EE 230
Lecture 20

Nonlinear Op Amp Applications

- The Comparator
- Nonlinear Analysis Methods

Quiz 14

What is the major purpose of compensation when designing an operatinal amplifier?

And the number is ?

1

3

8

5

4

?

2

6

9

7

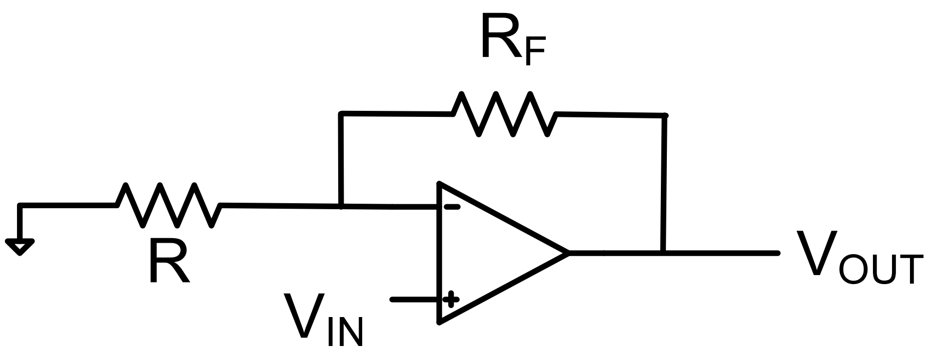
Quiz 14

What is the major purpose of compensation when designing an operatinal amplifier?

Compensation is used to make the frequency response of an operational amplifier approximately first-order

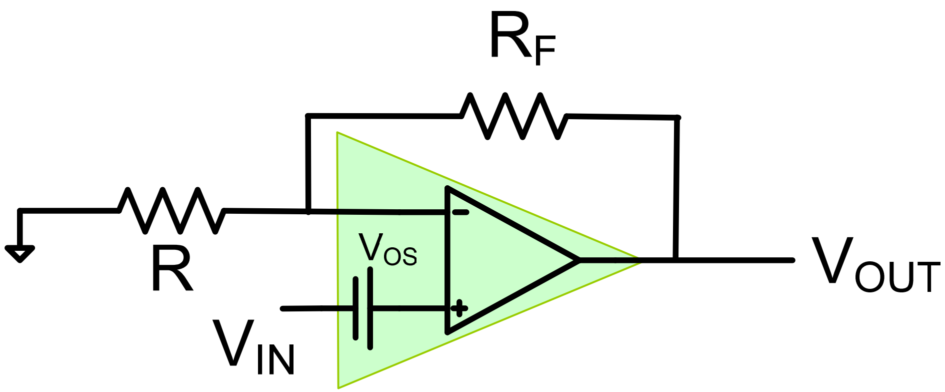
Offset Voltage

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

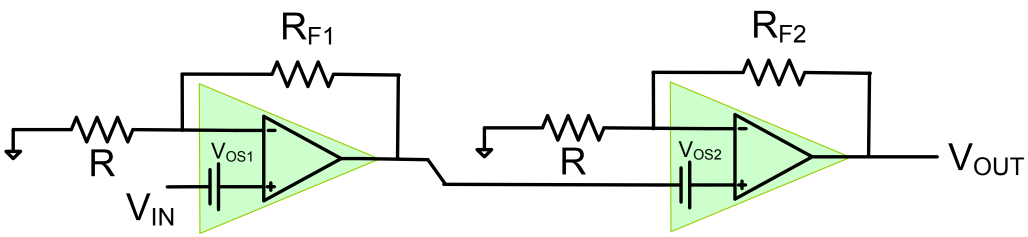
$$V_{OUT} = \left(1 + \frac{R_F}{R}\right) V_{IN} + \left(1 + \frac{R_F}{R}\right) V_{OS}$$

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

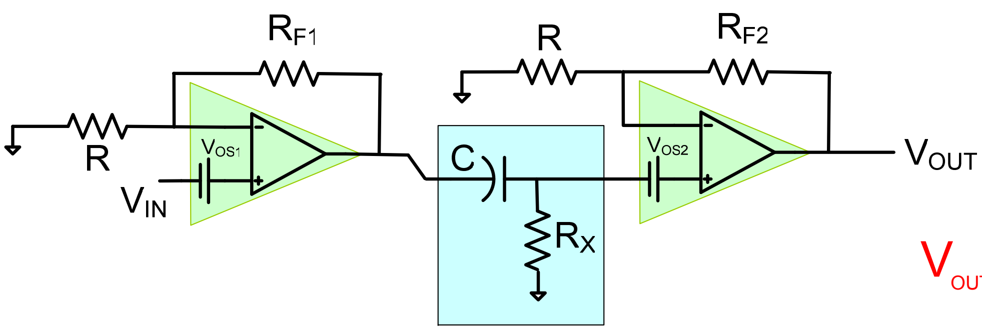
If the desired voltage gain is large, the effects of V_{OS} are a major problem

Management of V_{OS} with Capacitor Coupling

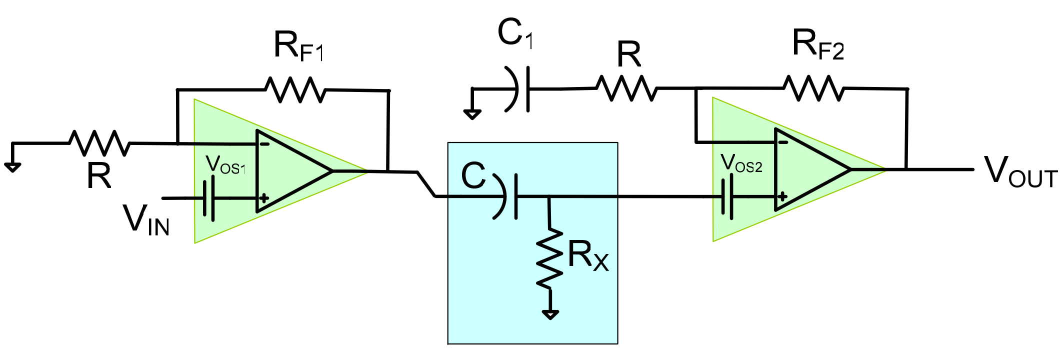
Effects can be reduced even further with a second blocking capacitor



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

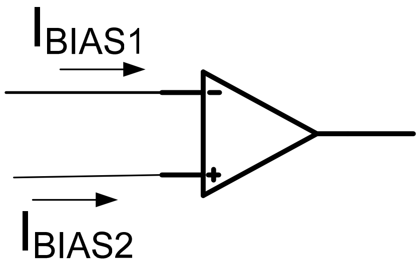


$$V_{OUT,\,OFFSET} = \left(1+\frac{R_{F2}}{R}\right)V_{OS2}$$



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

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)

