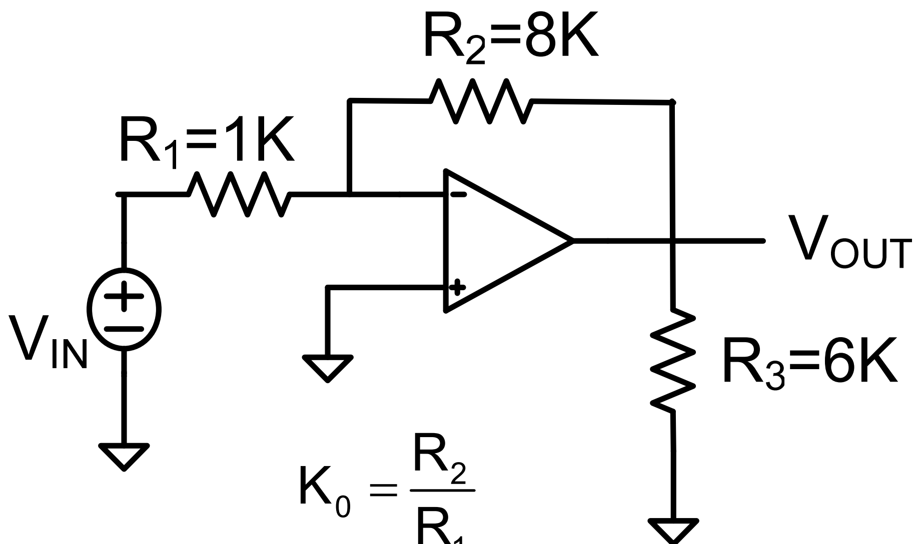
EE 230
Lecture 19

Nonideal Op Amp Characteristics

- Offset Voltage
- Common-mode input range
- Compensation

Quiz 13

The operational amplifier has a GB of 20MHz. Determine the 3dB bandwidth of the closed-loop amplifier.



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

And the number is ?

1 3 8

5 4

?

2 6

9 7

Slew Rate

The slew rate of an op amp is the maximum rate of change that can occur in the output voltage of an op amp

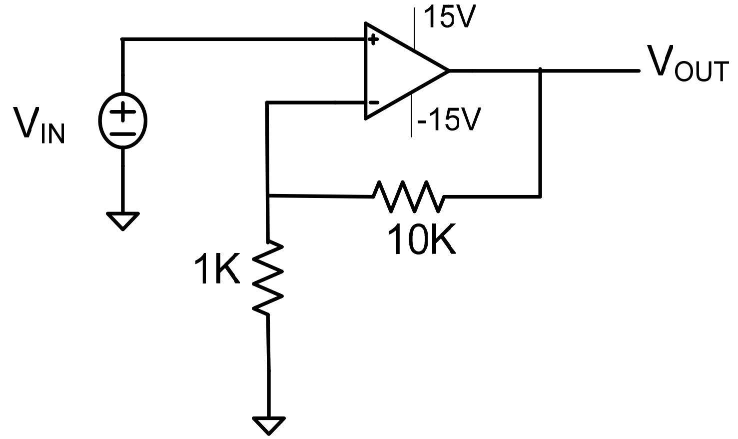
Usually the positive going slew rate and the negative going slew rate are the same

Slew rate is usually specified in the units of V/μsec

Slewing can occur in any circuit for any type of input waveform

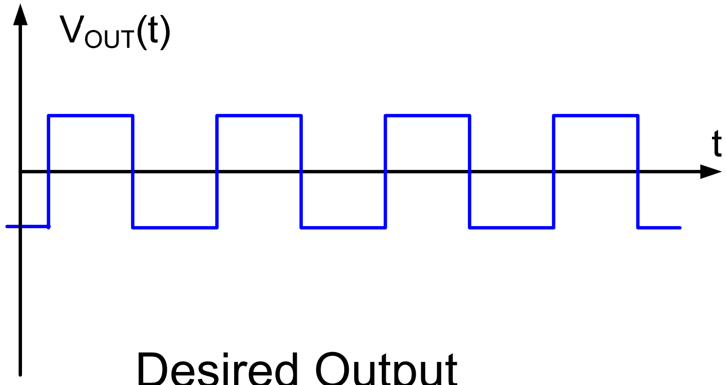
Slew is usually most problematic at higher frequencies when large output excursions are desired

Slew Rate

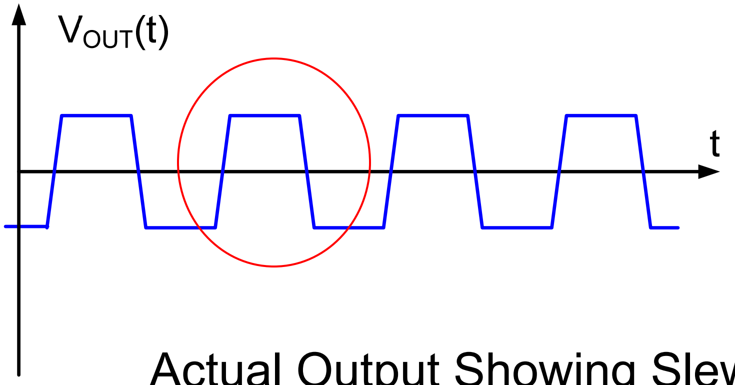


If V_{IN} is a square wave, this circuit will always exhibit slew rate limitations

Assume V_{IN} is a rather low amplitude, low frequency square wave

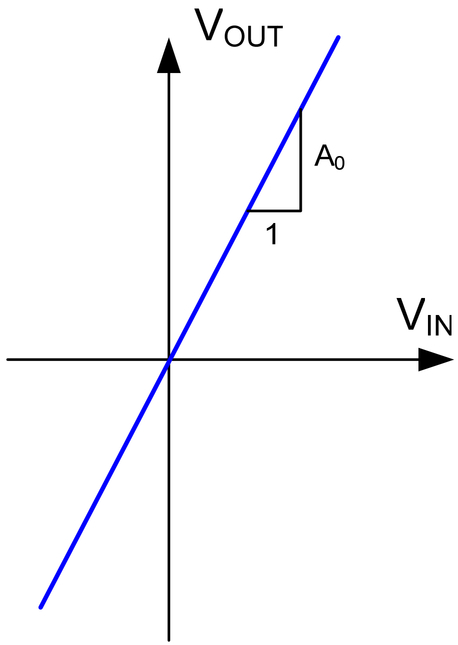


Desired Output

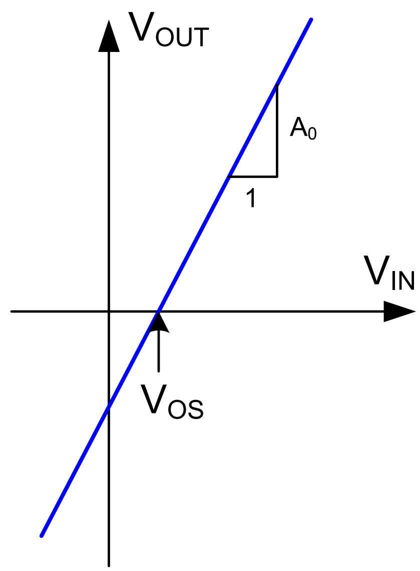


Actual Output Showing Slew

Offset Voltages



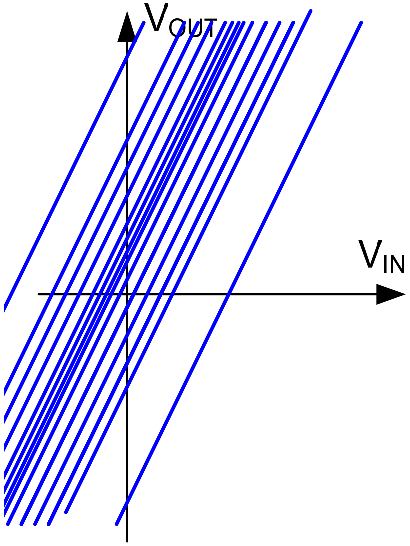
Ideal OA transfer characteristics



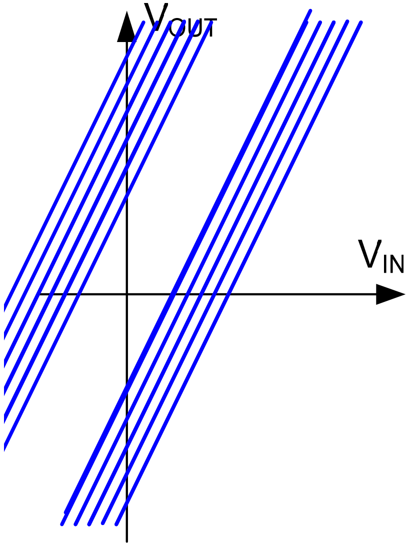
Actual typical OA transfer characteristics

A_0 is the dc gain of the Op Amp and is very large
V_{OS} is called the input offset voltage (or just offset voltage) and represents the dc shift from the ideal crossing at the origin
V_{OS} is a random variable at the design stage and varies from one device to another after fabrication
Can be positive or negative

