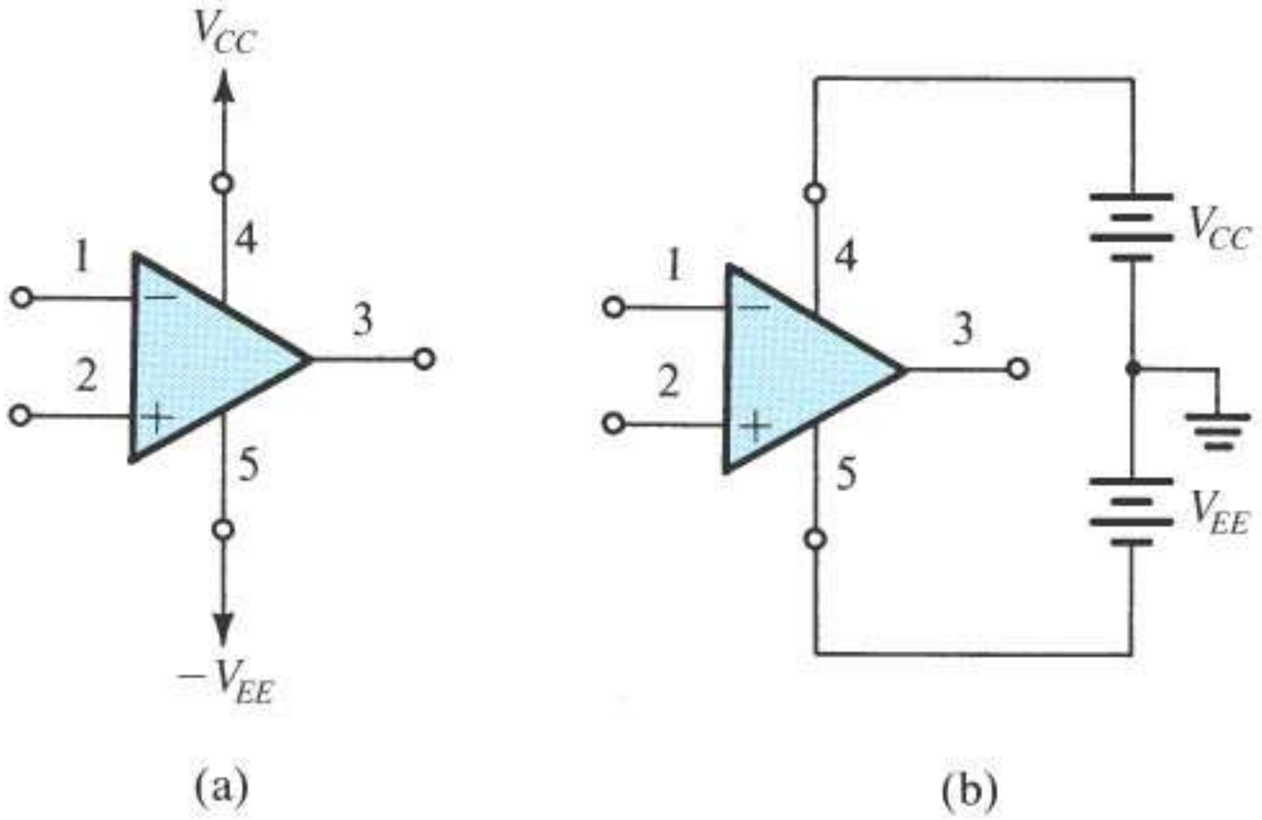
$A_0 = 1000,$ $V_{in} = 1$ V, and $V_{out} = 0.999$ V.

Op Amp with Supply Rails



- To explicitly show the supply voltages, V_{CC} and V_{EE} are shown.
- In some cases, V_{EE} is zero.

Op Amp with Supply Rail



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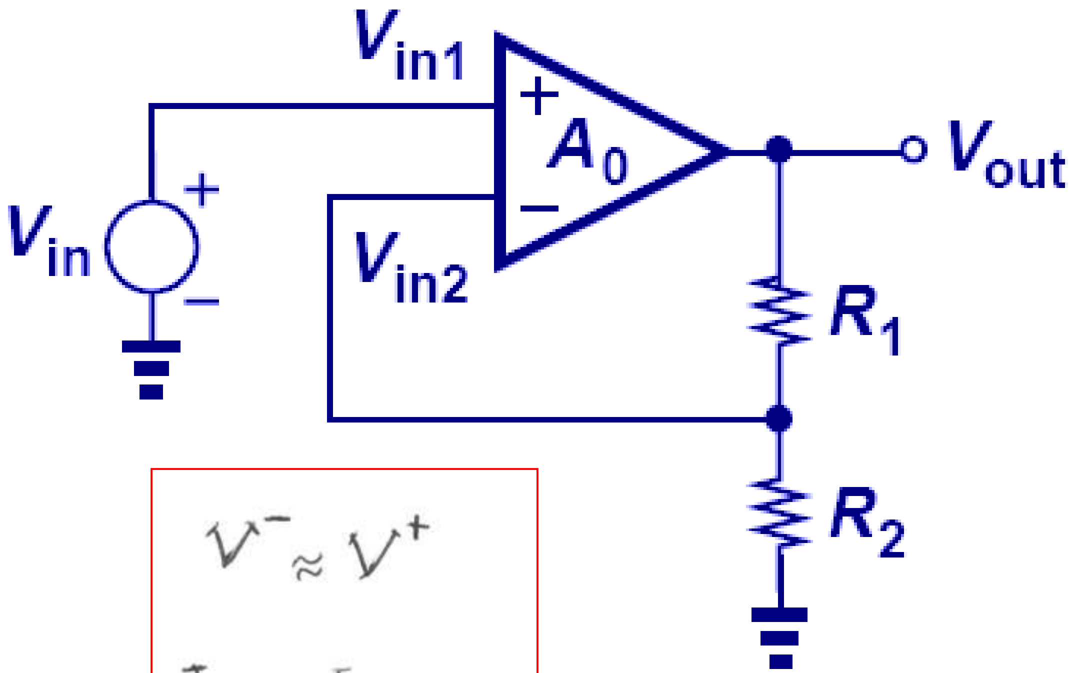
Noninverting Amplifier (Infinite A_0)



$$V_{in2} = \frac{R_2}{R_1 + R_2} V_{out}$$

$$V_{in1} \approx V_{in2}$$

$$V^- \approx V^+$$

$$I_{in_1} = I_{in_2} \approx 0$$

$$\frac{V_{out}}{V_{in}} = 1 + \frac{R_1}{R_2}$$

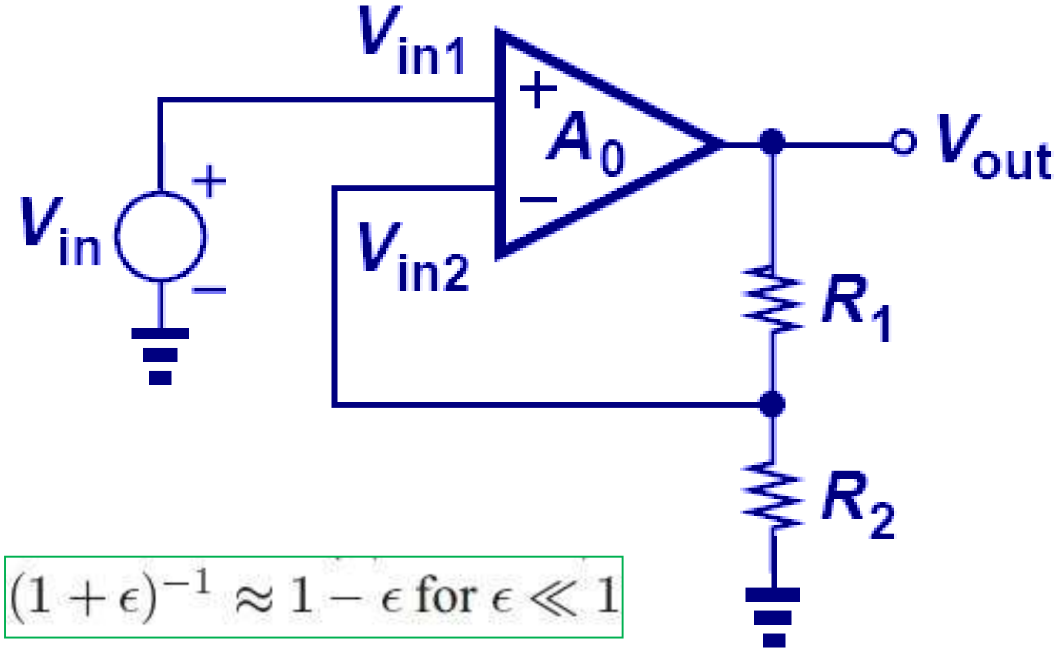
- **A noninverting amplifier returns a fraction of output signal thru a resistor divider to the negative input.**
- **With a high A_o, V_{out}/V_{in} depends only on ratio of resistors, which is very precise.**

Noninverting Amplifier (Finite A_0)

$$(V_{in1} - V_{in2})A_0 = V_{out}$$

$$\frac{V_{out}}{V_{in}} = \frac{A_0}{1 + \frac{R_2}{R_1 + R_2} A_0}.$$

$$A_0 R_2/(R_1 + R_2) \gg 1$$

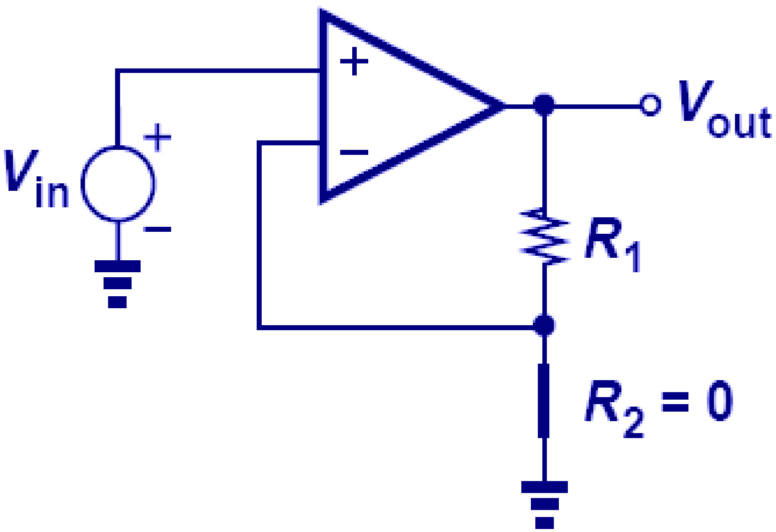


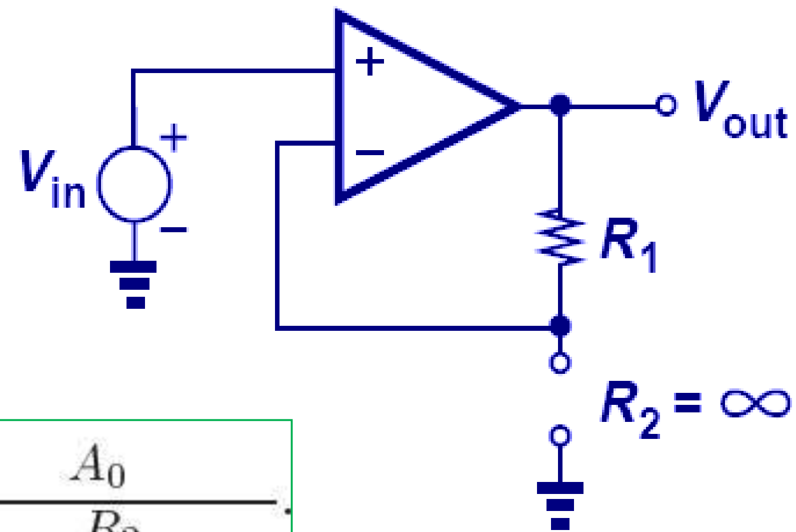
$$(1+\epsilon)^{-1} \approx 1 - \epsilon \text{ for } \epsilon \ll 1$$

$$\frac{V_{out}}{V_{in}} \approx \left(1+\frac{R_1}{R_2}\right)\left[1-\left(1+\frac{R_1}{R_2}\right)\frac{1}{A_0}\right]$$

- **The error term indicates the larger the closed-loop gain, the less accurate the circuit becomes.**

Example 8.2: Extreme Cases of R_2 (Infinite A_0)

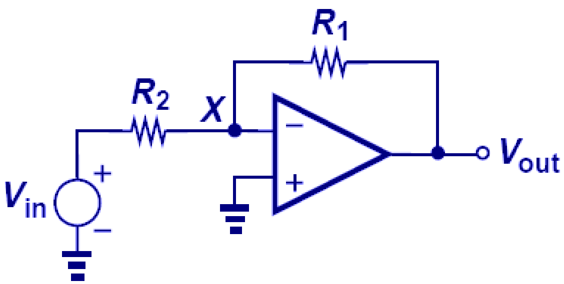




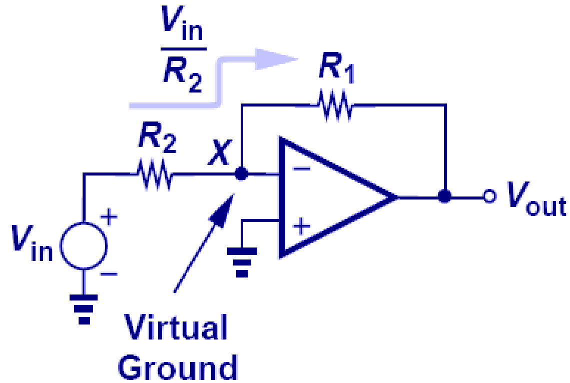
$$\frac{V_{out}}{V_{in}} = \frac{A_0}{1 + \frac{R_2}{R_1 + R_2} A_0}.$$

- **If R_2 is zero, the loop is open and V_{out}/V_{in} is equal to the intrinsic gain of the op amp.**
- **If R_2 is infinite, the circuit becomes a unity-gain amplifier and V_{out}/V_{in} becomes equal to one.**

Inverting Amplifier



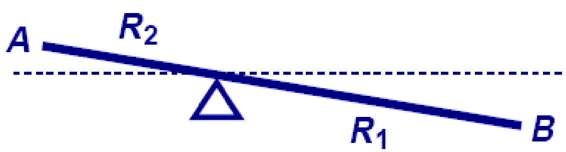
(a)



(b)

$V^- \approx V^+$

$I_{in_1} = I_{in_2} \approx 0$



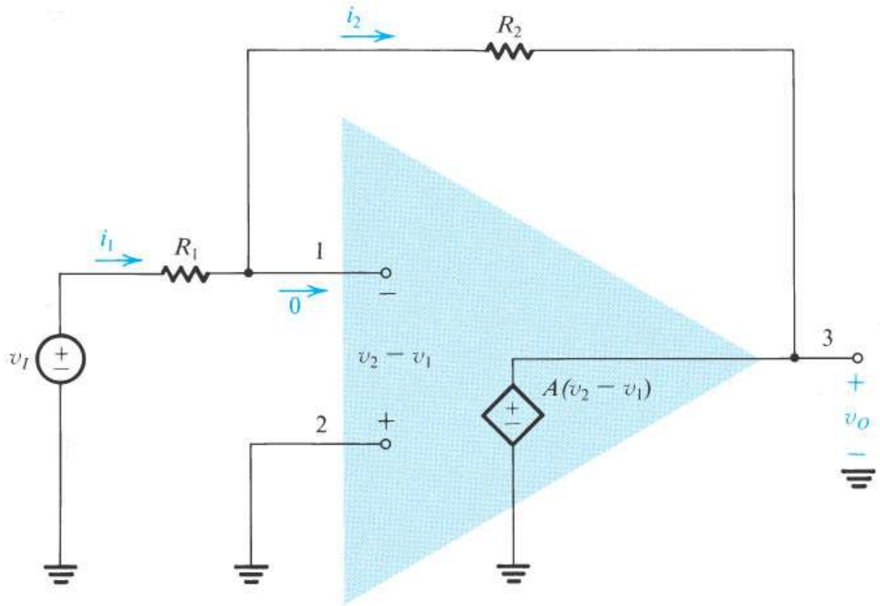
(c)

$$\frac{0 - V_{out}}{R_1} = \frac{V_{in}}{R_2}$$

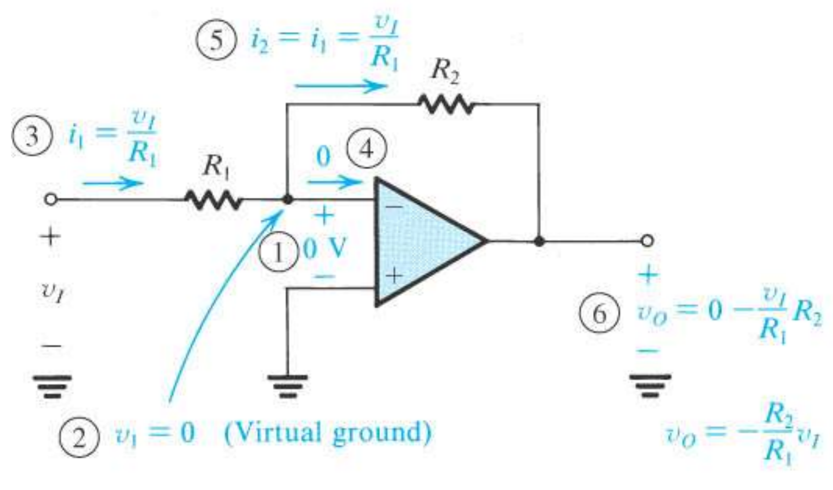
$$\frac{V_{out}}{V_{in}} = \frac{-R_1}{R_2}$$

- **Infinite A_0 forces the negative input to be a virtual ground.**

Inverting Amplifier



(a)

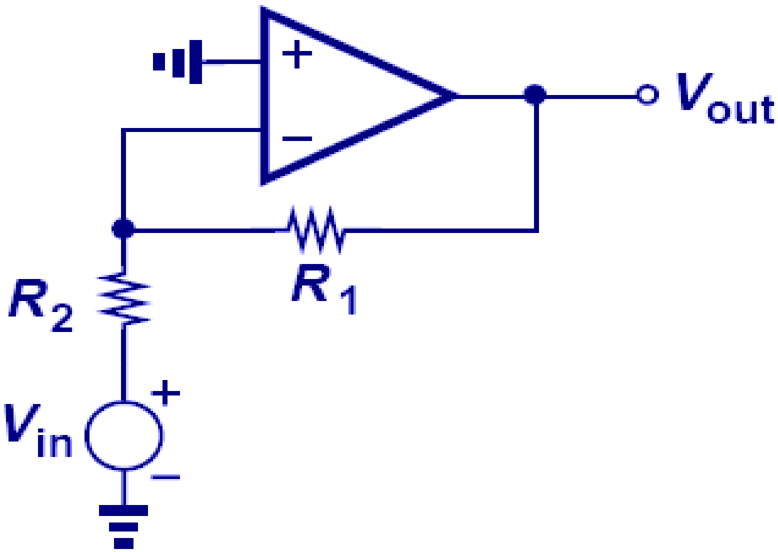


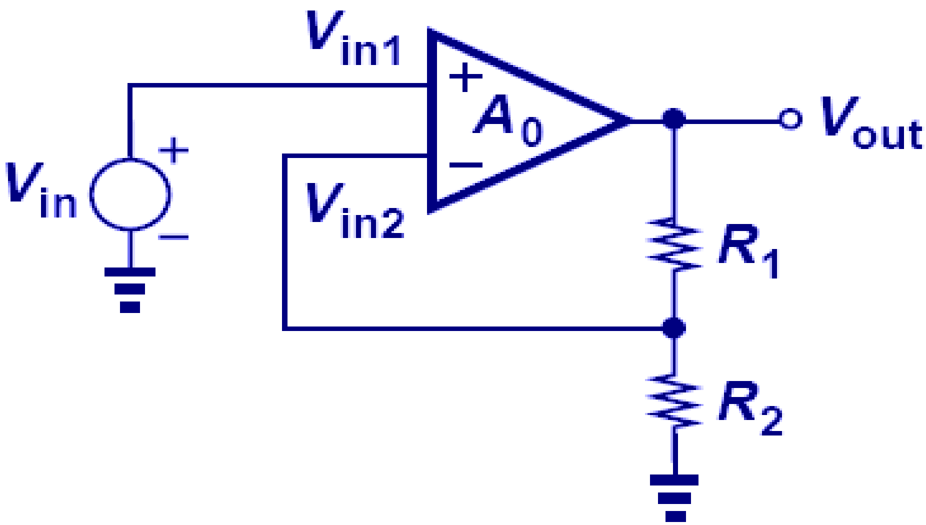
(b)

