

EE 435

Lecture 2:

Basic Op Amp Design

- Single Stage Low Gain Op Amps

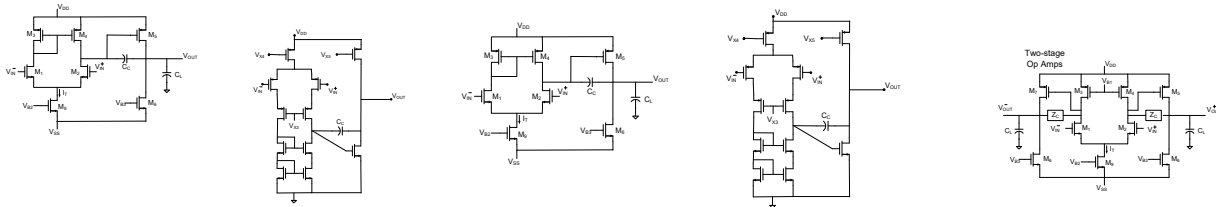
Review from last lecture:

Will Attempt in the Course to Follow, as
Much as Possible, the Following Approach

Understand



Synthesize



Analyze (if not available from the Understand step)

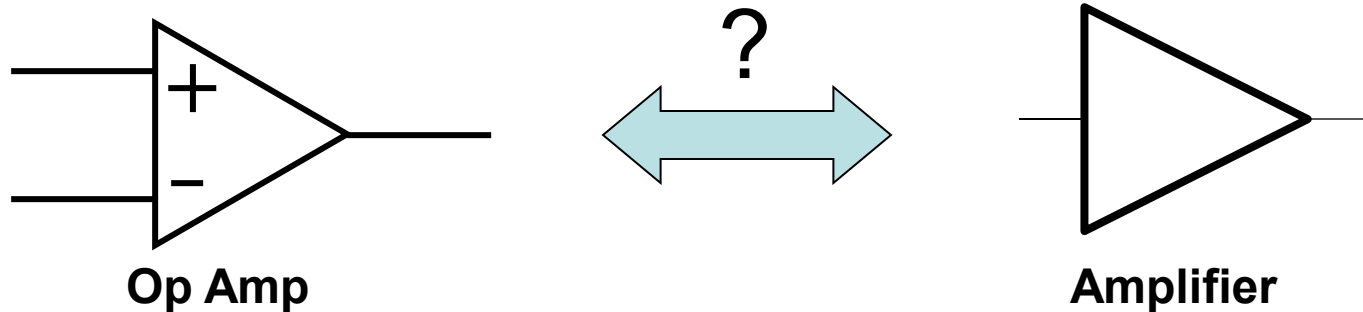
Modify, Extend, and Create



Simulate and Verify

Review from last lecture:

How does an amplifier differ from an operational amplifier?

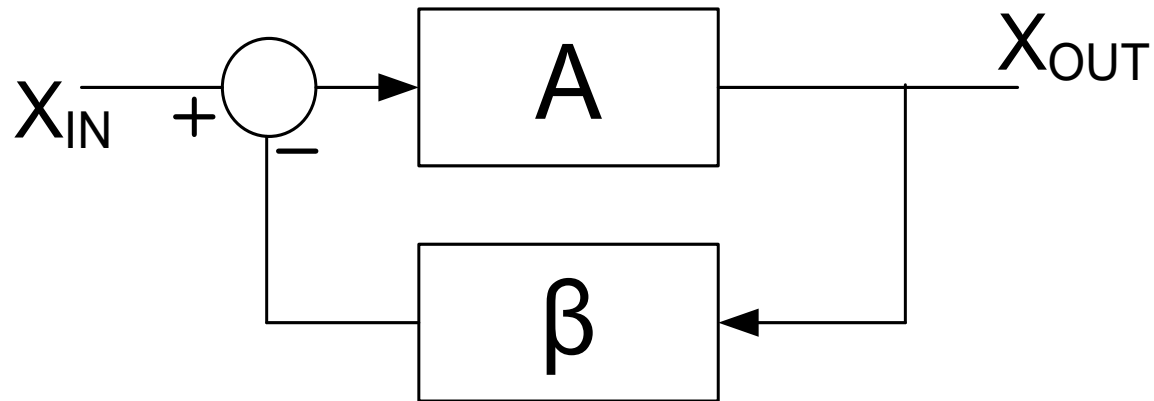


Amplifier used in open-loop applications

Operational Amplifier used in feedback applications

Review from last lecture:

Why are Operational Amplifiers Used?



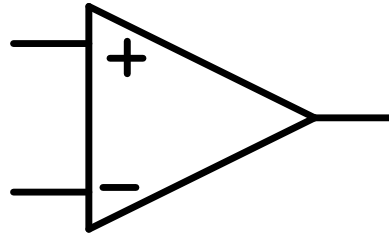
Input and Output Variables intentionally designated as “X” instead of “V”

$$\frac{X_{out}}{X_{in}} = A_F = \frac{A}{1 + A\beta} = \underset{\approx}{A \rightarrow \infty} \frac{1}{\beta}$$

Op Amp is Enabling Element Used to Build Feedback Networks !

Review from last lecture:

What is an Operational Amplifier?



Textbook Definition:

- Voltage Amplifier with Very Large Gain
 - Very High Input Impedance
 - Very Low Output Impedance
- Differential Input and Single-Ended Output

This represents the Conventional Wisdom !

Does this correctly reflect what an operational amplifier really is?

Review from last lecture:

From earlier edition

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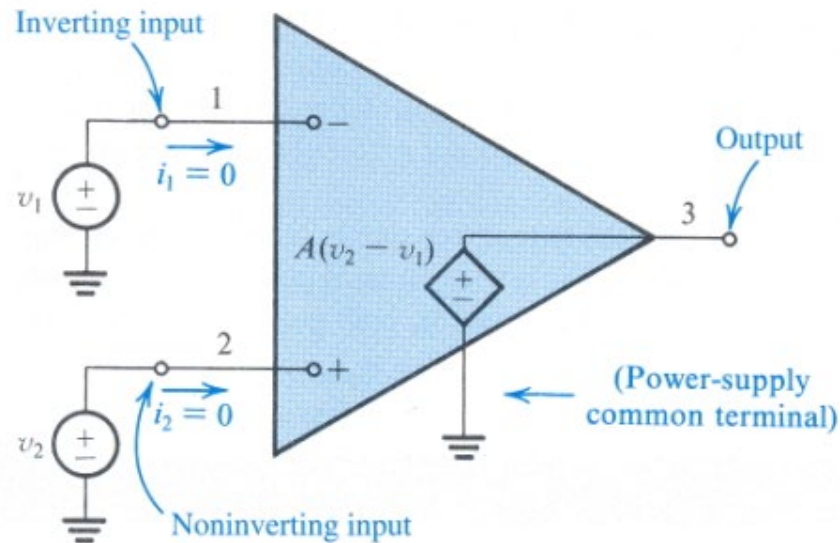


FIGURE 2.3 Equivalent circuit of the ideal op amp.

TABLE 2.1 Characteristics of the Ideal Op Amp

1. Infinite input impedance
2. Zero output impedance
3. Zero common-mode gain or, equivalently, infinite common-mode rejection
4. Infinite open-loop gain A
5. Infinite bandwidth

Review from last lecture:

What Characteristics are Really Needed for Op Amps?

$$A_F = \frac{A}{1 + A\beta} \approx \frac{1}{\beta} \quad A_{VF} = \frac{-A\beta_1}{1 + A\beta} \approx \frac{-\beta_1}{\beta}$$

1. Very Large Gain

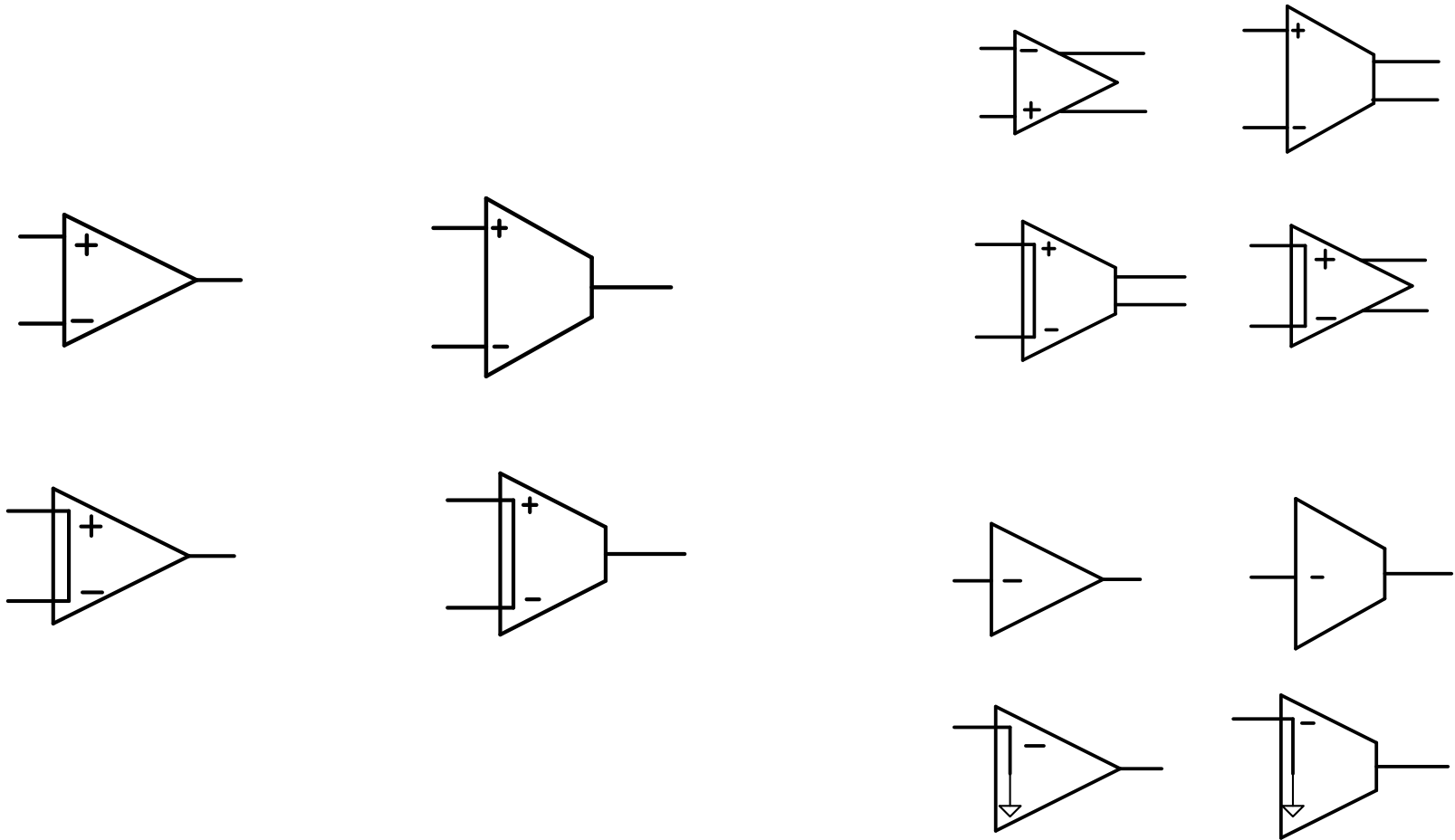
To make A_F (or A_{VF}) insensitive to variations in A

To make A_F (or A_{VF}) insensitive to nonlinearities of A

2. Port Configurations Consistent with Application

Review from last lecture:

Port Configurations for Op Amps



(Could also have single-ended input and differential output though less common)

Review from last lecture:

What Characteristics do Many Customers and Designers Assume are Needed for Op Amps?