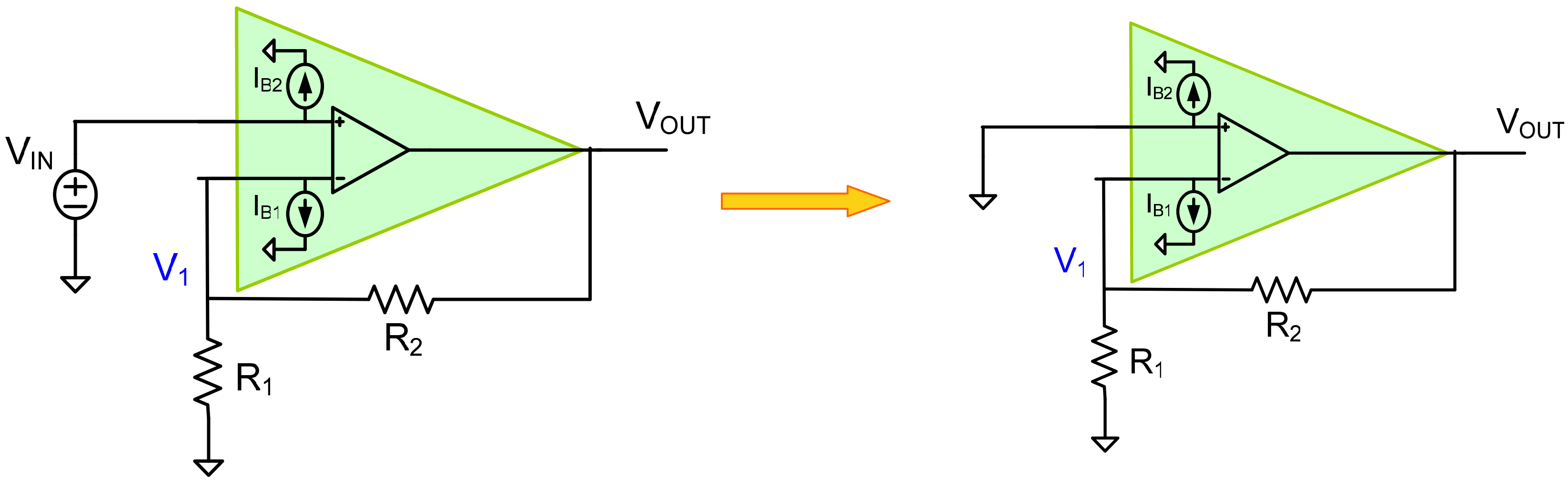
I_{OFFSET} is a random variable with zero mean for most designs

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



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

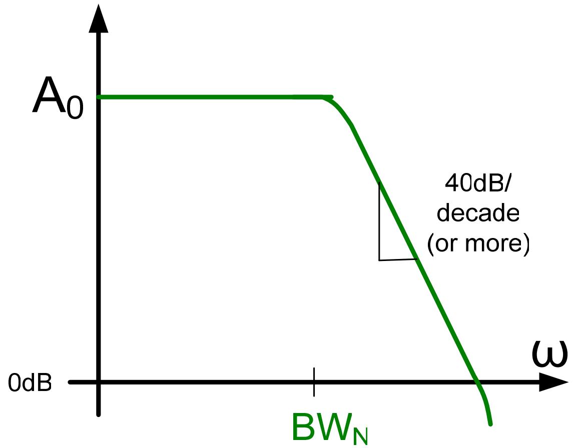
- Effects of bias currents on most other useful circuits is very small too
- In those rare applications where it is of concern, using a better Op Amp is a good solution

Compensation

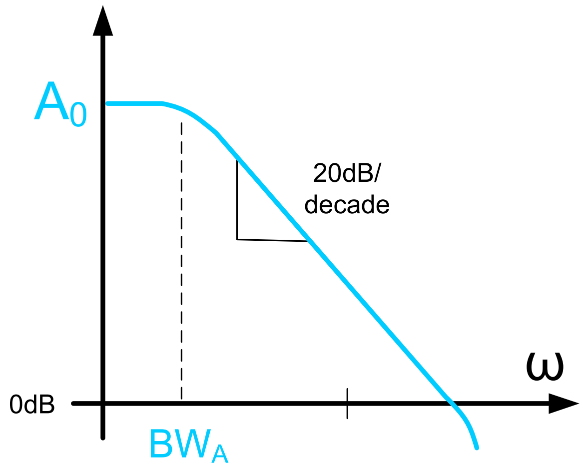
Compensation refers to adjusting the frequency dependent gain characteristics of the op amp so that the time and frequency domain performance of the feedback amplifier is acceptable