Offset Voltages

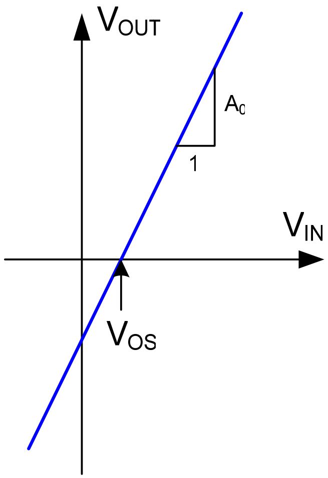


Typical distribution of transfer characteristics after fabrication

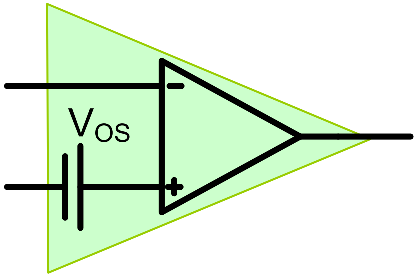


Distribution of commercial parts if premium parts have been removed

Offset Voltages



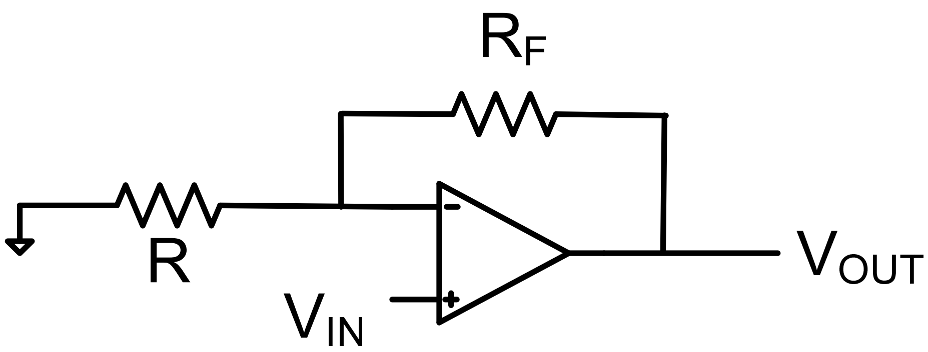
Model: $V_{OUT} = A_0 \left(V_{IN} - V_{OS} \right)$



Can be modeled with a dc voltage source in series with either terminal
Polarity of the source is not known on batch since can be positive or negative
Polarity of offset voltage for each individual op amp can be measured

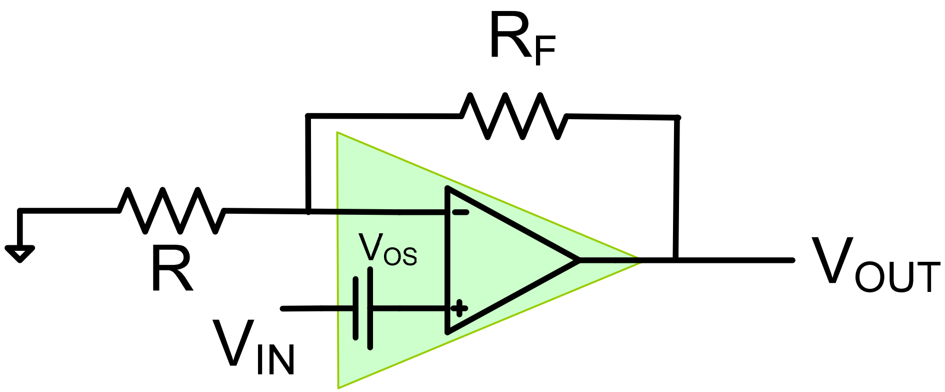
Offset Voltage

Consider a basic noninverting voltage amplifier



$$A_V = \frac{V_{OUT}}{V_{IN}} = 1 + \frac{R_F}{R}$$

If offset voltages are present



By superposition, it readily follows that

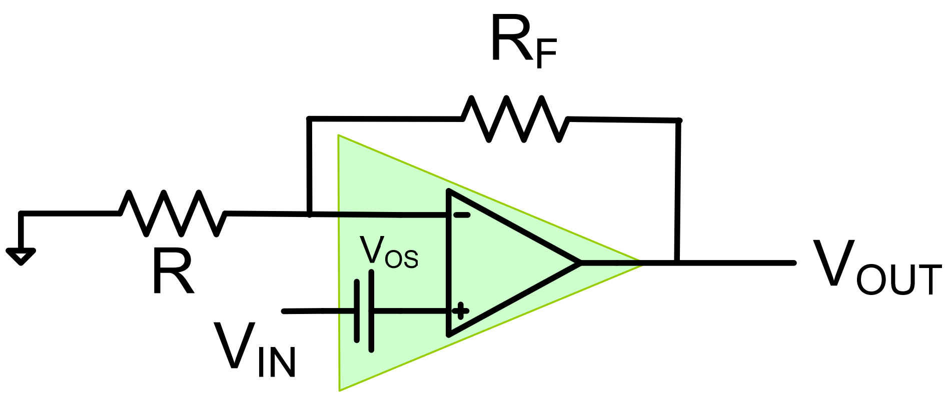
$$V_{OUT} = \left(1 + \frac{R_F}{R}\right) V_{IN} + \left(1 + \frac{R_F}{R}\right) V_{OS}$$

$$V_{OUT,OFFSET} = \left(1 + \frac{R_F}{R}\right) V_{OS}$$

If the desired voltage gain is large, the effects of V_{OS} are a major problem

Offset Voltage

Example: Determine the effects of the offset voltage on the output if the gain of the feedback amplifier is 500, the offset voltage is 3mV and the input is 0.001sin1000t



$$V_{OUT} = \left(1+\frac{R_F}{R}\right)V_{IN} + \left(1+\frac{R_F}{R}\right)V_{OS}$$

$$V_{OUT} = 500V_{IN} + 500V_{OS}$$

$$V_{OUT} = 0.5\sin 1000t + 1.5V$$

Note the offset voltage effects on the output are larger than the signal!

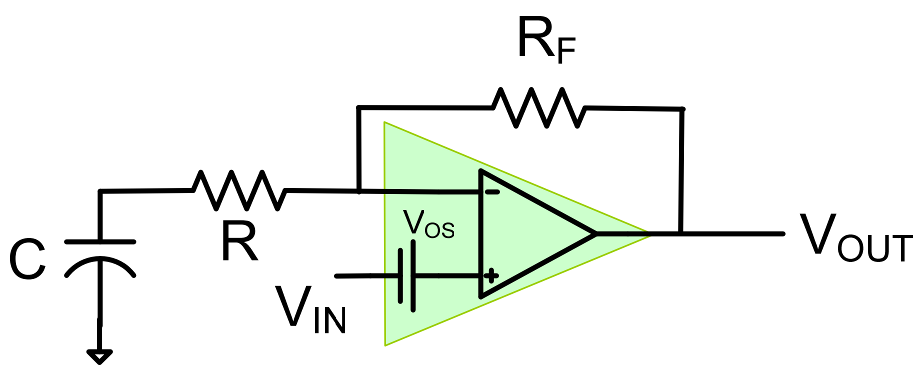
For larger gains, the effects are even worse!

Offsets can drive the amplifier output into saturation or cause clipping

Both the magnitude and sign of the offset are not predictable

Management of V_{OS} with Capacitor Coupling

Consider a noninverting voltage amplifier requirement and assume V_{IN} is a time-varying (sinusoidal) signal



The capacitor C blocks dc current In R

$$V_{OUT,OFFSET} = V_{OS}$$

Without the C, $V_{OUT,OFFSET}$ was

$$V_{OUT,OFFSET} = \left(1 + \frac{R_F}{R}\right) V_{OS}$$

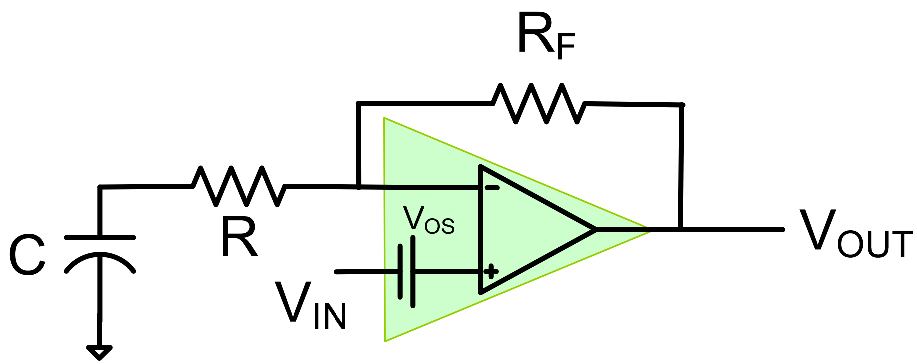
Note that the coupling capacitor can dramatically reduce effects of offset voltage if gain is large

But, in some applications, C can not be used because information in V_{IN} is at dc

