EE 230
Lecture 17

Nonideal Op Amp Characteristics

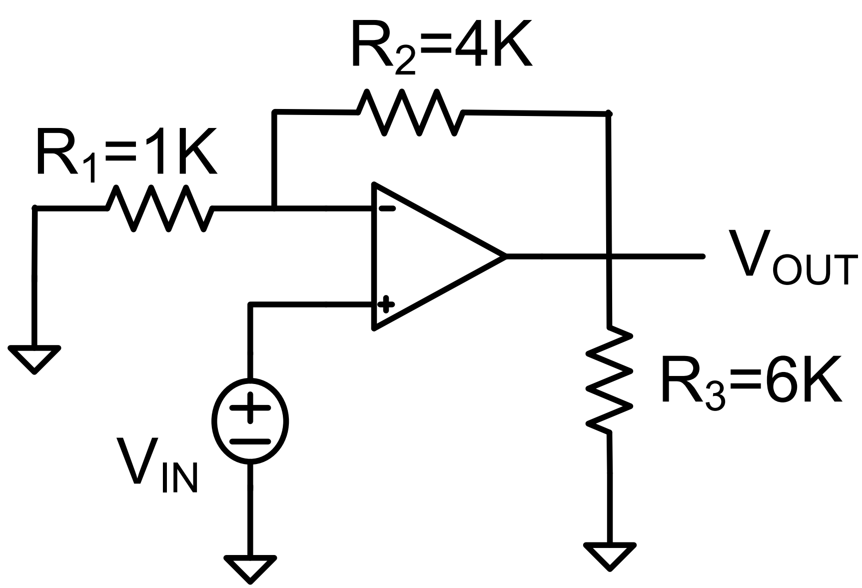
Quiz 11

The dc gain of this circuit was measured to be 5 and the 3dB bandwidth was measured to be 600KHz. Determine as many of the following as possible from this information if it is known that the op amp can be modeled as a single-pole lowpass amplifier.

Ao (dc gain of the Op Amp)

P (pole of the Op Amp)

GB (gain-bandwidth product of Op Amp)



And the number is ?

1

3

8

5

4

2

6

9

7

And the number is ?

1 3 8

5 5 4

2 6

9 7

Quiz 11 Solution:

The dc gain of this circuit was measured to be 5 and the 3dB bandwidth was measured to be 600KHz. Determine as many of the following as possible from this information if it is known that the op amp can be modeled as a single-pole lowpass amplifier.

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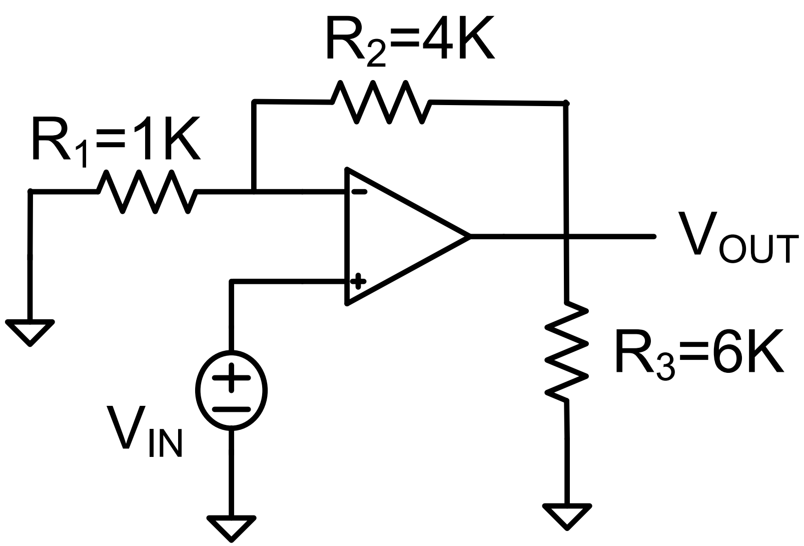
GB (gain-bandwidth product of Op Amp)

Insufficient information to determine A_o or GB



$$GB = K_o BW = \left(1 + \frac{R_2}{R_1}\right) BW$$

Quiz 11 Solution:

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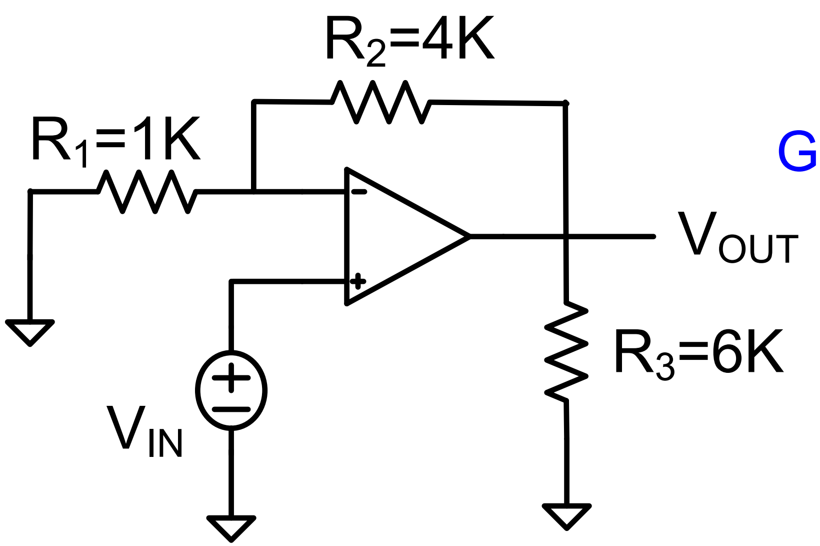
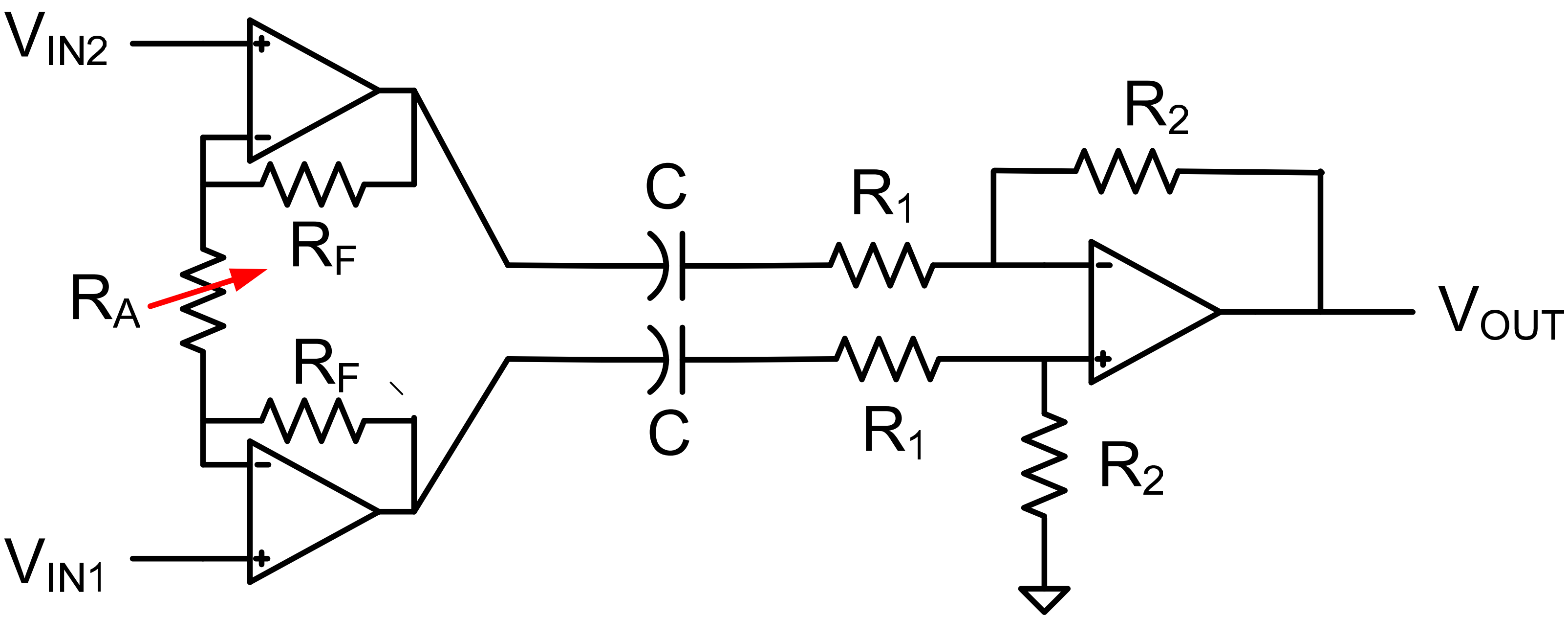