$V^- \approx V^+$

$I_{in_1} = I_{in_2} \approx 0$

Another View of Inverting Amplifier





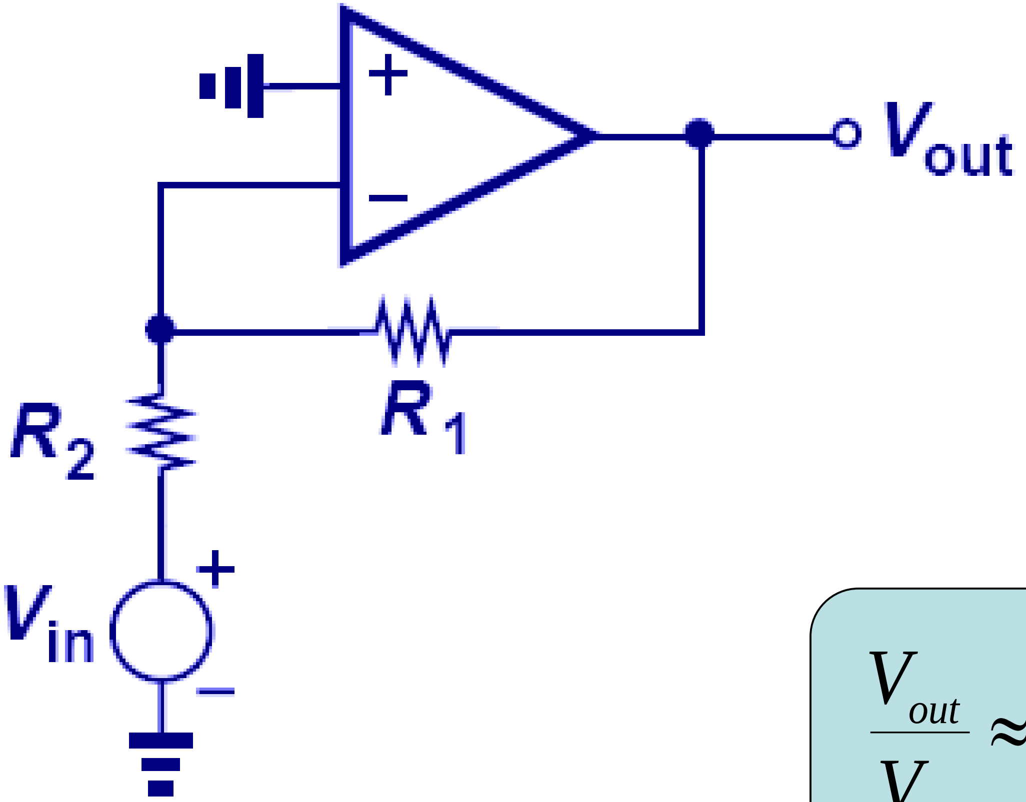
$$\frac{V_{out}}{V_{in}} = \frac{-R_1}{R_2}$$

$$\frac{V_{out}}{V_{in}} = 1 + \frac{R_1}{R_2}$$

Inverting

Noninverting

Gain Error Due to Finite A_0



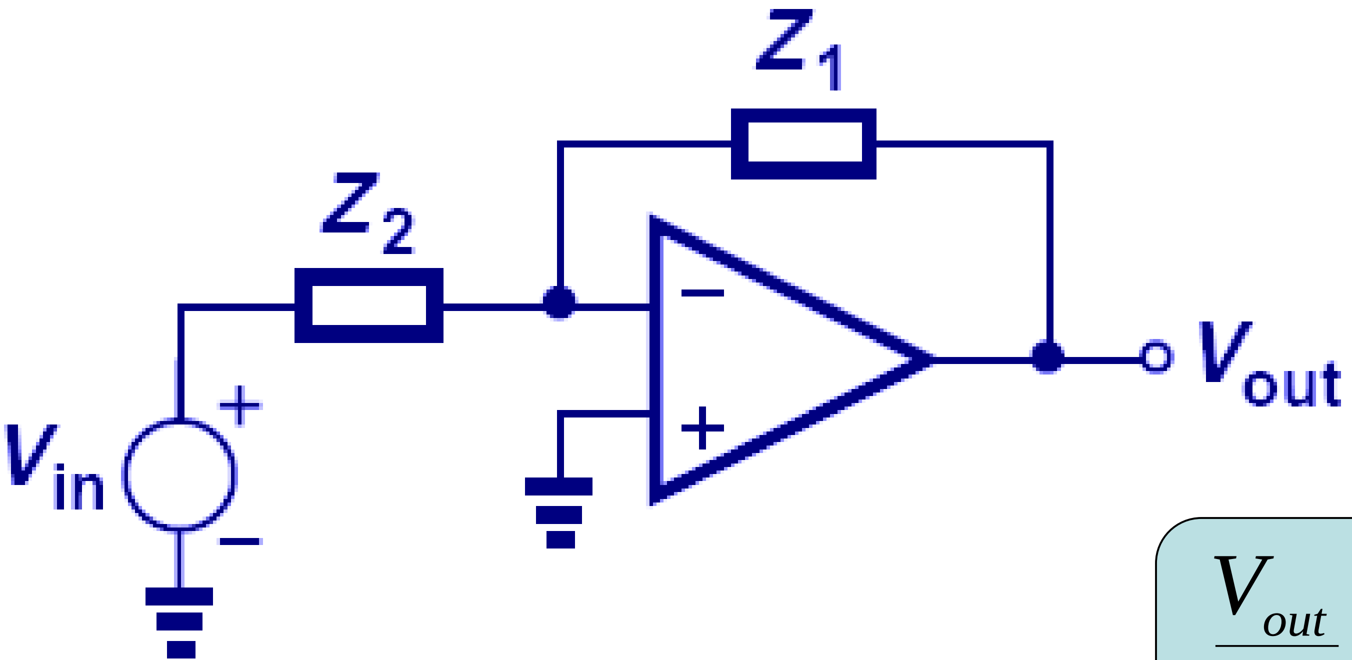
$$V_{out} = A_0(V_{in1} - V_{in2}) = -A_0 V_X.$$

$$\frac{V_{out}}{V_{in}} = -\frac{1}{\frac{1}{A_0} + \frac{R_2}{R_1}\left(\frac{1}{A_0} + 1\right)} = -\frac{1}{\frac{R_2}{R_1} + \frac{1}{A_0}\left(1 + \frac{R_2}{R_1}\right)}.$$

$$\frac{V_{out}}{V_{in}} \approx -\frac{R_1}{R_2}\left[1 - \frac{1}{A_0}\left(1 + \frac{R_1}{R_2}\right)\right]$$

- **The larger the closed loop gain, the more inaccurate the circuit is.**

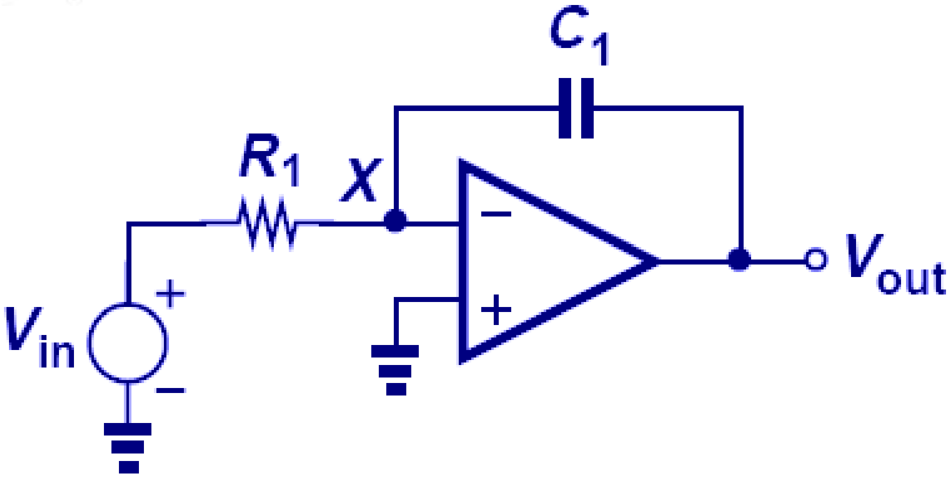
Complex Impedances Around the Op Amp

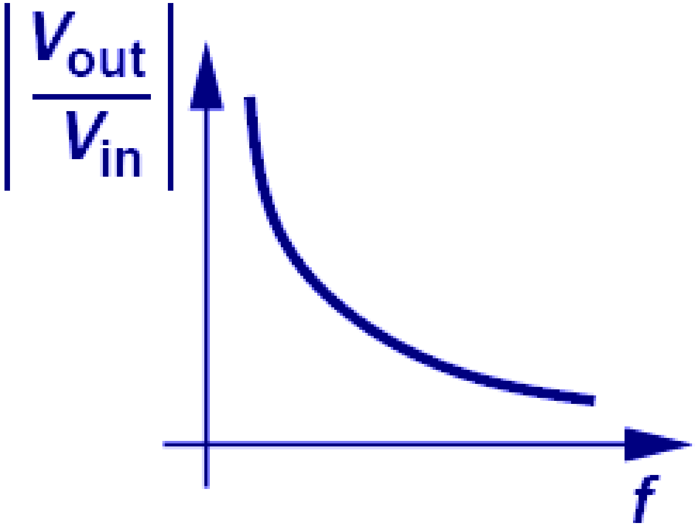


$$\frac{V_{out}}{V_{in}} \approx -\frac{Z_1}{Z_2}$$

- **The closed-loop gain is still equal to the ratio of two impedances.**

Integrator





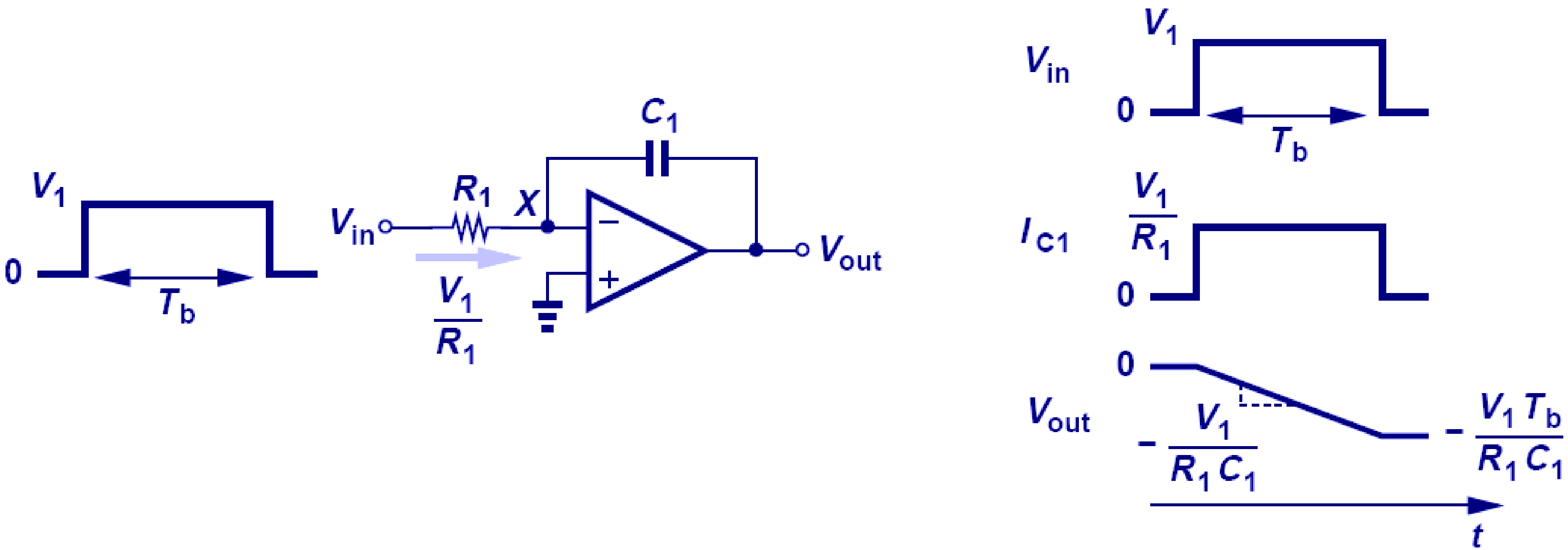
$$\frac{V_{out}}{V_{in}} = -\frac{\frac{1}{C_1 s}}{R_1}$$

$$\frac{V_{in}}{R_1} = -C_1 \frac{dV_{out}}{dt}$$

$$\frac{V_{out}}{V_{in}} = -\frac{1}{R_1 C_1 s}$$

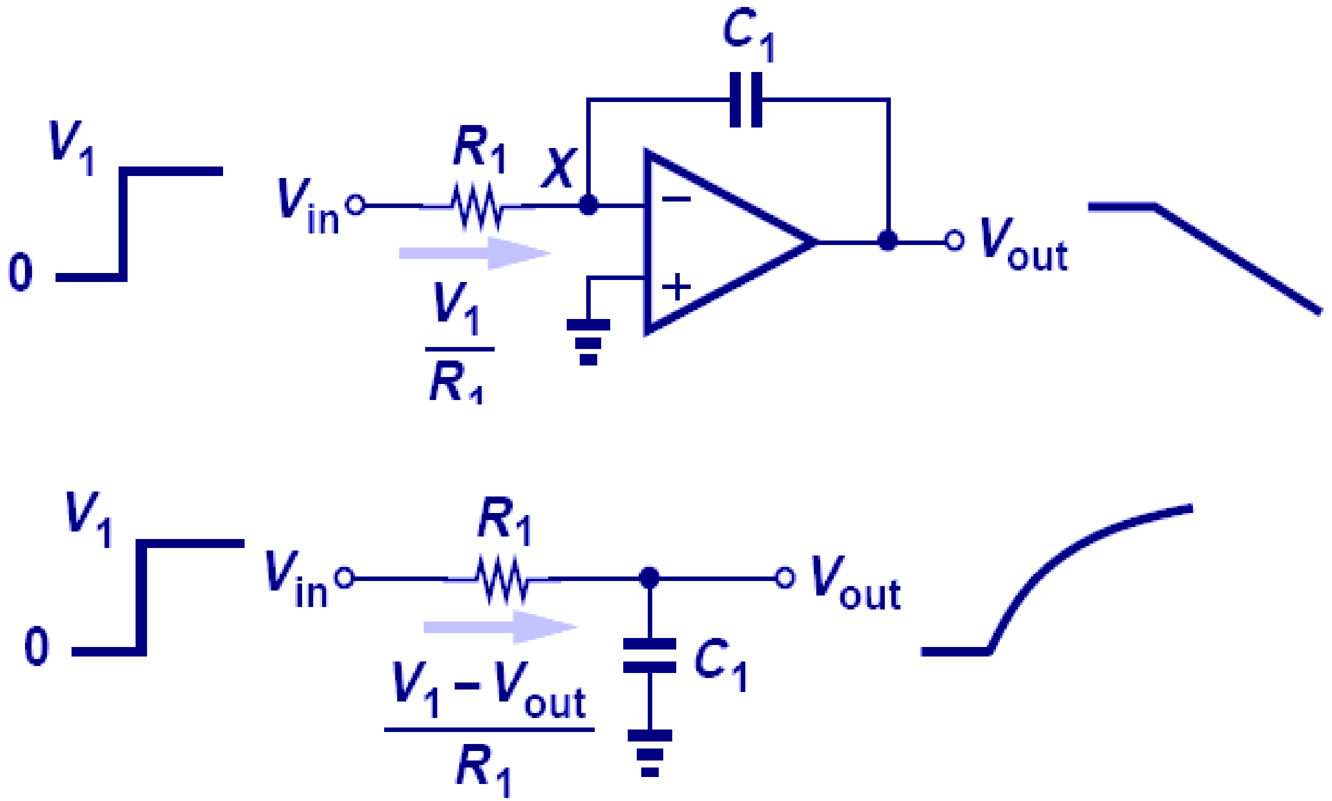
$$V_{out} = -\frac{1}{R_1 C_1}\int V_{in}\, dt$$

Example 8.5: Integrator with Pulse Input



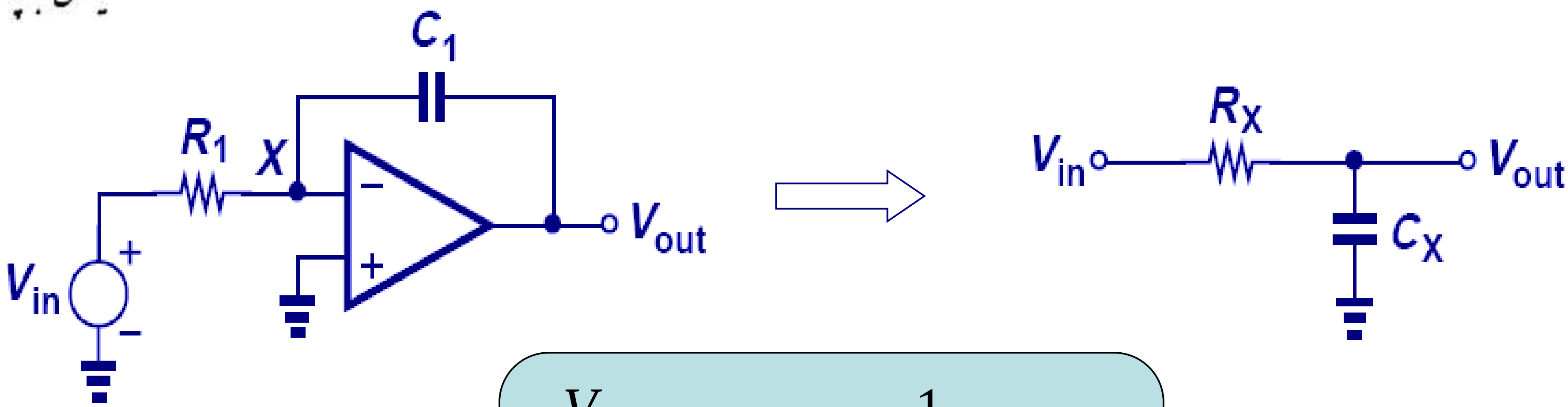
$$V_{out} = -\frac{1}{R_1C_1}\int V_{in}dt = -\frac{V_1}{R_1C_1}t \qquad 0 < t < T_b$$

Comparison of Integrator and RC Lowpass Filter



- The RC low-pass filter is actually a “passive” approximation to an integrator.
- With the RC time constant large enough, the RC filter output approaches a ramp.

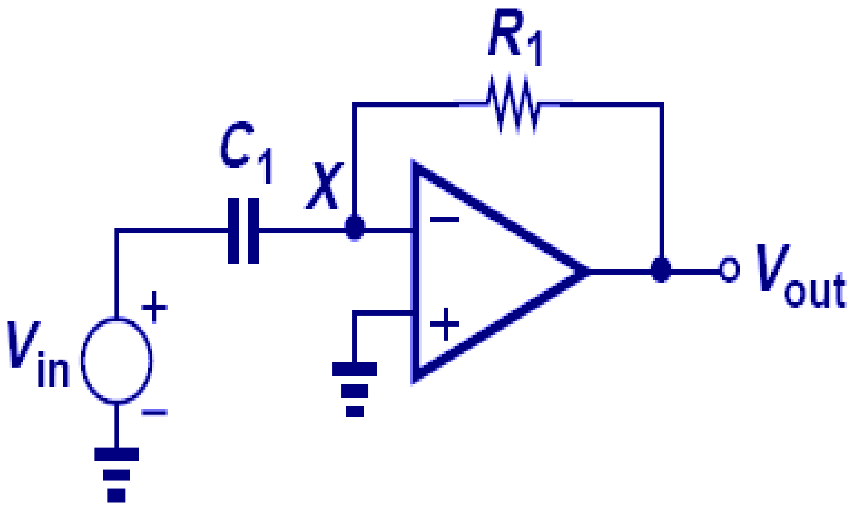
Lossy Integrator

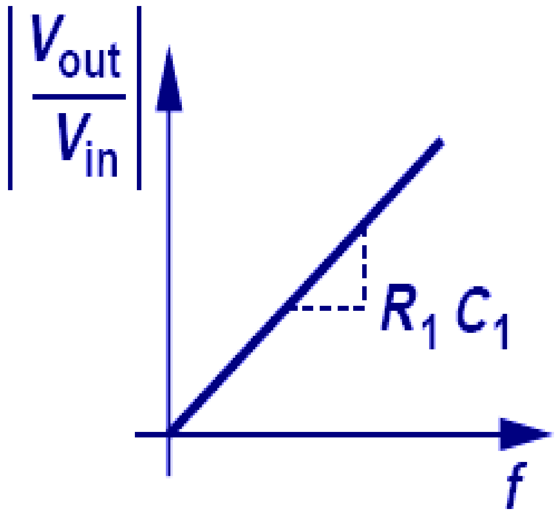


$$\frac{V_{out}}{V_{in}} = \frac{-1}{\frac{1}{A_0} + \left(1 + \frac{1}{A_0}\right) R_1 C_1 s}$$

- **When finite op amp gain is considered, the integrator becomes lossy as the pole moves from the origin to -1/[(1+A_0)$R_1$$C_1$].**
- **It can be approximated as an RC circuit with C boosted by a factor of A_0+1.**