Even if C can be used, is is often unacceptably large

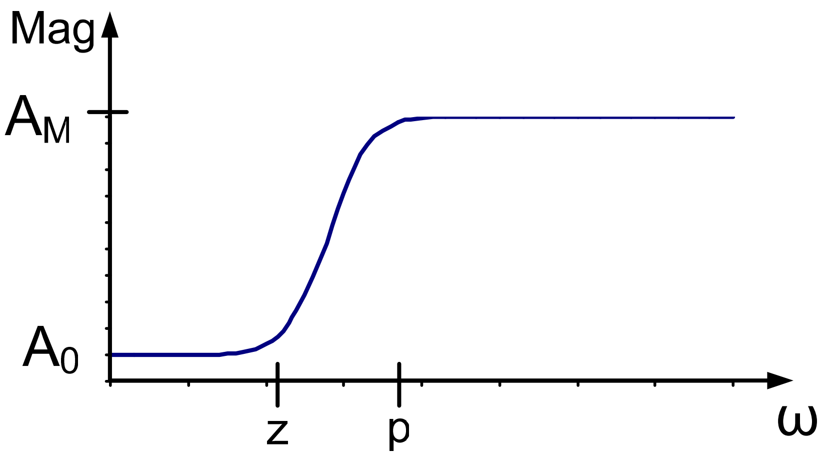
Management of V_{OS} with Capacitor Coupling

Consider a noninverting voltage amplifier requirement and assume V_{IN} is a time-varying (sinusoidal) signal



$$T(s)=\frac{1+sC(R+R_F)}{1+sRC}$$

$$T(s)=A_0\frac{\frac{s}{z}+1}{\frac{s}{p}+1}$$

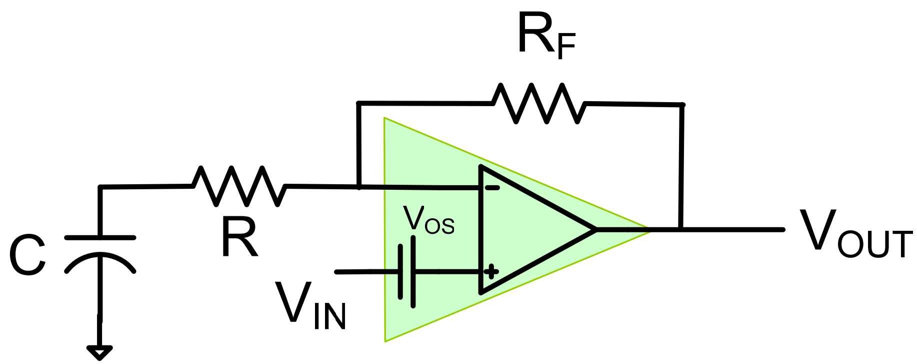


$$p=\frac{1}{RC} \qquad z=\frac{1}{(R+R_F)C}$$

$$A_0=1 \qquad A_M=1+\frac{R_F}{R}$$

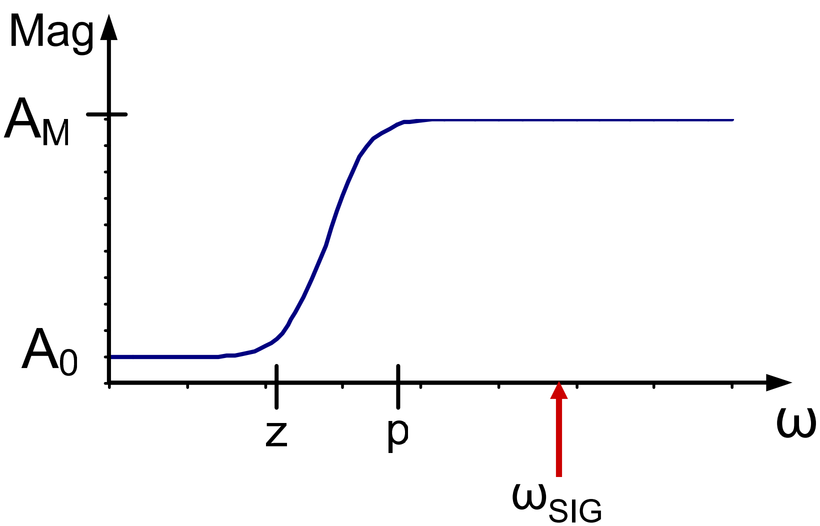
Management of V_{OS} with Capacitor Coupling

Consider a noninverting voltage amplifier requirement and assume V_{IN} is a time-varying (sinusoidal) signal



$$T(s)=\frac{1+sC(R+R_F)}{1+sRC}$$

$$p=\frac{1}{RC} \qquad z=\frac{1}{(R+R_F)C}$$

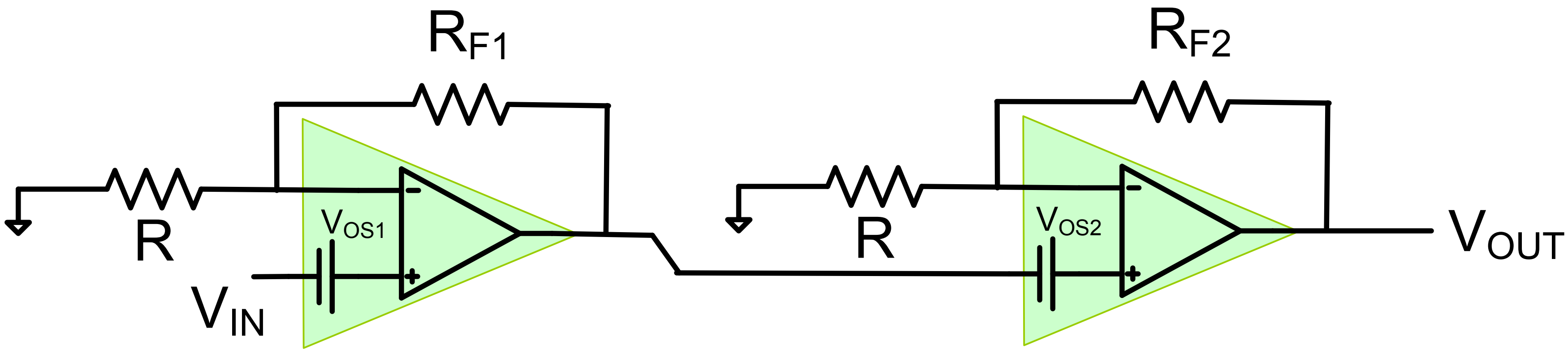


Must pick C so that $\omega_{SIG} >> p$

$$C >> \frac{1}{R\omega_{SIG}}$$

Management of V_{OS} with Capacitor Coupling

Consider Cascaded Amplifier



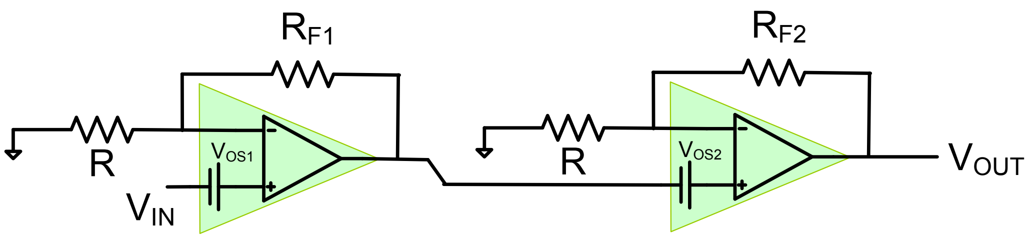
$$V_{OUT} = \left(1+\frac{R_{F1}}{R}\right)\left(1+\frac{R_{F2}}{R}\right)V_{IN} + \left(1+\frac{R_{F1}}{R}\right)\left(1+\frac{R_{F2}}{R}\right)V_{OS1} + \left(1+\frac{R_{F2}}{R}\right)V_{OS2}$$

$$V_{OUT,\ OFFSET} = \left(1+\frac{R_{F1}}{R}\right)\left(1+\frac{R_{F2}}{R}\right)V_{OS1} + \left(1+\frac{R_{F2}}{R}\right)V_{OS2}$$

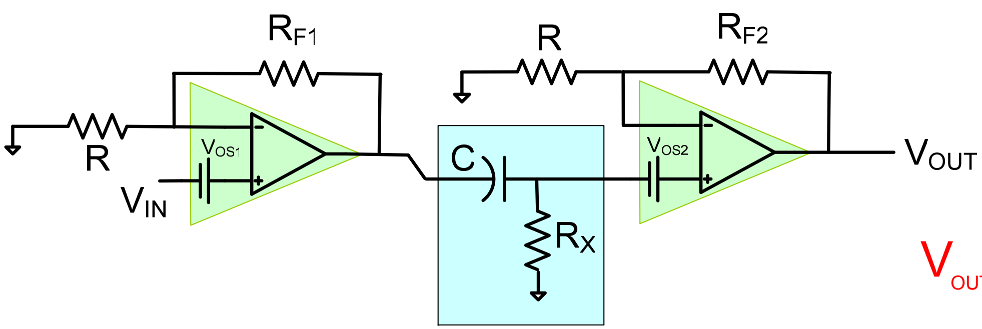
Offset voltage affects modestly worse than that for the single-stage amplifier if gain is the same