1. Very Large Voltage Gain

and ...

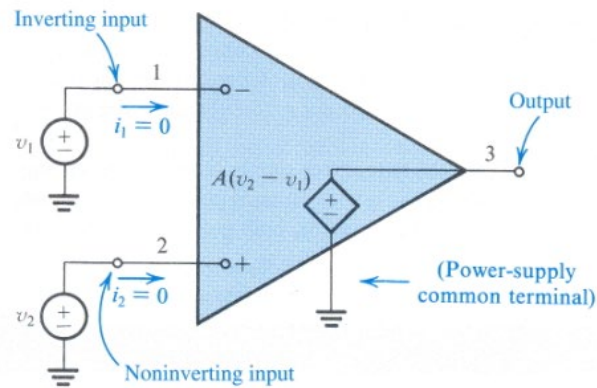
2. Low Output Impedance
3. High Input Impedance
4. Large Output Swing
3. Large Input Range
4. Good High-frequency Performance
5. Fast Settling
6. Adequate Phase Margin
7. Good CMRR
8. Good PSRR
9. Low Power Dissipation
10. Reasonable Linearity
11. . . .

Is This Another Quirk in Conventional Op Amp Wisdom ?

How many terminals (nodes) are included in the op amp model?

Four !

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ision: 2144 x 2632 pixels



Which one?
Does it make a difference?

FIGURE 2.3 Equivalent circuit of the ideal op amp.

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Terminals (nodes) in a commercial op amp

TL081, TL081A, TL081B, TL081H
TL082, TL082A, TL082B, TL082H
TL084, TL084A, TL084B, TL084H

SLOS081M – FEBRUARY 1977 – REVISED DECEMBER 2021



5 Pin Configuration and Functions

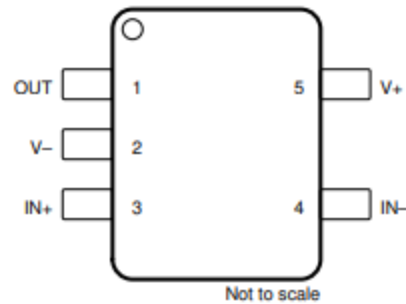


Figure 5-1. TL081H DBV Package
5-Pin SOT-23
(Top View)

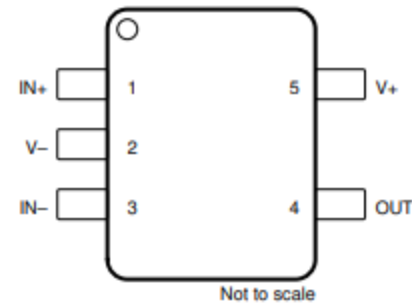
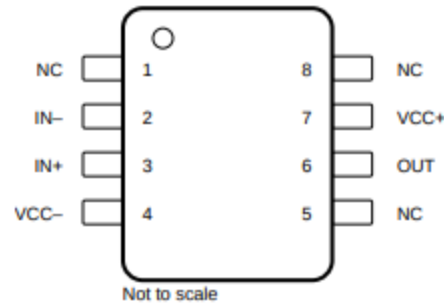


Figure 5-2. TL081H DCK Package
5-Pin SC70
(Top View)



NC- no internal connection

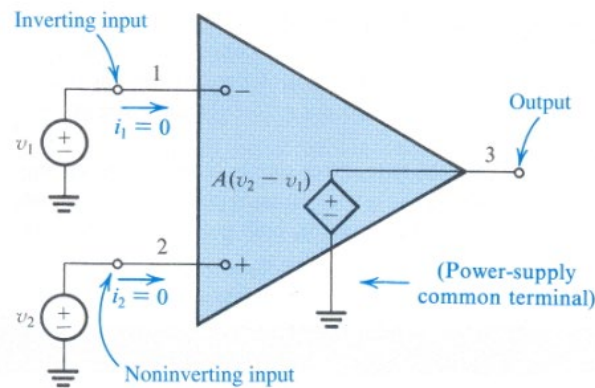
Figure 5-3. TL084H D Package

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FIGURE 2.3 Equivalent circuit of the ideal op amp.

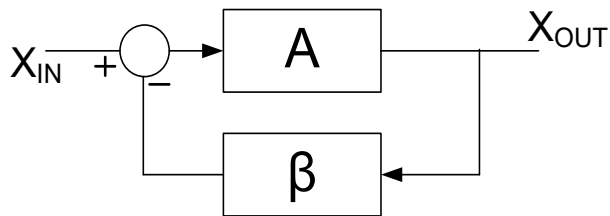
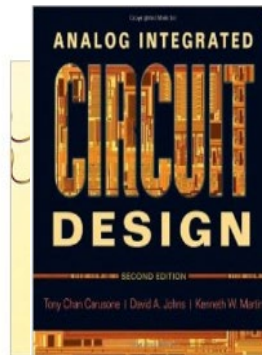
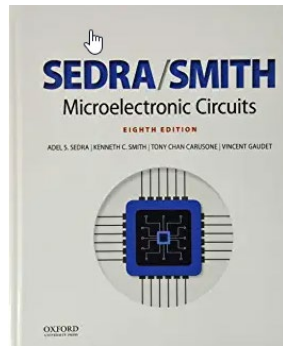
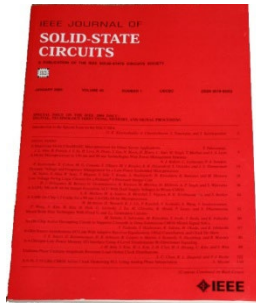
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See Homework Problem that focuses on the missing-terminal issue

What is an Operational Amplifier?

Lets see what the experts say !



Conventional Wisdom does not provide good guidance on what an amplifier or an operational amplifier should be!

What are the implications of this observation?

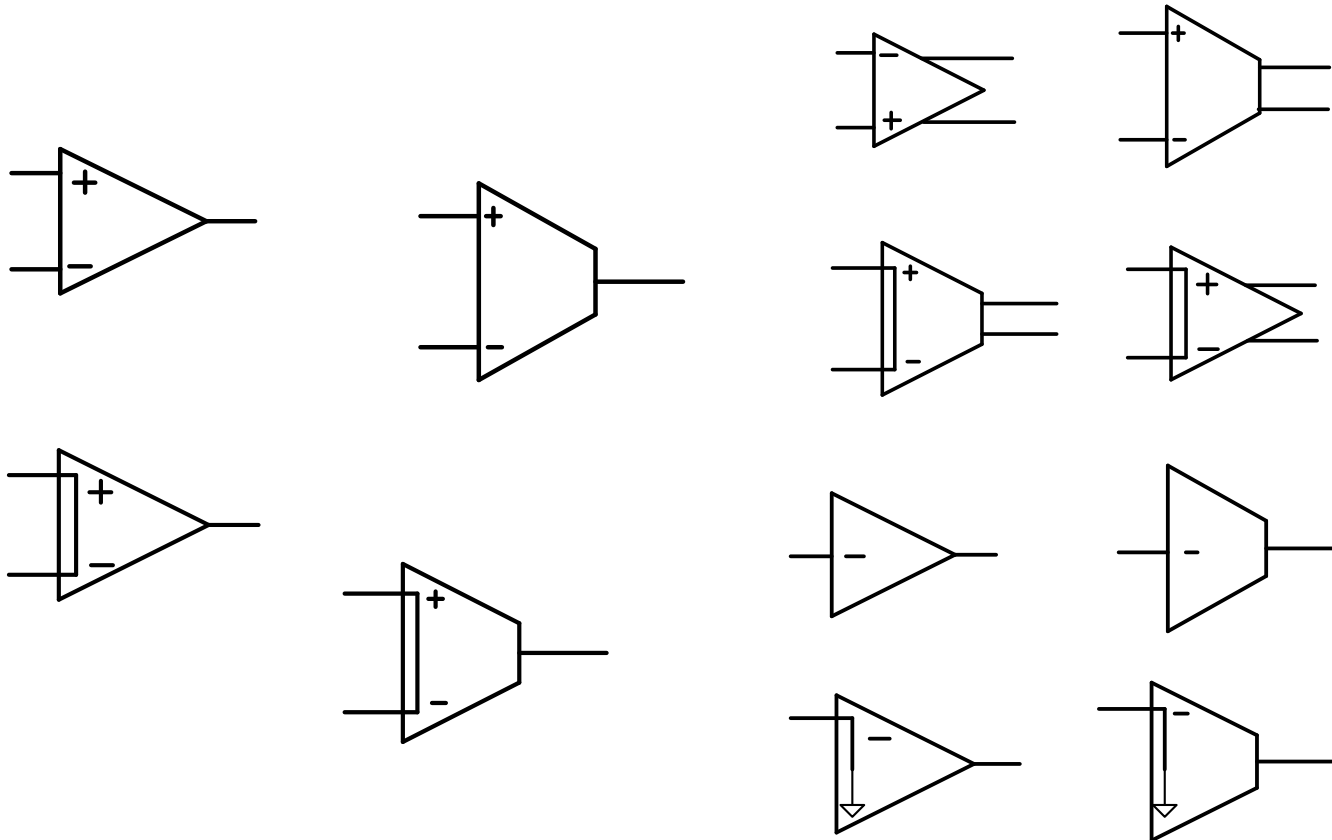
Conventional Wisdom Does Not Always Provide Correct Perspective –

even in some of the most basic or fundamental areas !!