$$GB = K_o BW = \left(1 + \frac{R_2}{R_1}\right) BW$$

$$GB = 5 \bullet 600KHz = 3MHz = (18.8M\,Rad/Sec)$$

Differential Amplifiers

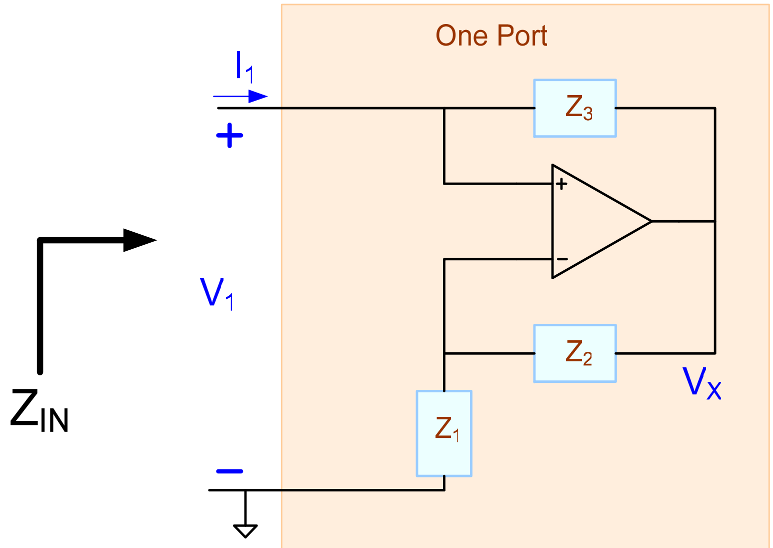
Instrumentation Amplifier



- Can reduce effects of dc offset if gain must be very large
- Must pick C to that frequencies of interest are in passband

Review from Last Time

Impedance Converters



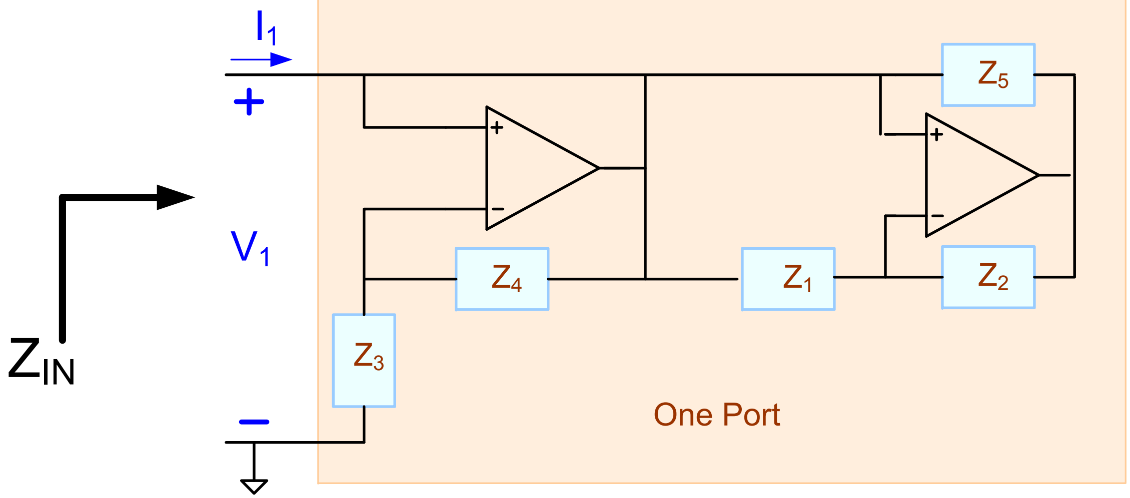
$$\left.\begin{aligned} V_1\left(G_1+G_2\right) &= V_X G_2 \\ I_1 &= \left(V_1-V_X\right)G_3 \end{aligned}\right\}$$

$$Z_{IN} = -\frac{Z_1 Z_3}{Z_2}$$

Observe this input impedance is negative!

Review from Last Time

Impedance Converters



$$Z_{IN} = \frac{Z_1 Z_3 Z_5}{Z_2 Z_4}$$

If Z_1=Z_3=Z_4= Z_5=R and Z_2=1/sC $\quad Z_{IN} = \left(R^2C\right)s \quad$ This is an inductor of value $L=R^2C$

If $Z_2=R_2$, $Z_3=R_3$, $Z_4=R_4$, $Z_5=R_5$ and Z_1=1/sC $\quad Z_{IN} = \dfrac{R_3R_5}{sCR_2R_4}$

This is a capacitor of value $\quad C_{EQ} = C\dfrac{R_2R_4}{R_3R_5} \quad$ (can scale capacitance up or down)

If Z_2=Z_4= Z_5=R and Z_1=Z_3=1/sC $\quad Z_{IN} = \left(R^3C^2\right)s^2 \quad$ This is a “super” capacitor of value R^3C^2

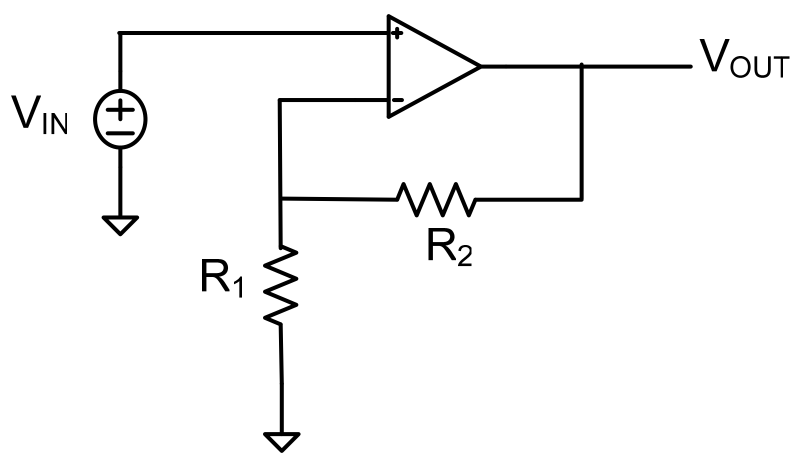
This circuit is often called a Gyrator

Nonideal Properties of Operational Amplifiers

In even the most basic applications, the laboratory performance of the circuit often differs dramatically from what is predicted for some op amps.

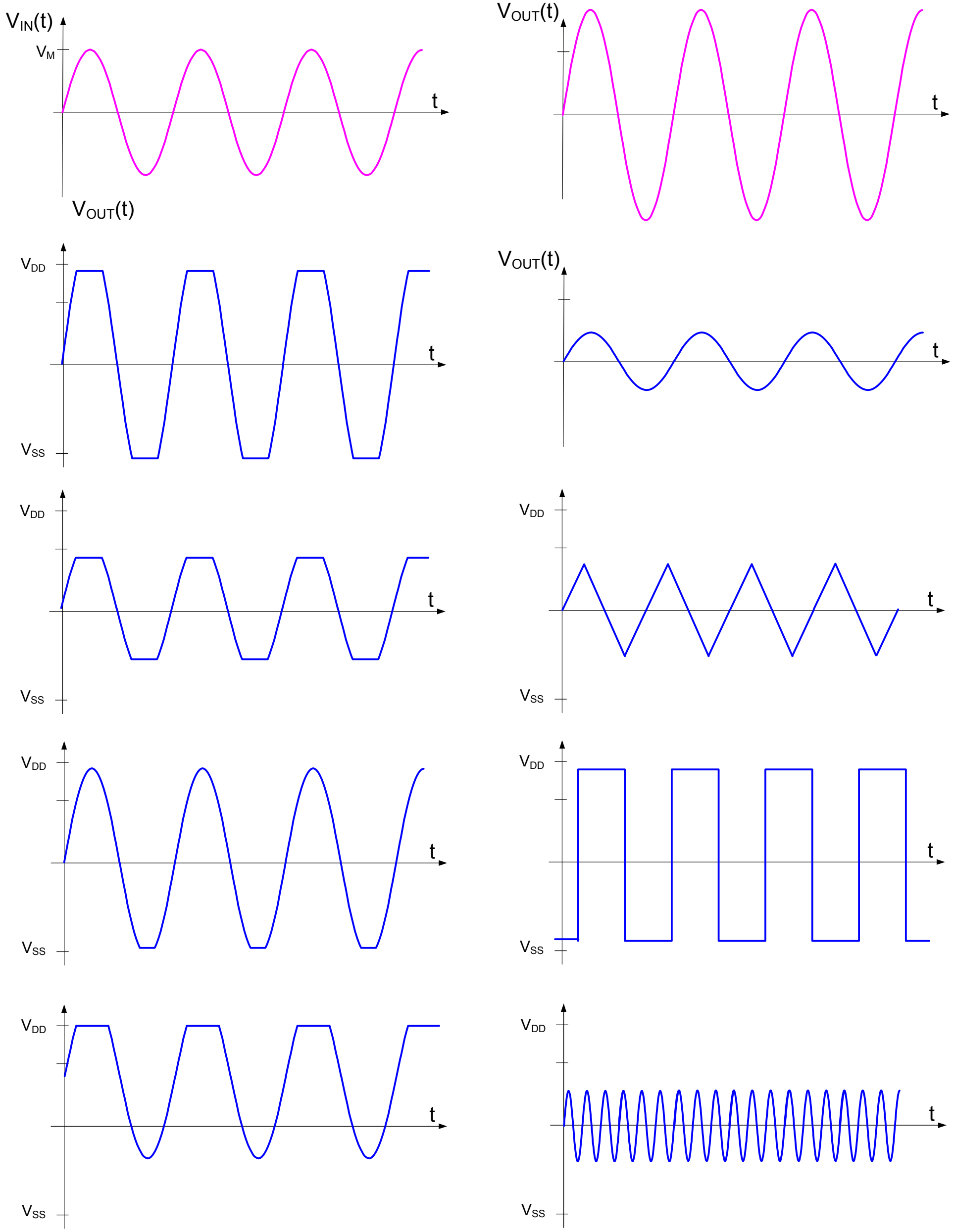
With proper knowledge of the characteristics of the op amp, designers can usually design circuits that behave almost like what is expected with ideal op amps