Management of V_{OS} with Capacitor Coupling

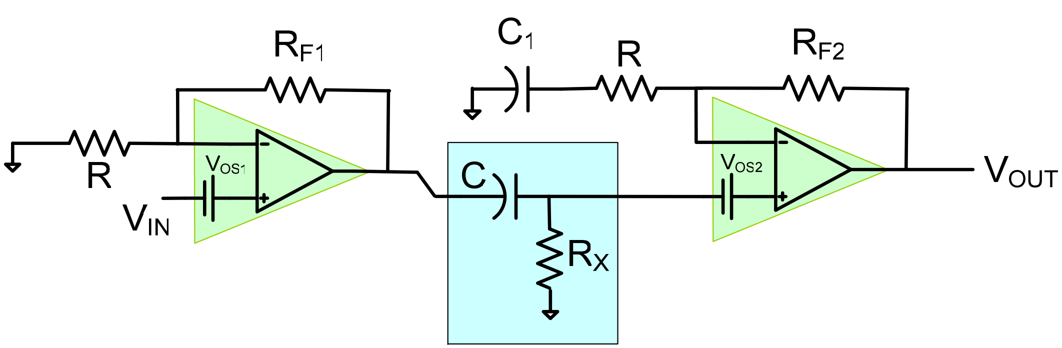
Effects can be reduced even further with a second blocking capacitor



$$V_{OUT,\ OFFSET} = \left(1+\frac{R_{F1}}{R}\right)\left(1+\frac{R_{F2}}{R}\right)V_{OS1} + \left(1+\frac{R_{F2}}{R}\right)V_{OS2}$$



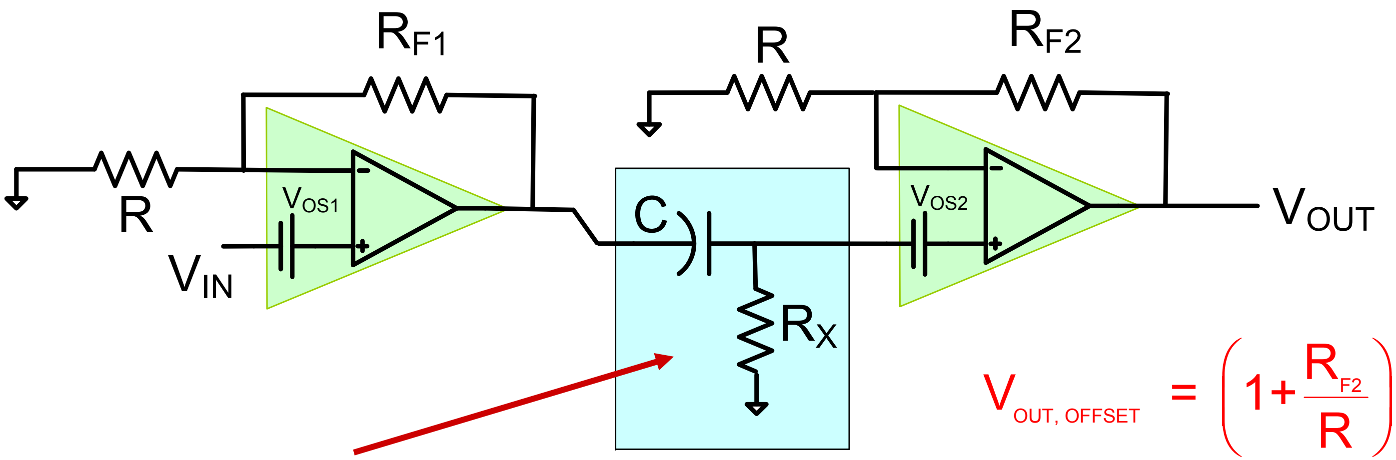
$$V_{OUT,\ OFFSET} = \left(1+\frac{R_{F2}}{R}\right)V_{OS2}$$