- Just because its published doesn't mean its correct
- Just because famous people convey information as fact doesn't mean they are right
- Keep an open mind about everything that is done and always ask whether the approach others are following is leading you in the right direction

Operational Amplifiers

Two-port network with a “large” gain that will be used in a feedback configuration



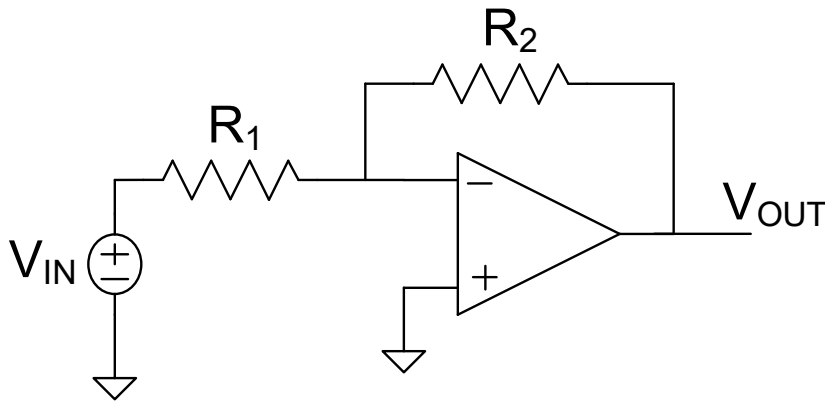
Do these models have the missing-terminal issue ?

Operational Amplifiers

How large must the gain be to be useful in a feedback amplifier?

Consider Op Amp with $GB=1\text{MHz}$, $A_{00}=10^5$, $R_2=100\text{K}$, $R_1=2\text{K}$, $V_{IN}=0.1\sin(2\pi\cdot 5000t)$

Ideally $A_{VFB} = -50$ $V_{OUT}=5\sin(2\pi\cdot 5000t)$



This might be considered to be a rather common audio frequency application

How big is the gain of the Op Amp at 5KHz?

Observation: Operational Amplifiers are Almost Always Designed to Have a Single-Pole Lowpass Response with gain

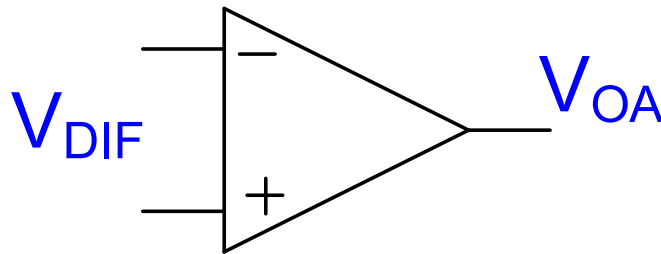
$$A_{OA}(s) = \frac{A_o p}{s + p} = \frac{GB}{s + p}$$

Operational Amplifiers

How large must the gain be to be useful in a feedback amplifier?

Consider Op Amp with $GB=1\text{MHz}$, $A_{00}=10^5$, $R_2=100\text{K}$, $R_1=2\text{K}$, $V_{IN}=0.1\sin(2\pi\cdot 5000t)$

Ideally $A_{VFB} = -50$ $V_{OUT}=5\sin(2\pi\cdot 5000t)$



$$A_{OA}(s) = \frac{A_o p}{s + p} = \frac{GB}{s + p} \quad p=62.8 \text{ rad/sec}$$

At $f=5\text{KHz}$

$$A_{OA}(j2\pi \cdot 5000) = \frac{2\pi \cdot 10 \cdot 10^5}{j2\pi \cdot 5000 + 10}$$

$$|A_{OA}(j2\pi \cdot 5000)| = \frac{10^6}{\sqrt{(2\pi \cdot 5000)^2 + 100}} \approx \frac{2\pi \cdot 10^6}{2\pi \cdot 5000} = 200$$

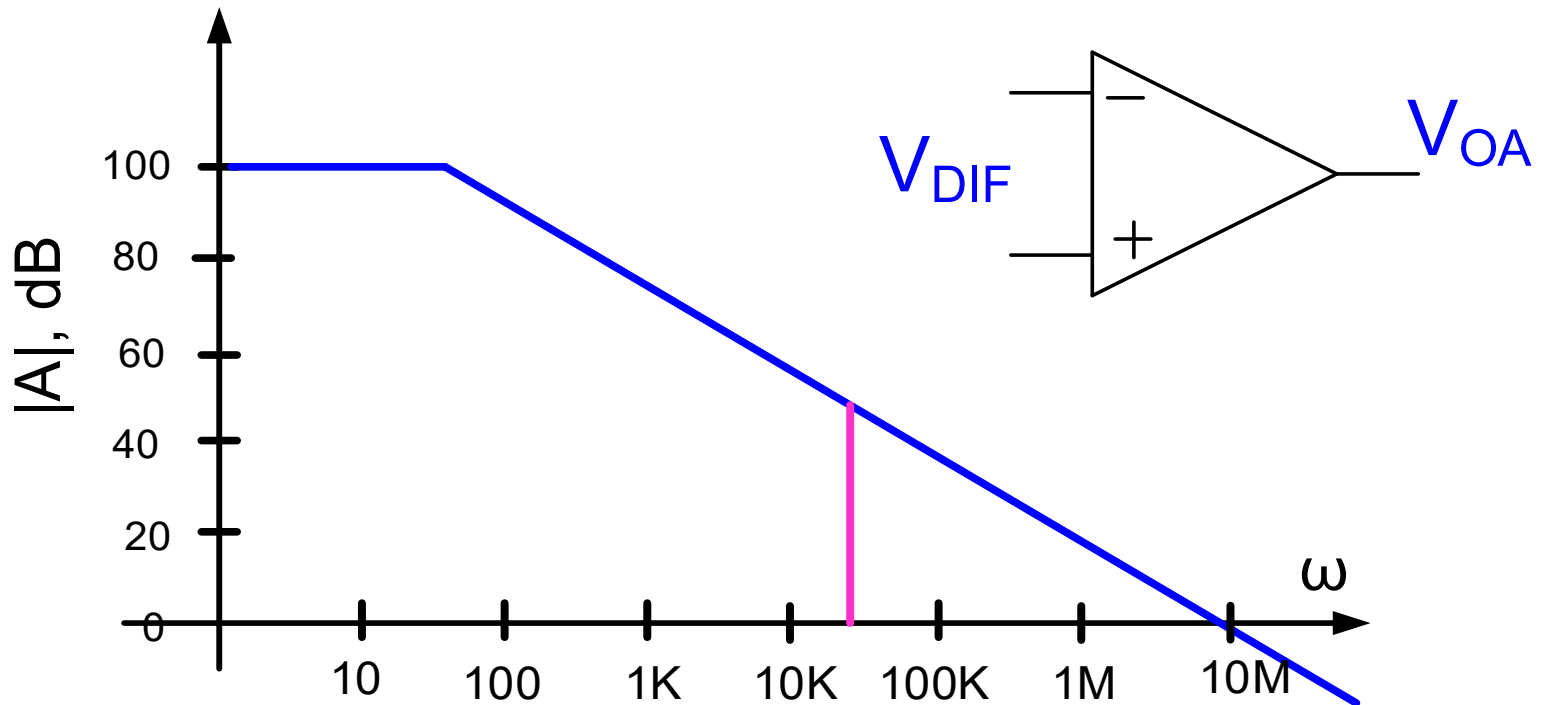
The gain of this operational amplifier at the operating frequency is only 200

$$20\log(20)=46\text{dB}$$

Operational Amplifiers

How large must the gain be to be useful in a feedback amplifier?


Consider Op Amp with $GB=1\text{MHz}$, $A_{00}=10^5$, $R_2=100\text{K}$, $R_1=2\text{K}$, $V_{IN}=0.1\sin(2\pi\cdot 5000t)$



At $\omega=2\pi\cdot 5\text{K}$ rad/sec $|A|=200$

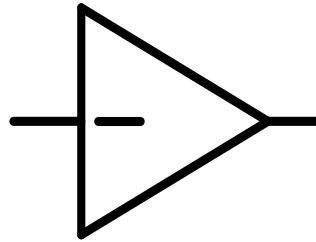
So will now investigate amplifiers that have varying “large” gains

Basic Op Amp Design Outline

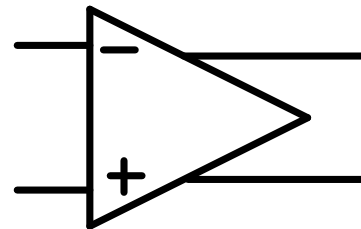
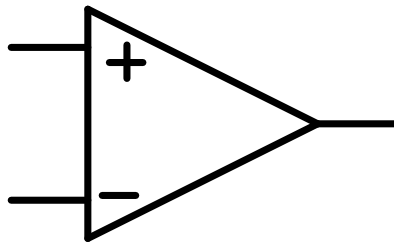
- Fundamental Amplifier Design Issues
-  • Single-Stage Low Gain Op Amps
- Single-Stage High Gain Op Amps
- Two-Stage Op Amp
- Other Basic Gain Enhancement Approaches

Single-Stage Low-Gain Op Amps

-  • Single-ended input



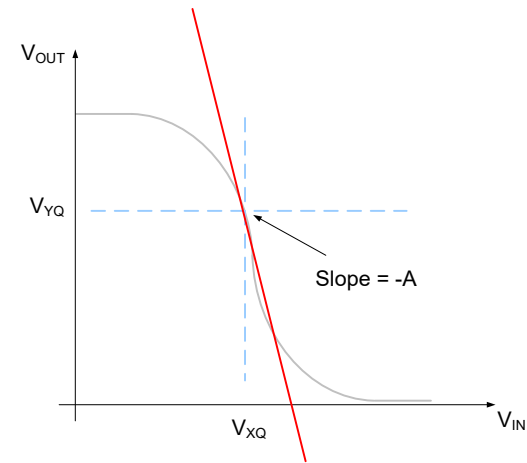
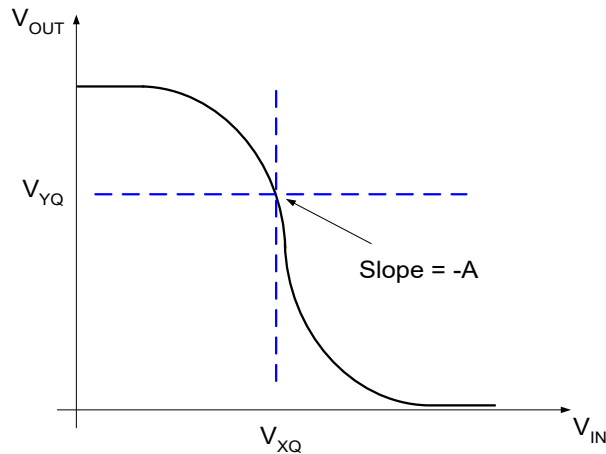
- Differential Input



(Symbol not intended to distinguish between different amplifier types)

Single-ended Op Amp (Inverting Amplifier)

Consider:



Assume Q-point at $\{V_{XQ}, V_{YQ}\}$

$$\mathbf{V}_{OUT} = \mathbf{f}(\mathbf{V}_{IN})$$

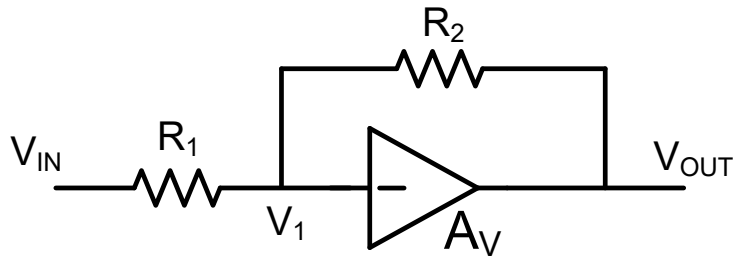
$$V_{OUT} \cong (-A)(V_{IN} - V_{XQ}) + V_{YQ}$$

When operating near the Q-point, the linear and nonlinear model of the amplifier are nearly the same

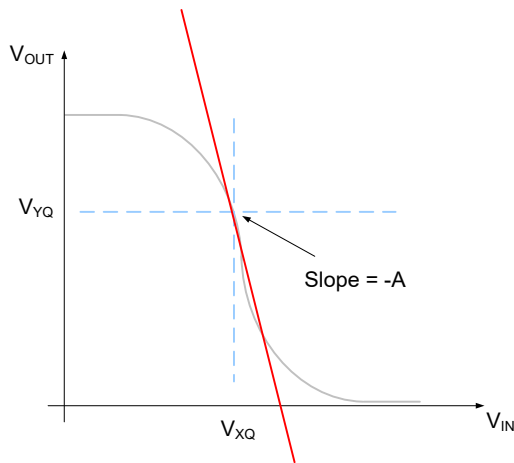
If the gain of the amplifier is large, V_{XQ} is a characteristic of the amplifier

Single-ended Op Amp (Inverting Amplifier)

(assume the feedback network does not affect the relationship between V_1 and V_{OUT})



$$\left. \begin{aligned} V_O &= (-A)(V_1 - V_{XQ}) + V_{YQ} \\ V_1 &= \frac{R_1}{R_1 + R_2} V_O + \frac{R_2}{R_1 + R_2} V_{IN} \end{aligned} \right\}$$



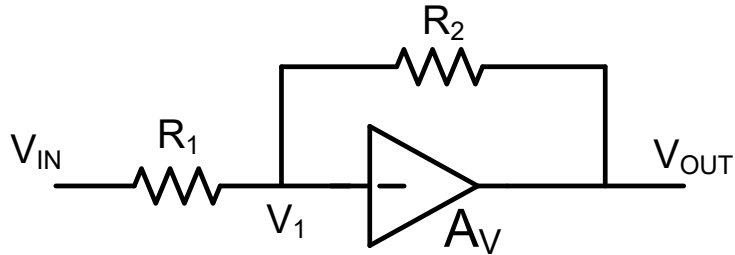
Eliminating V_1 we obtain:

$$V_O = (-A) \left(\frac{R_1}{R_1 + R_2} V_O + \frac{R_2}{R_1 + R_2} V_{IN} - V_{XQ} \right) + V_{YQ}$$

If we define V_{iSS} (small-signal) by $V_{IN} = V_{INQ} + V_{iSS}$

$$V_O = \left(\frac{-A \left(\frac{R_2}{R_1 + R_2} \right)}{1 + A \left(\frac{R_1}{R_1 + R_2} \right)} \right) (V_{iSS} + V_{INQ}) + \left(\frac{A}{1 + A \left(\frac{R_1}{R_1 + R_2} \right)} \right) V_{XQ} + \left(\frac{1}{1 + A \left(\frac{R_1}{R_1 + R_2} \right)} \right) V_{YQ}$$

Single-ended Op Amp Inverting Amplifier



$$V_O = \left(\frac{-A \left(\frac{R_2}{R_1 + R_2} \right)}{1 + A \left(\frac{R_1}{R_1 + R_2} \right)} \right) (V_{ISS} + V_{INQ}) + \left(\frac{A}{1 + A \left(\frac{R_1}{R_1 + R_2} \right)} \right) V_{XQ} + \left(\frac{1}{1 + A \left(\frac{R_1}{R_1 + R_2} \right)} \right) V_{YQ}$$

But if A is large, this reduces to

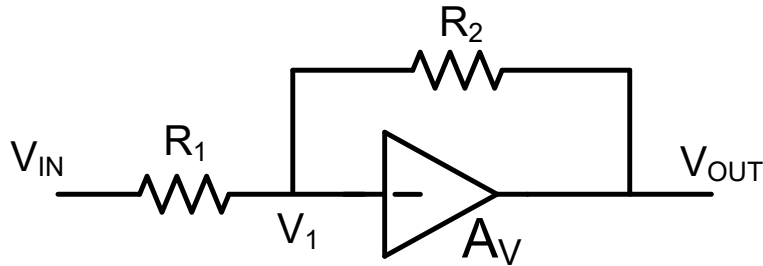
$$V_O = -\frac{R_2}{R_1} V_{ISS} + V_{XQ} + \frac{R_2}{R_1} (V_{XQ} - V_{INQ})$$

Note that as long as A is large, if V_{INQ} is close to V_{XQ}

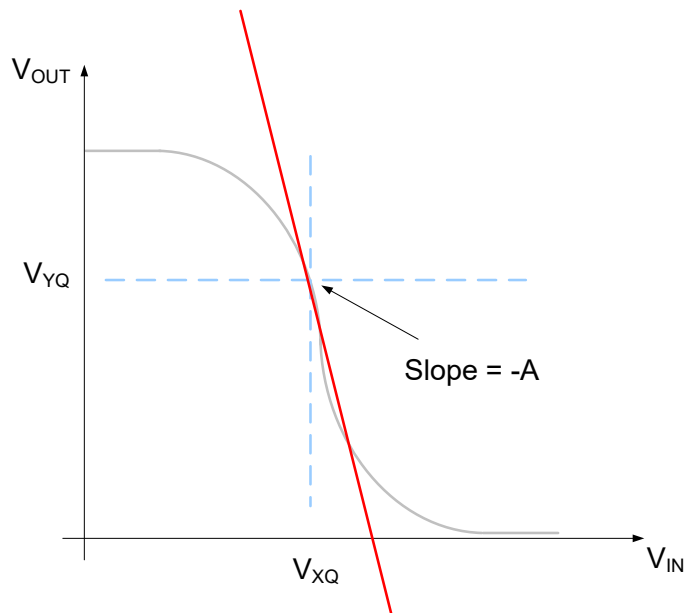
$$V_O \cong -\frac{R_2}{R_1} V_{ISS} + V_{XQ}$$

Single-ended Op Amp Inverting Amplifier

(assume the feedback network does not affect the relationship between V_1 and V_{OUT})



$$\left. \begin{aligned} V_O &= (-A)(V_1 - V_{XQ}) + V_{YQ} \\ V_1 &= \frac{R_1}{R_1 + R_2} V_O + \frac{R_2}{R_1 + R_2} V_{IN} \end{aligned} \right\}$$



Summary:

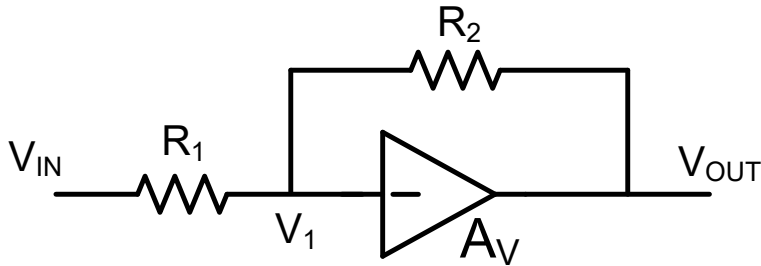
$$V_O = -\frac{R_2}{R_1} V_{iss} + V_{XQ} + \frac{R_2}{R_1} (V_{XQ} - V_{inQ})$$

Does this example have a missing ground-node issue?

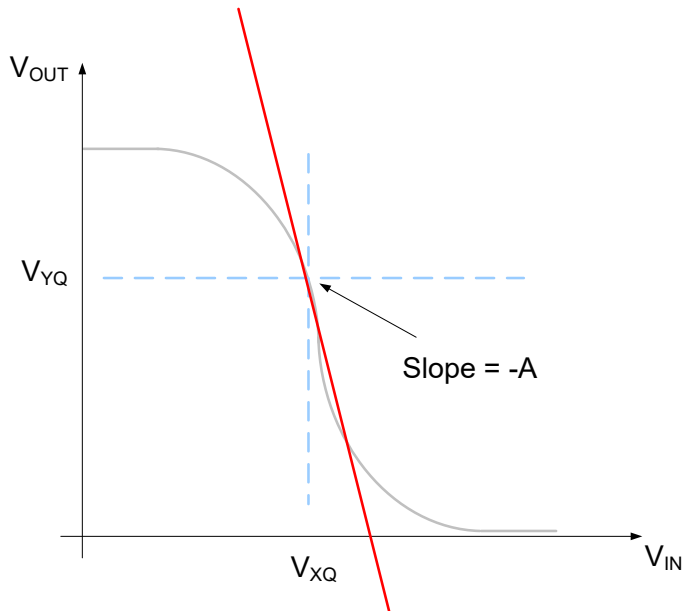
No! In this example, A is the slope, not the gain of a two-port amplifier!

Single-ended Op Amp Inverting Amplifier

(assume the feedback network does not affect the relationship between V_1 and V_{OUT})



$$\left. \begin{aligned} V_O &= (-A)(V_1 - V_{XQ}) + V_{YQ} \\ V_1 &= \frac{R_1}{R_1 + R_2} V_O + \frac{R_2}{R_1 + R_2} V_{IN} \end{aligned} \right\}$$