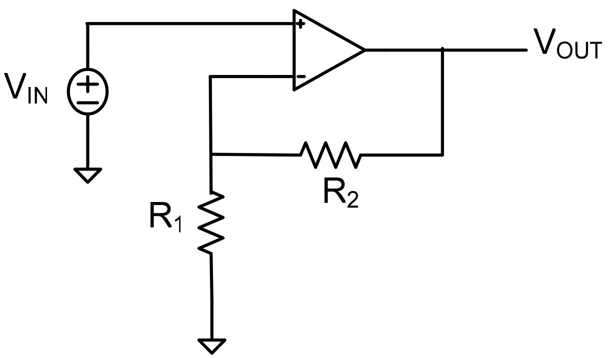
Essential to know nonideal properties of the op amp and how to manage them to be an effective design engineer



Review from Last Time

Some of the more common nonideal effects in Op Amp circuits





Will try to identify the source cause of all of these problems and how they can be resolved

Inventor of two-stage Op Amp

Robert Widlar

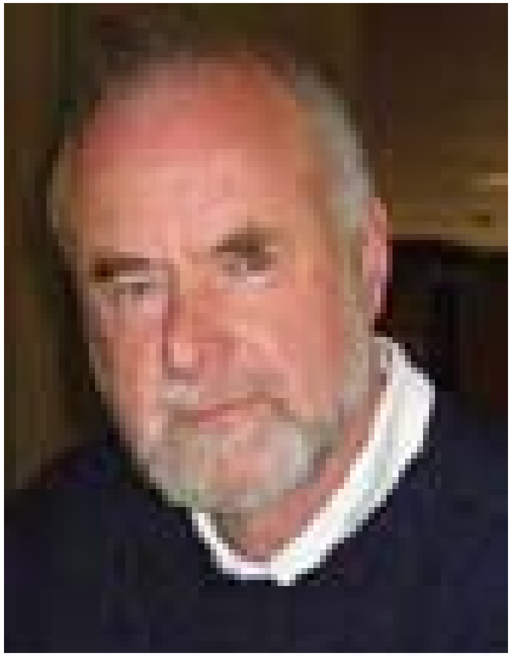
(considered by many as the most brilliant integrated circuit designer ever)

Widlar began his IC career at Fairchild semiconductor in Sept 63 at age of approx 26 where he designed several pioneering op amps. By 1966, the commercial success of his designs became apparent, and Widlar asked for a raise. He was turned down, and jumped ship to the fledgling National Semiconductor. At National he continued to turn out amazing designs, and was able to retire just before his 30th birthday in 1970.

Review from Last Time

Inventor of the internally-compensated Op Amp

Dave Fullagar



(from posted www site)

- Joined Fairchild in Jan 1966 and asked to design an op amp
- His design was the first internally-compensate op amp, the 741
- Fullagar was 26 years old when this was designed (introduced) in 1968
- Largest selling integrated circuit ever
- Still in high-volume production even though over 40 years old
- Fullagar later started the linear design activities at Intersil
- Cofounder (catalyst) of Maxim

Nonideal Op Amp Characteristics

- Absolute Maximum Ratings
- Electrical Characteristics
  - AC
  - DC

These are in the data sheets of the op amps along with connection information, occasionally application information, connection information, and sometimes even information about the design

Application notes, available from almost all manufacturers, often give more general information, definitions, more extensive application information, and other useful details.

Review from Last Time

Widely Varying Performance Characteristics (selected comparison)

Model	Type	Supply Min (V)	Supply Max (V)	Output Current (mA)	Supply Current/ Channel (mA)	GB (MHz)	Power (mW)	Min Price $	Max Price $
LMP2234 (quad)	Micro-power	1.6	5	5	.009	0.13	.056[1]	1.93	2.40
LM741	General Purpose	10	36	25	1.7	1.0	60[2]	0.25	11.40
LM3886	Power	18	84	11,500	50	3.0	125000[2]	3.30	
LMP 2231	Low Voltage	1.6	5.1	5	.01	0.13	.018[1]	0.95	1.40
LMH 6624	High Speed	5	12	100	11.4	1500	72	1.86	

[1] Minimum   [2] Maximum

Review from Last Time

Nonideal Op Amp Characteristics

Critical Parameters

- Gain-Bandwidth Product (GB)
- Offset Voltage
- Input Voltage Range
- Output Voltage Range
- Output Saturation Current
- Slew Rate

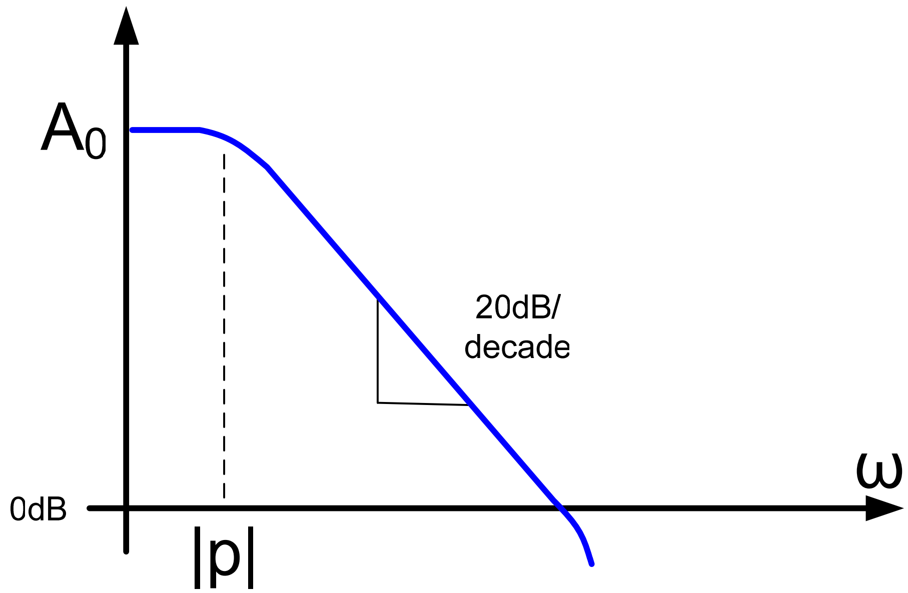
Usually Less Critical Parameters

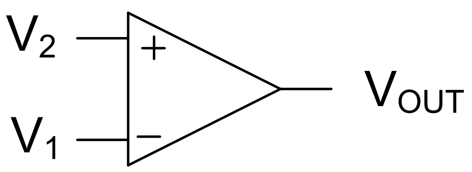
- DC voltage gain , A_0
- 3dB Bandwidth, BW

$\left.\begin{array}{l} \\ \end{array}\right\} GB=A_0BW$

- Common Mode Rejection Ratio (CMRR)
- Power Supply Rejection Ratio (PSRR)
- R_{IN} and R_{OUT}
- Bias Currents
- Full Power Bandwidth
- Compensation

Gain, Bandwidth and GB





$$A(s)=\frac{V_{OUT}}{V_2-V_1}$$

$$BW = -p$$

$$A(s)=\frac{A_0(-p)}{s-p}$$

Since $GB=A_0(-p)$

Alternatively $A(s)=\frac{GB}{s-p}$

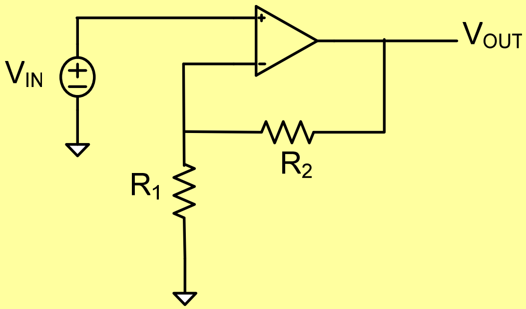
Almost all op amps are designed to have a first-order response down to unity gain

GB is one of the most important parameters in many op amp applications !