Differentiator

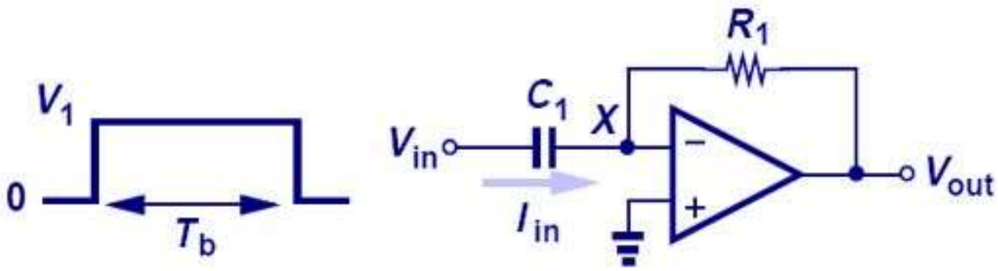


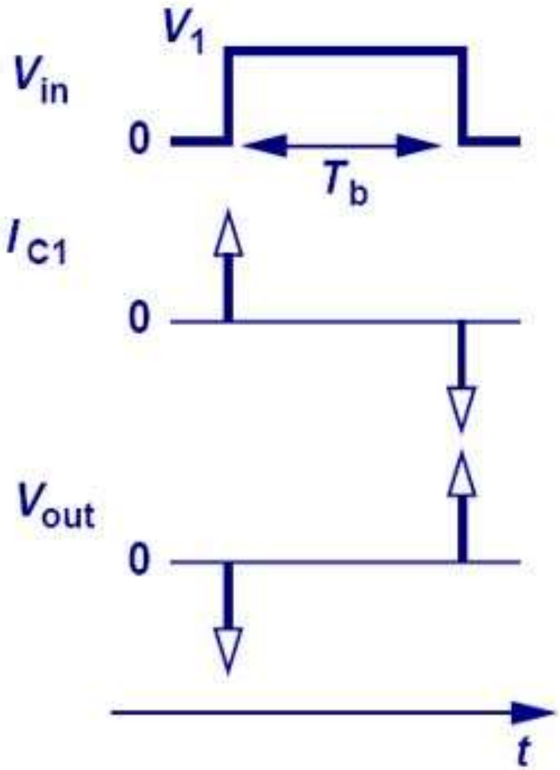


$$V_{out} = -R_1 C_1 \frac{dV_{in}}{dt}$$

$$\frac{V_{out}}{V_{in}} = -\frac{R_1}{\frac{1}{C_1 s}} = -R_1 C_1 s$$

Exaple 8.7: Differentiator with Pulse Input





$$I_{in} = C_1 \frac{dV_{in}}{dt} = C_1 V_1 \delta(t).$$

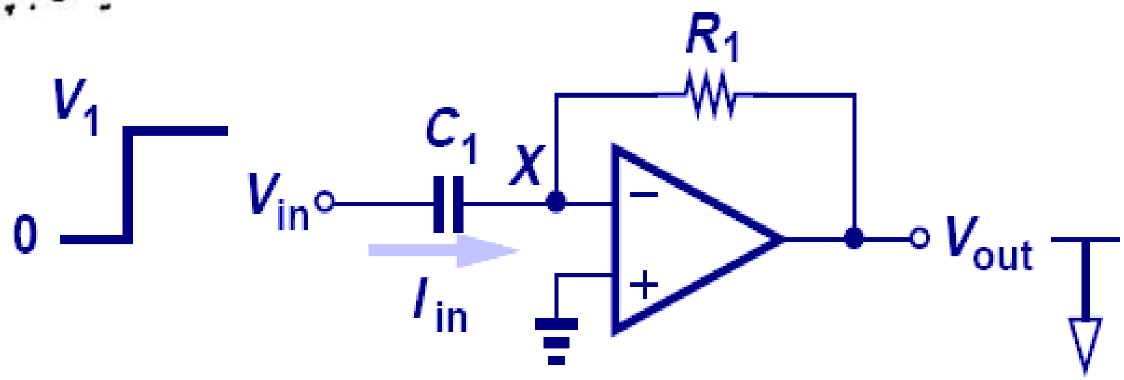
$$V_{out} = -I_{in} R_1 = -R_1 C_1 V_1 \delta(t).$$

$$I_{in} = C_1 \frac{dV_{in}}{dt} = C_1 V_1 \delta(t).$$

$$V_{out} = -I_{in} R_1 = R_1 C_1 V_1 \delta(t).$$

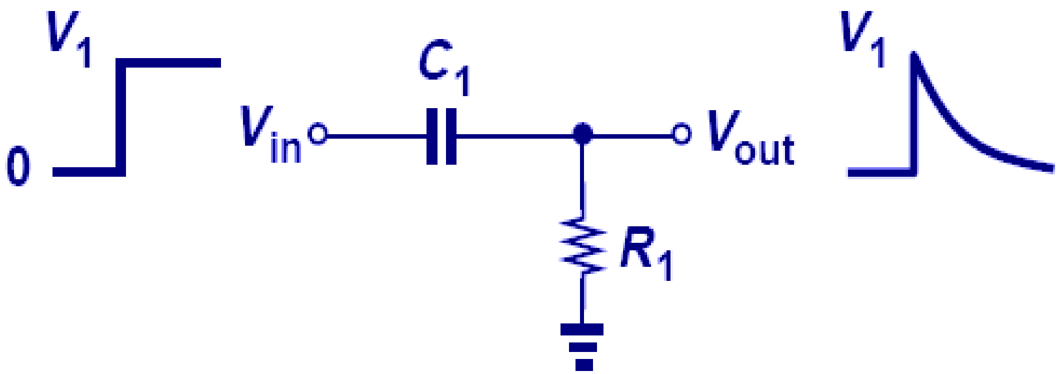
$$V_{out} = \mp R_1 C_1 V_1 \delta(t)$$

Comparison of Differentiator and High-Pass Filter



$$\frac{V_{in} - V_X}{\frac{1}{C_1 s}} = \frac{V_X - V_{out}}{R_1}.$$

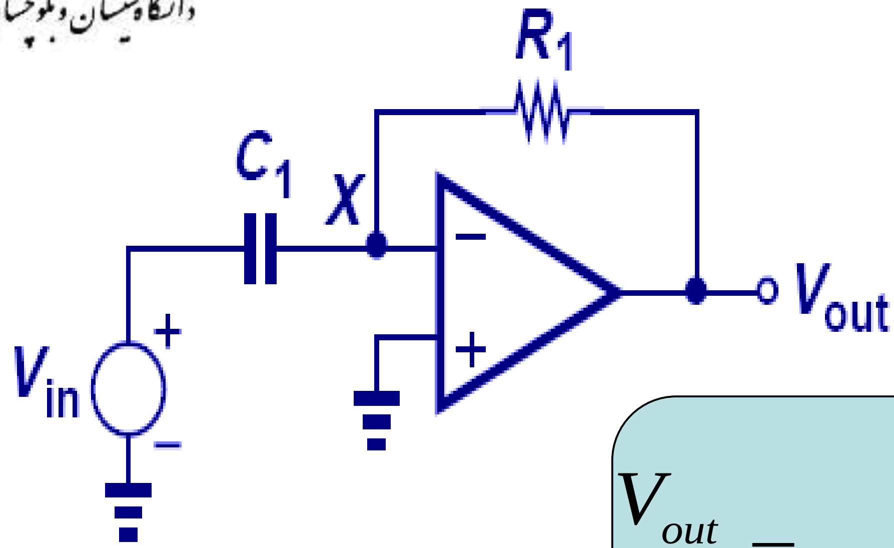
$$\frac{V_{out}}{V_{in}} = \frac{-R_1 C_1 s}{1 + \frac{1}{A_0} + \frac{R_1 C_1 s}{A_0}}.$$

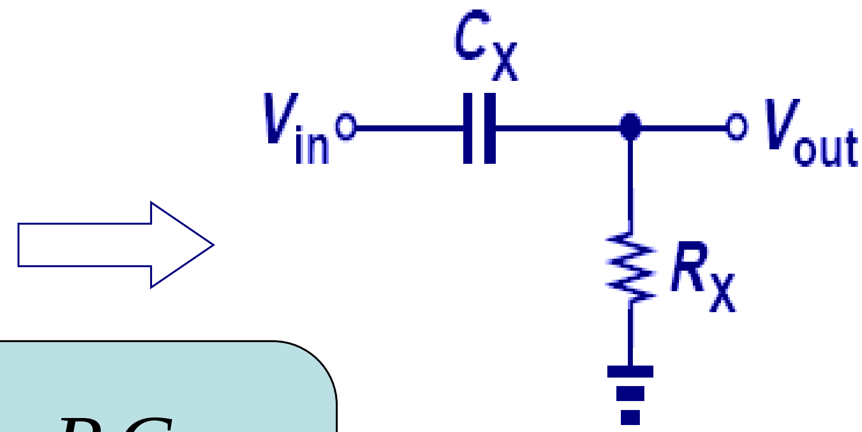


$$s_p = -\frac{A_0 + 1}{R_1 C_1}.$$

- **The RC high-pass filter is actually a passive approximation to the differentiator.**
- **When the RC time constant is small enough, the RC filter approximates a differentiator.**

Lossy Differentiator

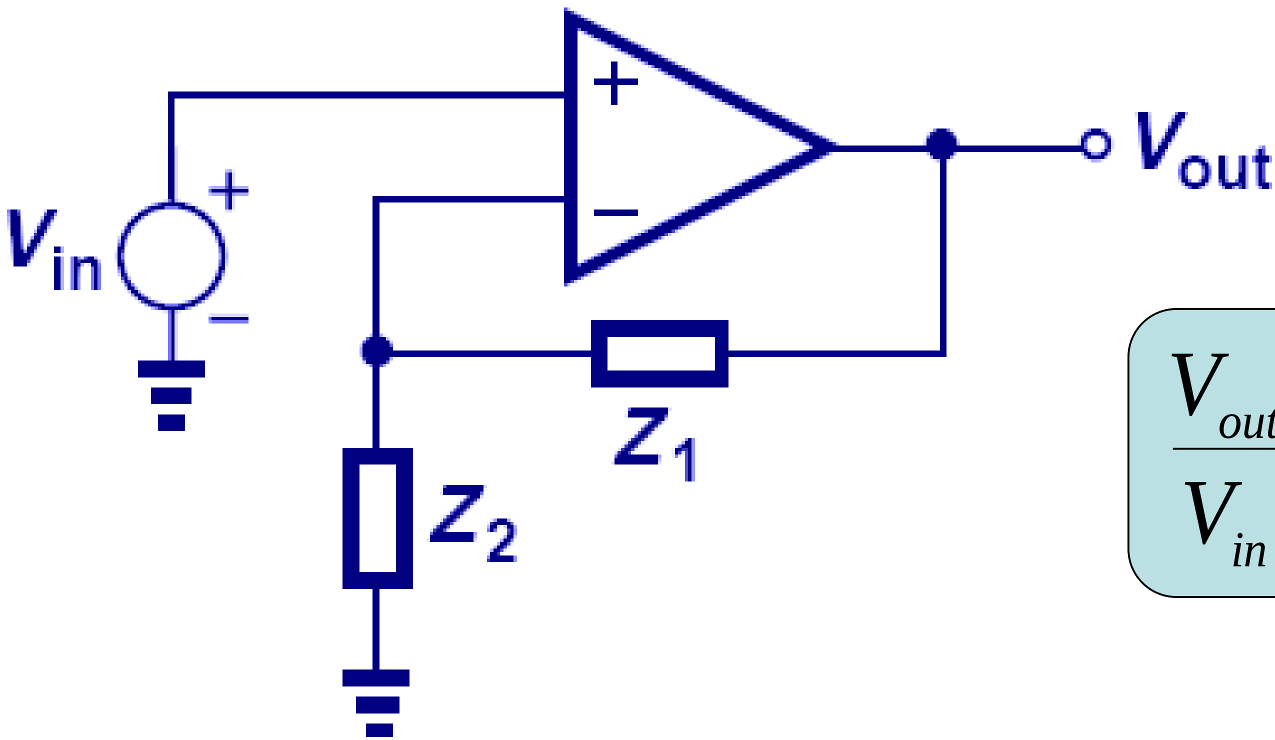




$$\frac{V_{out}}{V_{in}} = \frac{-R_1C_1s}{1+\dfrac{1}{A_0}+\dfrac{R_1C_1s}{A_0}}$$

- **When finite op amp gain is considered, the differentiator becomes lossy as the zero moves from the origin to –(A_0+1)/R_1C_1.**
- **It can be approximated as an RC circuit with R reduced by a factor of (A_0+1).**

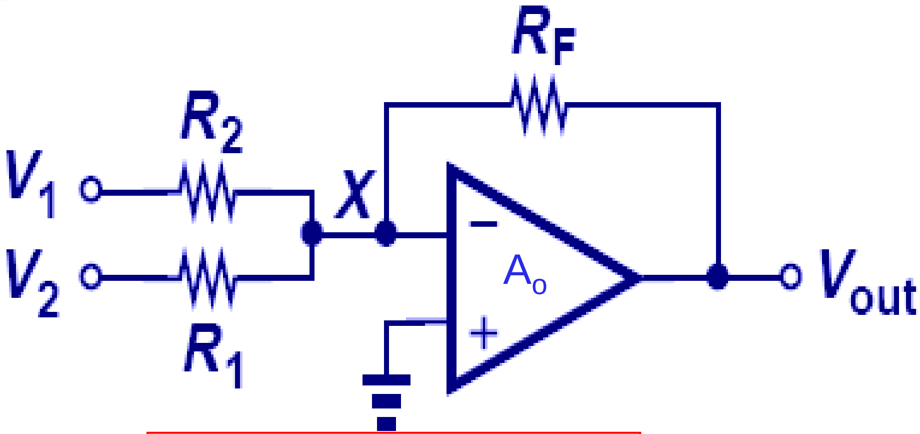
Op Amp with General Impedances



$$\frac{V_{out}}{V_{in}} = 1 + \frac{Z_1}{Z_2}$$

- **This circuit cannot operate as ideal integrator or differentiator.**

Voltage Adder



$$V^- \approx V^+$$

$$I_{in_1} = I_{in_2} \approx 0$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} = \frac{-V_{out}}{R_F}.$$

$$V_{out} = -R_F\left(\frac{V_1}{R_1} + \frac{V_2}{R_2}\right)$$

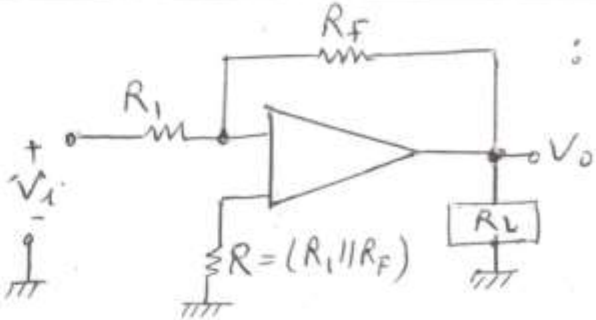
$$V_{out} = \frac{-R_F}{R}(V_1 + V_2)$$

If $R_1 = R_2 = R$

- If A_o is infinite, X is pinned at ground, currents proportional to V_1 and V_2 will flow to X and then across R_F to produce an output proportional to the sum of two voltages.

فصل ۱ بخش اول - کاربردهای «تقویت کننده عملیاتی» - وارونگر - غیر وارونگر

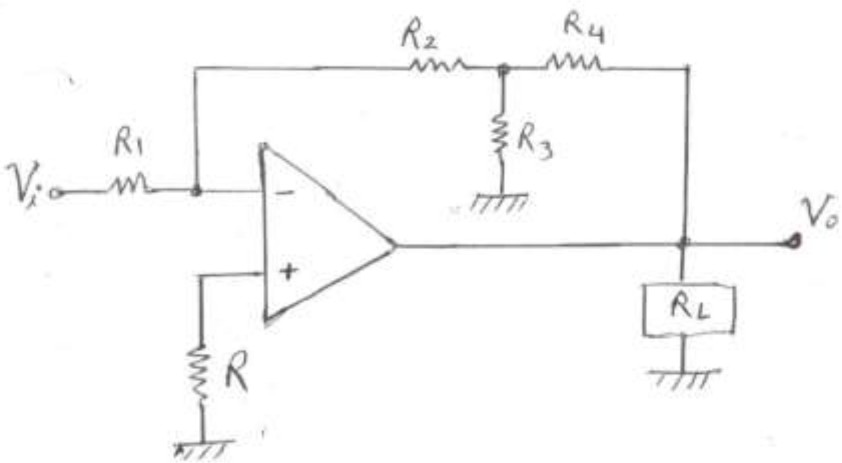
۱ - تقویت کننده وارونگر (inverting Ampl.) :



$$V_o = \frac{-R_f}{R_1} V_i \Rightarrow \frac{V_o}{V_i} = -\frac{R_f}{R_i}$$

$$R_i = \frac{V_i}{I_i} = R_1$$

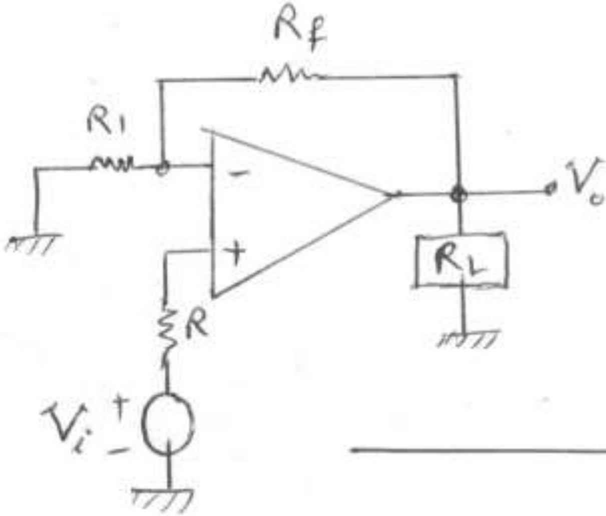
- برای افزایش بهره بدون استفاده از مقاومتهای بزرگ (استفاده از شبکه T می باشد) :



$$\frac{V_o}{V_i} = \frac{-R_2}{R_1}\left(1 + \frac{R_4}{R_2} + \frac{R_4}{R_3}\right)$$

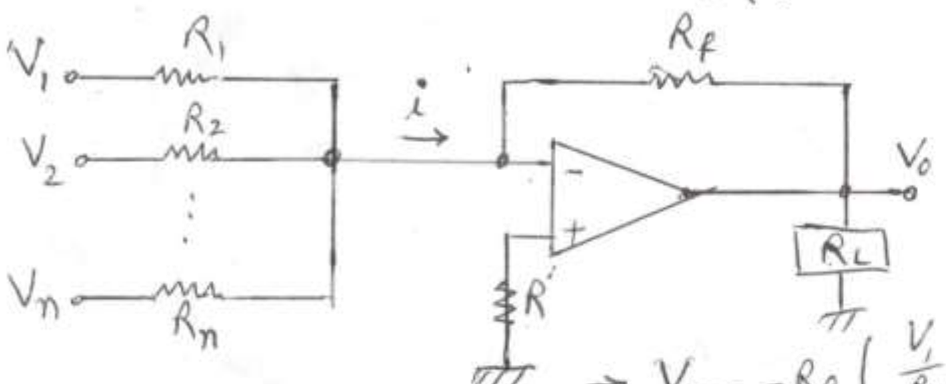
برای حصول بهترین نتیجه، لازم است از مقاومت هایی با تولرانس ۱٪ مورد استفاده قرار می گیرد.

۲ - تقویت کننده غیر وارونگر (Non inverting) :



$$\frac{V_o}{V_i} = \left(1 + \frac{R_f}{R_1}\right)$$

۳ - مدار جمع کننده وارونگر (مخلوط کننده صوتی) :



$$\begin{cases} i = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \cdots + \frac{V_n}{R_n} \\ V_o = -i R_f \end{cases}$$

$$\Rightarrow V_o = -R_f \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \cdots + \frac{V_n}{R_n} \right)$$

اگر: $R_1 = R_2 = \cdots = R_n = R \Rightarrow V_o = \frac{-R_f}{R} (V_1 + V_2 + \cdots + V_n)$

۲) بخش اول - کاربردهای تقویت کننده عملیاتی " - جمع کننده - تا جزء - متوسط گیر

۴ - تقویت کننده متوسط گیر وارونگر :

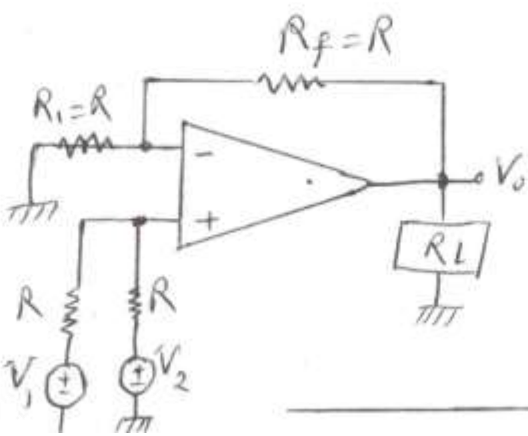
در مدار جمع کننده وارونگر : اگر

$$R_f = \frac{R}{n}$$

(n → تعداد ورودی ها)

$$\Rightarrow V_o = -\left(\frac{V_1 + V_2 + \cdots + V_n}{n}\right)$$

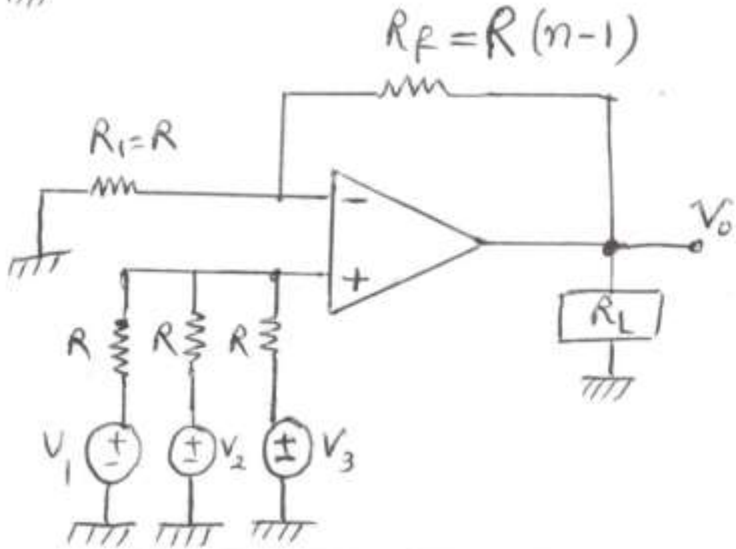
۵ - مدار جمع کننده ناوارونگر (با دو ورودی)



$$\begin{cases} V^+ = \dfrac{V_1 + V_2}{2} \\ V^- = V^+ \end{cases} \Rightarrow V_o = \left(1 + \frac{R}{R}\right) V^+$$

$$\Rightarrow V_o = 2\left(\frac{V_1 + V_2}{2}\right) = V_1 + V_2$$

۶- مدار جمع کننده ناوارونگر با n ورودی :

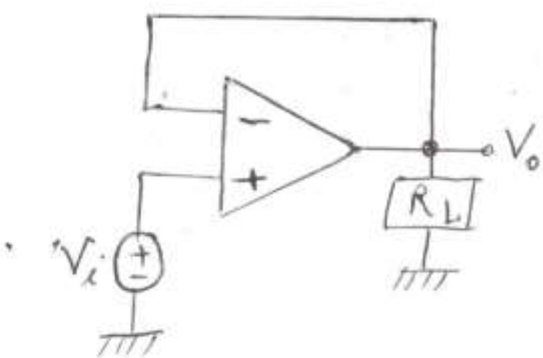


$$V_o = V_1 + V_2 + V_3$$

توجه : $V^+ \cong \frac{1}{3}(V_1 + V_2 + V_3)$

۷- دنبال کننده ولتاژ (Voltage follower)

- " " منبع (Source ")
- تقویت کننده با بهره واحد (Unity gain Amp.)
- " " میانگیر (بافر)
- " جداساز (Isolation Amp.)