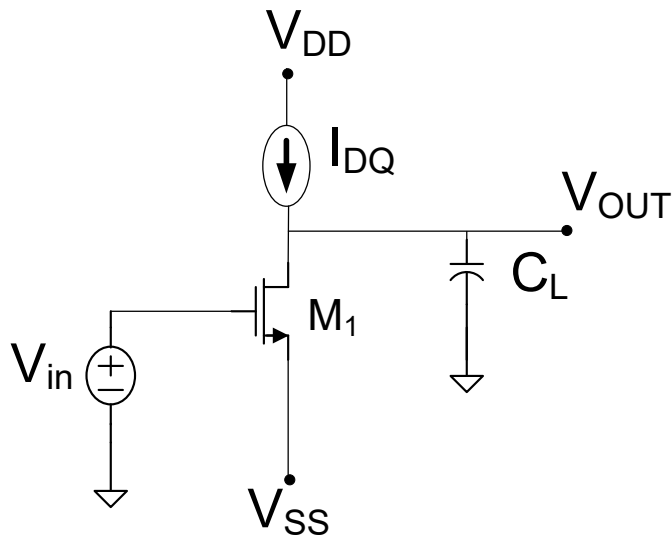


Summary:

$$V_O = -\frac{R_2}{R_1} V_{iss} + V_{XQ} + \frac{R_2}{R_1} (V_{XQ} - V_{inQ})$$

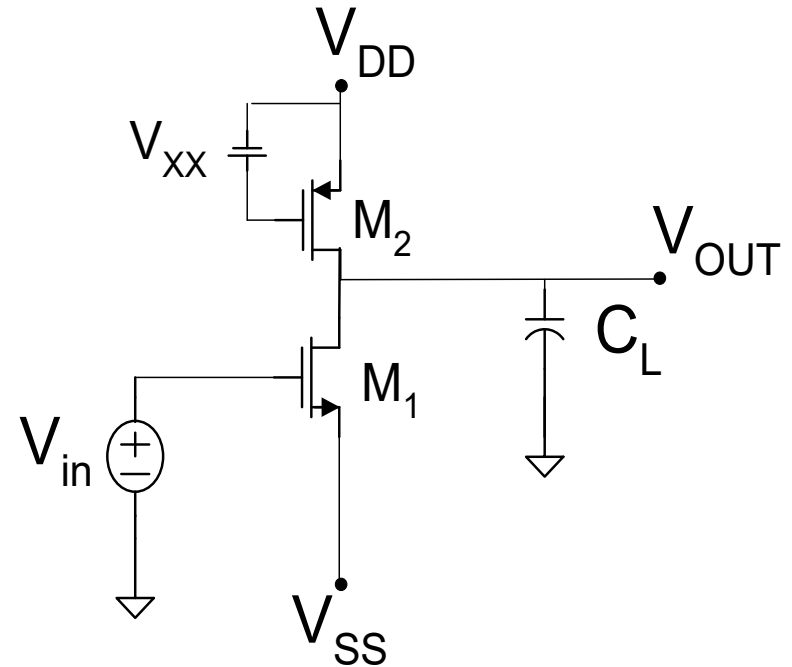
What type of circuits have the transfer characteristic shown?

Single-stage single-input low-gain op amp



Basic Structure

Have added the load capacitance to include frequency dependence of the amplifier gain



Practical Implementation

This is the common-source amplifier with current source biasing discussed in EE 330

This is not a new idea !



Gene Taatjes
JULY 1973

AN-88
CMC

CMOS LINEAR APPLICATIONS

PNP and NPN bipolar transistors have been used for many years in "complementary" type of amplifier circuits. Now, with the arrival of CMOS technology, complementary P-channel/N-channel MOS transistors are available in monolithic form. The MM74C04 incorporates a P-channel MOS transistor and an N-channel MOS transistor connected in complementary fashion to function as an inverter.

Due to the symmetry of the P- and N-channel transistors, negative feedback around the complementary pair will cause the pair to self bias itself to approximately 1/2 of the supply voltage. Figure 1 shows an idealized voltage transfer characteristic curve of the CMOS inverter connected with negative feedback. Under these conditions the inverter is biased for operation about the midpoint in the linear segment on the steep transition of the voltage transfer characteristic as shown in Figure 1.

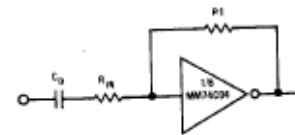
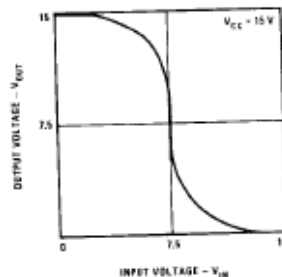


FIGURE 2. A 74CMOS Inverter Biased for Linear Mode Operation.

The power supply current is constant during dynamic operation since the inverter is biased for Class A operation. When the input signal swings near the supply, the output signal will become distorted because the P-N channel devices are driven into the non-linear regions of their transfer characteristics. If the input signal approaches the supply voltages, the P- or N-channel transistors become saturated and supply current is reduced to essentially zero and the device behaves like the classical digital inverter.

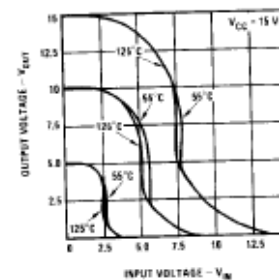
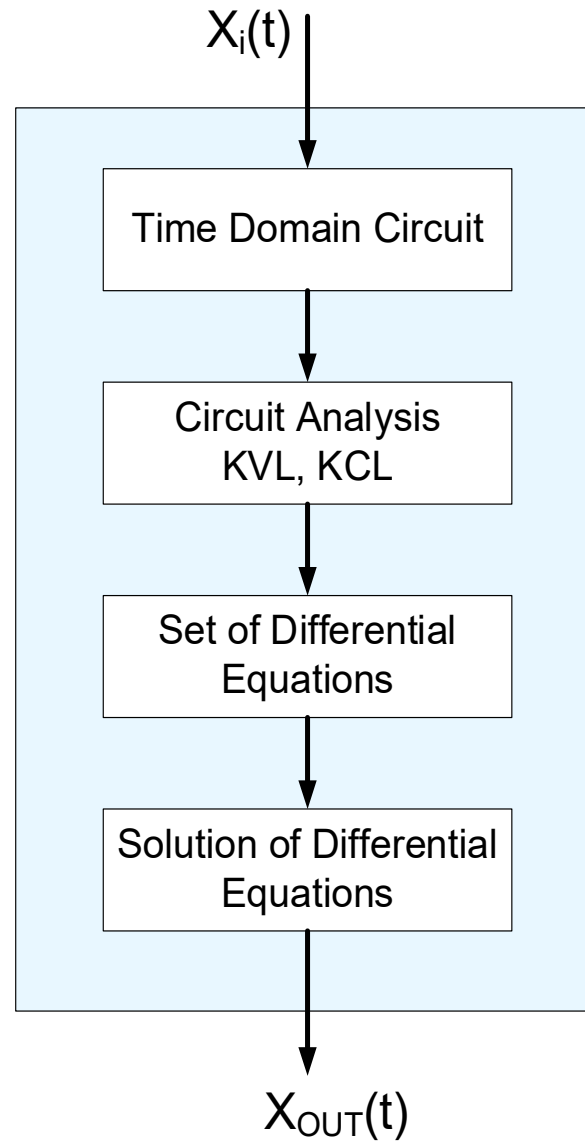


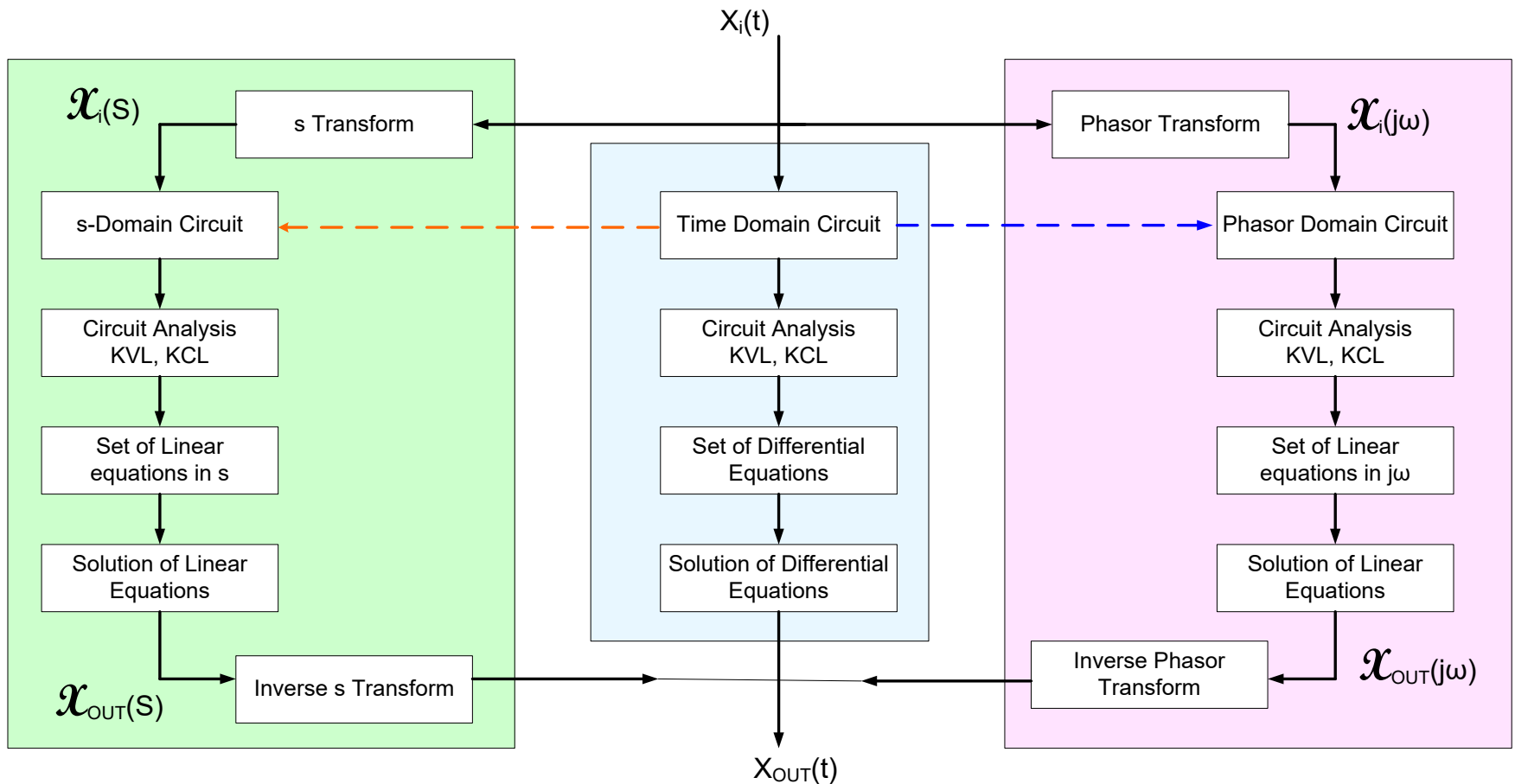
FIGURE 3. Voltage Transfer Characteristics for an Inverter Connected as a Linear Amplifier.