Review from Last Time

Gain, Bandwidth and GB

Summary of Effects of GB on Basic Inverting and Noninverting Amplifiers

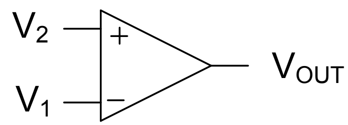


Basic Noninverting Amplifier

$$K_0 = 1 + \frac{R_2}{R_1}$$

$$BW = \frac{GB}{K_0}$$

$$A_{FB}(s) = \frac{K_0}{1 + s\dfrac{K_0}{GB}}$$

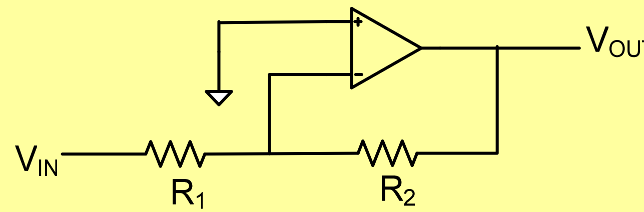


$$A_1(s) = \frac{GB}{s + BW_A}$$

$$GB = A_0 \bullet BW_A$$

$$A(s) = \frac{GB}{s}$$

Adequate model for most applications

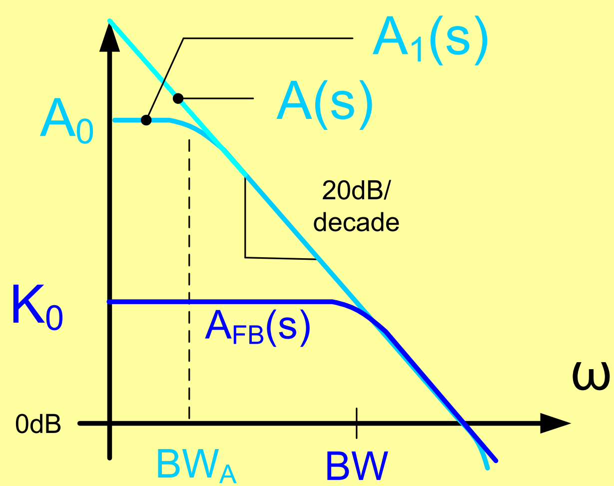


Basic Inverting Amplifier

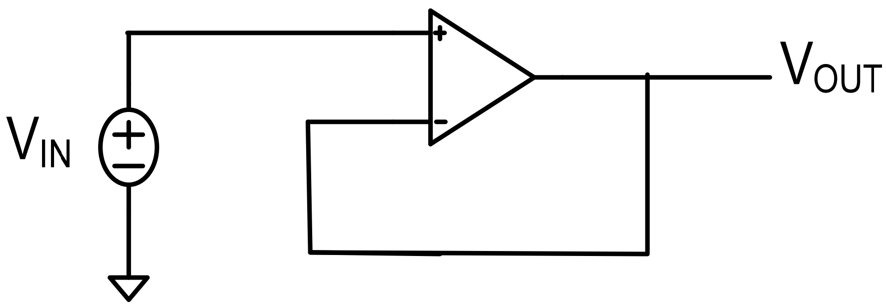
$$K_0 = \frac{R_2}{R_1}$$

$$BW = \frac{GB}{1 + K_0}$$

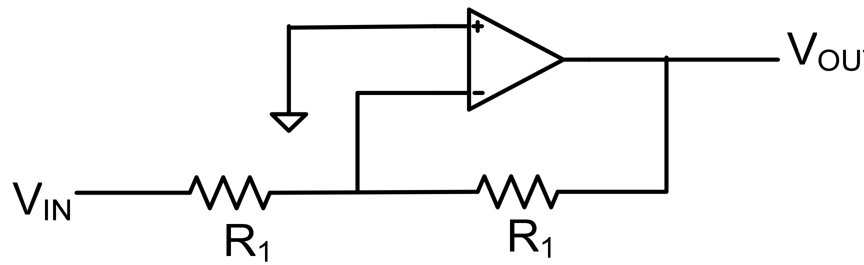
$$A_{FB}(s) = -\frac{K_0}{1 + s\dfrac{(1 + K_0)}{GB}}$$



Example: Compare the closed-loop BW for an inverting and noninverting amplifier where the magnitude of the closed loop gain is 1. Assume the op amp GB is 2 MHz.



Noninverting Amplifier



Inverting Amplifier

$$BW = \frac{GB}{K_0}$$

$$BW = \frac{GB}{1+K_0}$$

$$BW = \frac{2MHz}{1} = 2MHz$$

$$BW = \frac{2MHz}{1+1} = 1MHz$$

Note the difference in BW is significant when the gain is small !

Measurement of GB

Most direct: measure A_o $\Rightarrow$ $GB=A_o\omega_b$

measure ω_b

A_o is difficult to measure (and exact value usually not of concern)

ω_b is difficult to measure (and exact value seldom of concern)

Direct method of determining GB is not practical

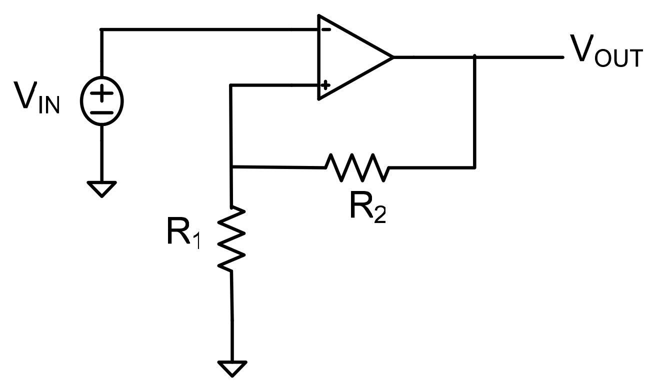
If a circuit is adversely affected be a parameter, then this circuit is often useful for measuring that parameter provided relationship between performance and parameter is determined/known.

Strategy for Measuring GB

1. Build FB noninverting amplifier with gain K_o

2. Measure BW

3. $GB=(K_0)(BW)$



Keep gain (K_0) quite large (maybe 100) and amplitude small enough so there is no SR distortion. With large K_0, frequency where gain drops 3dB will be small enough that it can be accurately measured.

Example: If an op amp has a GB of 1MHz and a dc gain of a closed loop amplifier of 1000, what is the BW of the closed loop amplifier?

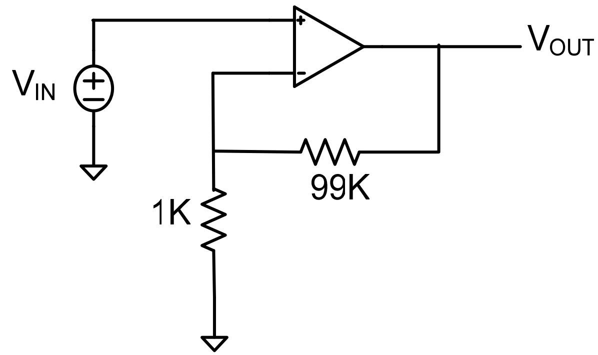
Solution: $$\mathrm{BW} = \frac{\mathrm{GB}}{\mathrm{K_o}} = \frac{1\mathrm{MHz}}{1000} = 1\mathrm{kHz}$$

Example: Determine the maximun dc gain of a noninverting FB amplifier if designed with an OA with GB=1MHz, if the closed loop BW must be greater than 20 kHz.

Solution: $$\mathrm{K_0 BW} = \mathrm{GB} \Rightarrow \mathrm{K_o} = \frac{\mathrm{GB}}{\mathrm{BW}} = \frac{1\,\mathrm{MHz}}{20\mathrm{kHz}} = 50$$

Example:

If the input to the amplifier is .01sin(2π10000t), determine the actual and desired output if the op amp is the LMP2231 biased with +/- 2.5V supplies.



The desired output is $\left(1+\frac{R_2}{R_1}\right)V_{IN}=100V_{IN}=\sin\left(2\pi\bullet 10000t\right)$

$$BW=\frac{GB}{K_0}=\frac{GB}{100}$$

Need GB to determine if BW is limiting performance of circuit

December 18, 2008

National Semiconductor

LMP2231 Single Micropower, 1.6V, Precision Operational Amplifier with CMOS Inputs

General Description

The LMP2231 is a single micropower precision amplifier designed for battery powered applications. The 1.6V to 5.5V operating supply voltage range and quiescent power consumption of only 16 µW extend the battery life in portable battery operated systems. The LMP2231 is part of the LMP® precision amplifier family. The high impedance CMOS input makes it ideal for instrumentation and other sensor interface applications.