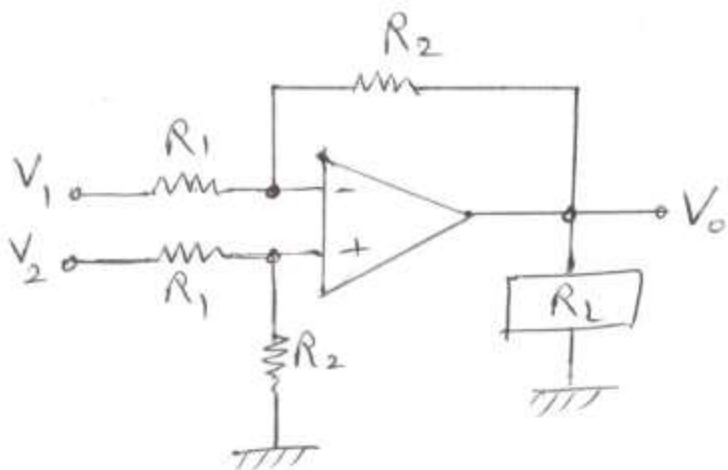


$$\boxed{V_o = V_i}$$

$$\left\{ \begin{array}{l} R_i \uparrow \, , \; Gain = 1 \\ R_o \downarrow \end{array} \right\}$$

۳) بخش اول: کاربردهای تقویت کننده عملیاتی - تفاضلی و ابزار دقیق

۸ - تقویت کننده تفریق کننده (تفاضلی) :

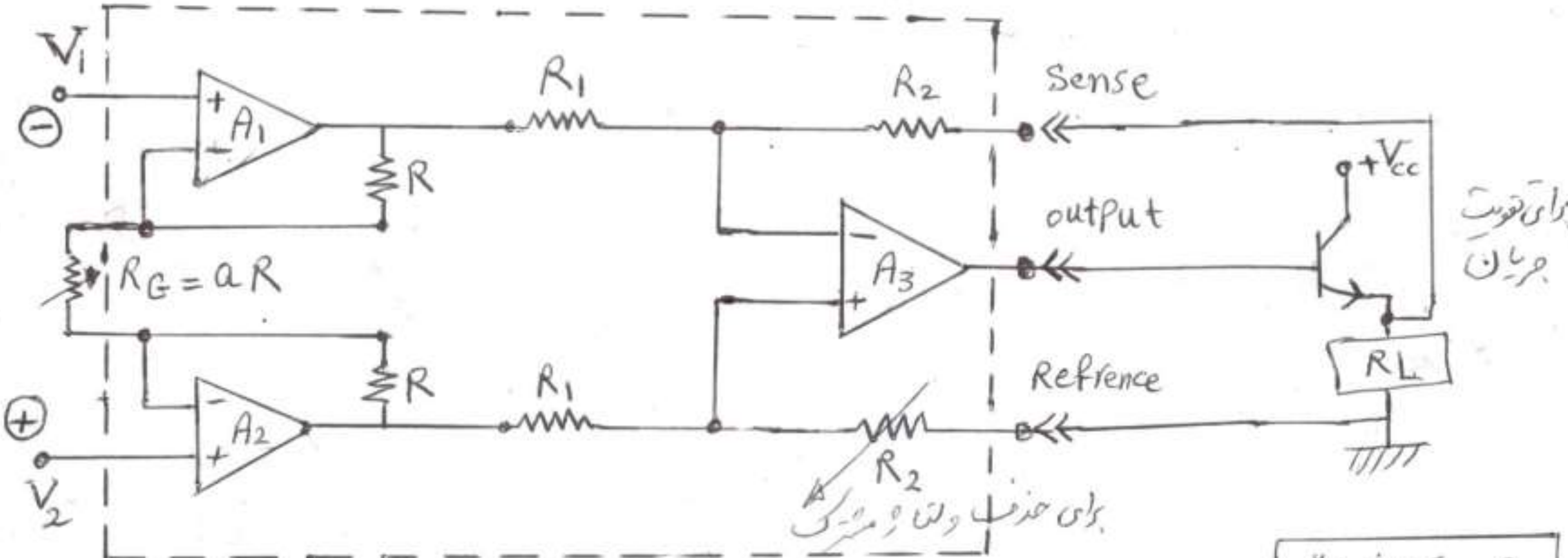


$$V_o = \left(\frac{R_2}{R_1}\right)(V_2 - V_1)$$

اثبات : (بهترین و کوتاه ترین راه، استفاده از جمع آثار می باشد)

۹ـ تقویت کنندهٔ ابزار دقیق (تفاضلی با فر ورودی) (Instrumentation Amp.)

(AD524, AD624)



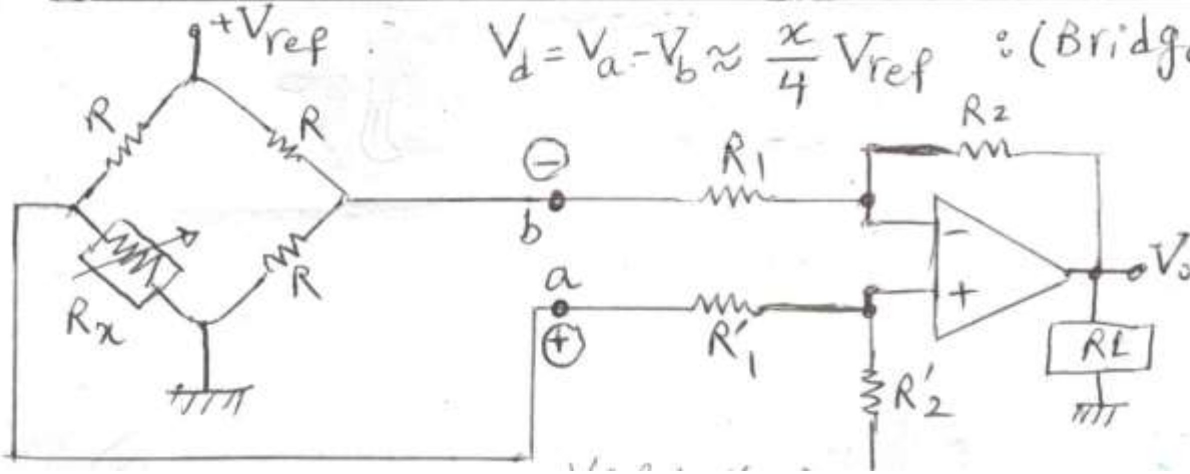
Rx می‌تواند نمایندهٔ سنسور و یا ترانسدیوسری باشد که در یک پل قرار گرفته است.

$$V_o = \left(1+\frac{2R}{R_G}\right)\left(\frac{R_2}{R_1}\right)(V_2-V_1) = \left(1+\frac{2}{a}\right)V_d$$

((اگر: $R_2 = R_1$ ، $R_G = aR$ ، $V_d = V_2 - V_1$))

۱۰ - استفاده از پل (Bridge):

$$V_d = V_a - V_b \approx \frac{x}{4} V_{ref}$$



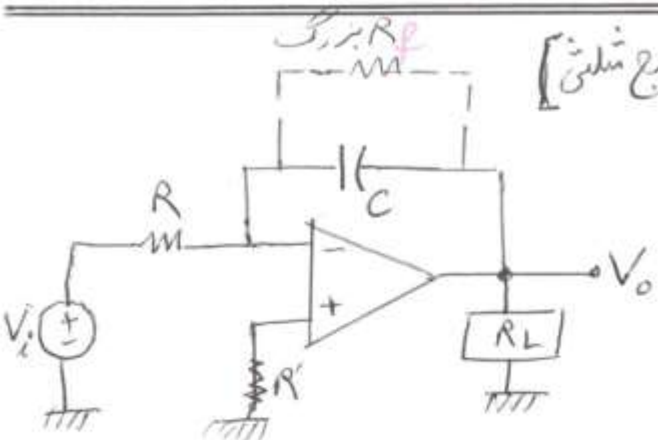
$$R_x = R \pm \Delta R = R\left(1 \pm \frac{\Delta R}{R}\right) = R(1+x)$$

$$\begin{cases} V_b = \dfrac{V_{ref}}{2} \\ V_a = \dfrac{1+x}{1+\frac{x}{2}} \cdot \dfrac{V_{ref}}{2} \end{cases}$$

بخش اول - کاربردهای تقویت کننده عملیاتی - انتگرال گیر و مشتق گیر

۱۱- مدار انتگرال گیر (وارونگر یا میلر) : [تبدیل موج مربعی به موج مثلثی]

(فیلتر پایین گذر با فرکانس قطع صفر)



$$\frac{V_o}{V_i} = \frac{-1}{SCR} = \frac{-1}{j\omega CR}$$

* برای انتگرال گیری مناسب، RC باید خیلی بزرگتر از دوره تناوب سیگنال ورودی باشد.

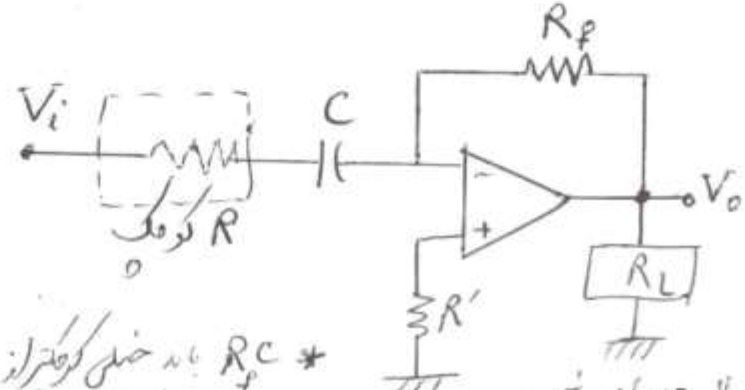
یا: $V_o(t) = V_c - \frac{1}{RC}\int_0^t v_i(t)\,dt$

چون در فرکانس صفر (dc) ← خازن مدار باز عمل می کند، لذا بهرهٔ حلقه بسته بی نهایت خواهد شد.

برای اصلاح مدار انتگرال گیر: ← با موازی کردن مقاومت بزرگ با خازن انتگرال گیر این کار را می توان انجام داد.

(متاسفانه این کار، انتگرال گیر را غیر ایده آل می کند).

۱۲ - مدار مشتق گیر (فیلتر بالاگذر با فرکانس قطع نامحدود)



$$\frac{V_o}{V_i} = -SCR_f = -j\omega CR_f$$

یا: $V_o(t) = -R_f C \frac{dV_i}{dt}$

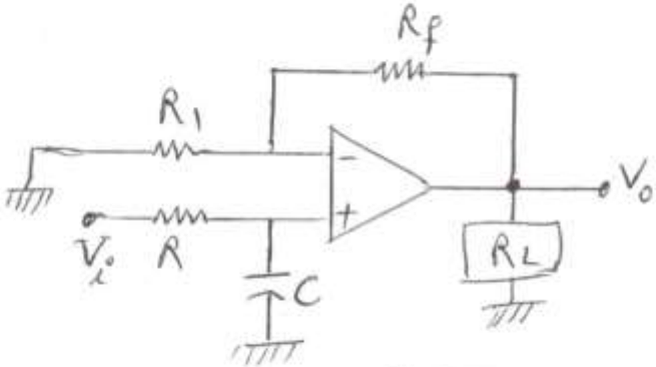
* R_fC باید خیلی کوچکتر از دوره تناوب سیگنال ورودی باشد .

خصوصیات ذاتی مدار مشتق گیر "بزرگ کننده نویز" می باشد .

* هر زمان که تغییر ناگهانی در $V_i(t)$ بوجود آید ، در خروجی جهشی ایجاد می شود.

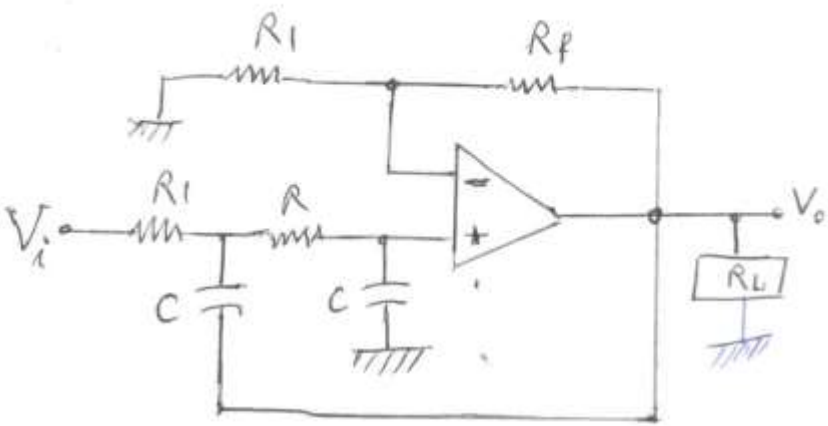
* در عمل از مدارهای مشتق گیر اجتناب می شود ، و اگر استفاده شود ، معمولاً لازم است مطابق شکل ، مقاومت کوچکی با خازن سری شود .

۱۳ - فیلتر پایین گذر درجه یک :



$$A_V(S) = \frac{V_o}{V_i} = \frac{R_1 + R_f}{R_1} \cdot \frac{1}{1 + SCR}$$

۱۴ - فیلتر پایین گذر درجه دوم :



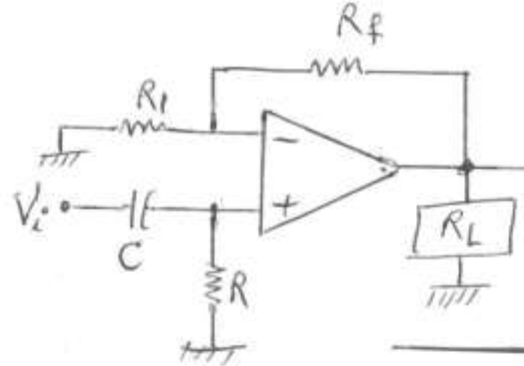
$$A_{V_o} \triangleq 1 + \frac{R_f}{R_1}$$

$$A_V(s) = \frac{V_o}{V_i} = \frac{A_{V_o}}{(SCR)^2 + (3 - A_{V_o})SCR + 1}$$

۱۵ - فیلتر پایین‌گذر درجه زوج: اگر دو فیلتر پایین‌گذر درجه دوم را با هم CasCade کنیم. فیلتر درجه چهارم بدست می‌آید و اگر از ۳ طبقه استفاده شود، درجه ششم بدست می‌آید و ...

۱۶ - فیلتر پایین‌گذر درجه فرد: اگر یک فیلتر درجه یک با یک فیلتر درجه دو با هم CasCade کنیم فیلتر درجه سوم و اگر یک فیلتر درجه یک با دو فیلتر درجه دو CasCade شود فیلتر درجه پنجم بدست می‌آید و ...

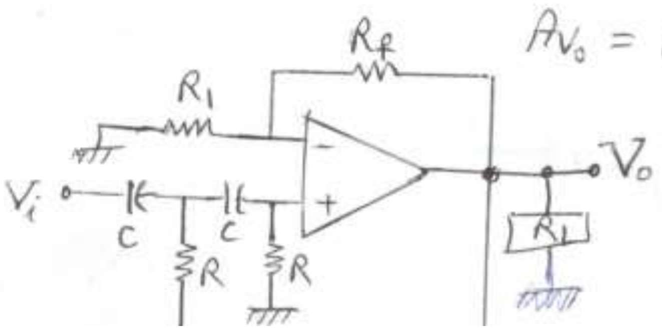
۱۷ - فیلتر بالاگذر: (درجه یک)



اگر جای خازن و مقاومت را در مدار شماره (۱۳) عوض کنیم تبدیل به فیلتر بالاگذر می‌شود.

$$A_V(S) = \frac{V_o}{V_i} = \left(1 + \frac{R_f}{R}\right) \frac{SCR}{1 + SCR}$$

۱۸ - فیلتر بالاگذر درجه دو:



$$A_{V_0} = 1 + \frac{R_f}{R_1}$$

$$A_V(S) = \frac{A_{V_0}}{\left(\frac{1}{SCR}\right)^2 + (3 - A_{V_0})\left(\frac{1}{SCR}\right) + 1}$$

Fundamentals of Microelectronics

الکترونیک ۲

فصل ۸ – تقویت کننده عملیاتی (آپ امپ)

قسمت دوم- کاربردهای غیرخطی

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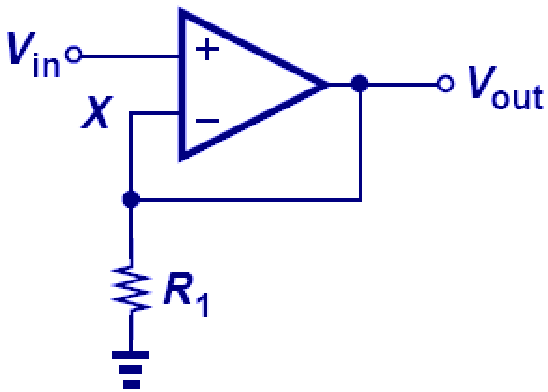
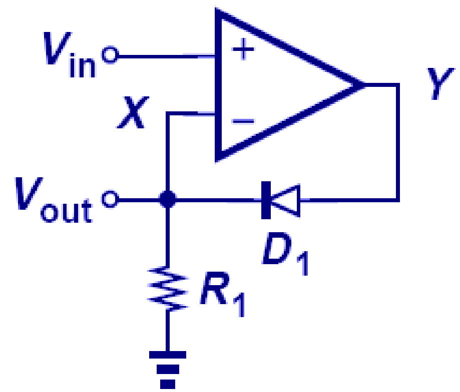
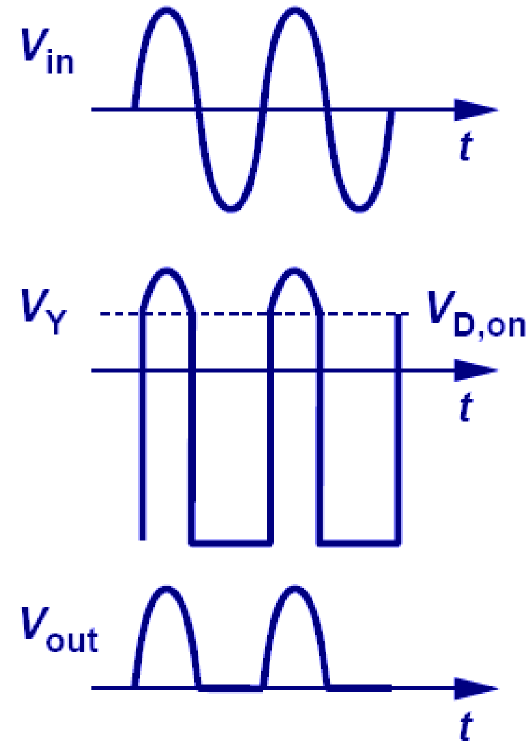
Precision Rectifier







$V^- \approx V^+$

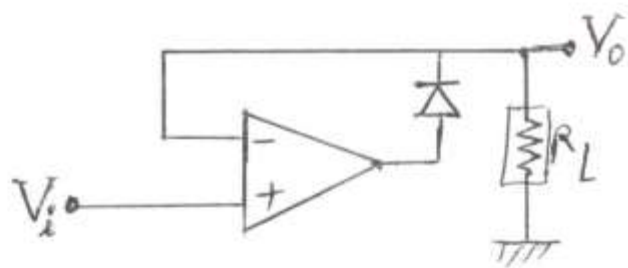
$I_{in_1} = I_{in_2} \approx 0$

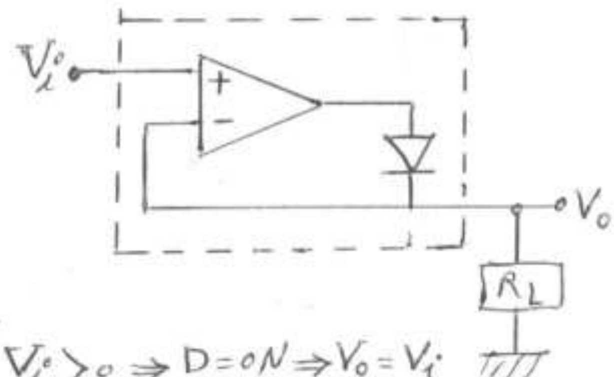
فقط وقتی که دیود روشن هست ، فیدبک برقرار
است و میتوان از این فرضیات استفاده نمود.

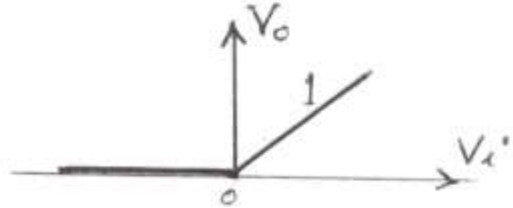
- When V_{in} is positive, the circuit in b) behaves like that in a), so the output follows input.
- When V_{in} is negative, the diode opens, and the output drops to zero. Thus performing rectification.