$$V_{OUT,\ OFFSET} = V_{OS2}$$

Management of V_{OS} with Capacitor Coupling

Consider Cascaded Amplifier with V_{IN} sinusoidal

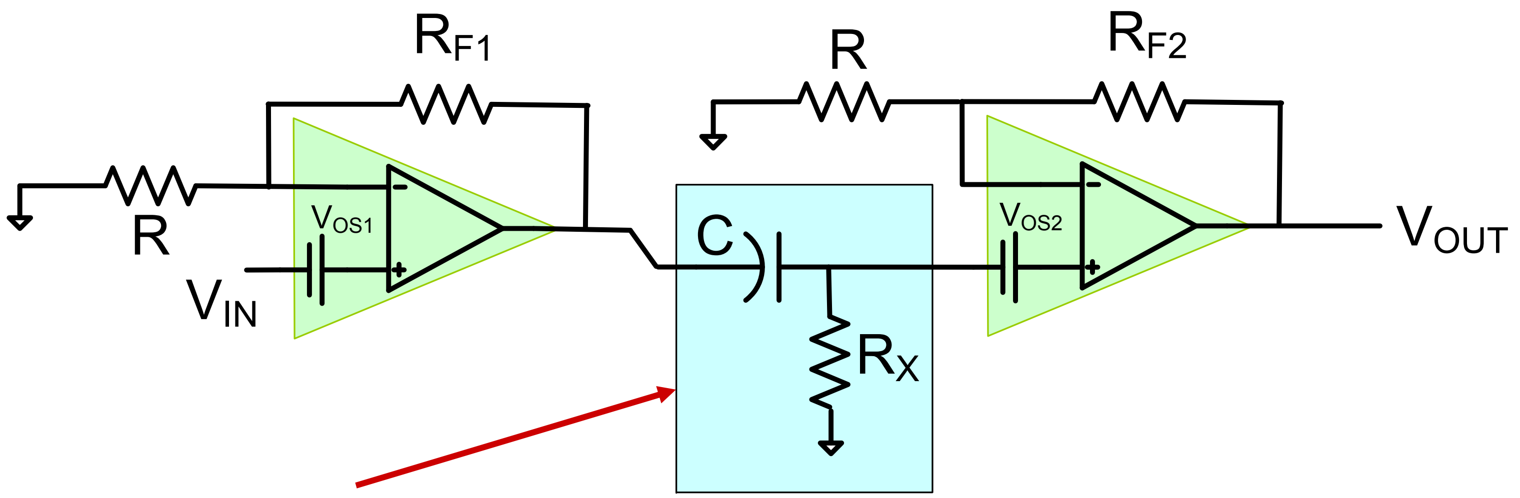


$$V_{OUT,\ OFFSET} = \left(1+\frac{R_{F2}}{R}\right) V_{OS2}$$

First-Order Highpass
Filter Blocks V_{OS1}

Management of V_{OS} with Capacitor Coupling

Consider Cascaded Amplifier with V_{IN} sinusoidal



First-Order Highpass Filter Blocks V_{OS1}

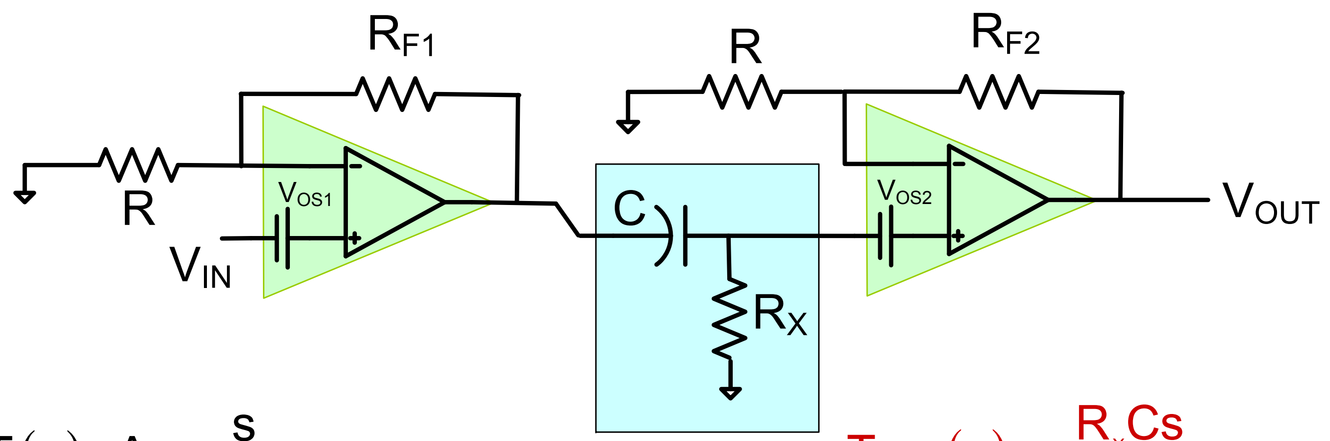
$$T_{FILTER}(s)=\frac{R_xCs}{1+R_xCs}$$

Pole at –p where

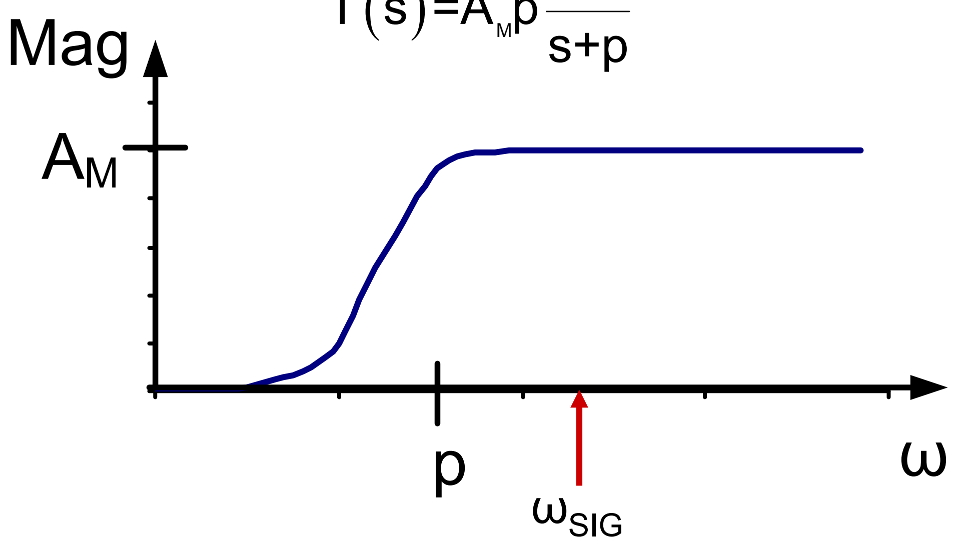
$$p=\frac{1}{R_xC}$$

Management of V_{OS} with Capacitor Coupling

Consider Cascaded Amplifier with V_{IN} sinusoidal



$$T(s)=A_M p\frac{s}{s+p}$$



$$T_{FILTER}(s)=\frac{R_x Cs}{1+R_x Cs}$$

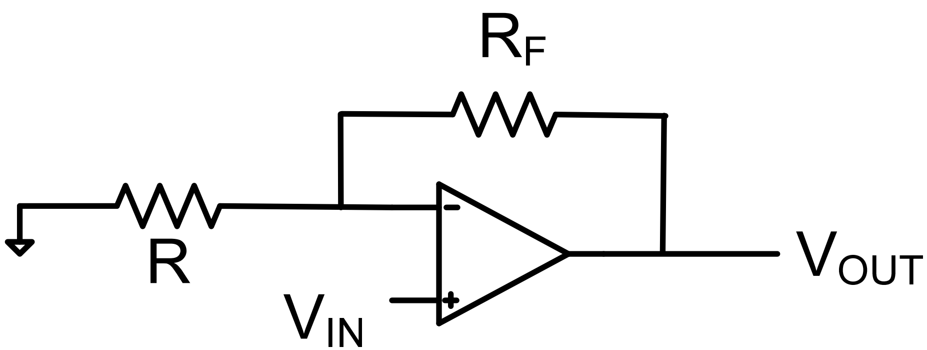
$$p=\frac{1}{R_x C}$$

Must pick C, R_X so that $\omega_{SIG} >> p$

$$C\,R_x >> \frac{1}{\omega_{SIG}}$$

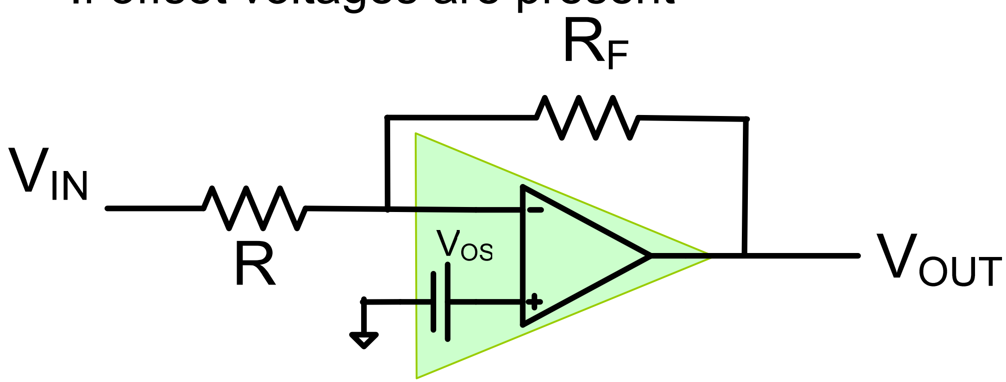
Offset Voltage

Consider a basic inverting voltage amplifier



$$A_V = \frac{V_{OUT}}{V_{IN}} = -\frac{R_F}{R}$$

If offset voltages are present



By superposition, it readily follows that

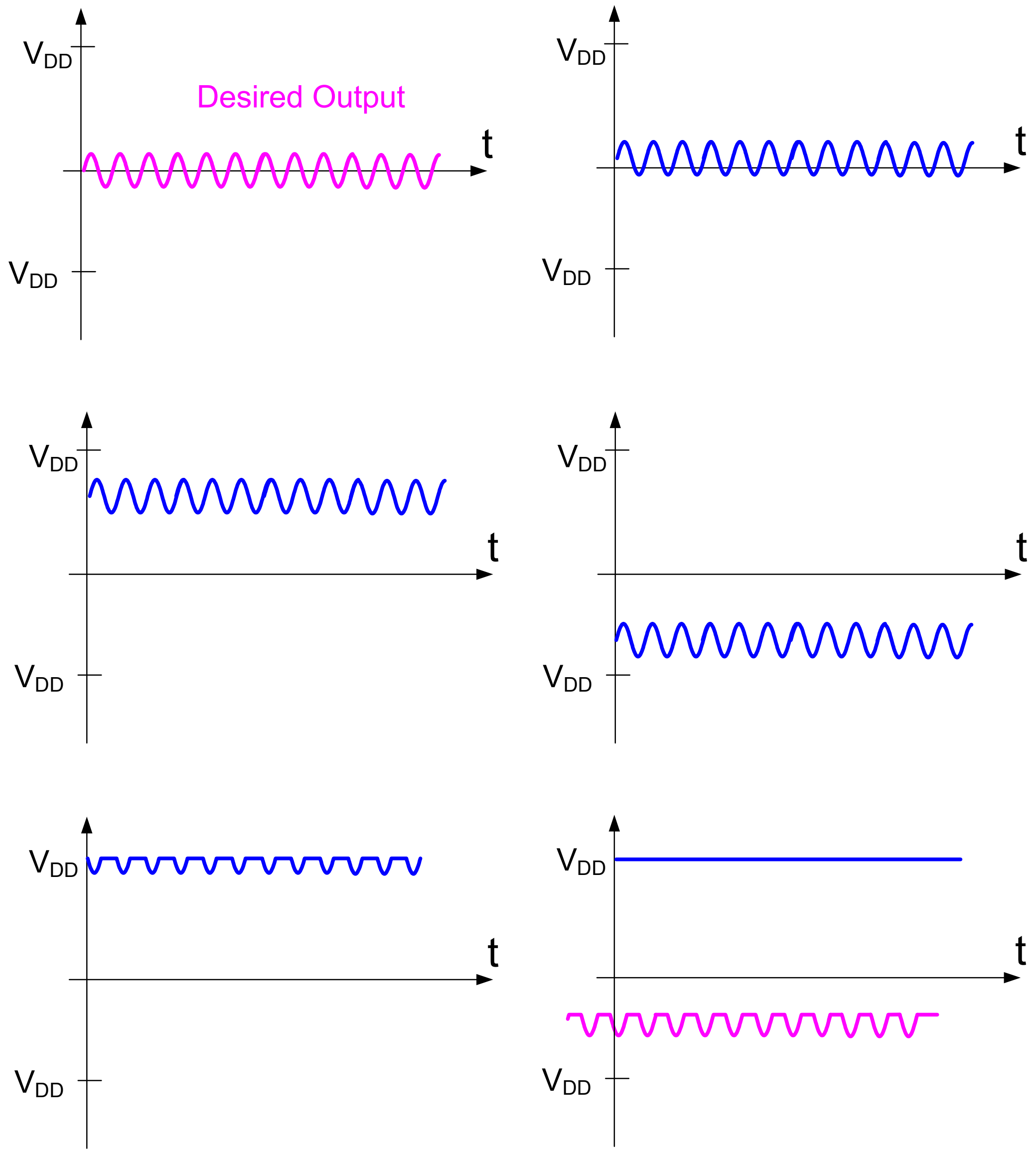
$$V_{OUT} = \left(-\frac{R_F}{R}\right)V_{IN} + \left(1+\frac{R_F}{R}\right)V_{OS}$$

$$V_{OUT,OFFSET} = \left(1+\frac{R_F}{R}\right)V_{OS}$$

Offset voltage contribution identical to that of the basic noninverting amplifier
Relative effects a little worse than for the noninverting amplifier for low gains