The LMP2231 has a maximum offset of 150 µV and maximum offset voltage drift of only 0.4 µV/°C along with low bias current of only ±20 fA. These precise specifications make the LMP2231 a great choice for maintaining system accuracy and long term stability.

The LMP2231 has a rail-to-rail output that swings 15 mV from the supply voltage, which increases system dynamic range.

Features

(For V_S = 5V, Typical unless otherwise noted)

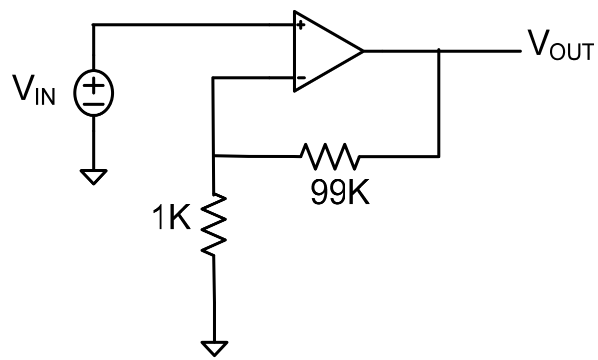
- Supply current 10 µA
- Operating voltage range 1.6V to 5.5V
- Low TCV_{OS} ±0.4 µV/°C (max)
- V_{OS} ±150 µV (max)
- Input bias current 20 fA
- PSRR 120 dB
- CMRR 97 dB
- Open loop gain 120 dB
- Gain bandwidth product 130 kHz
- Slew rate 58 V/ms
- Input voltage noise, f = 1 kHz 60 nV/√Hz
- Temperature range –40°C to 125°C

5V AC Electrical Characteristics (Note 4) Unless otherwise specified, all limits guaranteed for $T_A = 25°C$, $V^+ = 5V$, $V^- = 0V$, $V_{CM} = V_O = V^+/2$, and $R_L > 1$ MΩ. **Boldface** limits apply at the temperature extremes.

Symbol	Parameter	Conditions		Min (Note 6)	Typ (Note 5)	Max (Note 6)	Units
GBW	Gain-Bandwidth Product	C_L = 20 pF, R_L = 10 kΩ			130		kHz
SR	Slew Rate	A_V = +1	Falling Edge	33 **32**	58		V/ms
			Rising Edge	33 **32**	48		
θ_m	Phase Margin	C_L = 20 pF, R_L = 10 kΩ			78		deg
G_m	Gain Margin	C_L = 20 pF, R_L = 10 kΩ			27		dB
e_n	Input-Referred Voltage Noise Density	f = 1 kHz			60		$nV/\sqrt{Hz}$
	Input-Referred Voltage Noise	0.1 Hz to 10 Hz			2.3		μV_{PP}
i_n	Input-Referred Current Noise	f = 1 kHz			10		$fA/\sqrt{Hz}$
THD+N	Total Harmonic Distortion + Noise	f = 100 Hz, R_L = 10 kΩ			0.002		%

Example:

If the input to the amplifier is .01sin(2π10000t), determine the actual and desired output if the op amp is the LMP2231 biased with +/- 2.5V supplies.



$$V_{OUTDesired} = \sin(2\pi \bullet 10000t)$$

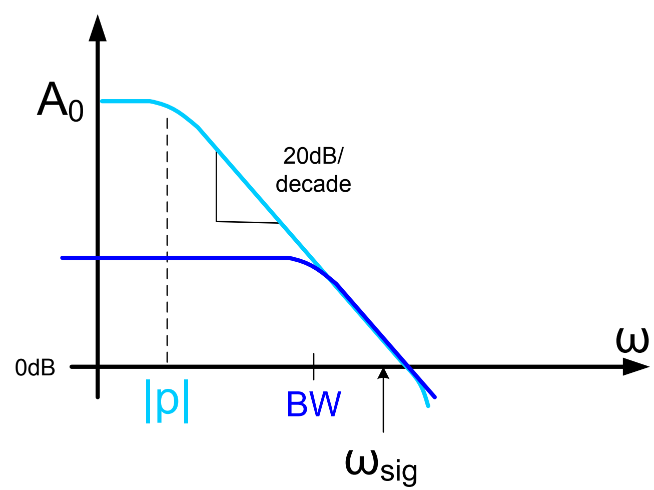
$$\omega_{SIG} = 2\pi \bullet 10000$$

$$\text{BW} = \frac{\text{GB}}{100} = \frac{130KHz}{100} = 1.3KHz$$

Thus input frequency is somewhat higher than band edge

$$A_{FB}(s) = \frac{K_0}{1+\frac{K_0}{GB}s}$$

$$A_{FB}(s) = \frac{100}{1+\frac{100}{2\pi \bullet 10000}s}$$



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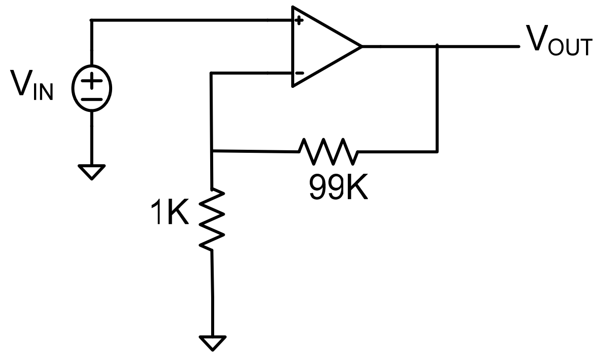

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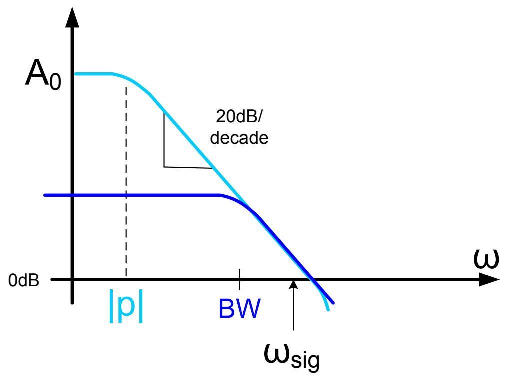


$$A_{FB}(s) = \frac{100}{1+\dfrac{100}{2\pi \bullet 10000}s}$$

$$A_{FB}(j\omega) = \frac{100}{1+\dfrac{100}{2\pi \bullet 130000}j(2\pi \bullet 10000)}$$

$$A_{FB}(j\omega) = \frac{100}{1+j7.7}$$

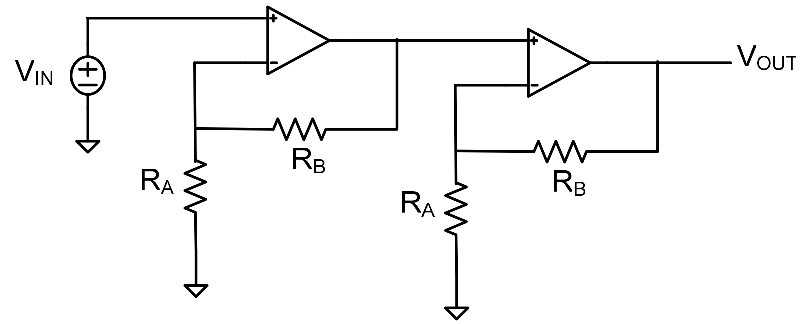
$$|A_{FB}(j\omega)| = \frac{100}{\sqrt{1+7.7^2}} = 12.9$$

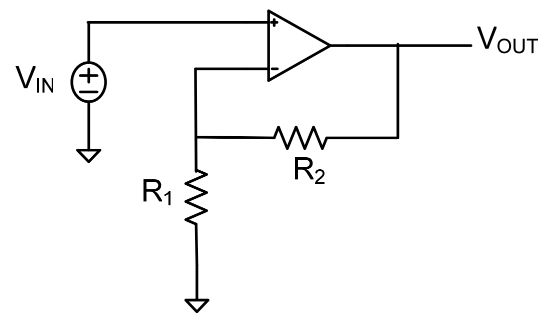
$$\angle A_{FB}(j\omega) = -\tan^{-1}\left(\frac{j7.7}{1}\right) = -82.6^o$$

$$V_{OUT} = .01 * 12.9 \sin(2\pi \bullet 10000t - 82.6^o)$$

$$V_{OUT} = .12 \sin(2\pi \bullet 10000t - 82.6^o)$$

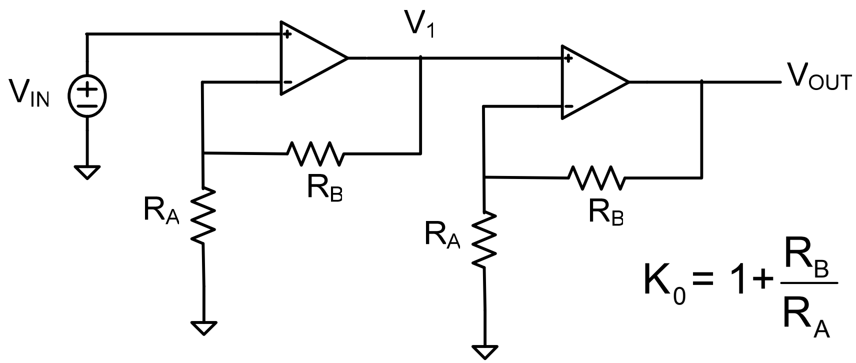
Addressing Bandwidth Limitations





If both amplifiers have the same total gain of A_{V0}=100, compare the bandwidths of the two amplifiers if the Op Amps all have the same GB