بخش اول - کاربردهای تقویت کننده عملیاتی - یکسوکننده ها

۱۹- یکسوساز نیم موج دقیق :

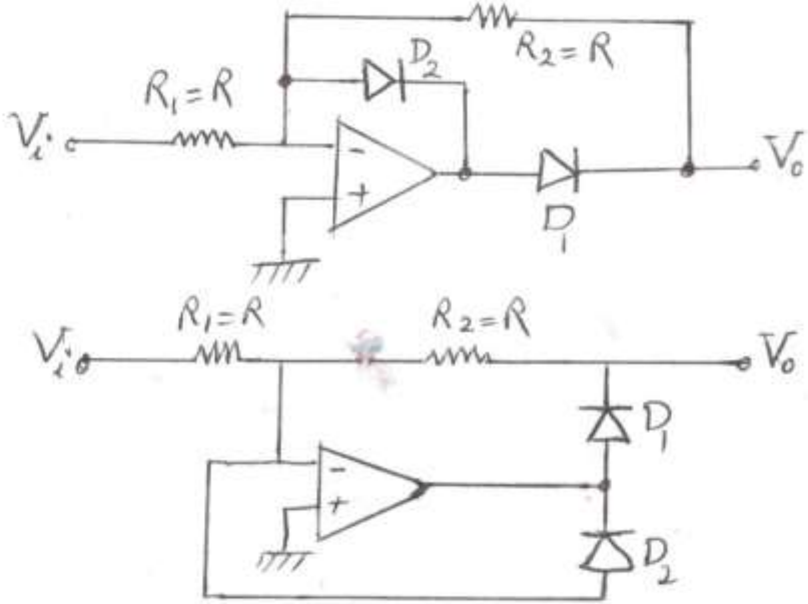


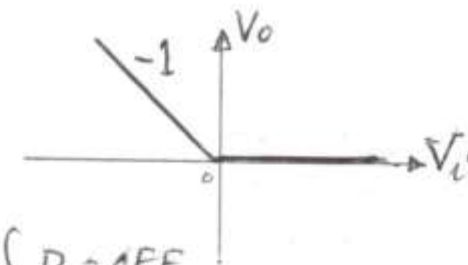




$$\begin{cases} V_i > 0 \Rightarrow D = ON \Rightarrow V_o = V_i \\ V_i < 0 \Rightarrow D = off \Rightarrow V_o = 0 \end{cases}$$

۲۰ - یکسوساز نیم موج دقیق اصلاح شده :

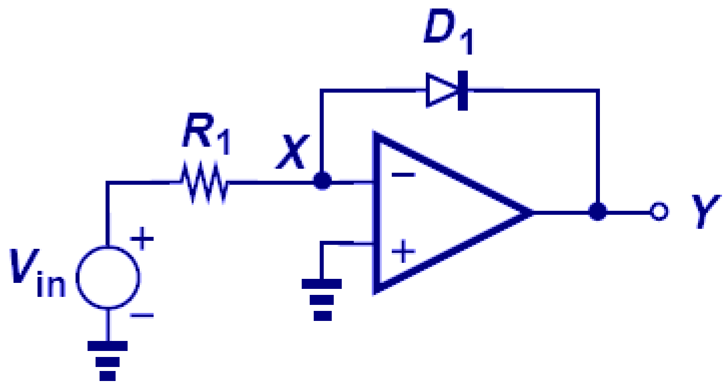


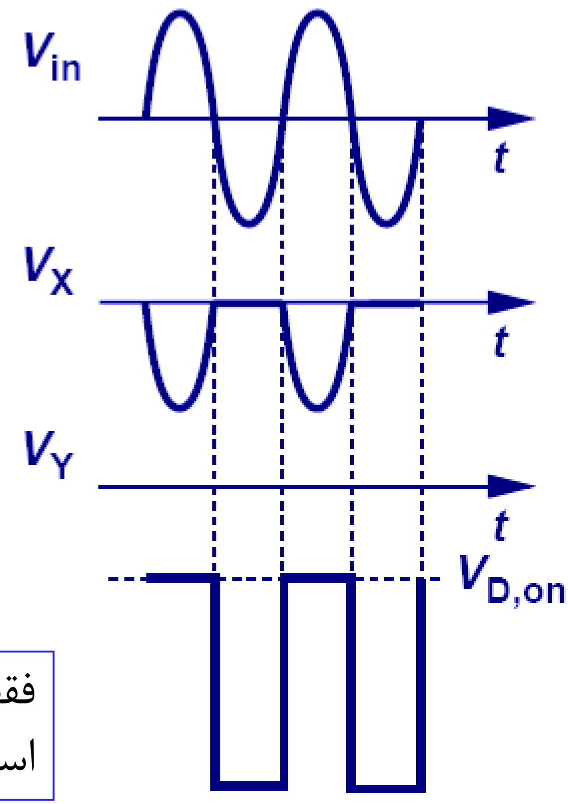


$$V_i > 0 \Rightarrow \begin{cases} D_1 = OFF \\ D_2 = ON \end{cases} \Rightarrow V_o = 0$$

$$V_i < 0 \Rightarrow \begin{cases} D_1 = ON \\ D_2 = OFF \end{cases} \Rightarrow V_o = -V_i$$

Inverting Precision Rectifier





$V^- \approx V^+$

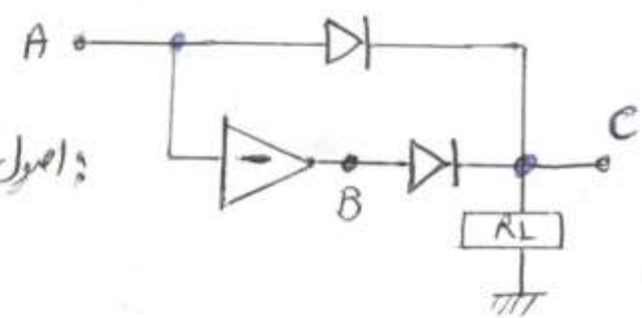
$I_{in_1} = I_{in_2} \approx 0$

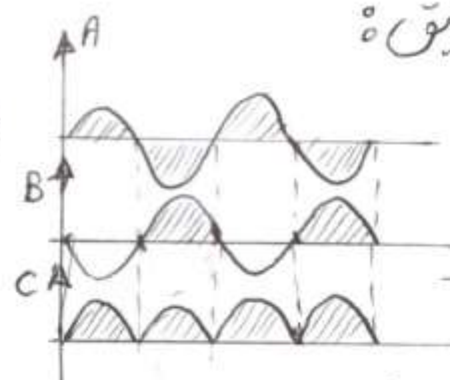
فقط وقتی که دیود روشن هست ، فیدیک برقرار است و میتوان از این فرضیات استفاده نمود.

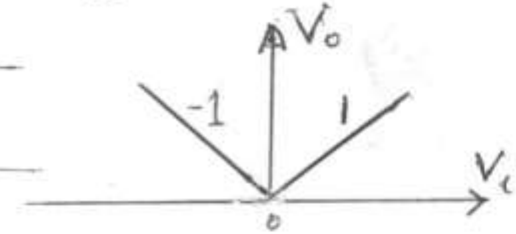
- **When V_{in} is positive, the diode is on, V_y is pinned around $V_{D,on}$, and V_x at virtual ground.**
- **When V_{in} is negative, the diode is off, V_y goes extremely negative, and V_x becomes equal to V_{in}.**

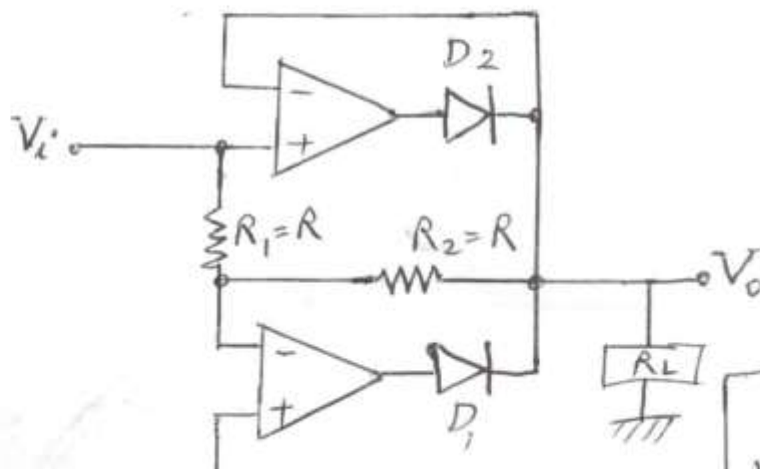
۲۱ - یکسوساز تمام موج دقیق:

اصول یکسوسازی:



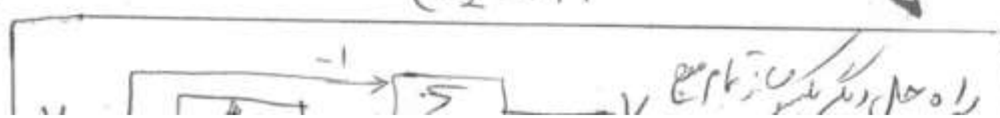






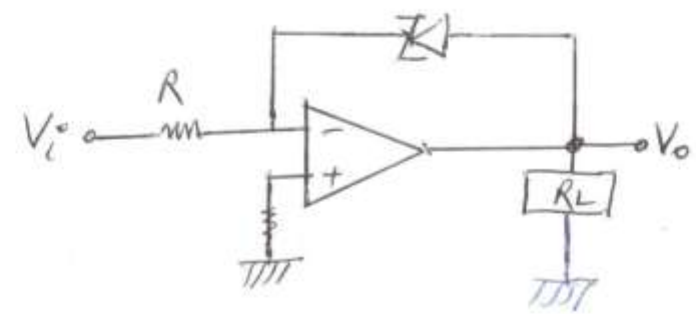
$$V_i > 0 \Rightarrow \begin{cases} D_2 = ON \\ D_1 = off \end{cases} \Rightarrow V_o = V_i$$

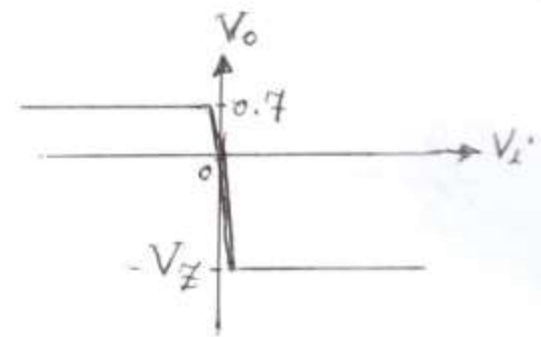
$$V_i < 0 \Rightarrow \begin{cases} D_1 = ON \\ D_2 = OFF \end{cases} \Rightarrow V_o = -V_i$$



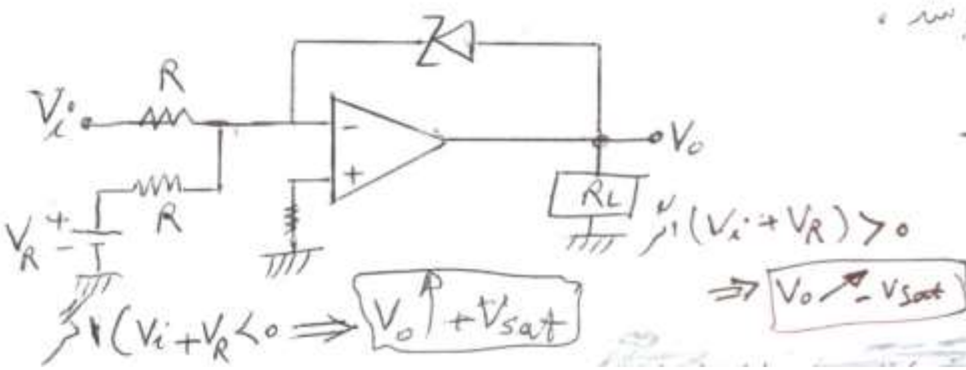
بخش اول - کاربردهای تقویت کننده عملیاتی - مقایسه کننده‌ها و محدودکننده‌ها

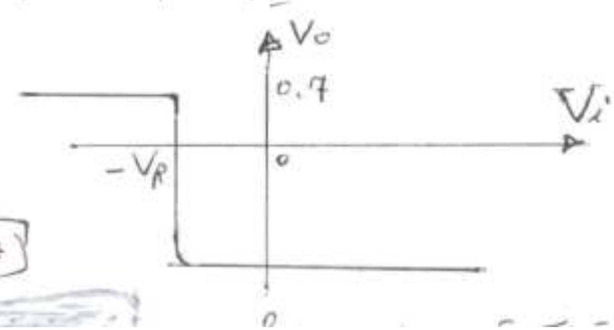
۲۲ - ولتاژ آستانه (مقایسه)، صفر ولت می‌باشد.



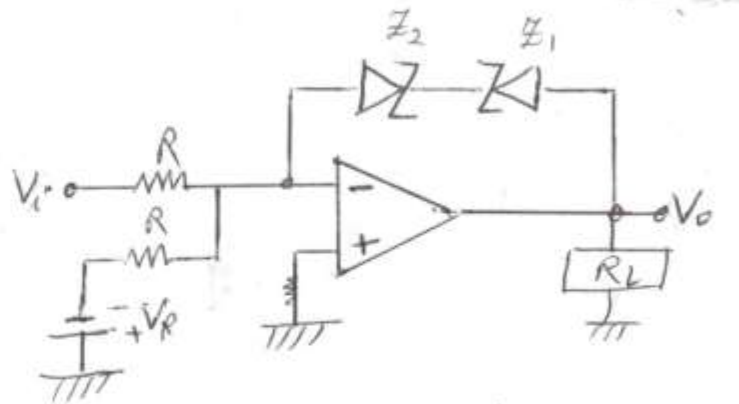


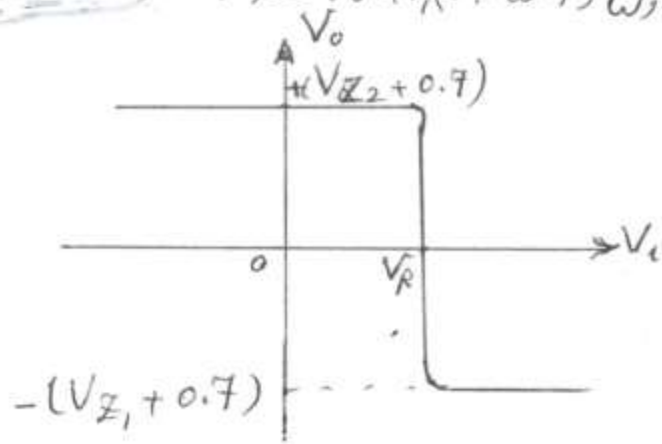
۲۳ - ولتاژ آستانه (مقایسه)، $-V_R$ می‌باشد.



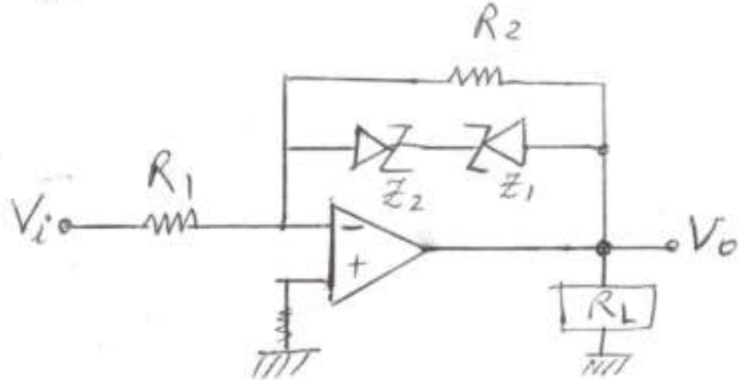


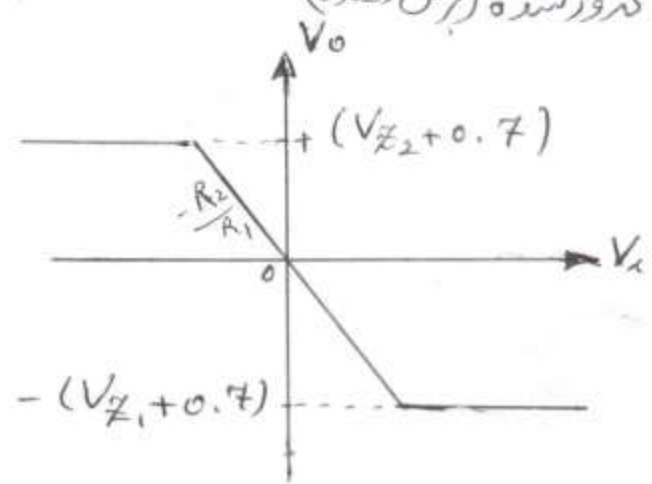
۲۴- وقتی در آشکارساز V_R + باشد.





۲۵- محدودکننده (برش دهنده)

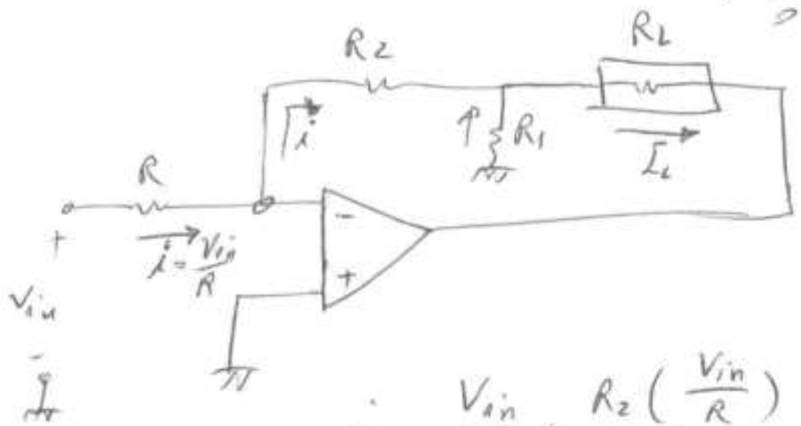




بخش دوم - کاربرد مدارات مجتمع خطی - مبدل ولتاژ به جریان V-I-C

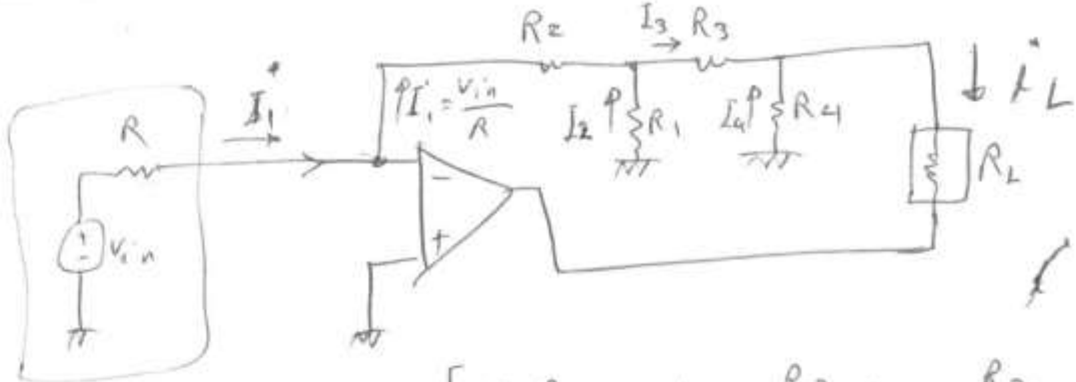
استفاده از شبکه T برای تقویت جریان‌های کوچک :

(K)



$$i_L = \frac{V_{in}}{R}\left(1+\frac{R_2}{R_1}\right)$$

$$i_L = \frac{V_{in}}{R} + \frac{R_2\left(\frac{V_{in}}{R}\right)}{R_1} = \frac{V_{in}}{R}\left[\frac{R_1+R_2}{R_1}\right] = \frac{V_{in}}{R}\left(1+\frac{R_2}{R_1}\right)$$



$$i_L = \frac{V_{in}}{R}\left[\left(\frac{R_2}{R_4}\right)\left(1+\frac{R_3}{R_1}\right)+\frac{R_2}{R_1}+\frac{R_3}{R_4}+1\right]$$

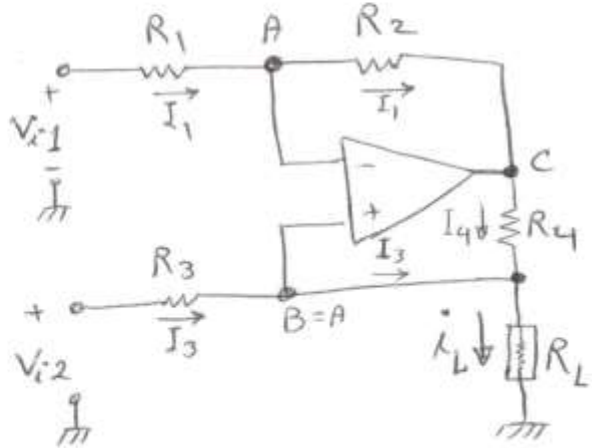
اثبات: $I_1 = \frac{V_{in}}{R}$

$$I_2 = \frac{I_1 R_2}{R_1} \longrightarrow I_3 = I_1 + I_2 = I_1\left(1+\frac{R_2}{R_1}\right)$$

$$I_4 = \frac{R_3 I_3 + R_2 I_1}{R_4} = \frac{\left(R_3\left(1+\frac{R_2}{R_1}\right)+R_2\right)I_1}{R_4}$$

$$I_L = I_3 + I_4 = I_1\left(\left(1+\frac{R_2}{R_1}\right)+\frac{R_2}{R_4}+\left(\frac{R_3\left(1+\frac{R_2}{R_1}\right)}{R_4}\right)\right) = \cdots$$

① مبدل ولتاژ به جریان Howland :



با شرط $\frac{R_4}{R_3} = \frac{R_2}{R_1}$:

$$i_L = \frac{V_{i2} - V_{i1}}{R_3}$$

$$R_o = \frac{R_4}{\frac{R_2}{R_1} - \frac{R_4}{R_3}} \overset{\text{با شرط}}{=} \infty$$

اثبات :

$$I_1 = \frac{V_{i1} - V_A}{R_1} = \frac{V_A - V_C}{R_2} \rightarrow V_A - V_C = \frac{R_2}{R_1}(V_{in1} - V_A)$$

$$I_3 = \frac{V_{i2} - V_A}{R_3} \quad , \quad I_4 = \frac{V_C - V_A}{R_4}$$

$$i_L = I_3 + I_4 = \frac{V_{i2} - V_A}{R_3} + \frac{V_C - V_A}{R_4} = \frac{R_2}{R_1 R_4}(V_A - V_{i1}) + \frac{V_{i2} - V_A}{R_3} = \frac{V_A}{R_L}$$

$$\Rightarrow V_A \left[\frac{R_2}{R_1 R_4} - \frac{1}{R_3} - \frac{1}{R_L} \right] = V_{i1}\left(\frac{R_2}{R_1 R_4}\right) - V_{i2}\left(\frac{1}{R_3}\right)$$

$$\Rightarrow V_A = \frac{V_{i2}\left(\frac{1}{R_3}\right) - V_{i1}\left(\frac{R_2}{R_1 R_4}\right)}{\frac{1}{R_3} + \frac{1}{R_L} - \frac{R_2}{R_1 R_4}} = [\ "\ ]$$

$$\Rightarrow V_A = \frac{V_{i2}\left(\frac{1}{R_3}\right) - V_{i1}\left(\frac{R_2}{R_1R_4}\right)}{\frac{1}{R_3} + \frac{1}{R_L} - \frac{R_2}{R_1R_4}} = [\ " \ ]$$

$$i_L = \frac{V_A}{R_L} = \frac{1}{R_L}[\ " \ ] \Rightarrow \text{مخرج کسر} = \left(\frac{R_L}{R_3} + 1 - \frac{R_2R_L}{R_1R_4}\right)$$