Offset Voltage

What offset voltage can do if serious enough

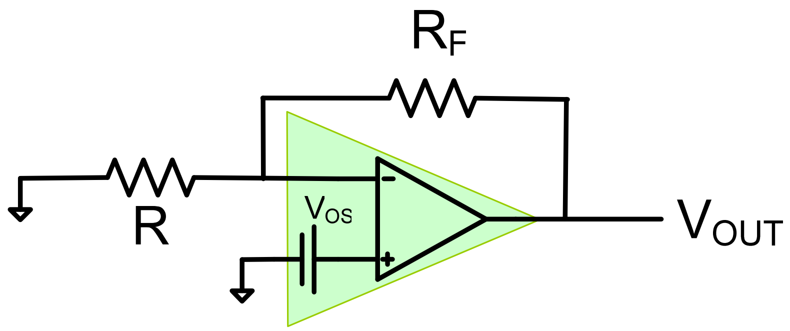


Offset Voltage

- Remember that offset voltage is random at the manufacturing level
- Offset voltage affects many other circuits too
- One of the major nonideal effects of op amps
- Particularly difficult to manage when the information that must be amplified is also dc
- Circuit techniques or better op amps can be used to minimize effects of offset voltage

Measurement of Offset Voltage

Recall circuits that are adversely affected by a parameter can often be used to measure that parameter



$$V_{OUT} = V_{OFF}\left(1+\frac{R_F}{R}\right)$$

Make R_F/R large (maybe 100 or more, depending on Op Amp) so that output can be easily measured

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

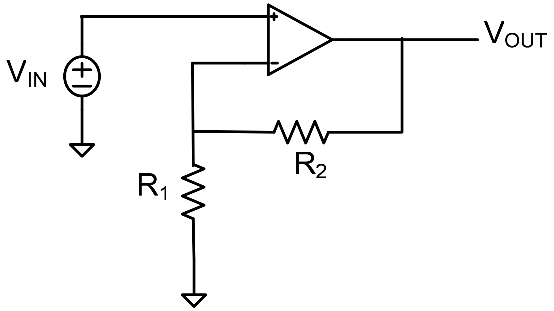
$GB = A_0 BW$

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

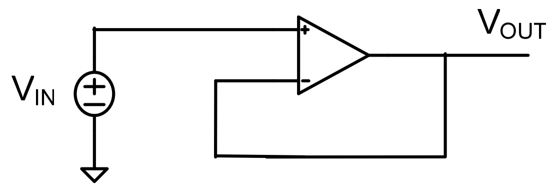
Input Voltage Range

The input voltage range is the maximum range of common-mode input voltages that can be applied to the op amp while still operating as an Op Amp

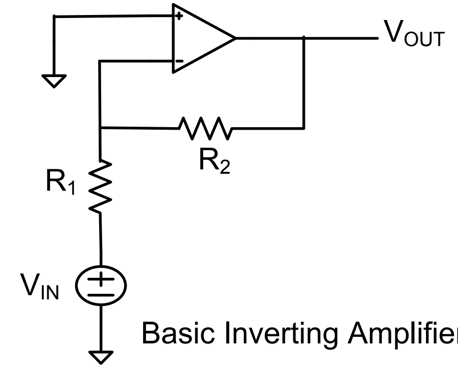
Some op amps have rail-to-rail inputs and others may be bounded away from the upper and lower rails by a little bit



Basic Noninverting Amplifier



Basic Buffer Amplifier



Basic Inverting Amplifier

Nonideal Op Amp Characteristics

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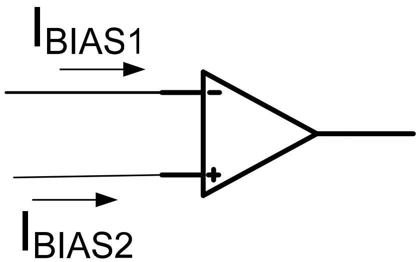
Bias and Offset Currents



I_{BIAS} is the current that must flow for the internal transistors to operate correctly

I_{BIAS} is small for bipolar input op amps, extremely small for FET input op amps

Can be neglected in most designs regardless of whether FET or Bipolar input

$I_{OFSET} = I_{BIAS1} - I_{BIAS2}$ is significantly smaller (/5 to /20)

I_{OFFSET} is a random variable with zero mean for most designs

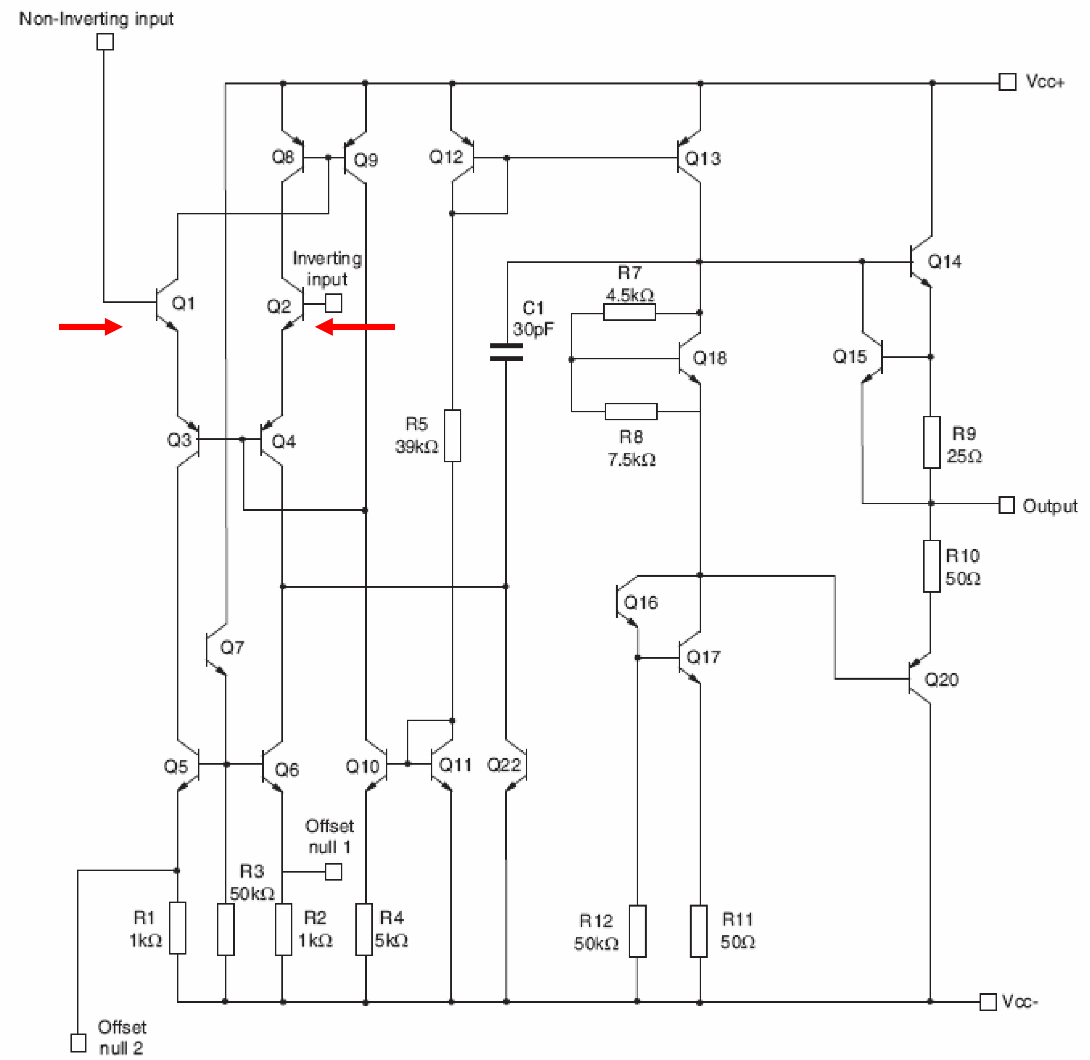
I_{BIAS} around 50 nA for 741, I_{OFFSET} around 3nA