Review of ss steady-state analysis

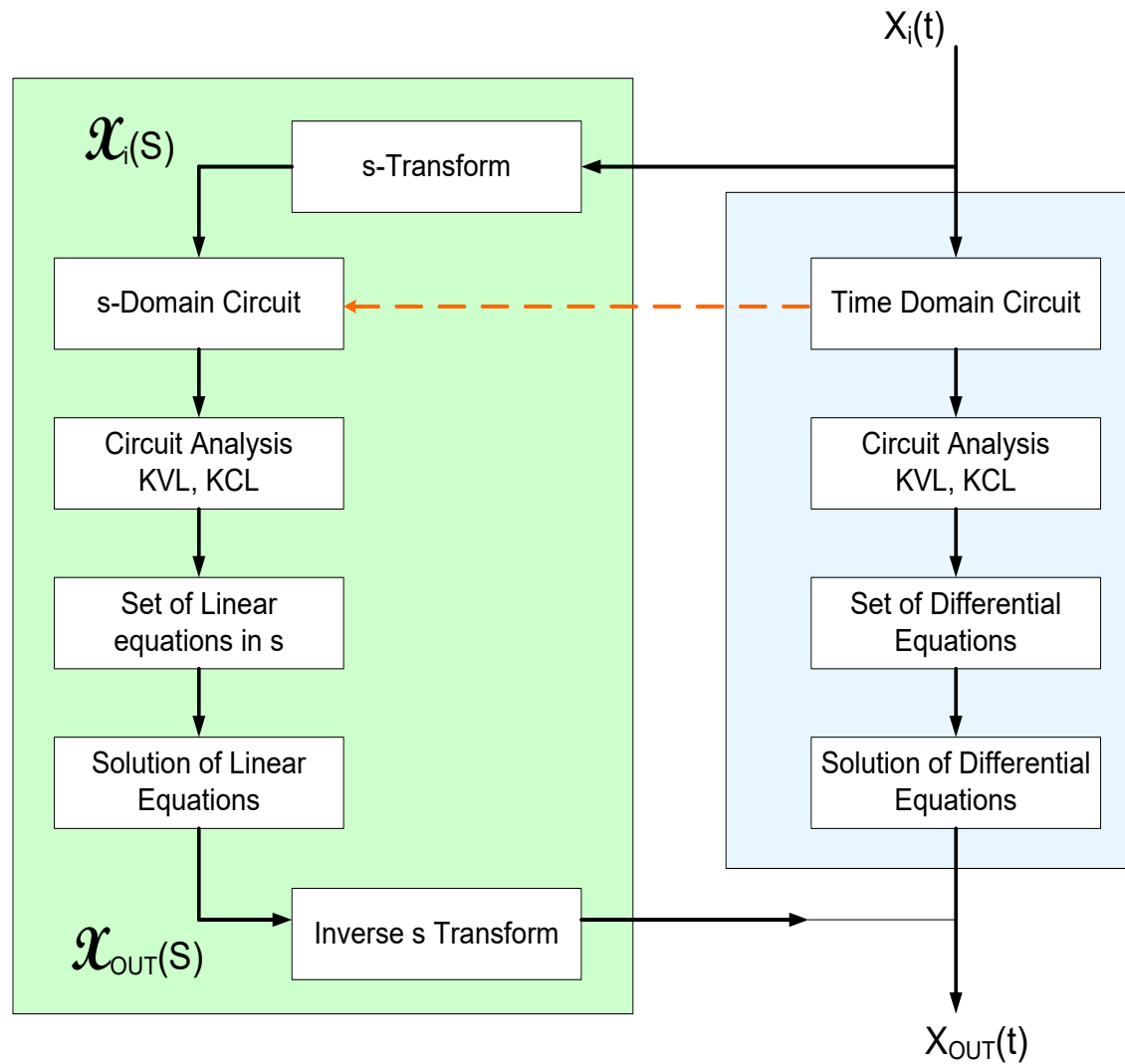
Standard Formal Approach to Circuit Analysis



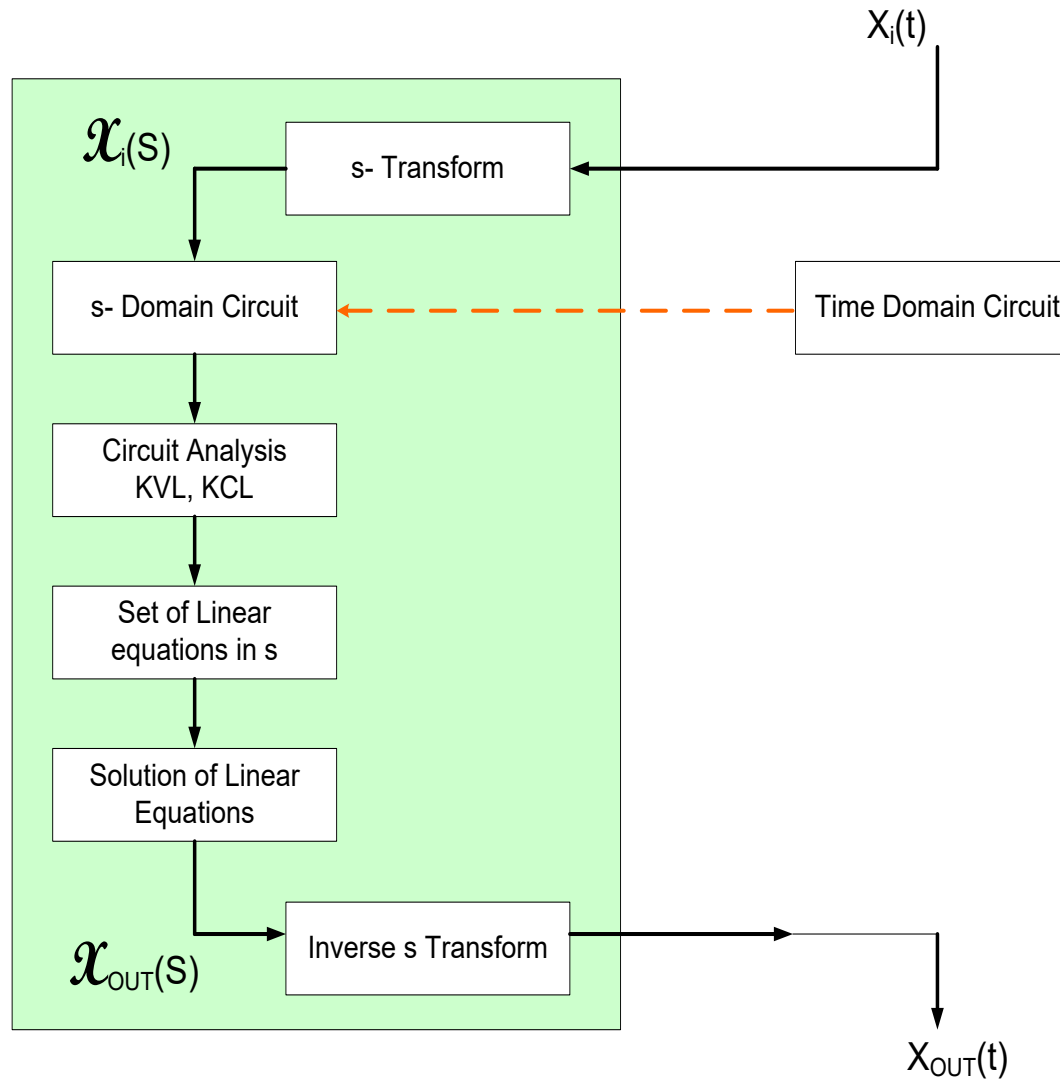
Time, Phasor, and s- Domain Analysis



Time and s- Domain Analysis

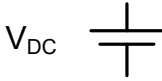
















s- Domain Analysis


















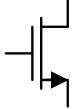
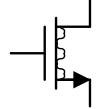

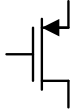
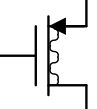
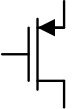
Review of ss steady-state analysis

Dc and small-signal equivalent elements

	Element	ss equivalent	dc equivalent
dc Voltage Source	V_{DC} 		V_{DC} 
ac Voltage Source	V_{AC} 	V_{AC} 	
dc Current Source	I_{DC} 		I_{DC} 
ac Current Source	I_{AC} 	I_{AC} 	
Resistor	R 	R 	R 


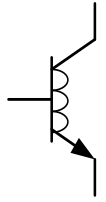
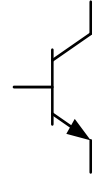

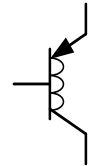
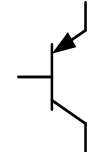






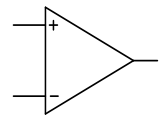
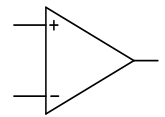
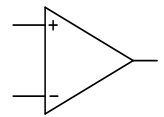
Review of ss steady-state analysis

Dc and small-signal equivalent elements

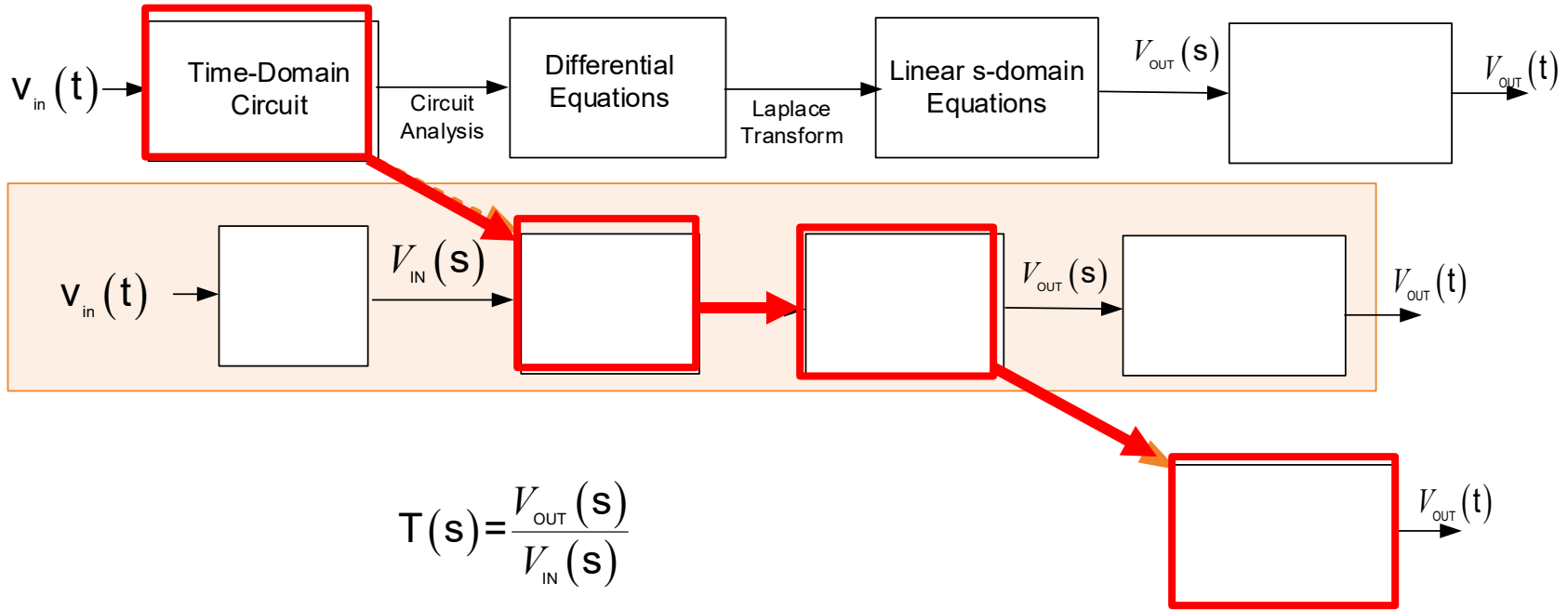
	Element	ss equivalent	dc equivalent
Capacitors	<p>C</p>  <p>Large</p>		
	<p>C</p>  <p>Small</p>	<p>C</p> 	
Inductors	<p>L</p>  <p>Large</p>		
	<p>L</p>  <p>Small</p>	<p>L</p> 	
Diodes			 <p>Simplified</p>
MOS transistors			 <p>Simplified</p>
			 <p>Simplified</p>