برای آنکه جریان i_L مستقل از R_L باشد باید شرط زیر برقرار باشد:

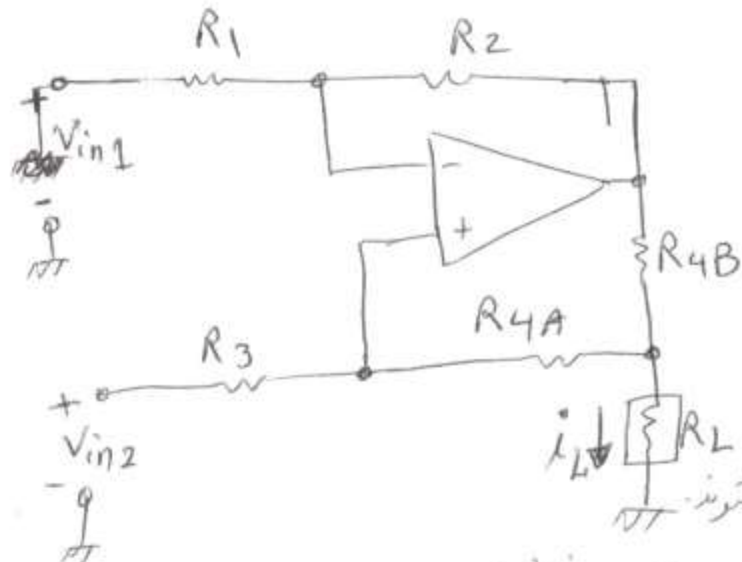
$$\frac{1}{R_3} = \frac{R_2}{R_1R_4} \rightarrow \boxed{\frac{R_4}{R_3} = \frac{R_2}{R_1}}$$

$$i_L = V_{i2}\left(\frac{1}{R_3}\right) - V_{i1}\underbrace{\left(\frac{R_2}{R_1R_4}\right)}_{(1/R_3)} \Rightarrow \boxed{i_L = \frac{V_{i2} - V_{i1}}{R_3}}$$

حالت ۲ : Howland inverting $\quad \boxed{V_{i2} = 0} \Rightarrow \boxed{i_L = \frac{-V_{i1}}{R_3}}$

حالت ۳ : Howland noninverting $\quad \boxed{V_{i1} = 0} \Rightarrow \boxed{i_L = \frac{V_{i2}}{\ }}$

" Howland Improved " (۴)



باشرط :

$$\frac{R_{4A}+R_{4B}}{R_3} = \frac{R_2}{R_1}$$

$$i_L = (V_{i2}-V_{i1})\left(\frac{R_2}{R_1 R_{4B}}\right)$$

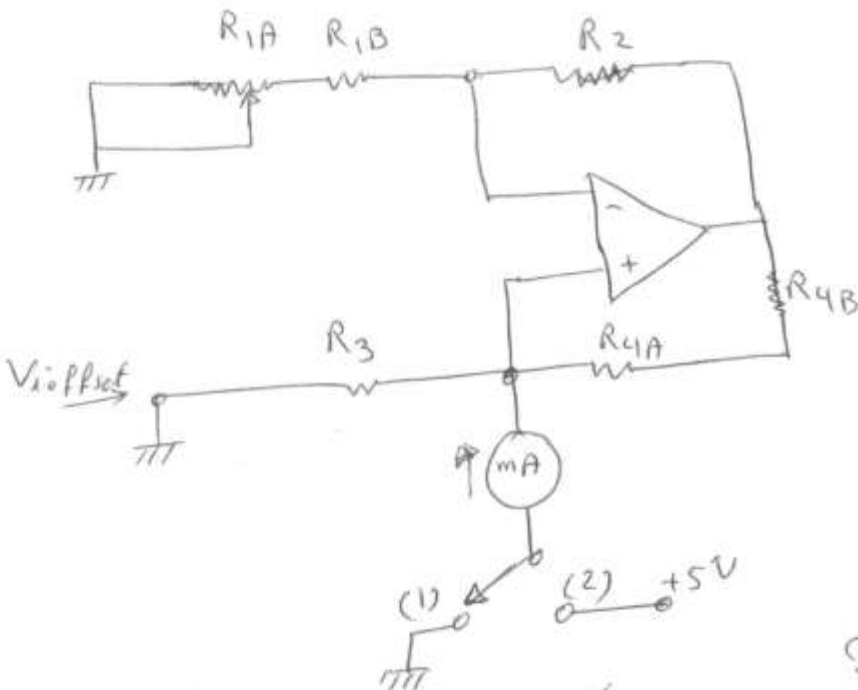
R_1 و R_2 و R_3 و R_4 بزرگ انتخاب می‌شوند

و R_{4B} تا حد ممکن کوچک انتخاب می‌شود . (به دو منظور) :

۱- حساسیت (تابع انتقال) مدار زیاد شود .

۲- فاصله V_d تا V_L و V_{com} از V_L کوچکتر شود .

۵) مدار کالیبره کردن (Improved V-I-C) :



برای کالیبره کردن باید:

$$\frac{R_1}{R_3} = \frac{R_2}{R_4}$$

$(R_{1A} + R_{1B} = R_1)$

R_{1A} باید جبران خطای ناهمجوری مقاومتها را بکند.

روش کالیبره کردن:

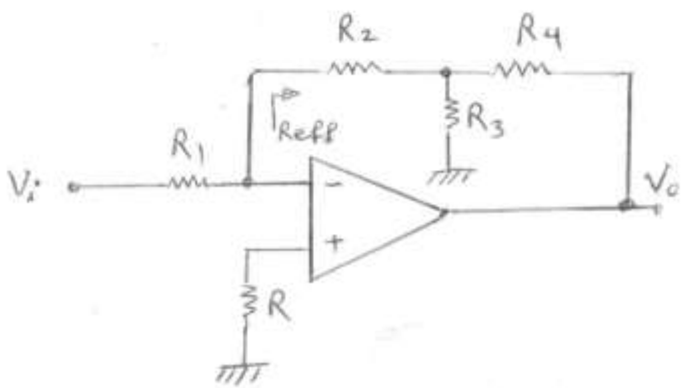
R_{1A} را آنقدر تغییر می‌دهیم تا درحالیکه $V_i=0$ تغییر وضعیت کلید از حالت (۱) به (۲) و بالعکس هیچ جریانی از آمپرمتر عبور نکند.

دراینصورت: $R_o = R_3 \parallel (-R_3) = \infty$ خواهد شد.

بخش سوم - کاربرد مدارات مجتمع خطی

فصل دوازدهم: بزرگ کردن و شبیه سازی قطعات پسیو الکترونیکی توسط IC

۱۲-۱) افزایش مقاومت (برای دستیابی به بهره بیشتر توسط مقاومتهای کوچک):



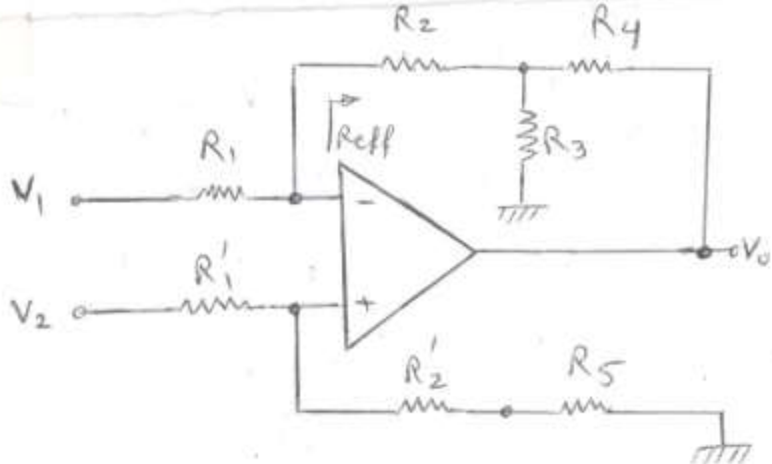
* استفاده از شبکه T

$$R_{eff} = R_2 + R_4 + \frac{R_2 R_4}{R_3}$$

$$V_o = -Gain \cdot V_i$$

$$Gain = \frac{R_{eff}}{R_1}$$

★ در حالت تفاضلی :



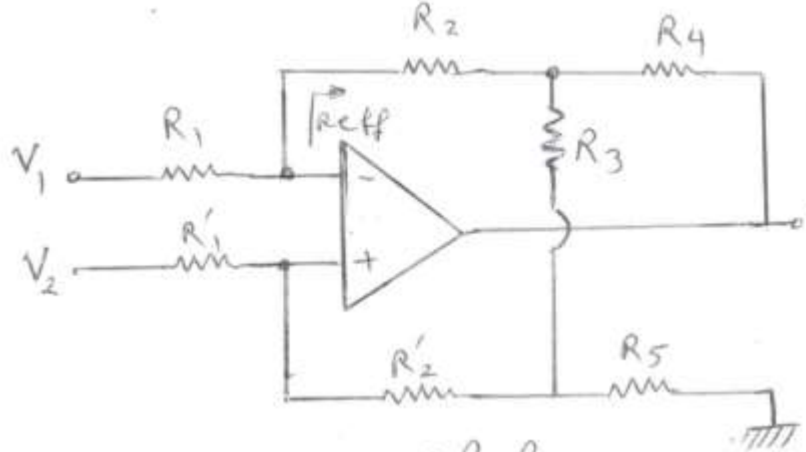
$$\left.\begin{aligned} R_1 &= R_1' \\ R_2 &= R_2' \\ R_5 &= R_4 \parallel R_3 \end{aligned}\right\} \text{با فرض}$$

$$R_{eff} = R_2 + R_4 + \frac{R_2 R_4}{R_3}$$

$$V_o = (V_2 - V_1)\,Gain$$

$$Gain = \frac{R_{eff}}{R_1}$$

★ مدار بهتر برای حالت تفاضلی :



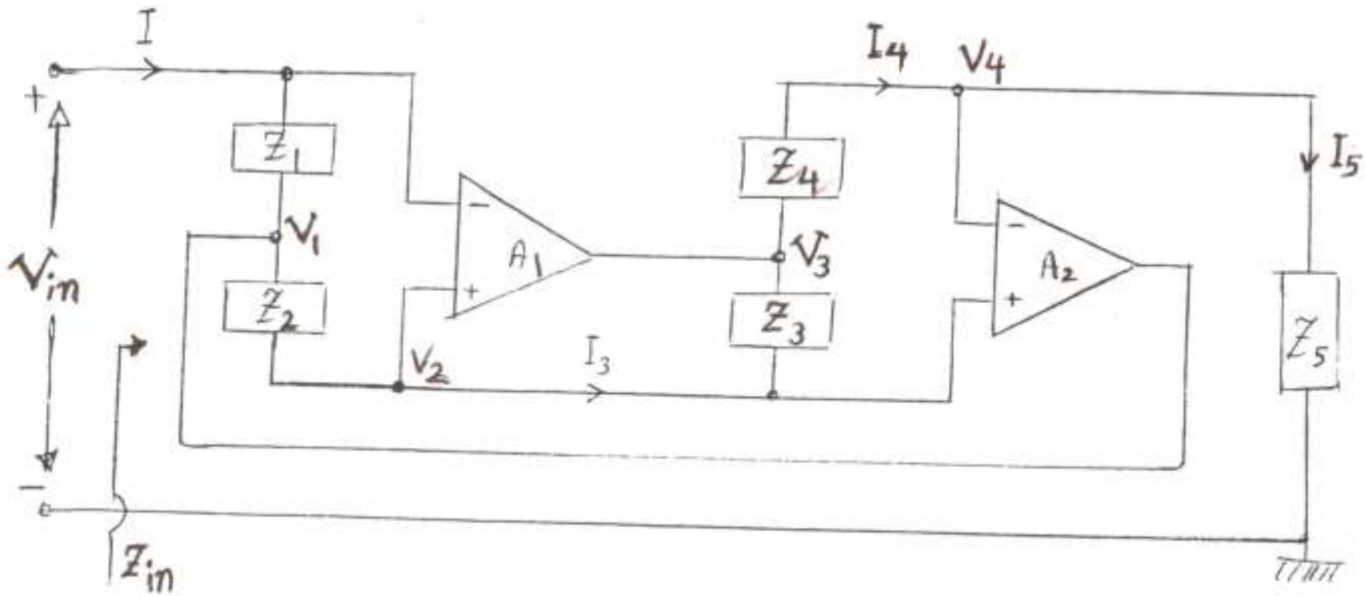
$$\left.\begin{aligned} R_1 &= R_1' \\ R_2 &= R_2' \\ R_5 &= R_4 \end{aligned}\right\} \text{با فرض:}$$

$$R_{eff} = R_2 + R_4 + \frac{2 R_2 R_4}{R_3}$$

$$V_o = (V_2 - V_1)\,Gain$$

$$Gain = \frac{R_{eff}}{}$$

* مدار کلی مبدل امپدانس (GIC): (General Impedance Converter)



با توجه به قرائن OP-Amp داریم:

$$V_{in} = V_2 = V_4 \quad , \quad I_4 = I_5 = \frac{V_4}{Z_5}$$

$$V_3 = V_4 + I_4 Z_4 \quad , \quad I_3 = \frac{V_2 - V_3}{Z_3} = -V_{in}\frac{Z_4}{Z_3 Z_5}$$

$$I = \frac{V_{in} - V_1}{Z_1} = V_{in}\frac{Z_4 Z_2}{Z_1 Z_3 Z_5} \Longrightarrow \boxed{Z_{in} = \frac{V_{in}}{I} = \frac{Z_1 Z_3 Z_5}{Z_2 Z_4}}$$

$$I = \frac{V_{in} - V_1}{Z_1} = V_{in} \frac{Z_4 Z_2}{Z_1 Z_3 Z_5} \Longrightarrow \boxed{Z_{in} = \frac{V_{in}}{I} = \frac{Z_1 Z_3 Z_5}{Z_2 Z_4}}$$

I) * حال اگر در این رابطه Z_2 و یا Z_4 خازن باشند (و بقیه مقاومت) داریم:

$$Z_{in} = \frac{R_1 R_3 R_5}{\frac{1}{j\omega C_2} \cdot R_4} = j\omega C_2 \frac{R_1 R_3 R_5}{R_4}$$

و کل مدار مثل یک سلف عمل می‌کند که در آن داریم:

$$L = C_2 \frac{R_1 R_3 R_5}{R_4}$$

II) اگر Z_1 و یا Z_3 و یا Z_5 خازن باشند در آن صورت:

$$C_{in} = C_1 \frac{R_2 R_4}{R_3 R_5}$$

مثال عددی ①: اگر در مدار فوق داشته باشیم:

$R_1 = R_3 = R_5 = R_4 = 10K$, $C_2 = 1nF$

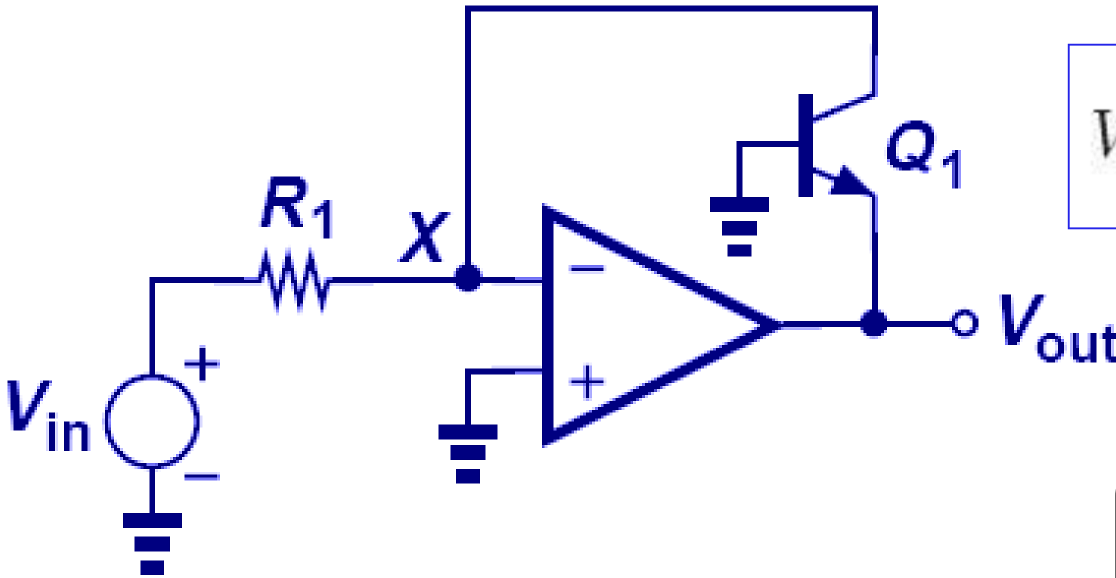
$\Rightarrow L = 0.1\,H$

(ترم: کمک این مدار می‌توان مقاومت‌های منفی ساخت)

مثال عددی ②: فرض کنید: $Z_1 = Z_3 = Z_5 = 2K\Omega$, $Z_4 = 0.02\mu F \parallel 69K\Omega$, $Z_2 = 1K\Omega$

$\Leftarrow \boxed{Z_{in} = 116 + j\omega\, 0.16}$

Logarithmic Amplifier



$$V_{BE} = V_T \ln \frac{V_{in}/R_1}{I_S}.$$

$$V_{out} = -V_T \ln \frac{V_{in}}{R_1 I_S}$$

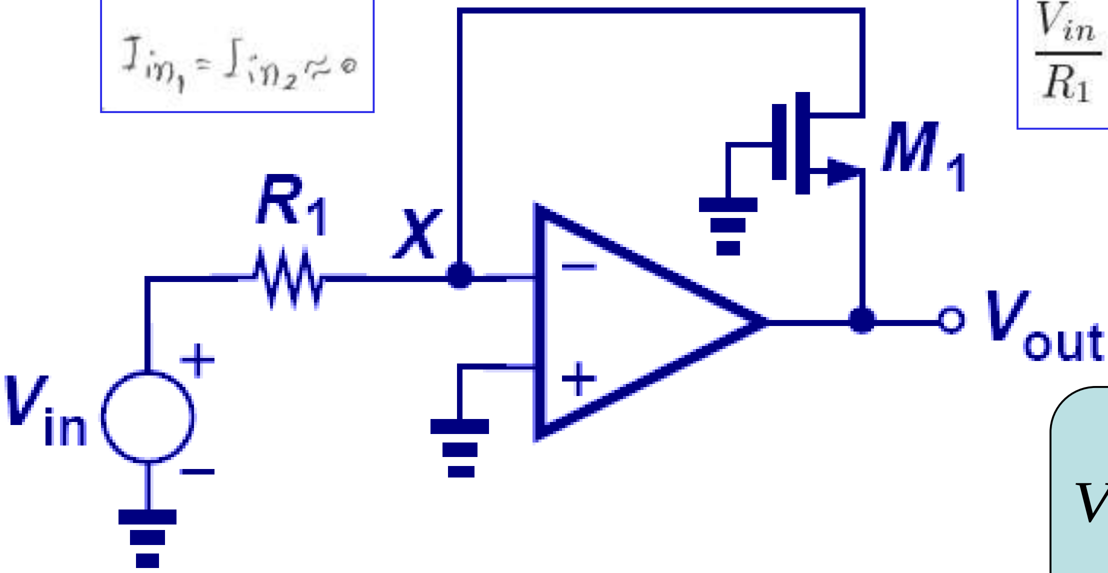
- By inserting a bipolar transistor in the loop, an amplifier with logarithmic characteristic can be constructed.
- This is because the current to voltage conversion of a bipolar transistor is a natural logarithm.

Square-Root Amplifier

$V^- \approx V^+$

$I_{in_1} = I_{in_2} \approx 0$

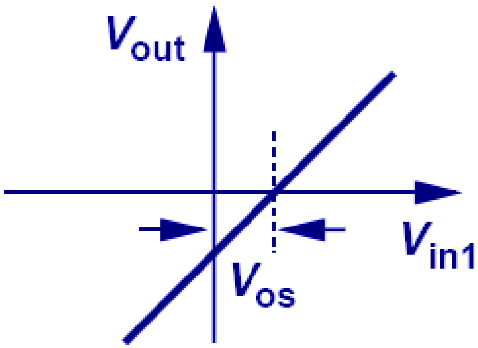
$$\frac{V_{in}}{R_1} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2.$$

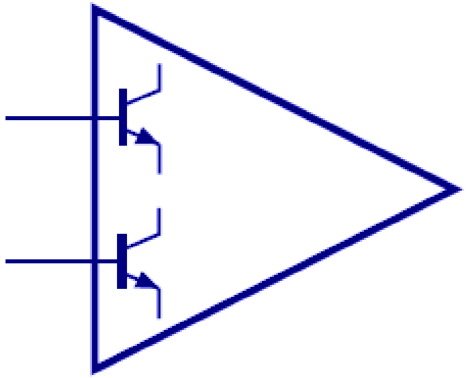


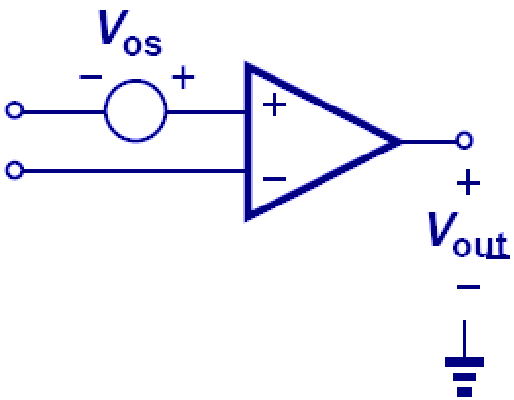
$$V_{out} = -\sqrt{\frac{2V_{in}}{\mu_n C_{ox}\frac{W}{L}R_1}} - V_{TH}$$

- By replacing the bipolar transistor with a MOSFET, an amplifier with a square-root characteristic can be built.
- This is because the current to voltage conversion of a MOSFET is square-root.