I_{BIAS} around 20 fA for LMP2231, I_{OFFSET} around 5fA

Have been a question about I_{BIAS} on many interviews

Bias and Offset Currents

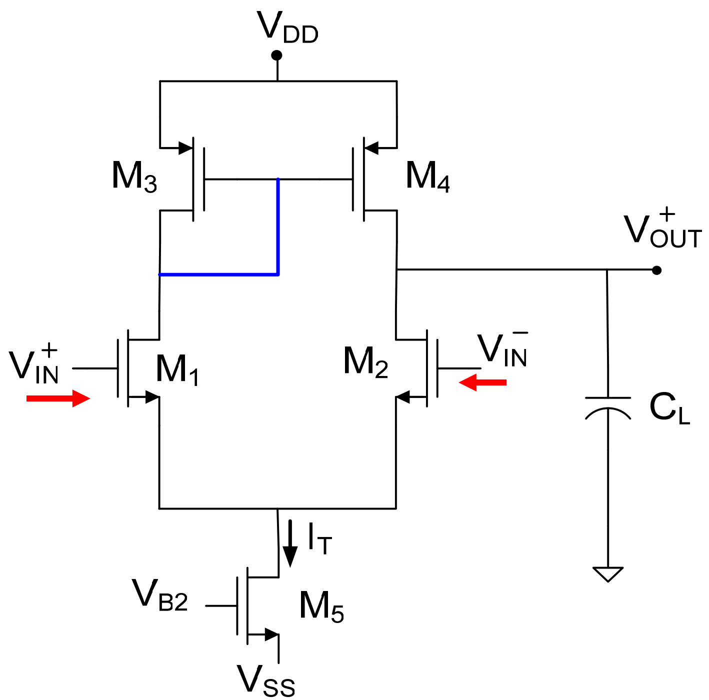
Schematic of the 741



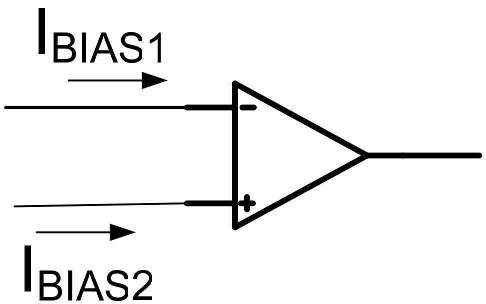
From STMicroelectronics datasheet

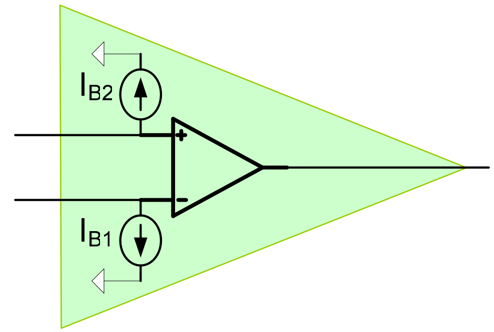
Bias and Offset Currents

Schematic of basic single-stage CMOS Op Amp



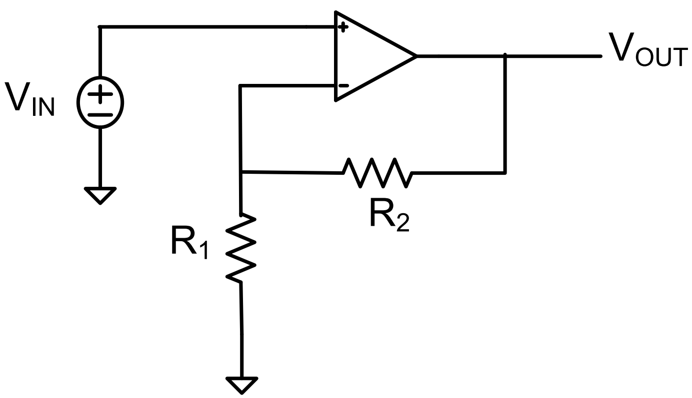
Bias and Offset Currents





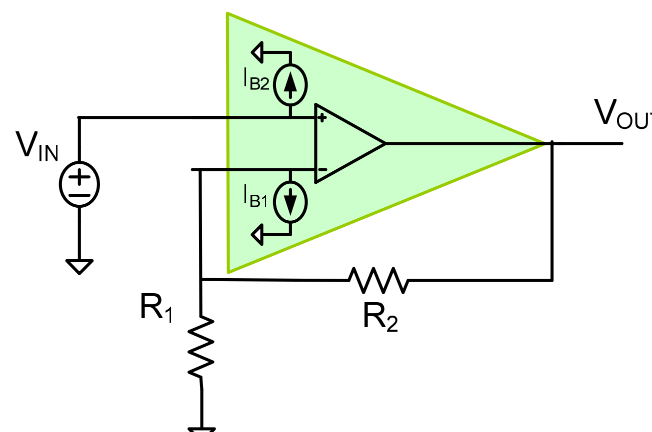
Model with I_{BIAS} effects

Example: Determine the effects of bias currents on the following circuit

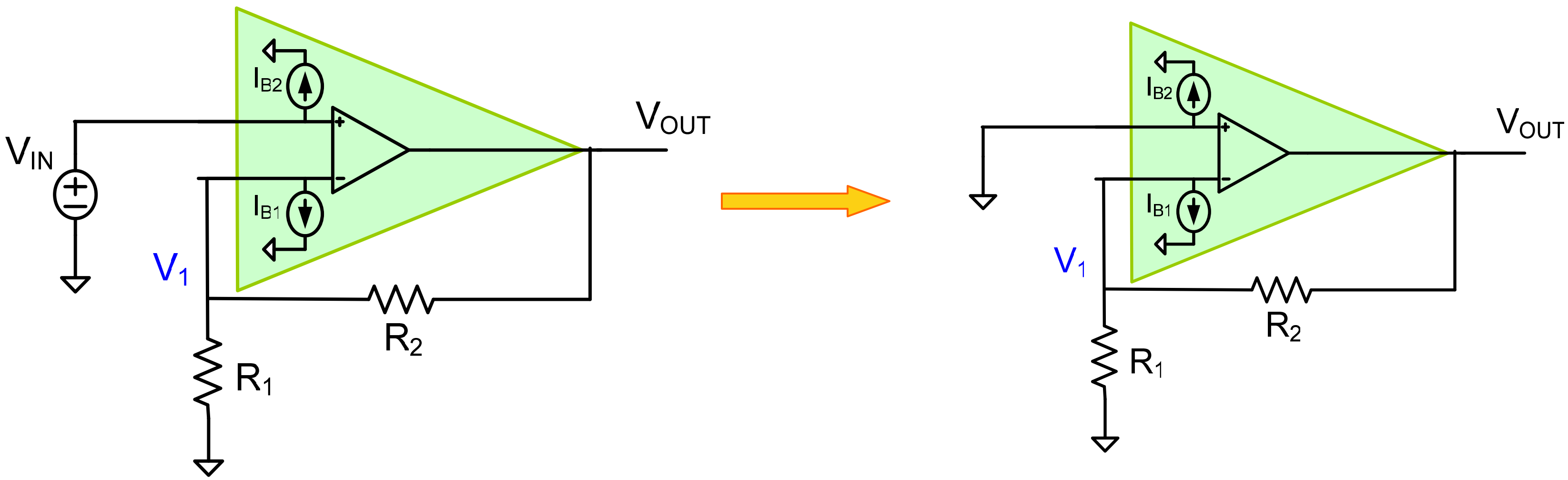


Basic Noninverting Amplifier

Circuit with I_{BIAS} model



Bias and Offset Currents



Can use superposition

Will consider only the contributions by I_{B1} and I_{B2}

$$V_{OUT} \simeq I_{B1}R_2$$

For 741, if R2=10K, VOUT ≈50nA*10K=.5mV

if R2=1M, VOUT ≈50nA*1M=50mV

For LMP2231, if R2=10K, VOUT ≈20fA*10K=.0.2nV

if R2=1M, VOUT ≈20fA*1M=20nV

- Effects of bias currents on most other useful circuits is very small too
- In those rare applications where it is of concern, using a better Op Amp is a good solution

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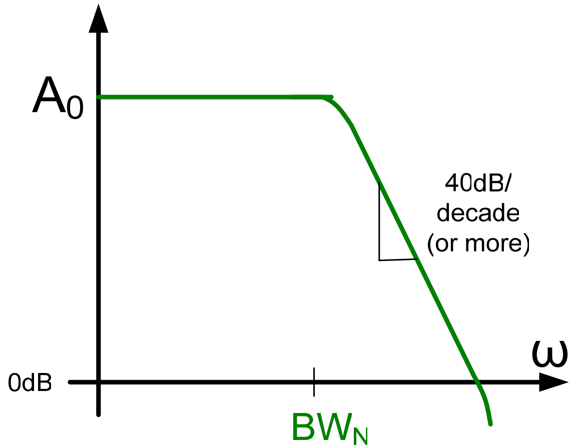
- Bias Currents
- Full Power Bandwidth
- Compensation

Compensation

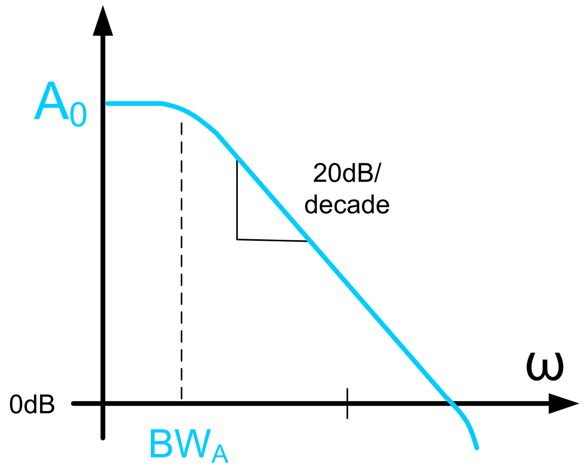
Compensation refers to adjusting the frequency dependent gain characteristics of the op amp so that the time and frequency domain performance of the feedback amplifier is acceptable

Usually involves making the amplifier look like a first-order lowpass circuit

If compensation is not done on cascaded-type op amps, feedback circuits using the op amp are usually unstable