Addressing Bandwidth Limitations



$$K_0 = 1+\frac{R_B}{R_A}$$

$$A_{CASCADE} = \frac{V_{OUT}}{V_{IN}} = \frac{V_{OUT}}{V_1}\frac{V_1}{V_{IN}}$$

the frequency-dependent noninverting amplifier was derived earlier: $A_{FB}(s) = \dfrac{K_0}{1+s\dfrac{K_0}{GB}}$

$$A_{CASCADE}(s) = \left(\frac{K_0}{1+s\frac{K_0}{GB}}\right)\left(\frac{K_0}{1+s\frac{K_0}{GB}}\right)$$

the dc gain is given by

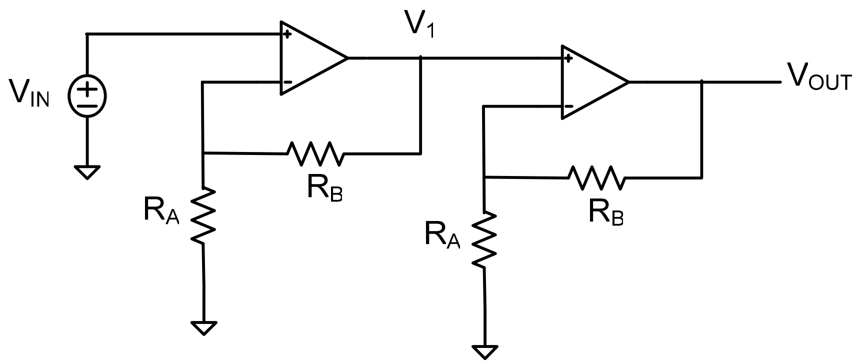
$$\left|A_{CASCADE}(j0)\right| = \left(\frac{K_0}{1+j0\frac{K_0}{GB}}\right)^2 = K_0^2 = 100$$

$$A_{CASCADE}(j\omega) = \left(\frac{K_0}{1+j\omega\frac{K_0}{GB}}\right)^2$$

to find the 3dB BW, must solve following

$$\frac{\left|A_{CASCADE}(j\omega)\right|}{\sqrt{2}} = \frac{K_0^2}{\sqrt{2}}$$

Addressing Bandwidth Limitations



$$\frac{|A_{CASCADE}(j\omega)|}{\sqrt{2}} = \frac{K_0^2}{\sqrt{2}}$$

where

$$K_0 = 1 + \frac{R_B}{R_A} = \sqrt{A_{v0}} = 10$$

but the gain magnitude of the cascade is given by

$$|A_{CASCADE}(j\omega)| = \left| \left(\frac{K_0}{1 + j\omega \frac{K_0}{GB}} \right)^2 \right| = \left| \left(\frac{K_0}{1 + j\omega \frac{K_0}{GB}} \right) \right|^2$$

$$|A_{CASCADE}(j\omega)| == \left| \left(\frac{K_0}{\sqrt{1 + \omega^2 \left(\frac{K_0}{GB} \right)^2}} \right) \right|^2 = \frac{K_0^2}{1 + \omega^2 \left(\frac{K_0}{GB} \right)^2}$$

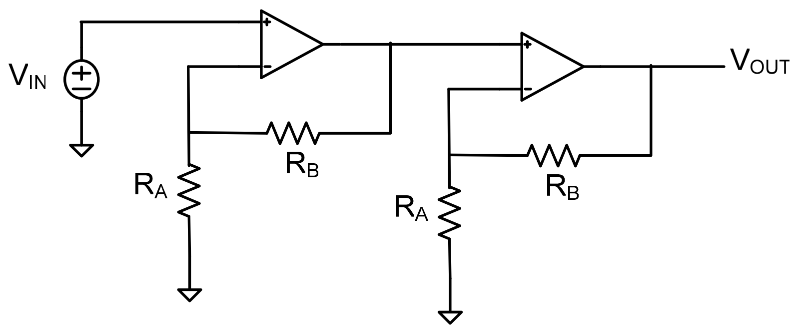
so, $BW_{CASCADE}$ is the solution of

$$\frac{K_0^2}{1 + \omega^2 \left(\frac{K_0}{GB} \right)^2} = \frac{K_0^2}{\sqrt{2}}$$

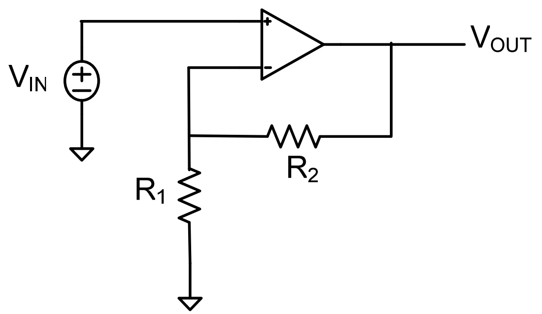
$$\omega = \left(\frac{\sqrt{\sqrt{2} - 1}}{K_0} \right) GB$$

$$\therefore \quad BW_{CASCADE} = \left(\frac{\sqrt{\sqrt{2} - 1}}{K_0} \right) GB$$

Addressing Bandwidth Limitations



$$BW_{CASCADE} = GB\sqrt{\frac{\sqrt{2}-1}{A_{V0}}}$$



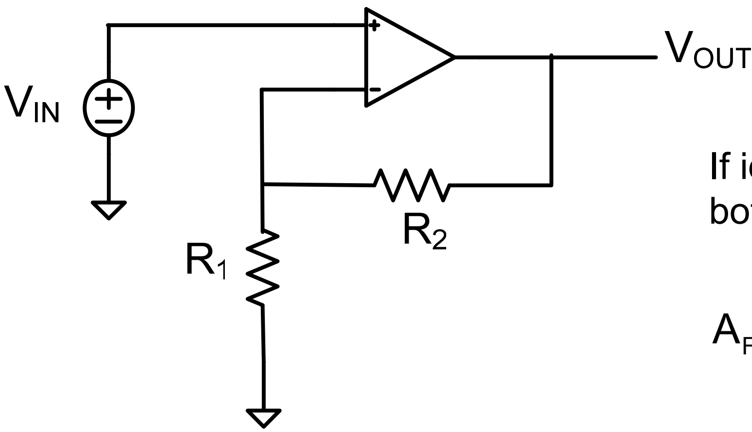
$$BW = \frac{GB}{A_{V0}}$$ (derived before)

Comparing the bandwidths with the same $A_{V0}=100$, obtain

$$BW_{CASCADE} = GB\sqrt{\frac{\sqrt{2}-1}{100}} = .064GB \qquad BW = \frac{GB}{100} = .01GB$$

A major improvement in BW is possible if a large gain is required !
Even more improvement if more stages cascaded if gain is large

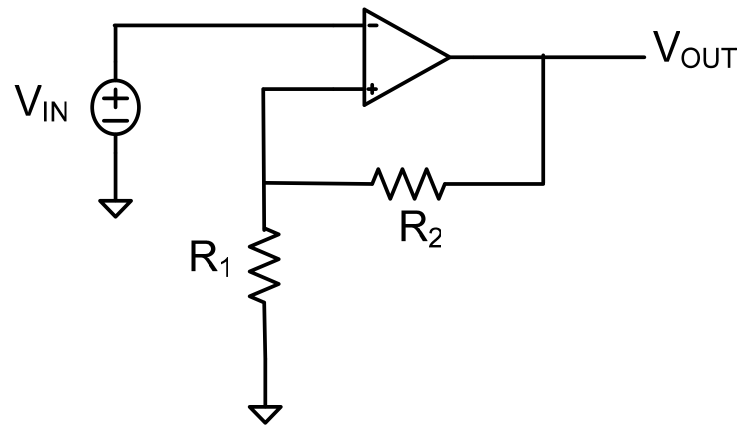
Determination of proper Op Amp orientation