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



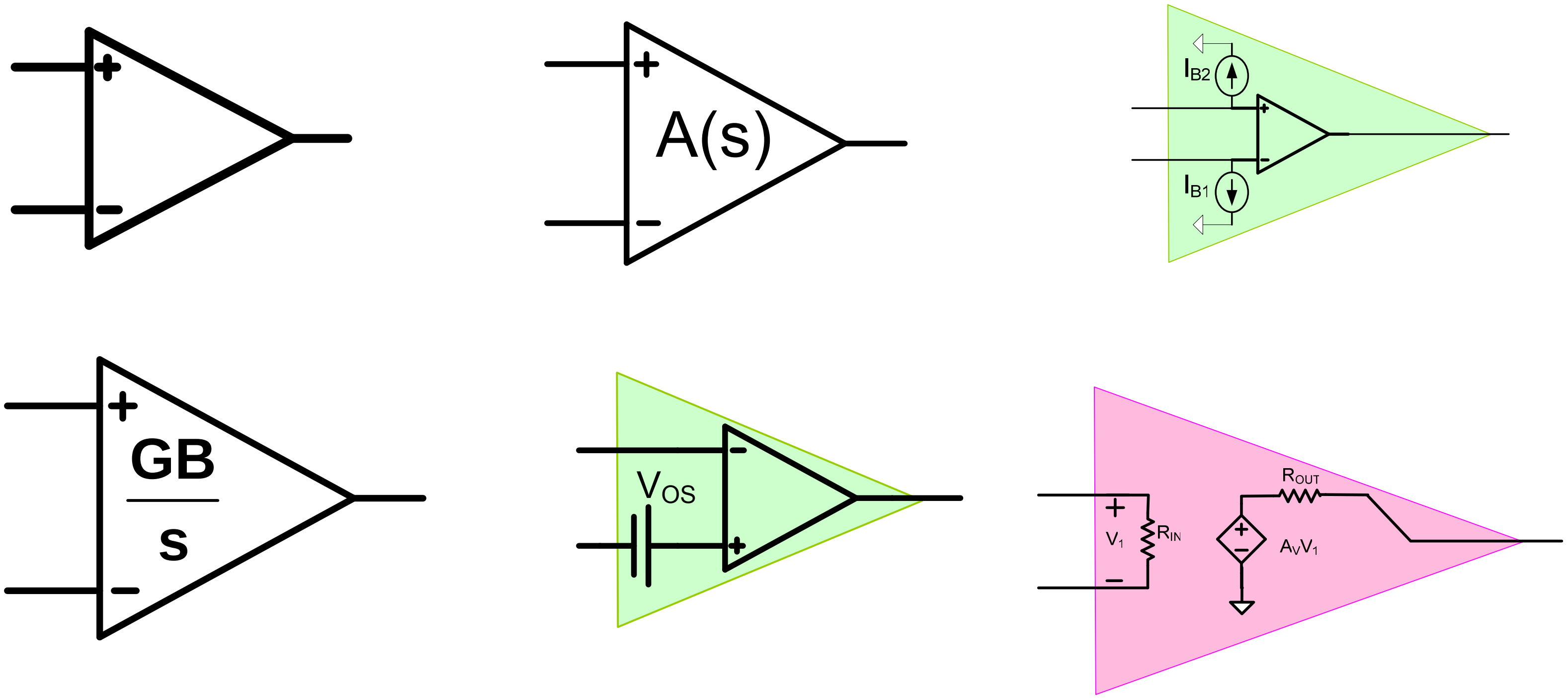
Natural type of response



Compensated Response

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

Models of Nonideal Effects

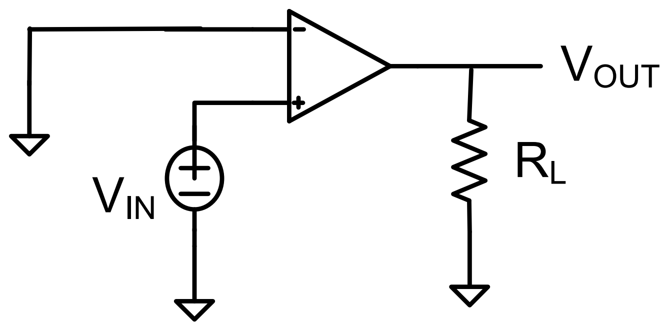


Many different models have been introduced and more exist

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

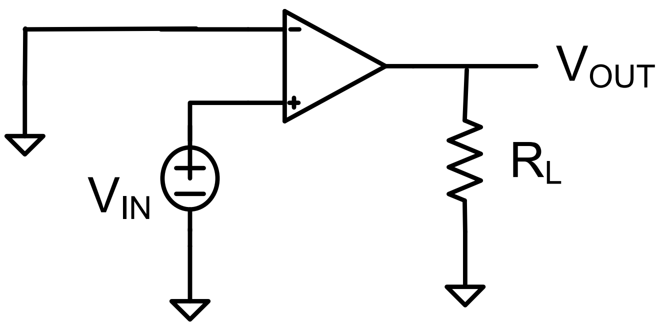
Application and op amp used will often determine which are of most concern

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



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

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



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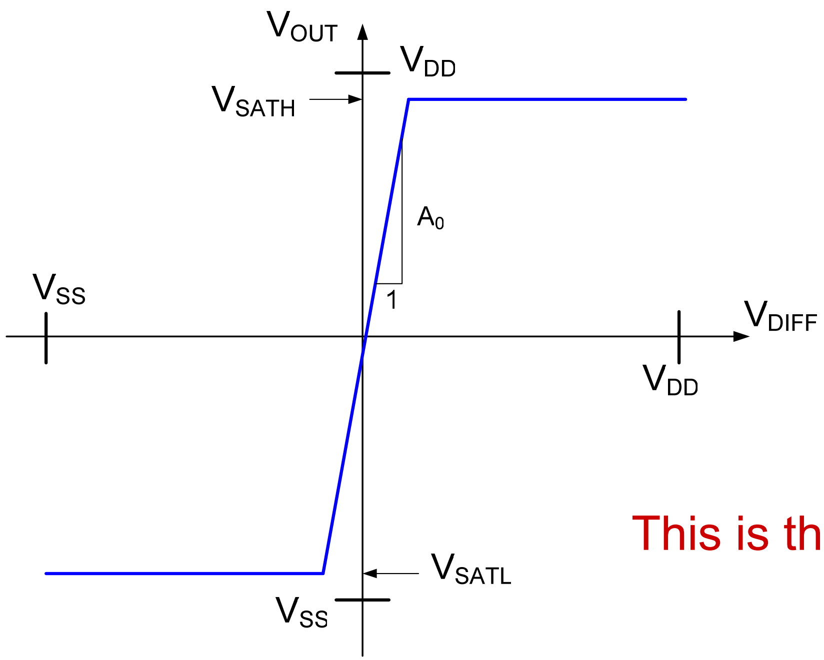
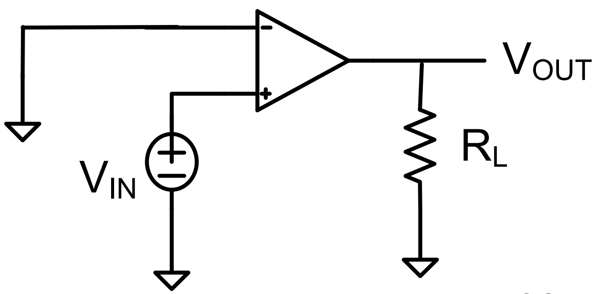
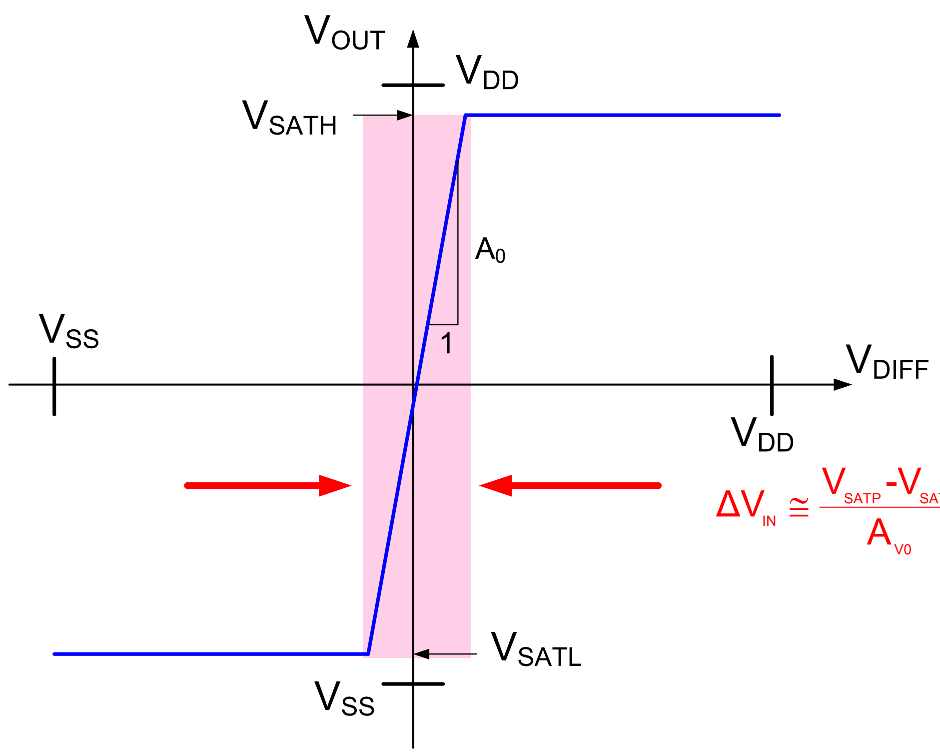