Review of ss steady-state analysis

Dc and small-signal equivalent elements

	Element	ss equivalent	dc equivalent
Bipolar Transistors			 Simplified
			 Simplified
Dependent Sources			
			
			

Summary of Sinusoidal Steady-State Analysis Methods for Linear Networks



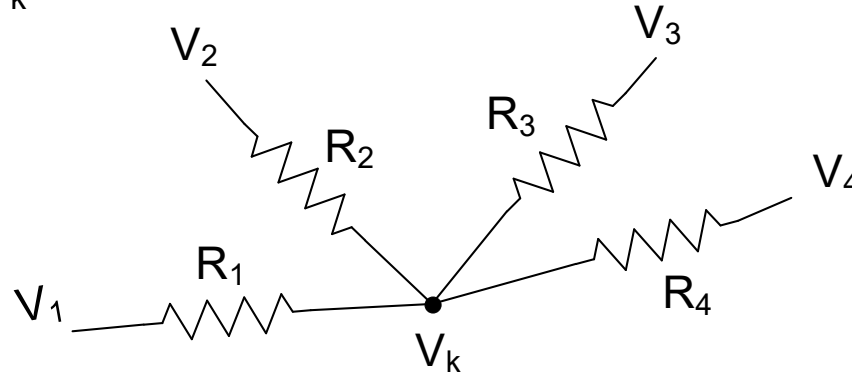
$$T(s) = \frac{V_{OUT}(s)}{V_{IN}(s)}$$

$$V_{out}(t) = V_M |T(j\omega)| \sin(\omega t + \theta + \angle T(j\omega))$$

Nodal Analysis (A Brief Review)

Widely used to analyze electronic circuits – and for good reason!

Example: Determine V_k



From KCL

$$\left(\frac{V_k - V_1}{R_1}\right) + \left(\frac{V_k - V_2}{R_2}\right) + \left(\frac{V_k - V_3}{R_3}\right) + \left(\frac{V_k - V_4}{R_4}\right) = 0$$

$$V_k \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}\right) = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \frac{V_4}{R_4}$$

$$V_k = V_1 \frac{1}{R_1 \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}\right)} + V_2 \frac{1}{R_2 \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}\right)} + V_3 \frac{1}{R_3 \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}\right)} + V_4 \frac{1}{R_4 \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}\right)}$$

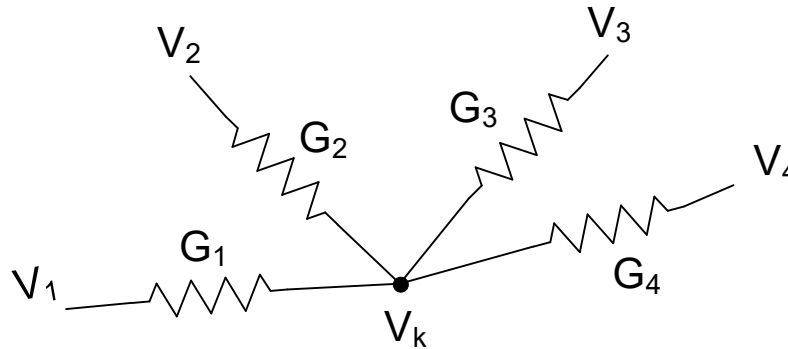
$$V_k = V_1 \frac{R_2 R_3 R_4}{(R_2 R_3 R_4 + R_1 R_3 R_4 + R_2 R_1 R_4 + R_2 R_3 R_1)} + V_2 \frac{R_1 R_3 R_4}{(R_2 R_3 R_4 + R_1 R_3 R_4 + R_2 R_1 R_4 + R_2 R_3 R_1)} + V_3 \frac{R_2 R_1 R_4}{(R_2 R_3 R_4 + R_1 R_3 R_4 + R_2 R_1 R_4 + R_2 R_3 R_1)} + V_4 \frac{R_2 R_3 R_1}{(R_2 R_3 R_4 + R_1 R_3 R_4 + R_2 R_1 R_4 + R_2 R_3 R_1)}$$

- Time consuming and tedious for even simple circuits
- And if there are several nodes in a circuit, complexity of resultant equations is overwhelming

Nodal Analysis (A Brief Review)

Widely used to analyze electronic circuits – and for good reason!

Example: Determine V_k



From KCL
$$V_k (G_1 + G_2 + G_3 + G_4) = G_1 V_1 + G_2 V_2 + G_3 V_3 + G_4 V_4$$

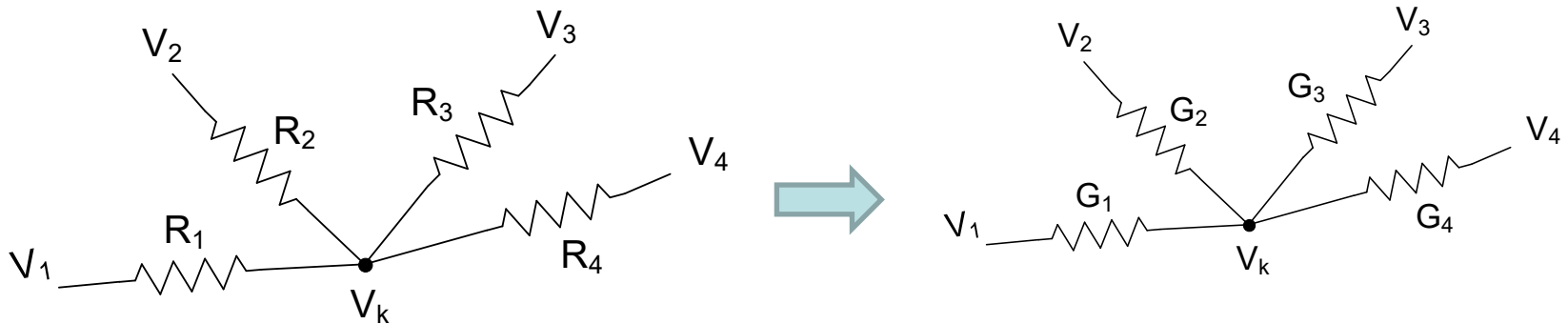
$$V_k = V_1 \frac{G_1}{G_1 + G_2 + G_3 + G_4} + V_2 \frac{G_2}{G_1 + G_2 + G_3 + G_4} + V_3 \frac{G_3}{G_1 + G_2 + G_3 + G_4} + V_4 \frac{G_4}{G_1 + G_2 + G_3 + G_4}$$

Often much simpler to work with conductances than with resistances!

And expressions much simpler

Nodal Analysis (A Brief Review)

Widely used to analyze electronic circuits – and for good reason!



And expressions much simpler (compare in standard rational fraction form)

$$V_k = V_1 \frac{R_2 R_3 R_4}{(R_2 R_3 R_4 + R_1 R_3 R_4 + R_2 R_1 R_4 + R_2 R_3 R_1)} + V_2 \frac{R_1 R_3 R_4}{(R_2 R_3 R_4 + R_1 R_3 R_4 + R_2 R_1 R_4 + R_2 R_3 R_1)} + V_3 \frac{R_2 R_1 R_4}{(R_2 R_3 R_4 + R_1 R_3 R_4 + R_2 R_1 R_4 + R_2 R_3 R_1)} + V_4 \frac{R_2 R_3 R_1}{(R_2 R_3 R_4 + R_1 R_3 R_4 + R_2 R_1 R_4 + R_2 R_3 R_1)}$$

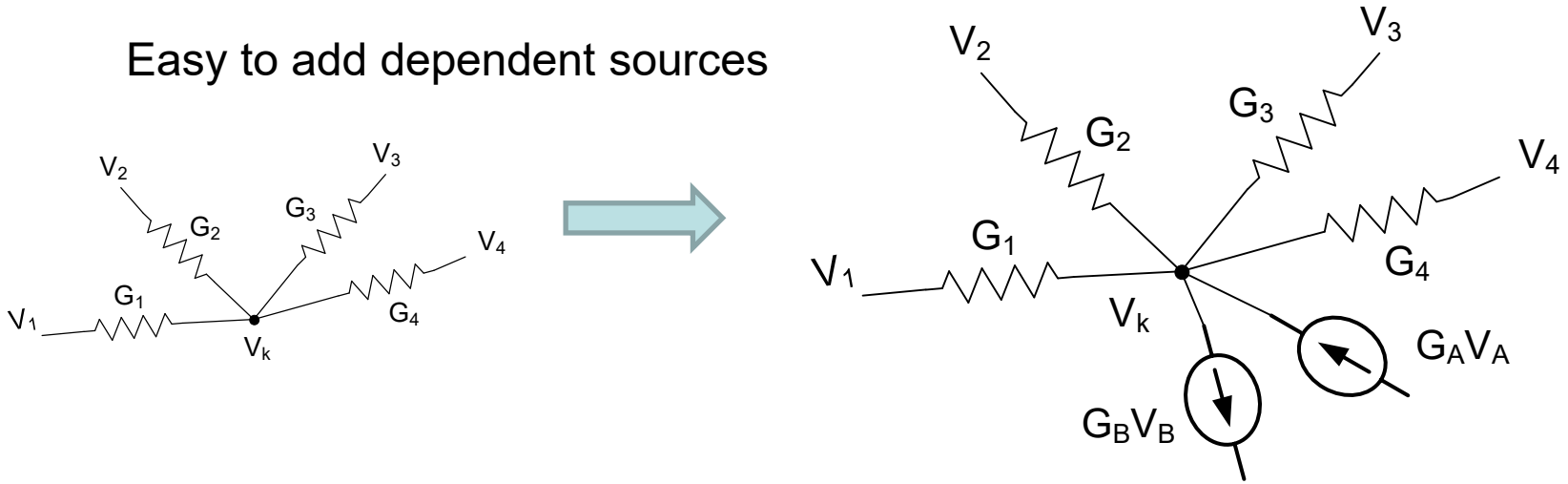
$$V_k = V_1 \frac{G_1}{G_1 + G_2 + G_3 + G_4} + V_2 \frac{G_2}{G_1 + G_2 + G_3 + G_4} + V_3 \frac{G_3}{G_1 + G_2 + G_3 + G_4} + V_4 \frac{G_4}{G_1 + G_2 + G_3 + G_4}$$

Nodal Analysis (A Brief Review)

Widely used to analyze electronic circuits – and for good reason!