Op Amp Nonidealities: DC Offsets

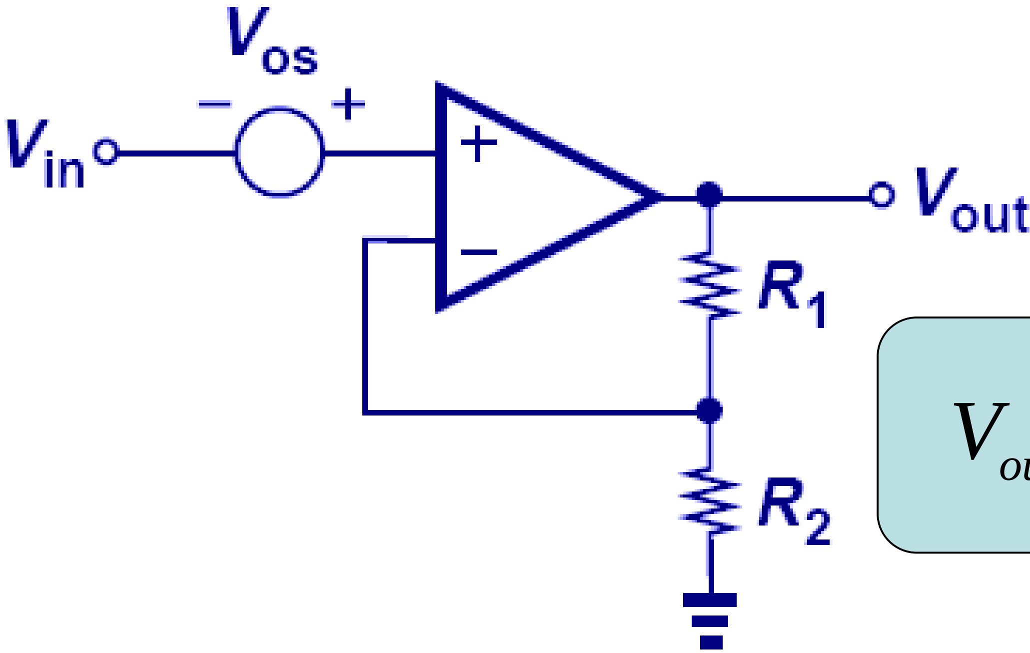






- Offsets in an op amp that arise from input stage mismatch cause the input-output characteristic to shift in either the positive or negative direction (the plot displays positive direction).

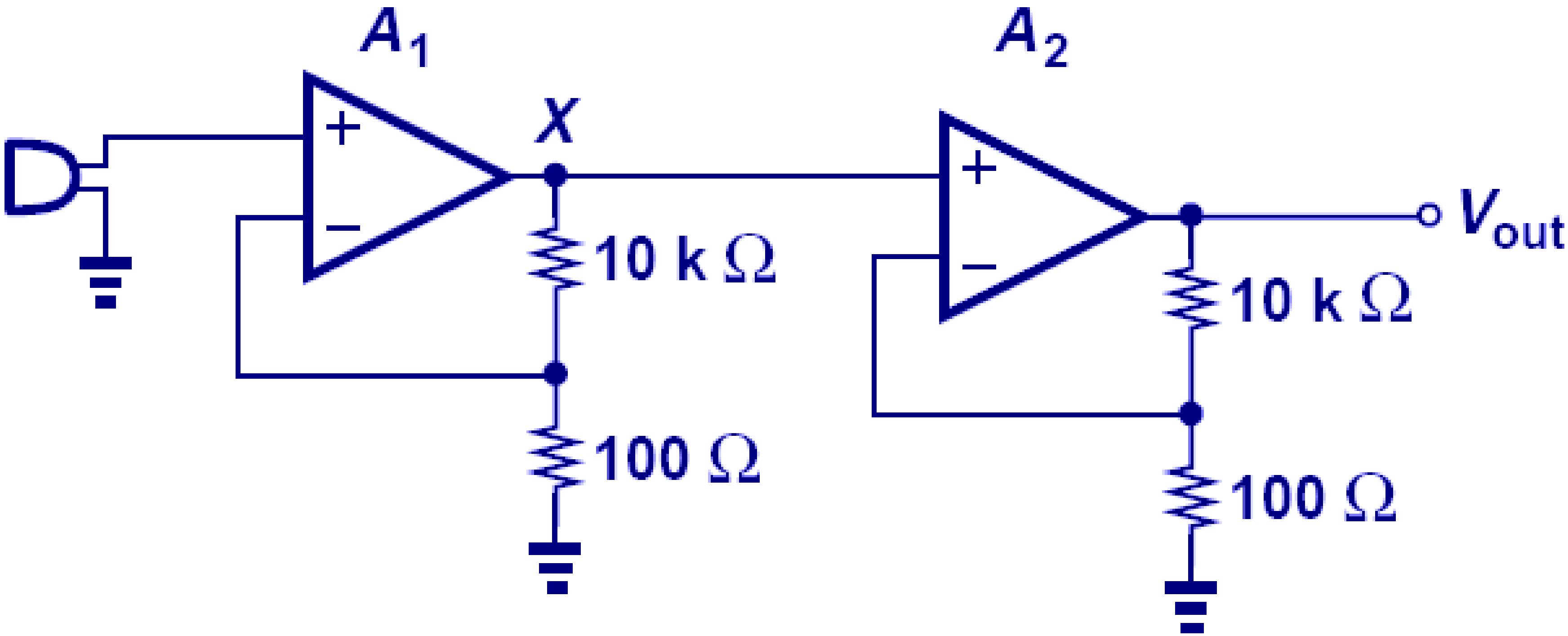
Effects of DC Offsets



$$V_{out} = \left(1 + \frac{R_1}{R_2}\right)(V_{in} + V_{os})$$

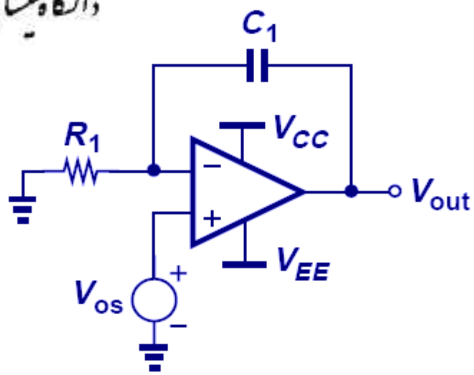
- As it can be seen, the op amp amplifies the input as well as the offset, thus creating errors.

Saturation Due to DC Offsets

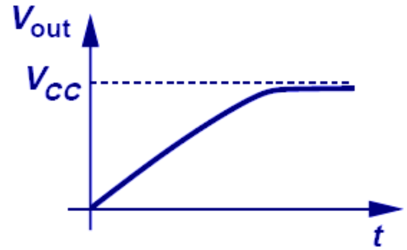


- **Since the offset will be amplified just like the input signal, output of the first stage may drive the second stage into saturation.**

Offset in Integrator

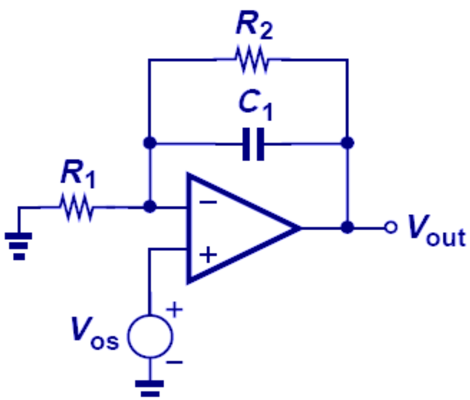


(a)

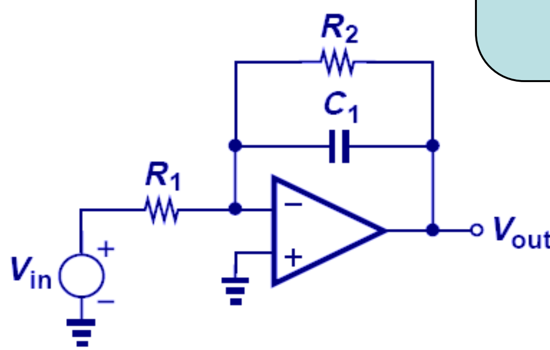


(b)

$$\frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}\frac{1}{R_2 C_1 s + 1}$$



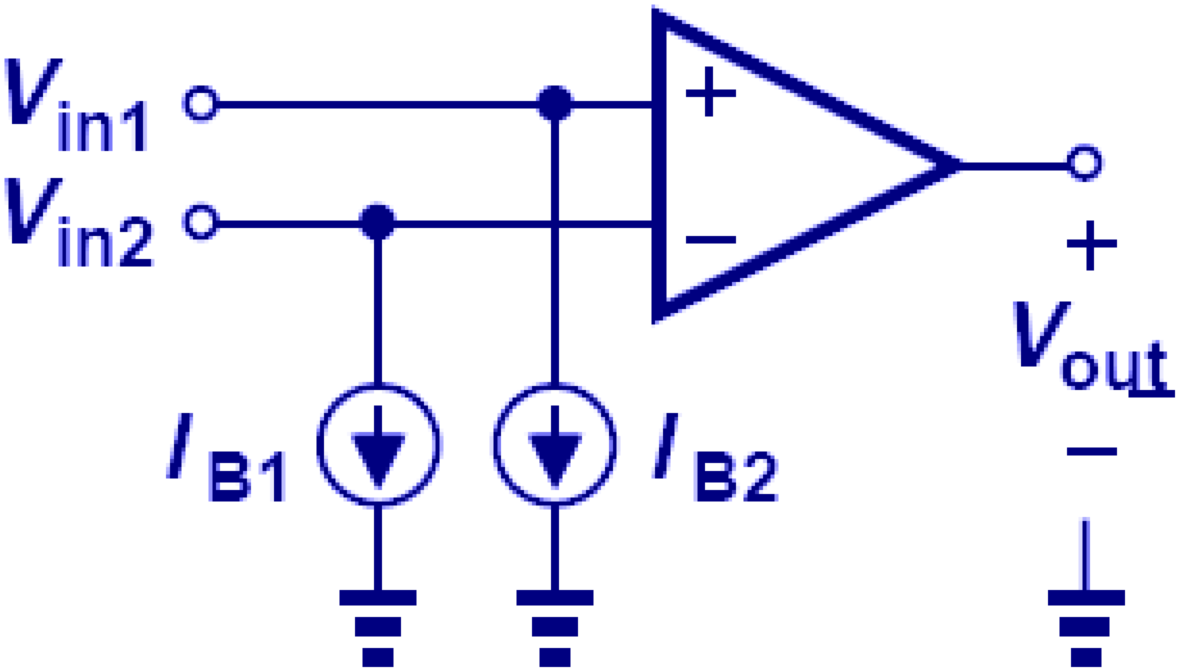
(c)



(d)

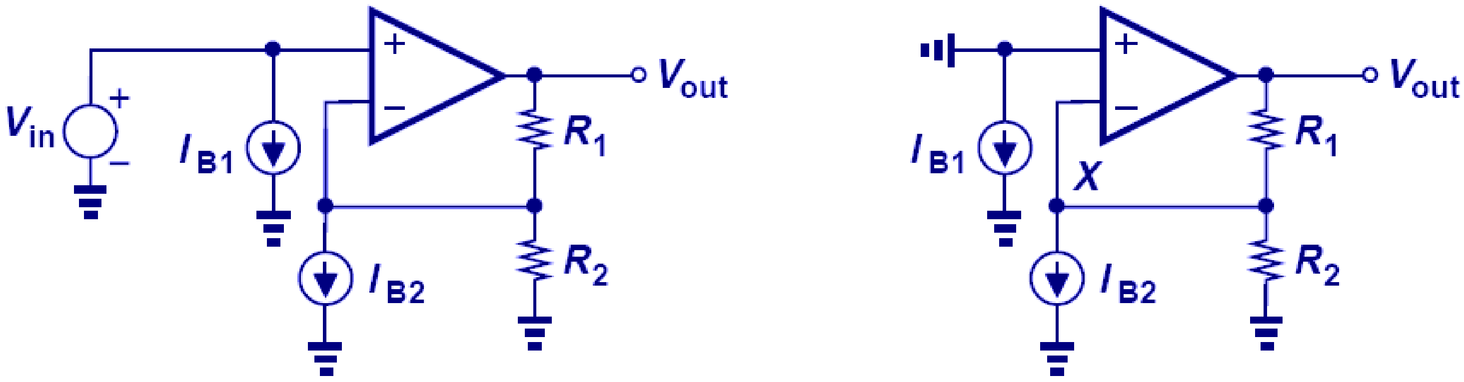
- A resistor can be placed in parallel with the capacitor to “absorb” the offset. However, this means the closed-loop transfer function no longer has a pole at origin.

Input Bias Current

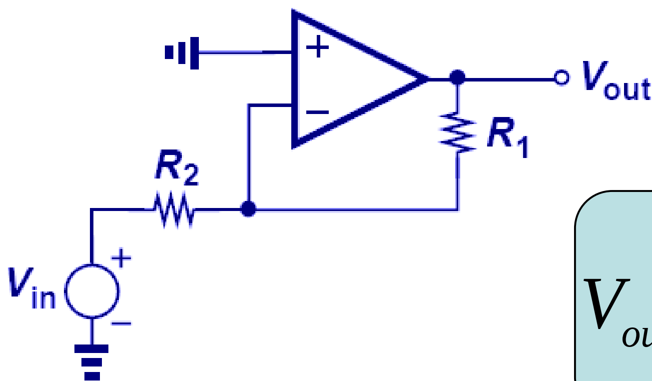


➢ **The effect of bipolar base currents can be modeled as current sources tied from the input to ground.**

Effects of Input Bias Current on Noninverting Amplifier



(a) (b)

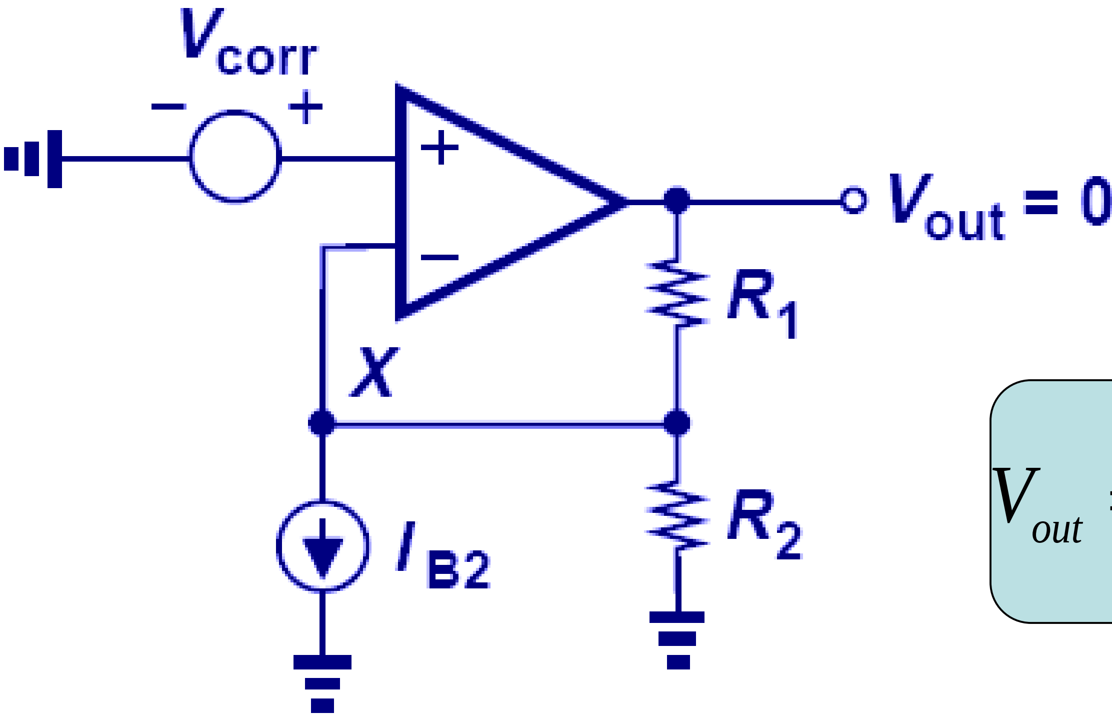


(c)

$$V_{out} = -R_2 I_{B2}\left(-\frac{R_1}{R_2}\right) = R_1 I_{B2}$$

- It turns out that I_{B1} has no effect on the output and I_{B2} affects the output by producing a voltage drop across R_1.

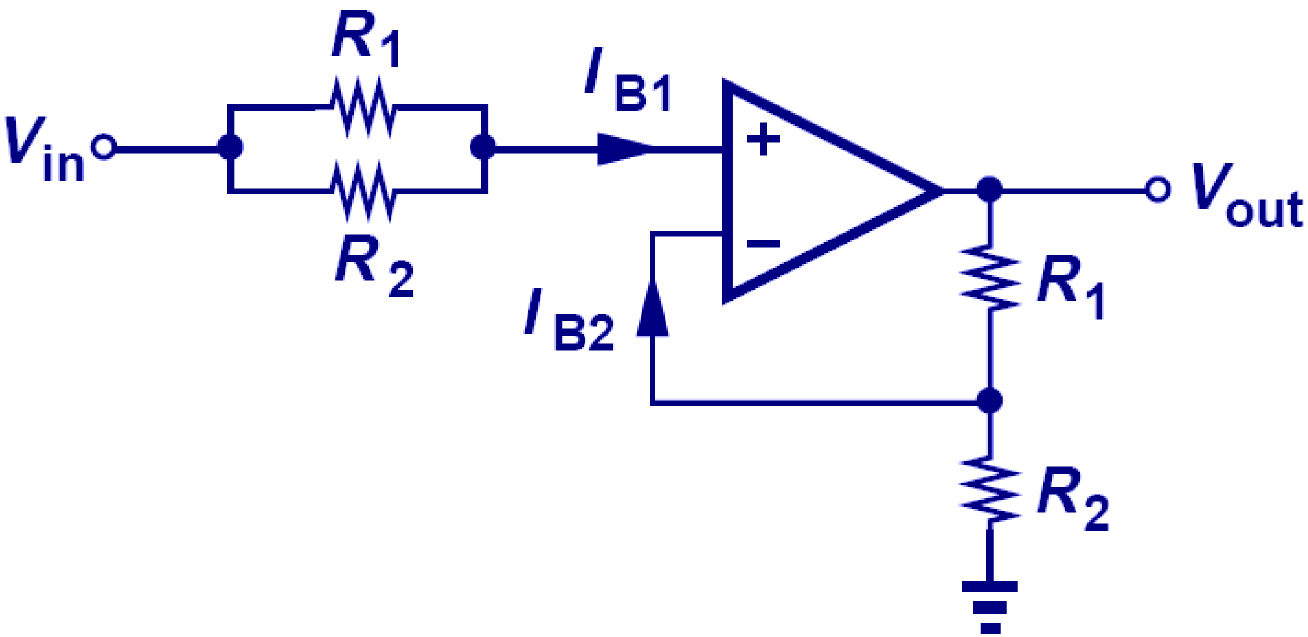
Input Bias Current Cancellation



$$V_{out} = V_{corr}\left(1+\frac{R_1}{R_2}\right) + I_{B2}R_1$$

- We can cancel the effect of input bias current by inserting a correction voltage in series with the positive terminal.
- In order to produce a zero output, $V_{corr} = -I_{B2}(R_1 || R_2)$.

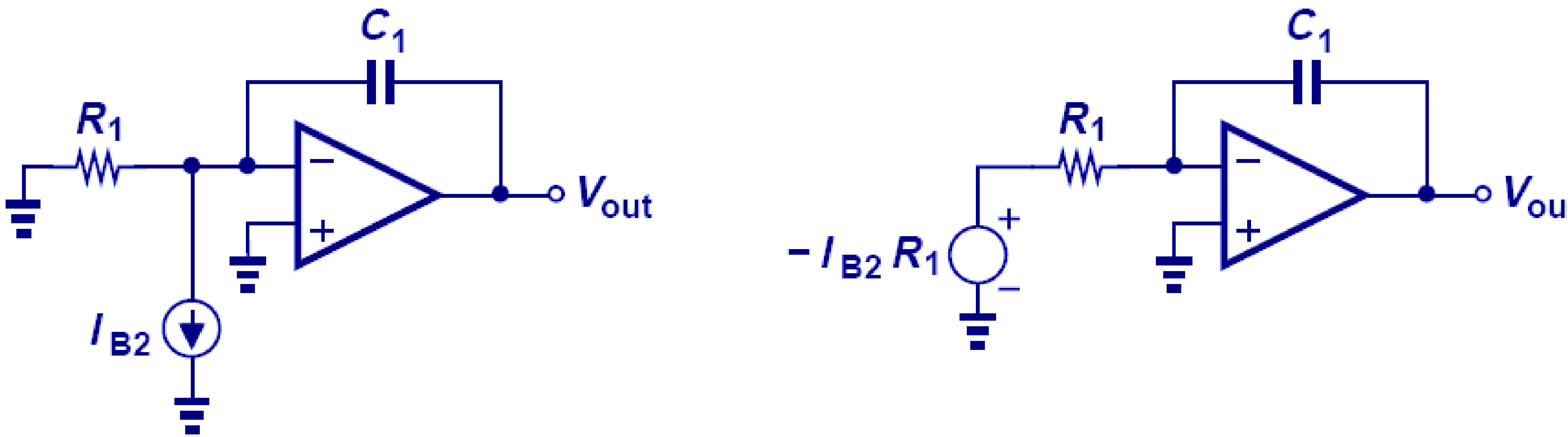
Correction for β Variation



$$I_{B1} = I_{B2}$$

- Since the correction voltage is dependent upon β, and β varies with process, we insert a parallel resistor combination in series with the positive input. As long as $I_{B1}= I_{B2}$, the correction voltage can track the β variation.