Usually the good circuit

If ideal op amps both have gain

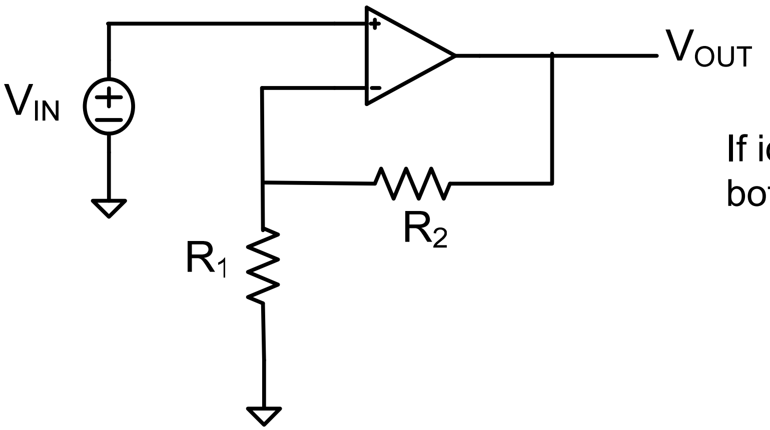
$$A_{FB}=1+\frac{R_2}{R_1}$$



Usually the bad circuit

Lets see what happens to the bad to determine if that will give insight into what the problem is

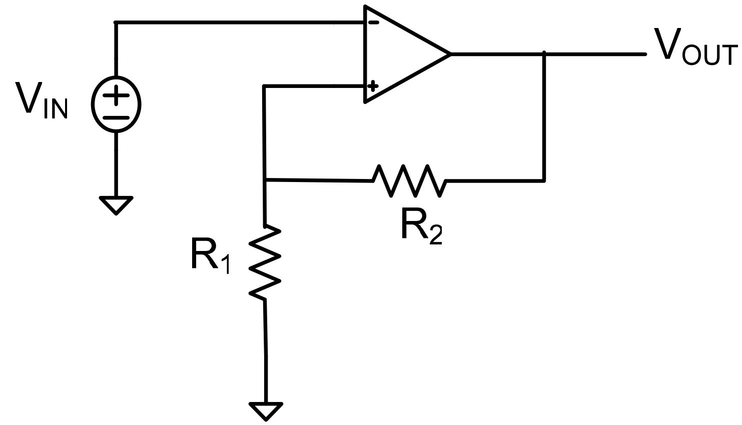
Determination of proper Op Amp orientation



Usually the good circuit

If ideal op amps both have gain

$$A_{FB}=1+\frac{R_2}{R_1}$$

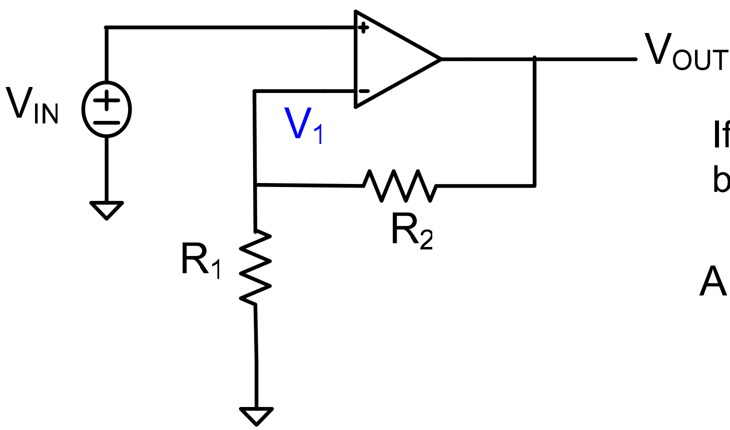


Usually the bad circuit

If configured as above, the circuit on the left will amplify the signal as desired and that on the right will latch up to either V_{DD} or V_{SS}

Sounds like it might be a stability problem associated with a pole on the positive real axis in the RHP

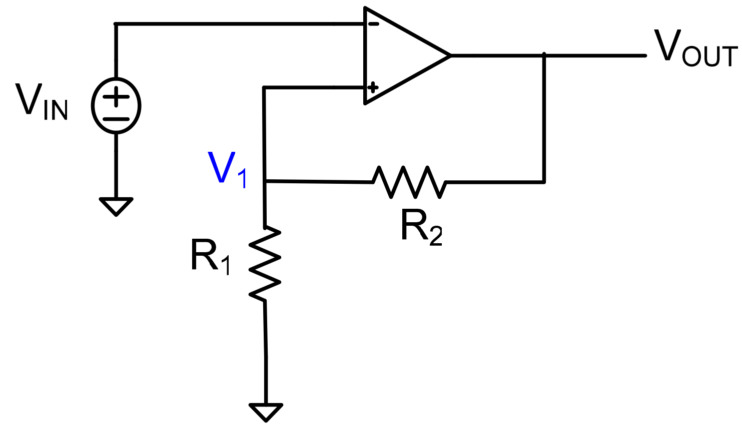
Determination of proper Op Amp orientation



Usually the good circuit

If ideal op amps both have gain

$$A_{FB} = 1 + \frac{R_2}{R_1} = \frac{1}{\beta}$$



Usually the bad circuit

Check stability with model of Op Amp

$$A(s) = \frac{GB}{s-p}$$

$$\left.\begin{aligned} V_1(G_1+G_2) &= V_{OUT}G_2 \\ V_{OUT} &= \frac{GB}{s-p}(V_{IN}-V_1) \end{aligned}\right\}$$

$$A_{FB}(s) = \frac{GB}{s-p+\left(\frac{R_1}{R_1+R_2}\right)GB}$$

$$A_{FB}(s) = \frac{GB}{s-p+\beta GB}$$

$$p_{FB} = p - \beta GB$$

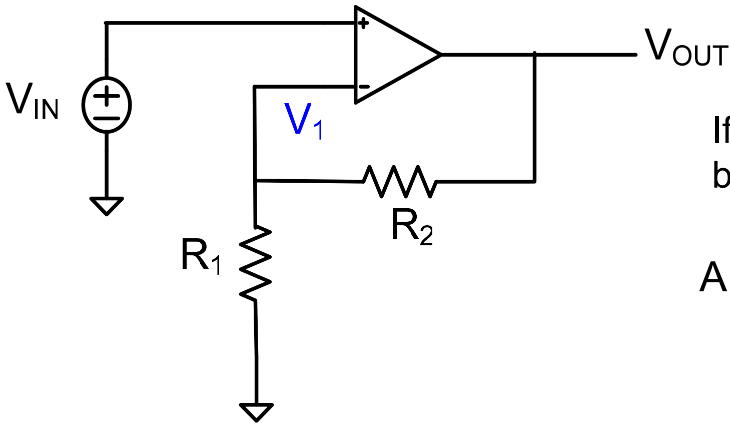
$$\left.\begin{aligned} V_1(G_1+G_2) &= V_{OUT}G_2 \\ V_{OUT} &= -\frac{GB}{s-p}(V_{IN}-V_1) \end{aligned}\right\}$$

$$A_{FB}(s) = \frac{-GB}{s-p-\left(\frac{R_1}{R_1+R_2}\right)GB}$$

$$A_{FB}(s) = \frac{-GB}{s-p-\beta GB}$$

$$p_{FB} = p + \beta GB$$

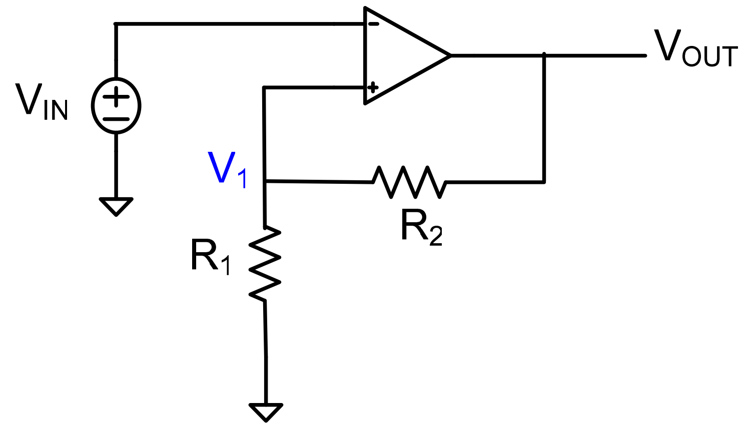
Determination of proper Op Amp orientation