This is the I/O characteristics of this circuit !

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

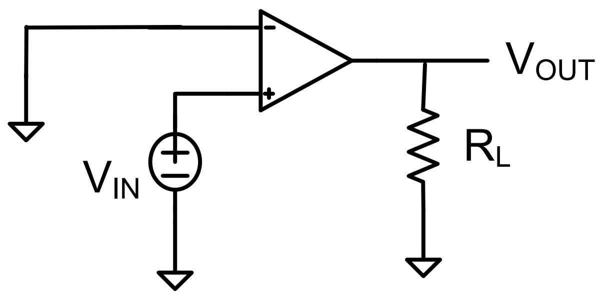


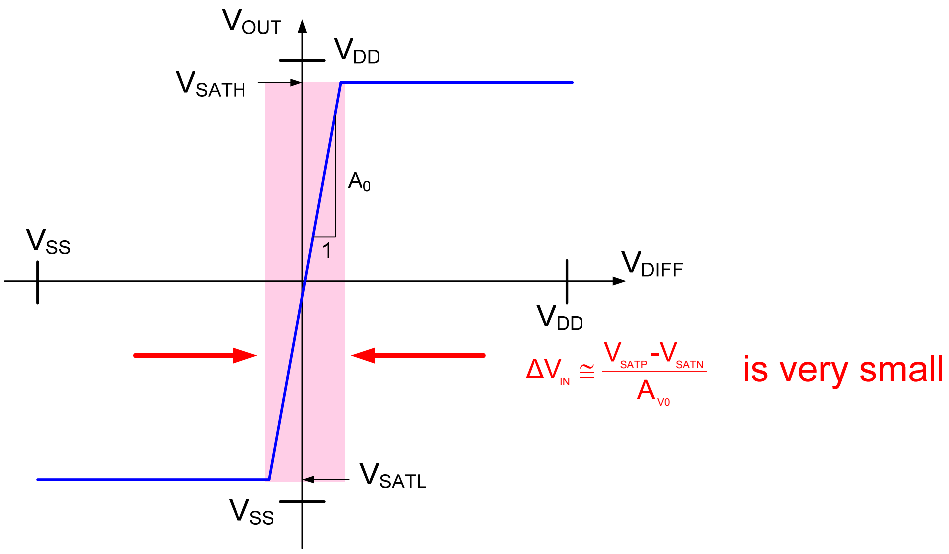


$\Delta V_{IN} \cong \frac{V_{SATP} - V_{SATN}}{A_{V0}}$ is very small

This is the I/O characteristics of this circuit !

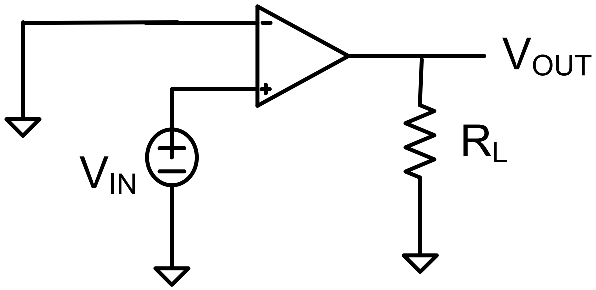
Op Amp Is Almost Never Used as an Open Loop High Gain Amplifier !!





$$V_{OUT} \cong \begin{cases} V_{SATH} & V_{IN} > 0 \\ V_{SATL} & V_{IN} < 0 \end{cases}$$

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



$$V_{OUT} \cong \begin{cases} V_{SATH} & V_{IN} > 0 \\ V_{SATL} & V_{IN} < 0 \end{cases}$$

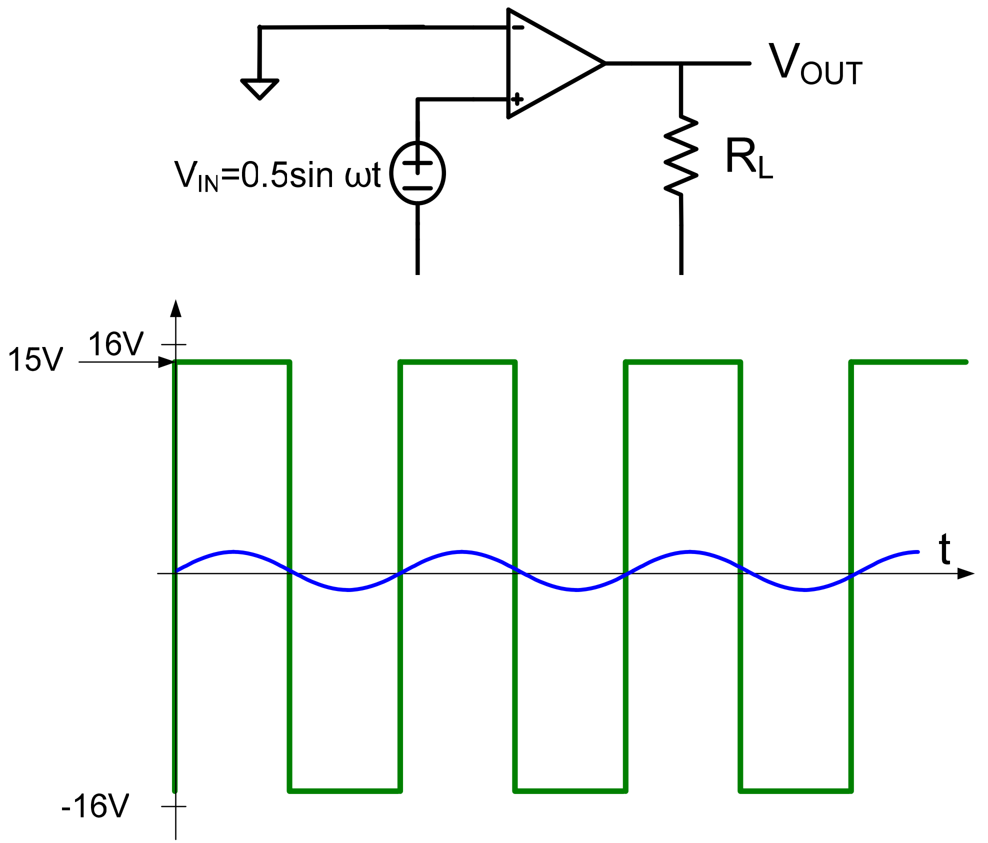
This circuit serves as a comparator !