Natural type of response

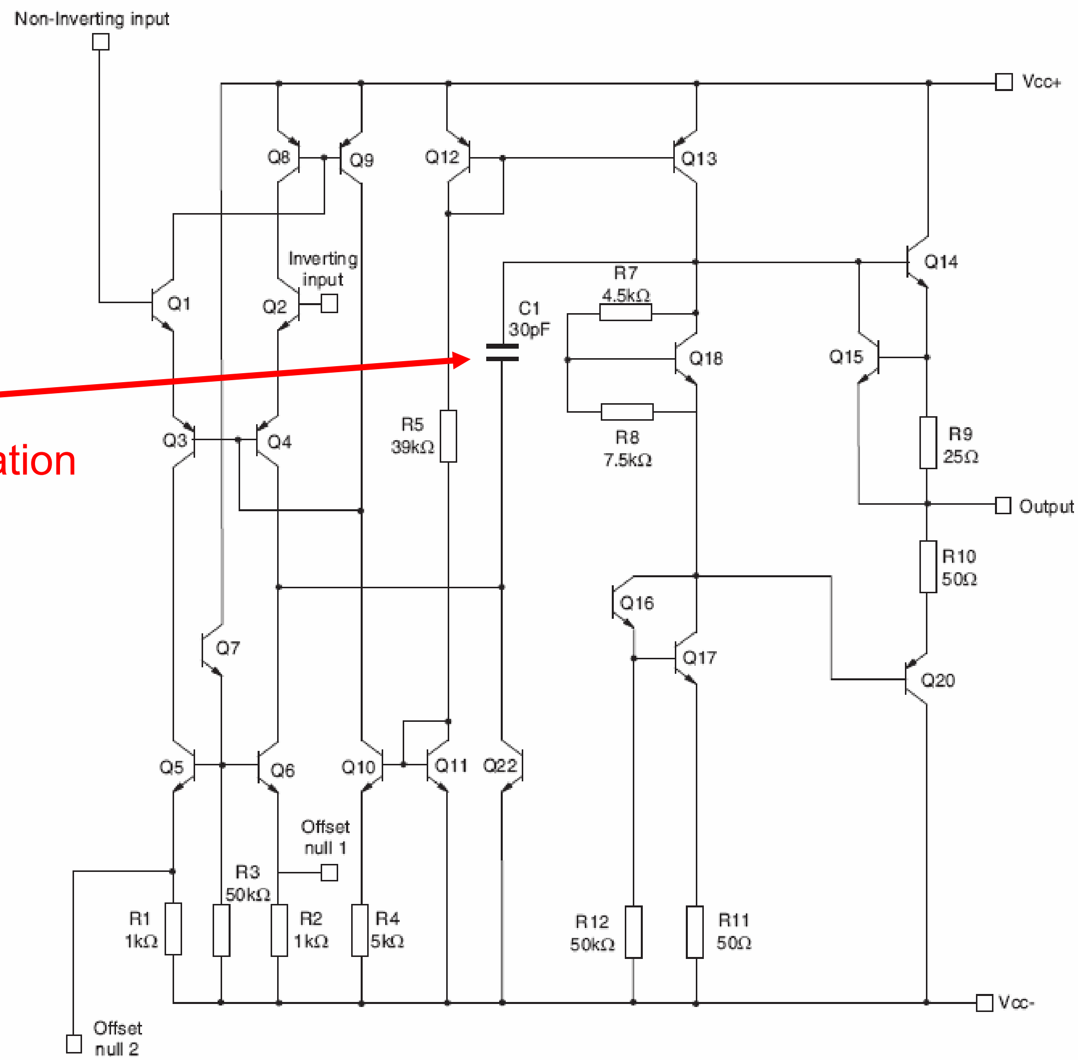


Compensated Response

Compensation often done with a capacitor which can be internal or external but usually it is internal to the Op Amp

Compensation

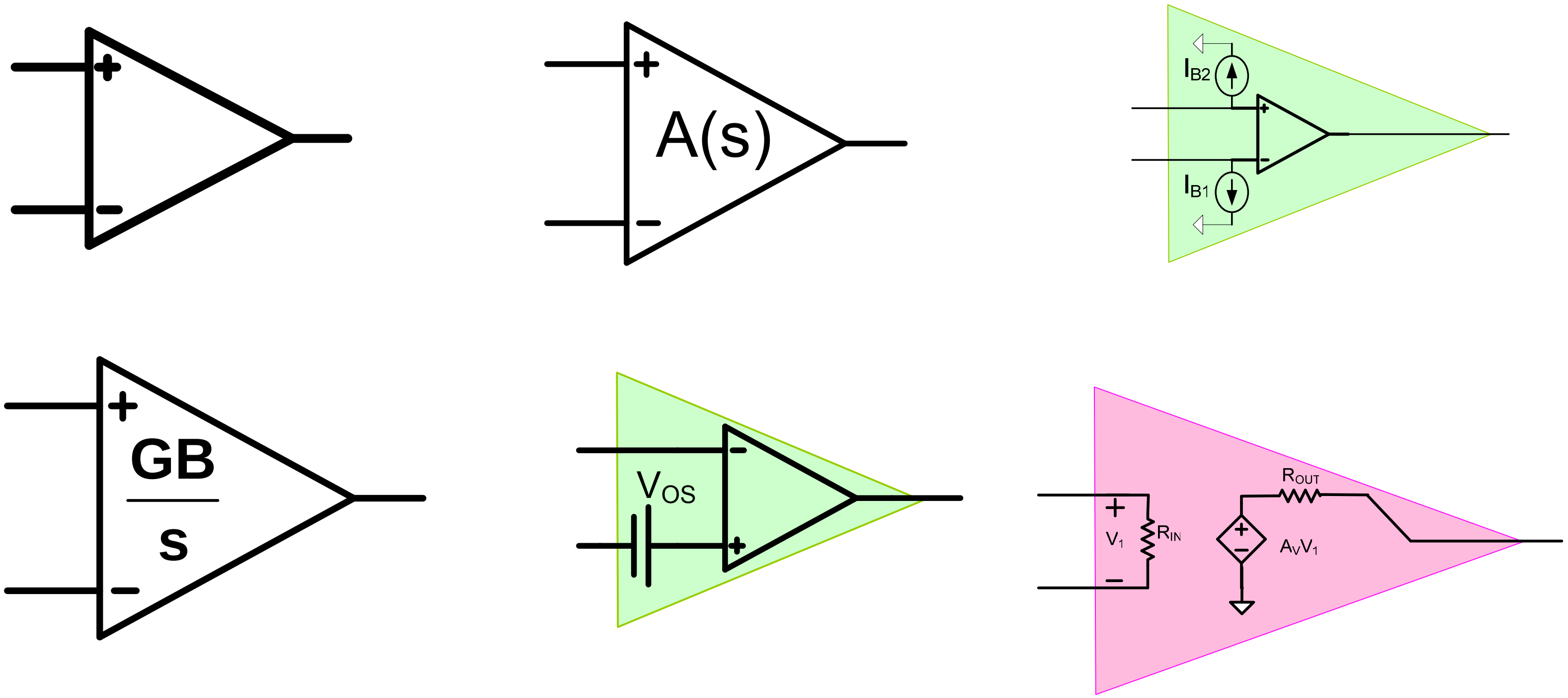
Schematic of the 741



Internal Compensation Capacitor

From STMicroelectronics datasheet

Models of Nonideal Effects

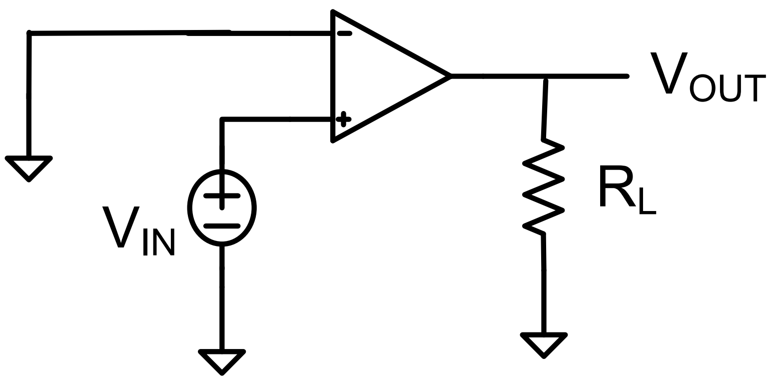


Many different models have been introduced and more exist

Typically consider nonideal effects one at a time but realize all are present

Application and op amp used will often determine which are of most concern

Op Amp Is Almost Never Used as an Open Loop High Gain Amplifier !!



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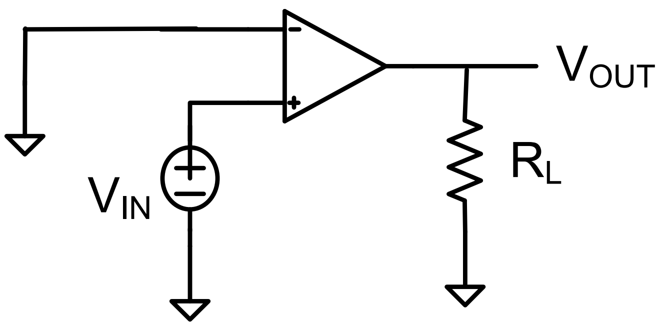

But what will happen if an
engineer attempts to use
this circuit as an amplifier?

End of Lecture 19