Usually the good circuit

If ideal op amps both have gain

$$A_{FB} = 1 + \frac{R_2}{R_1} = \frac{1}{\beta}$$



Usually the bad circuit

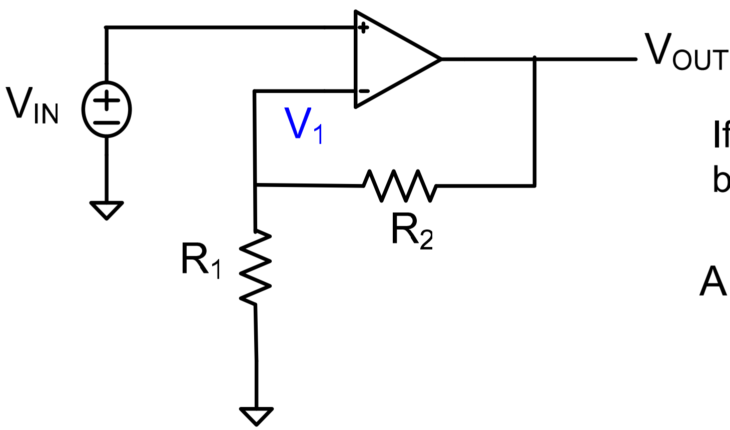
Check stability with model of Op Amp

$p_{FB} = p - \beta GB$

$p_{FB} = p + \beta GB$

Recall: A system is stable iff all poles of the system lie in the open LHP

Determination of proper Op Amp orientation

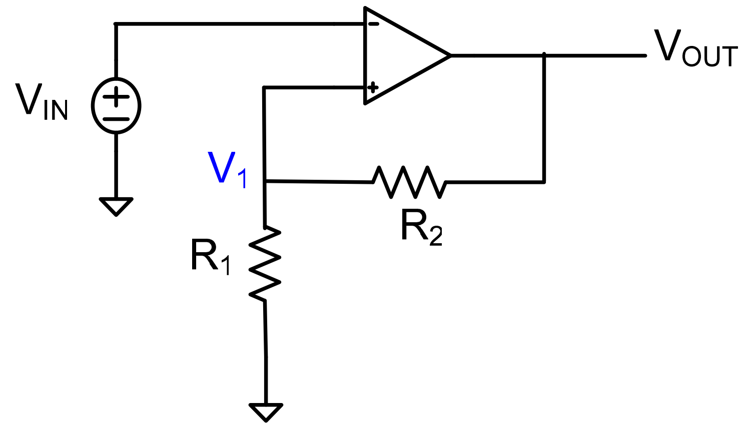


Usually the good circuit

If ideal op amps both have gain

$$A_{FB}=1+\frac{R_2}{R_1}=\frac{1}{\beta}$$

$$A(s)=\frac{GB}{s-p}$$



Usually the bad circuit

Check stability with model of Op Amp

$p_{FB}= p-\beta GB$

$p_{FB}= p+\beta GB$

Since p is negative, $p_{FB}<<0$

Although p negative, $p<<\beta GB$

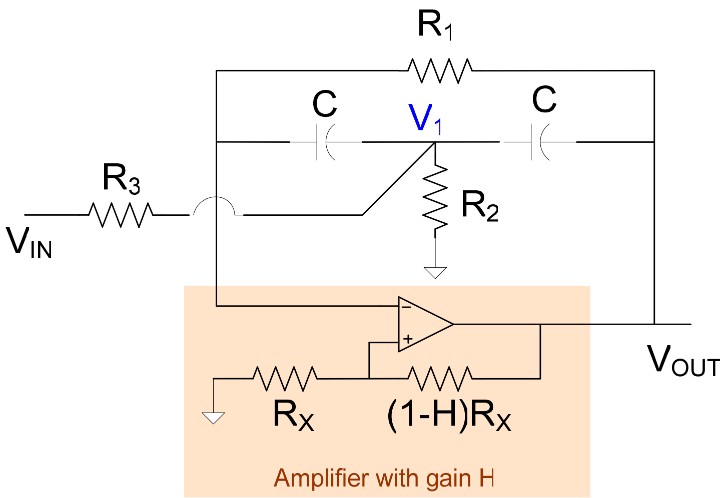
Pole far in LHP on negative real axis

Pole far in RHP on positive real axis !!

Thus, circuit on left is stable but one on right is unstable and thus not useful as an amplifier

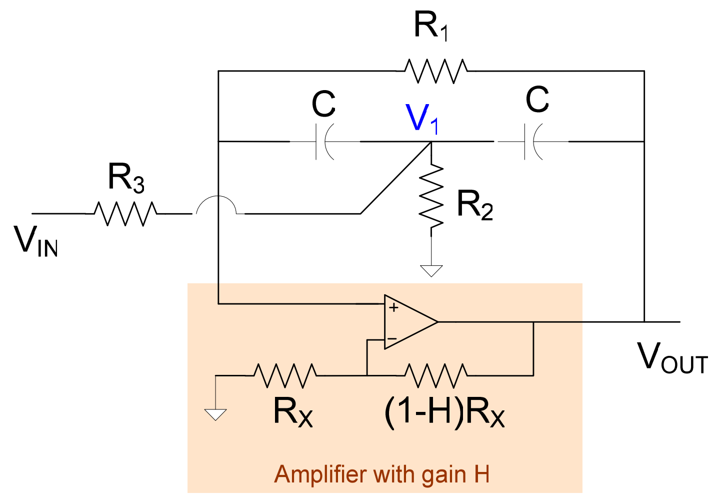
Would have observed same results with simpler model $A(s)=\frac{GB}{s}$

Determination of proper Op Amp orientation



The good circuit

$$A(s)=\frac{GB}{s}$$



The bad circuit

If we put in the model for A(s) we will find the circuit on the left has all poles in the LHP and the one on the right has a pole far in the RHP on the positive real axis

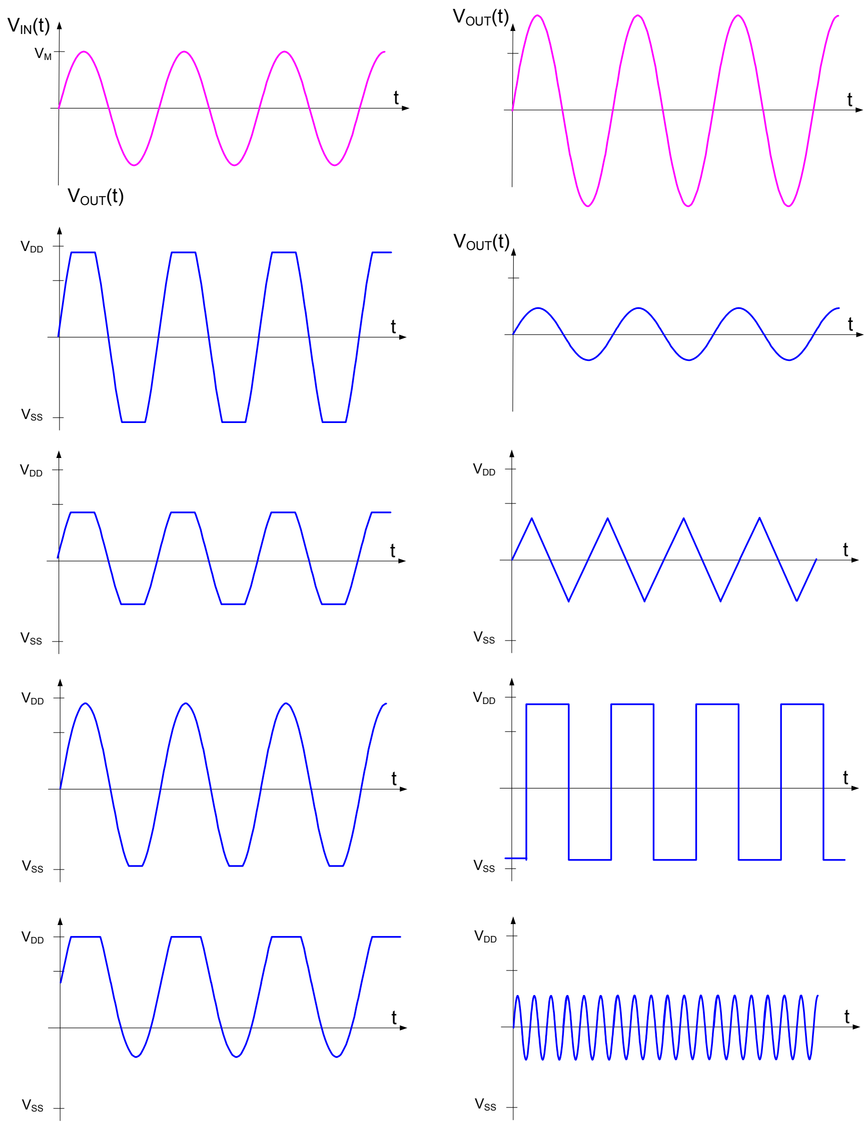
Determination of proper Op Amp orientation

Put in frequency dependent model for op amp $A(s)=\frac{GB}{s}$

in the OVERALL CIRCUIT and determine which orientation of the op amp has all poles in LHP

- In almost all op amp circuits of interest, there will be a unique op amp orientation that will provide a stable circuit
- This can be somewhat tedious if there are several op amps because they must all be oriented correctly
- Experience is useful at providing guidance on how to orient the op amps
- An unstable circuit can be embedded in a larger circuit that is stable and a stable circuit can be embedded in a larger circuit and make it unstable so can not consider only the stability of a subcircuit but rather must consider the overall circuit
- One of the major reasons the concept of stability was discussed in this course was to have a method of correctly orienting the op amps in op amp circuits

Stability Problems



Stability Problem

End of Lecture 17