This circuit serves as a 1-bit analog to digital converter (ADC)

This circuit compares V_{IN} to ground and provides a 2-level output

What will happen if the sinusoidal signal is put in?

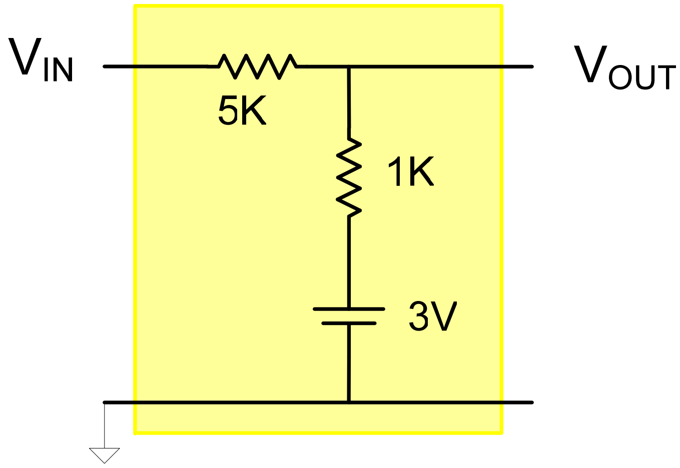
(Assume op amp biased with +/- 16V supplies and $|V_{OUTSAT}|=15V$



$$V_{OUT} = \begin{cases} 15 & \text{for } V_{IN}>0 \\ -15 & \text{for } V_{IN}<0 \end{cases}$$

Even though it is not an amplifier, is this a useful circuit?

What are the transfer characteristics of this simple circuit?



By superposition $$V_{OUT} = \left(\frac{1}{6}\right)V_{IN} + \left(\frac{5}{6}\right)3V$$

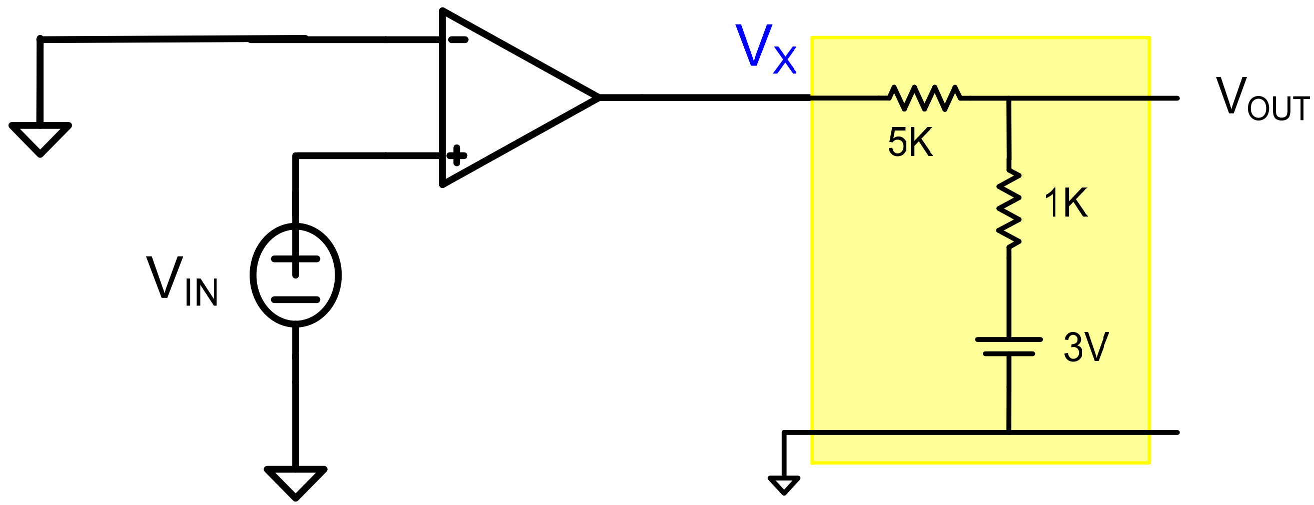
What if V_{IN} takes on one of two values, +15V, or -15V?

$$V_{OUT} = \begin{cases} 5V & \text{when } V_{IN}=15V \\ 0V & \text{when} V_{IN}=-15V \end{cases}$$

Comparator with Controlled Boolean Output Levels

(Assume op amp biased with +/- 16V supplies and $|V_{OUTSAT}|=15V$

What are the transfer characteristics of this simple circuit?



$$V_X = \begin{cases} 15 & \text{for } V_{IN}>0 \\ -15 & \text{for } V_{IN}<0 \end{cases}$$

$$V_{OUT} = \begin{cases} 5V & \text{when } V_X = 15V \\ 0V & \text{when } V_X = -15V \end{cases}$$

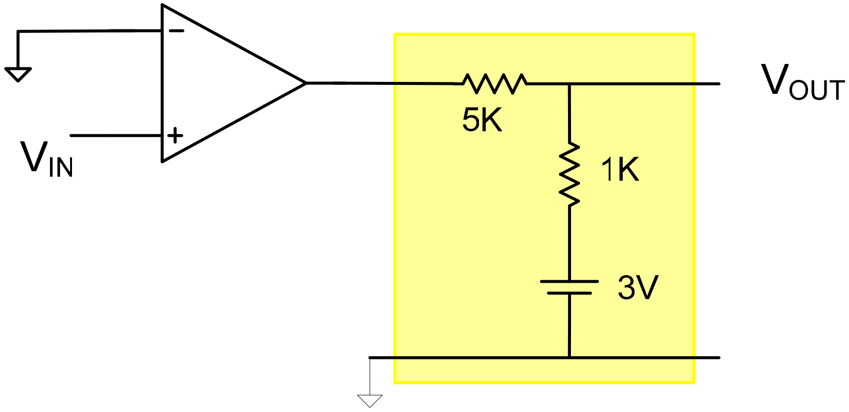
$$V_{OUT} = \begin{cases} 5V & \text{when } V_{IN} < 0 \\ 0V & \text{when } V_{IN} > 0 \end{cases}$$