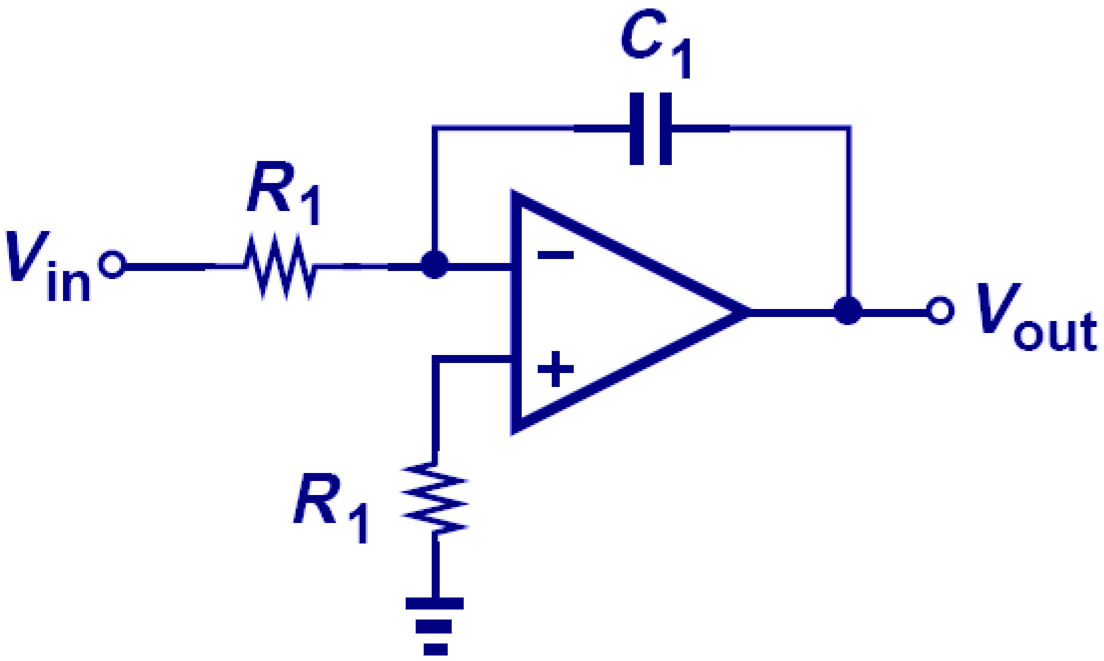
Effects of Input Bias Currents on Integrator



$$V_{out} = -\frac{1}{R_1 C_1}\int \left(-I_{B2} R_1\right) dt$$

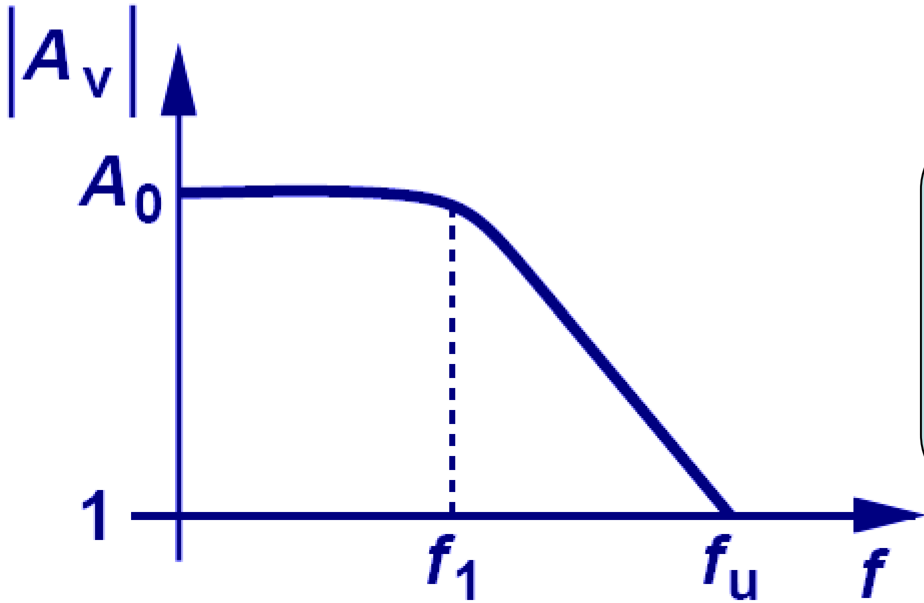
- **Input bias current will be integrated by the integrator and eventually saturate the amplifier.**

Integrator's Input Bias Current Cancellation



- By placing a resistor in series with the positive input, integrator input bias current can be cancelled.
- However, the output still saturates due to other effects such as input mismatch, etc.

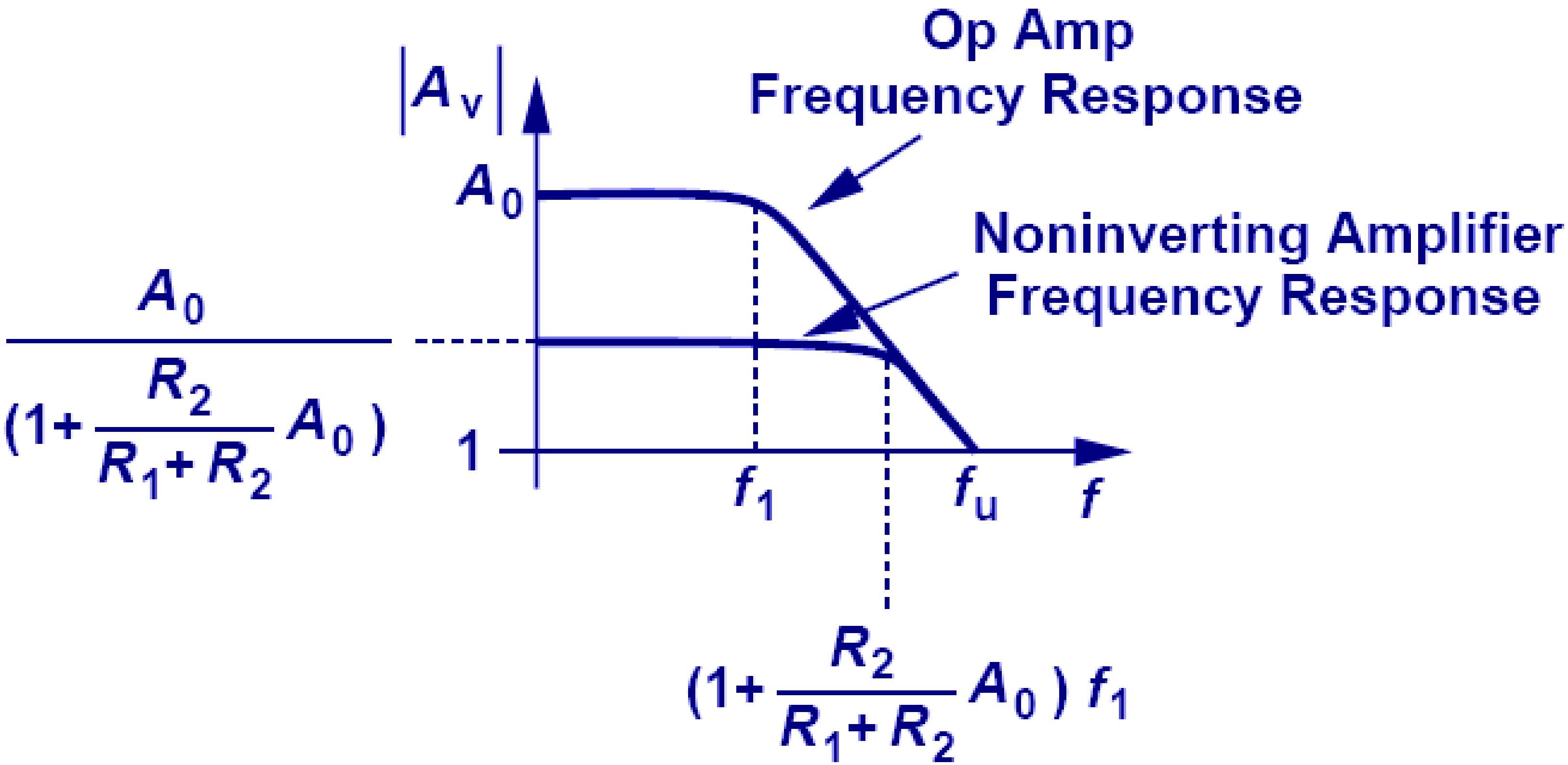
Speed Limitation



$$\frac{V_{out}}{V_{in1}-V_{in2}}(s)=\frac{A_0}{1+\frac{s}{\omega_1}}$$

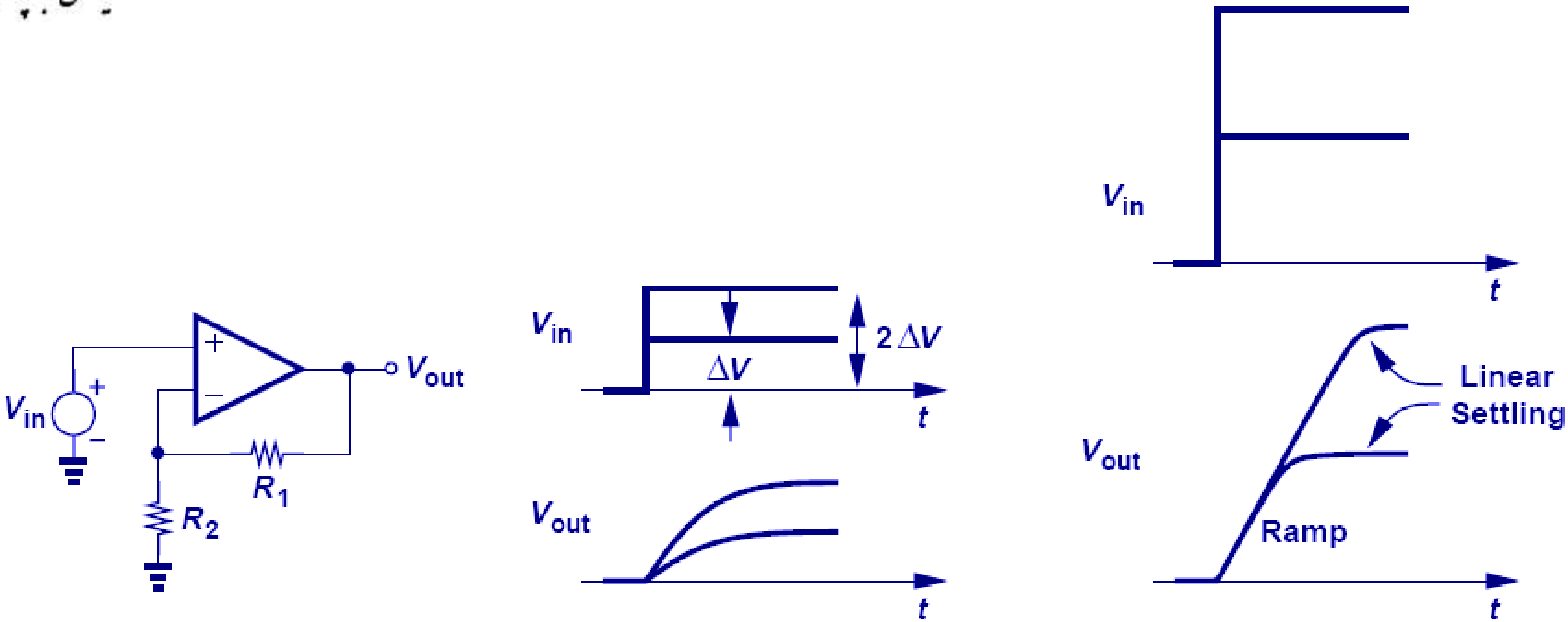
- **Due to internal capacitances, the gain of op amps begins to roll off.**

Bandwidth and Gain Tradeoff



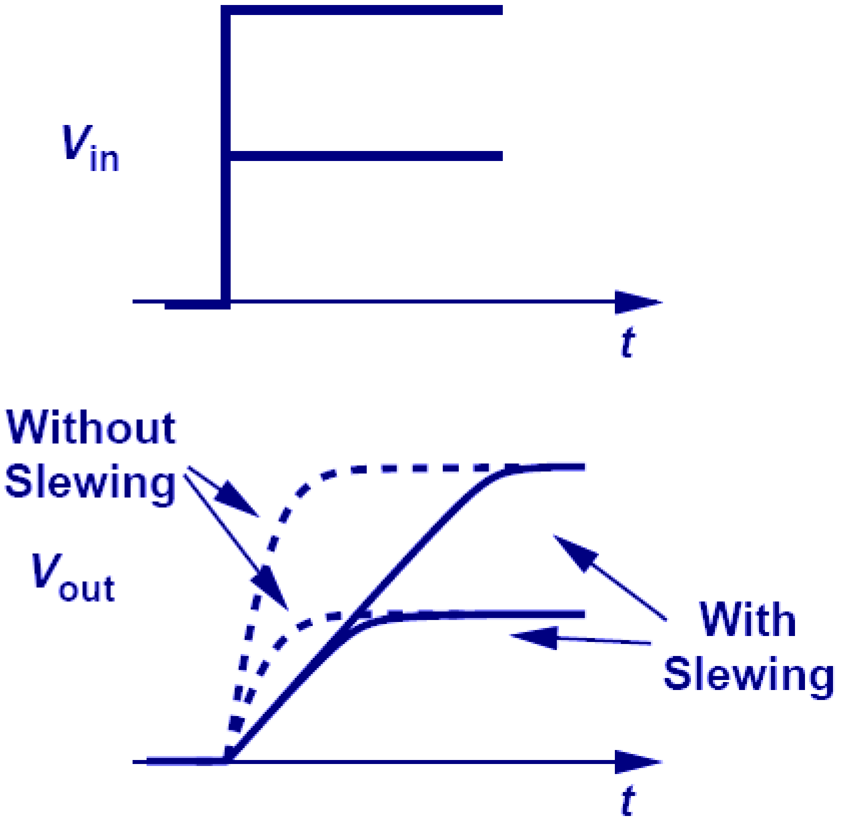
- Having a loop around the op amp (inverting, noninverting, etc) helps to increase its bandwidth. However, it also decreases the low frequency gain.

Slew Rate of Op Amp



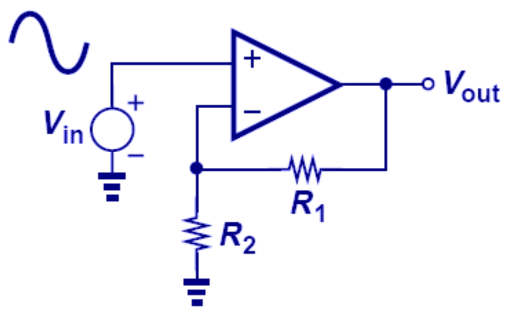
- **In the linear region, when the input doubles, the output and the output slope also double. However, when the input is large, the op amp slews so the output slope is fixed by a constant current source charging a capacitor.**
- **This further limits the speed of the op amp.**

Comparison of Settling with and without Slew Rate

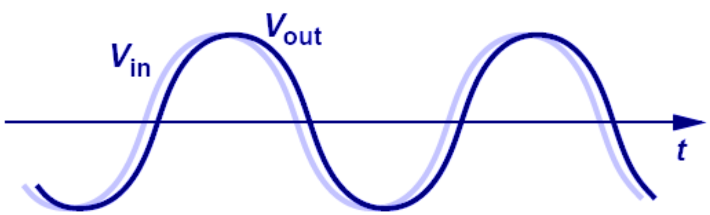


- **As it can be seen, the settling speed is faster without slew rate (as determined by the closed-loop time constant).**

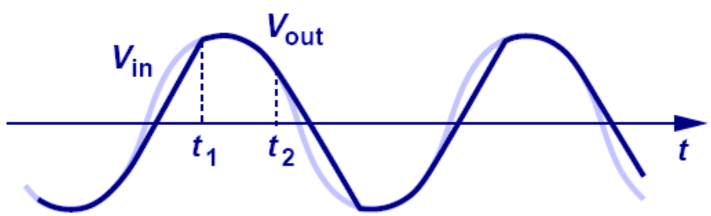
Slew Rate Limit on Sinusoidal Signals



(a)



(b)

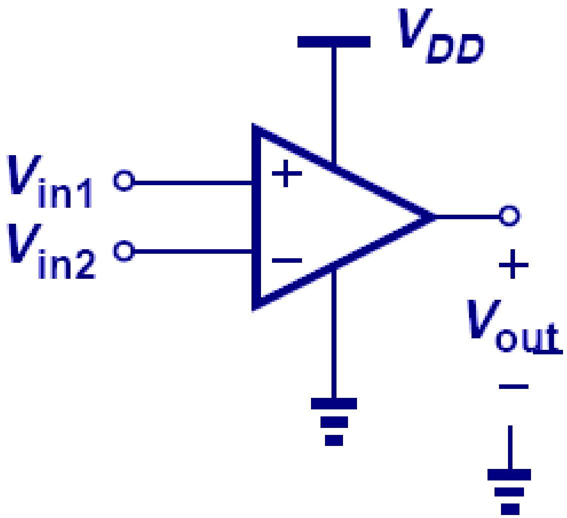


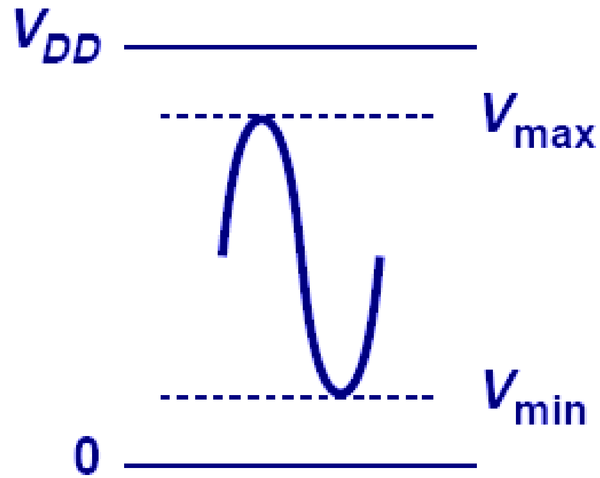
(c)

$$\frac{dV_{out}}{dt} = V_0\left(1+\frac{R_1}{R_2}\right)\omega\cos\omega t$$

- As long as the output slope is less than the slew rate, the op amp can avoid slewing.
- However, as operating frequency and/or amplitude is increased, the slew rate becomes insufficient and the output becomes distorted.

Maximum Op Amp Swing

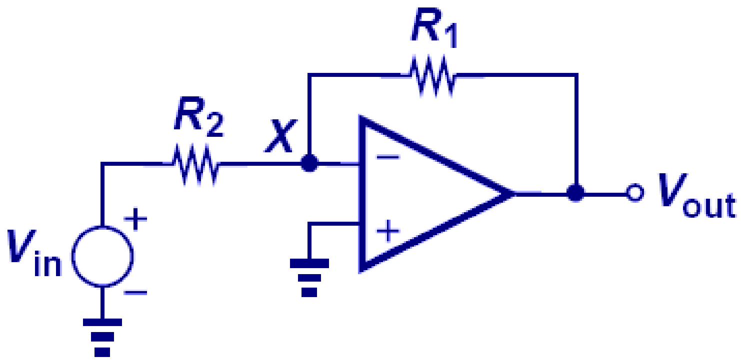


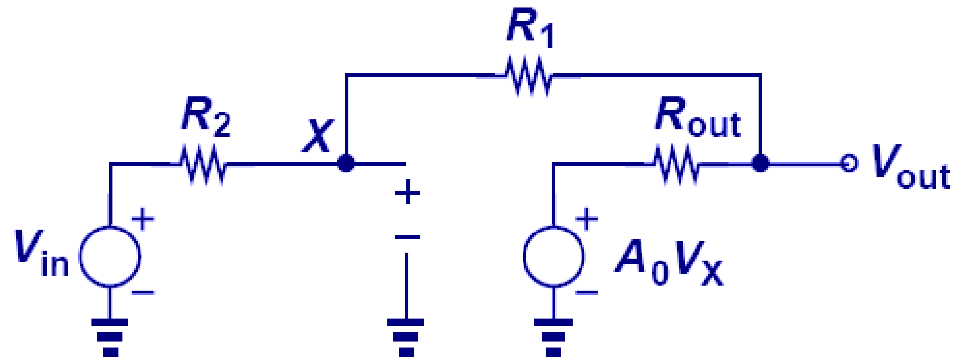


$$V_{out} = \frac{V_{max} - V_{min}}{2} \sin \omega t + \frac{V_{max} + V_{min}}{2} \qquad \omega_{FP} = \frac{SR}{\frac{V_{max} - V_{min}}{2}}$$

- **To determine the maximum frequency before op amp slews, first determine the maximum swing the op amp can have and divide the slew rate by it.**

Nonzero Output Resistance





$$\frac{v_{out}}{v_{in}} = -\frac{R_1}{R_2}\frac{A_0 - \dfrac{R_{out}}{R_1}}{1+\dfrac{R_{out}}{R_2}+A_0+\dfrac{R_1}{R_2}}$$

- **In practical op amps, the output resistance is not zero.**
- **It can be seen from the closed loop gain that the nonzero output resistance increases the gain error.**

Design Examples

- Many design problems are presented at the end of the chapter to study the effects of finite loop gain, restrictions on peak to peak swing to avoid slewing, and how to design for a certain gain error.

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