The circuit in yellow is termed an interface circuit

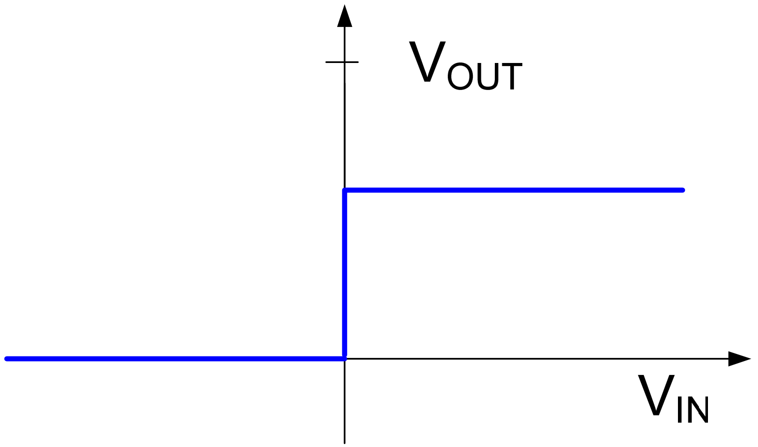
Applications of Comparators

(Assume op amp biased with +/- 16V supplies and $|V_{OUTSAT}|=15V$

This I/O relationship holds for any input !

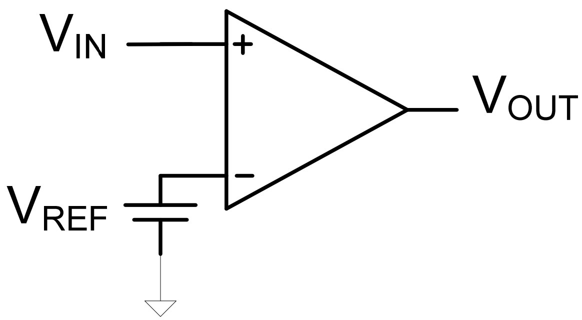


$$V_{OUT} = \begin{cases} \mathbf{5V} & \textbf{when } V_{IN} < 0 \\ \mathbf{0V} & \textbf{when } V_{IN} > 0 \end{cases}$$

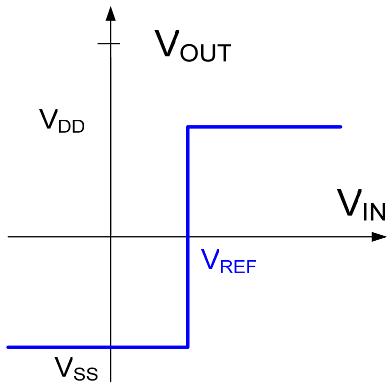


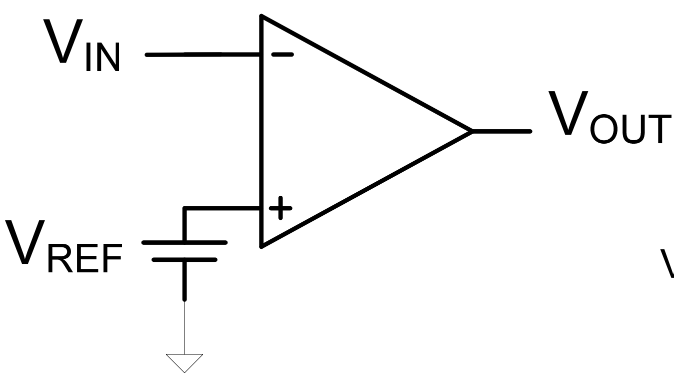
The Comparators

(Assume $V_{SATH}=V_{DD}$, $V_{SATL}=V_{SS}$)

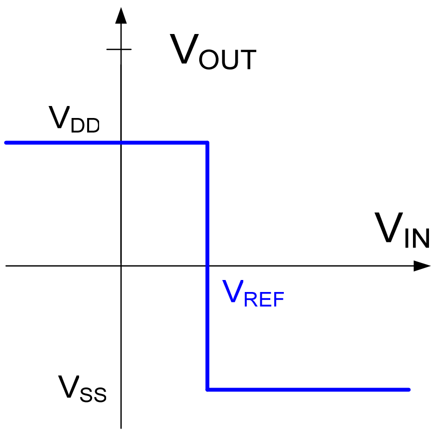


$$V_{OUT}=\begin{cases} V_{DD} & \text{for } V_{IN}>V_{REF} \\ V_{SS} & \text{for } V_{IN}<V_{REF} \end{cases}$$

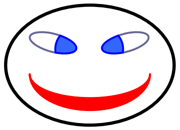




$$V_{OUT}=\begin{cases} V_{DD} & \text{for } V_{IN}<V_{REF} \\ V_{SS} & \text{for } V_{IN}>V_{REF} \end{cases}$$



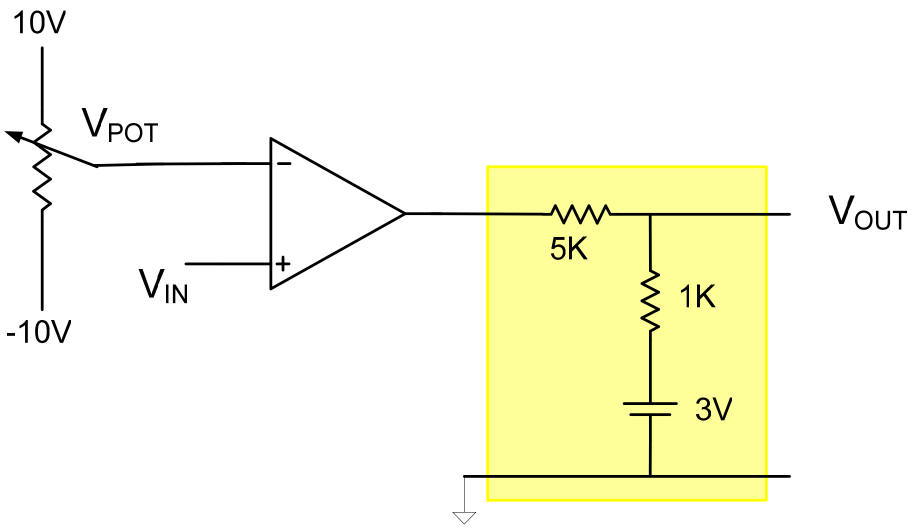
Op Amps make good comparators when operated open-loop



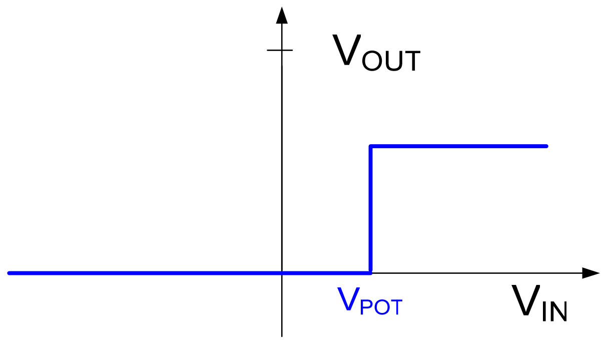
Some ICs are manufactured to serve only as comparators and often have better performance than op amps

Programmable Threshold Comparator

(Assume op amp biased with +/- 16V supplies and $|V_{OUTSAT}|=15V$



$$V_{OUT} = \begin{cases} 5V & \text{when } V_{IN} > V_{POT} \\ 0V & \text{when } V_{IN} < V_{POT} \end{cases}$$



What if the input is the output of a temperature sensor?

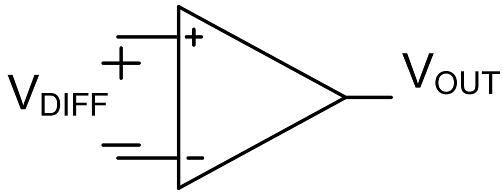
Could serve as a thermostat !

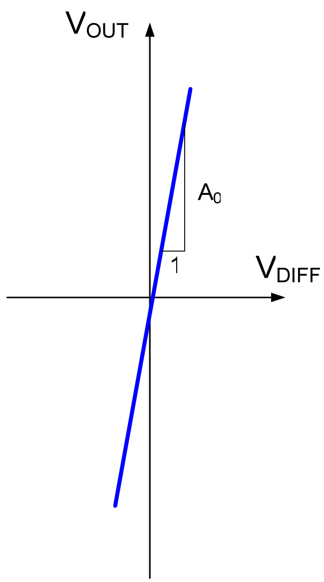
But may work too good since no hysteresis

What if the input is the output of a light sensor ?

Could be used to turn lights on at dusk, off at dawn!

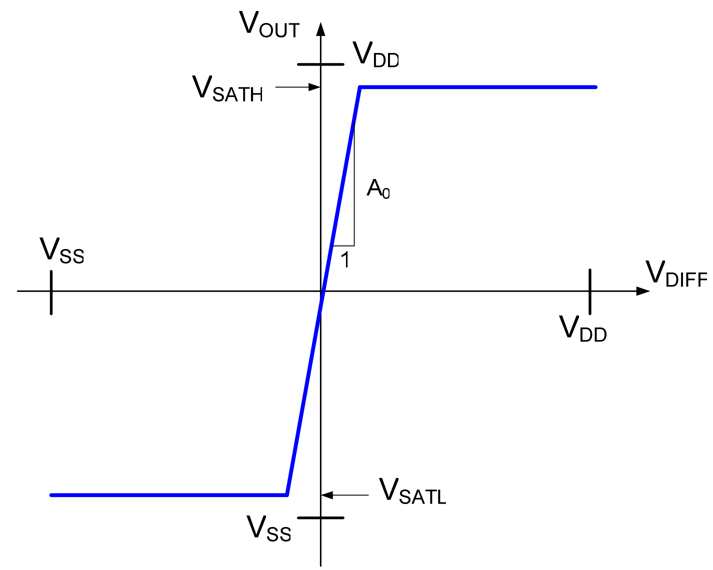
The Op Amp is Highly Nonlinear when Over-Driven





Previous (linear) model

$$\mathbf{V_{OUT} = A_0 V_{IN}}$$

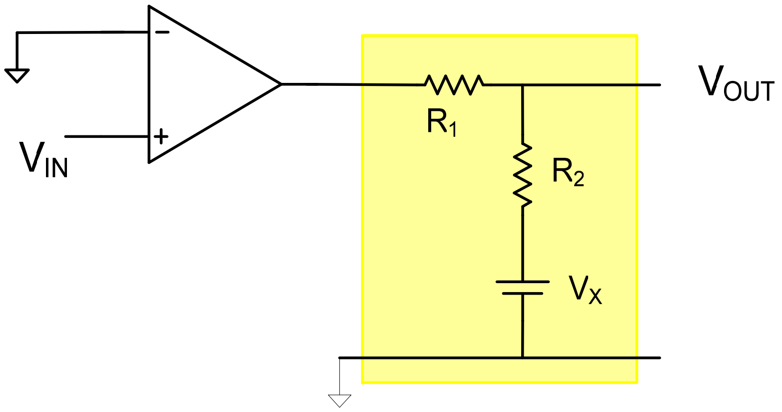


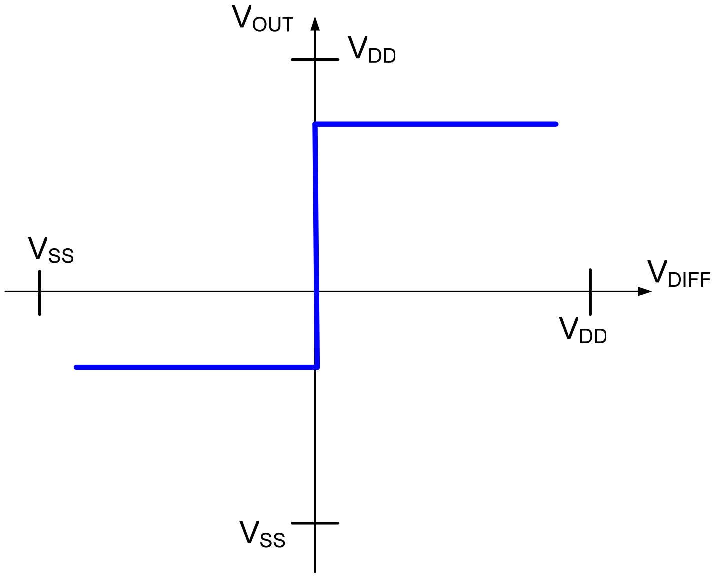
Nonlinear model

$$\mathbf{V_{OUT}} = \begin{cases} \mathbf{V_{SATH}} & \mathbf{V_{DIFF} > V_{SATH}/A_0} \\ \mathbf{A_0 V_{IN}} & \mathbf{V_{SATL}/A_0 < V_{DIFF} < V_{SATH}/A_0} \\ \mathbf{V_{SATL}} & \mathbf{V_{DIFF} < V_{SATL}/A_0} \end{cases}$$

- Nonlinear model is a piecewise linear model
- Continuity at transitions but derivatives are not continuous

The Op Amp is Highly Nonlinear when Over-Driven





The comparator circuit is also highly nonlinear

Many useful applications of op amps when operating nonlinearly

Many other nonlinear devices exist that are also very useful

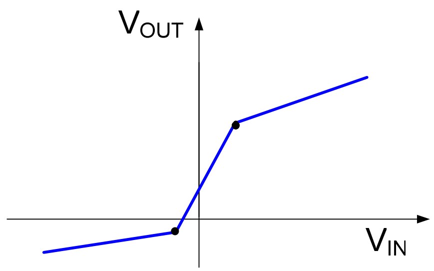
Nonlinear Circuits and Applications

Definition: A circuit is nonlinear if one or more devices in the circuit do not operate linearly

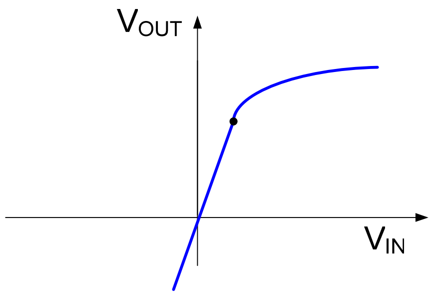
- Superposition can not be used to analyze circuit
- Nonlinear circuit applications
  - Will first consider applications where op amp operates nonlinearly
  - Will then consider other nonlinear devices

Will <u>first</u> discuss the concepts of nonlinear circuits and nonlinear circuit analysis techniques

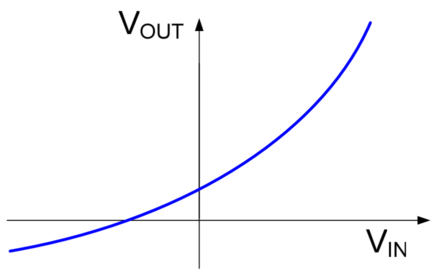
Some common types of nonlinearity



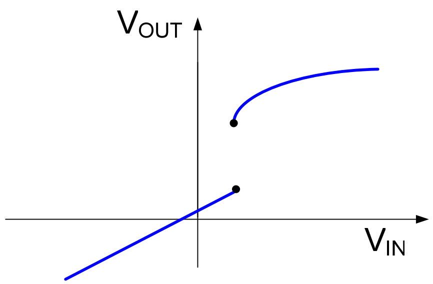
Piecewise Linear, continuous but not differentiable at knots



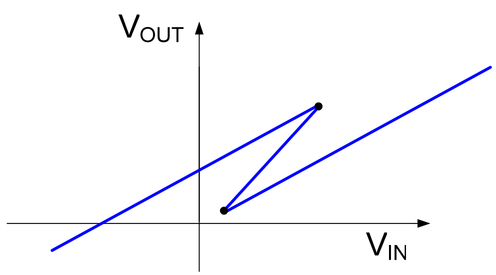
Piecewise Linear, continuous and differentiable at knots



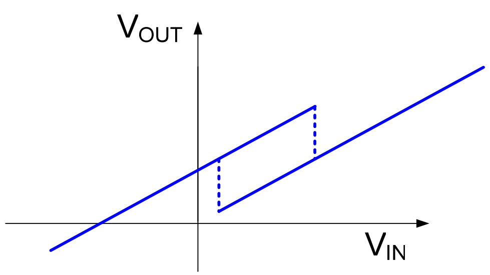
Continuous and Differentiable throughout



Discontinuous at transitions



Mujltivalued



Multi-valued and discontinuous

Observations: Nonlinear Circuits

- Nonlinear analysis is often more difficult than linear analysis

- Nonlinear analysis is sometimes less difficult than linear analysis

- Some very useful circuits are based upon nonlinear operation
  - Almost all logic circuits
  - ADCs and DACs

- Many nearly linear circuits are designed by using a large number of nonlinear devices
  - MOSFET
  - BJT
  - Diode

Observations: Nonlinear Circuits

Nonlinear analysis is often more difficult than linear analysis because a large number of devices and circuits that are not linear are lumped into the category of “nonlinear” circuits but there are many different types of nonlinearities and each may require special considerations for analysis, design, and understanding

Methods of Analysis of Nonlinear Circuits

- KCL and KVL apply to both linear and nonlinear circuits
- Superposition, voltage divider and current divider equations, Thevenin and Norton equivalence apply only to linear circuits!
- Some other analysis techniques that have been developed may apply only to linear circuits as well

Methods of Analysis of Nonlinear Circuits

Will consider three different analysis requirements and techniques for some particularly common classes of nonlinear circuits

1. Circuits with continuously differential devices

   Interested in obtaining transfer characteristics of these circuits or outputs for given input signals

2. Circuits with piecewise continuous devices

   interested in obtaining transfer characteristics of these circuits or outputs for a given input signals

3. Circuits with small-signal inputs that vary around some operating point

   Interested in obtaining relationship between small-signal inputs and the corresponding small-signal outputs. Will assume these circuits operate linearly in some suitably small region around the operating point

Other types of nonlinearities may exist and other types of analysis may be required but we will not attempt to categorize these scenarios in this course

1. Nonlinear circuits with continuously differential devices

Analysis Strategy:

Use KVL and KCL for analysis

Represent nonlinear models for devices either mathematically or graphically

Solve the resultant set of equations for the variables of interest

2. Circuits with piecewise continuous devices

e.g. $$f(x) = \begin{cases} f_1(x) & x < x_1 \quad \text{region 1} \\ f_2(x) & x > x_1 \quad \text{region 2} \end{cases}$$

Analysis Strategy:

Guess region of operation

Solve resultant circuit using the previous method

Verify region of operation is valid

Repeat the previous 3 steps as often as necessary until region of operation is verified

It helps to guess right the first time but a wrong guess will not result in an incorrect solution because a wrong guess can not be verified

3. Circuits with small-signal inputs that vary around some operating point

Interested in obtaining relationship between small-signal inputs and the corresponding small-signal outputs. Will assume these circuits operate linearly in some suitably small region around the operating point

Analysis Strategy:

Determine the operating point (using method 1 or 2 discussed above after all small signal independent inputs are set to 0)

Develop small signal (linear) model for all devices in the region of interest (around the operating point or "Q-point")

Create small signal equivalent circuit by replacing all devices with small-signal equivalent

Solve the resultant small-signal (linear) circuit

Can use KCL, KVL, and other linear analysis tools such as superposition, voltage and current divider equations, Thevenin and Norton equivalence

Determine boundary of region where small signal analysis is valid

End of Lecture 20