Example: Determine V_k

Easy to add dependent sources



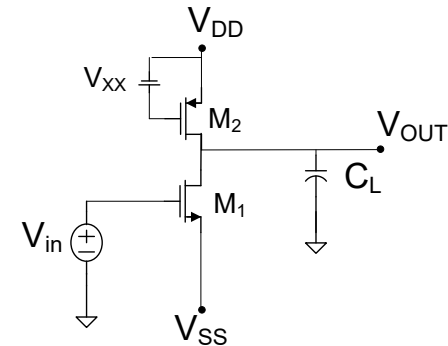
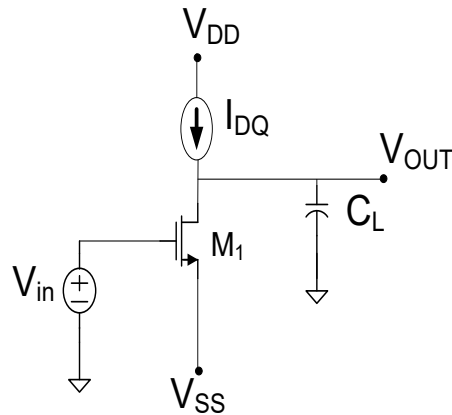
$$\text{From KCL} \quad V_k (G_1 + G_2 + G_3 + G_4) + G_B V_B - G_A V_A = G_1 V_1 + G_2 V_2 + G_3 V_3 + G_4 V_4$$

$$V_k = V_1 \frac{G_1}{G_1 + G_2 + G_3 + G_4} + V_2 \frac{G_2}{G_1 + G_2 + G_3 + G_4} + V_3 \frac{G_3}{G_1 + G_2 + G_3 + G_4} + V_4 \frac{G_4}{G_1 + G_2 + G_3 + G_4} + V_A \frac{G_A}{G_1 + G_2 + G_3 + G_4} - V_B \frac{G_B}{G_1 + G_2 + G_3 + G_4}$$

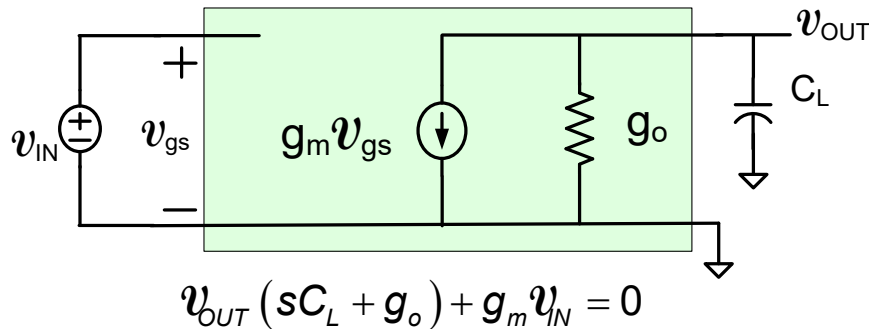
Often much simpler to work with conductances than with resistances!

Do we really need the concept of both a resistor and a conductor?

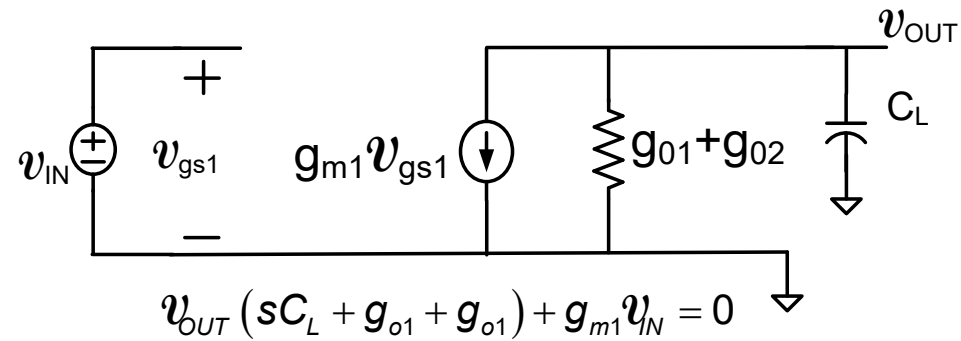
Two single-stage single-input low-gain op amps



Small Signal Models



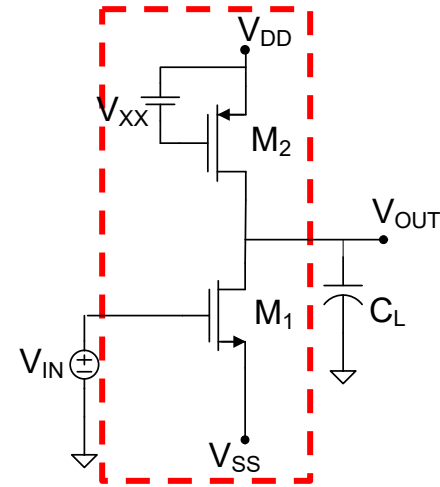
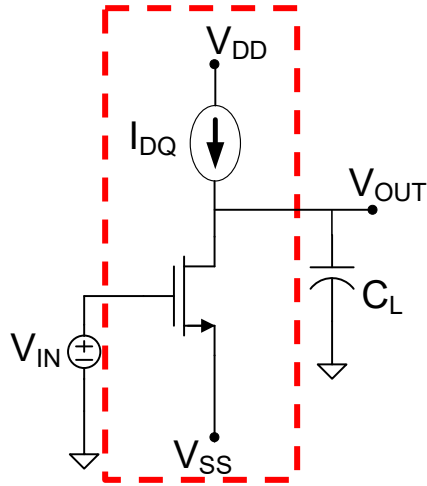
$$A_V = \frac{-g_m}{sC_L + g_o}$$



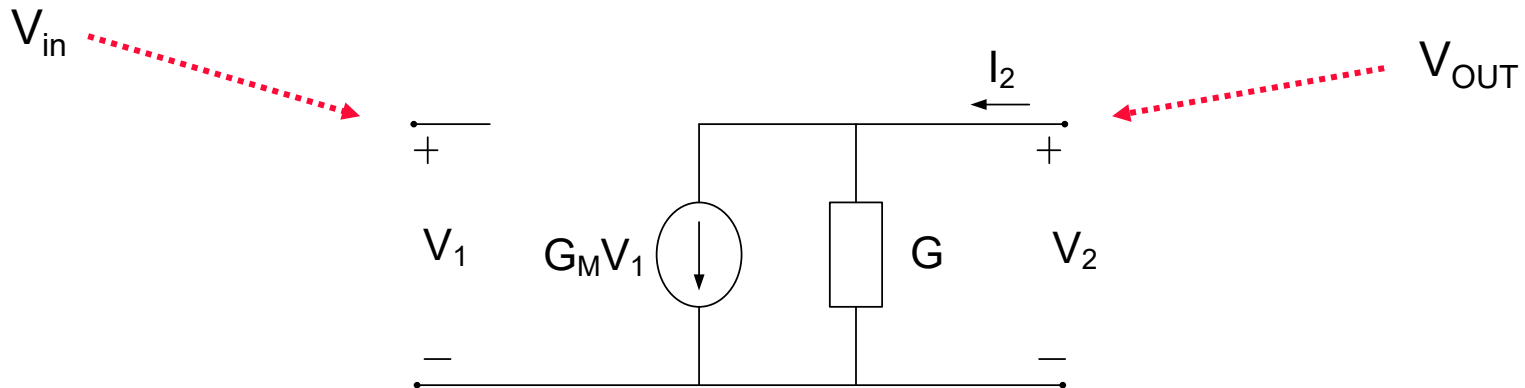
$$A_V = \frac{-g_{m1}}{sC_L + g_{o1} + g_{o2}}$$

dc Voltage gain is ratio of overall transconductance gain to output conductance

Two single-stage single-input low-gain op amps



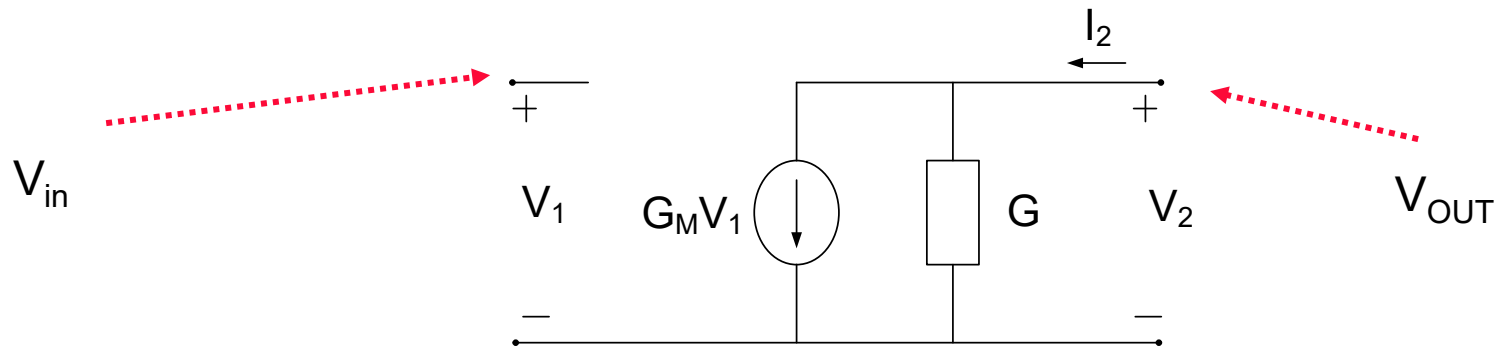
Observe in either case the small signal equivalent circuit is a two-port of the form:



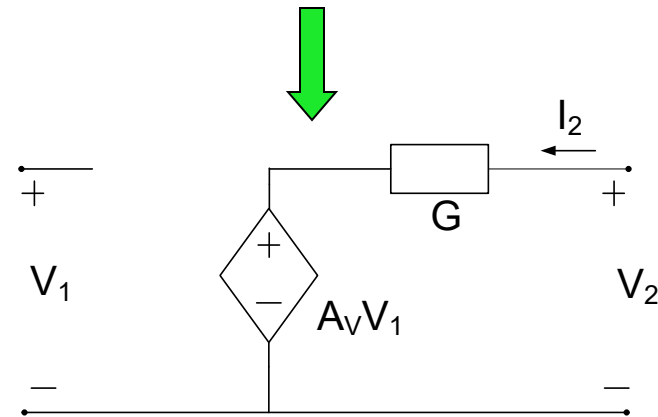
All properties of the linear small-signal circuit are determined by G_M and G

General single-stage single-input low-gain op amp

Small Signal Model of the op amp (unilateral with $R_{IN}=\infty$)



Alternate equivalent small signal model obtained by Norton to Thevenin transformation

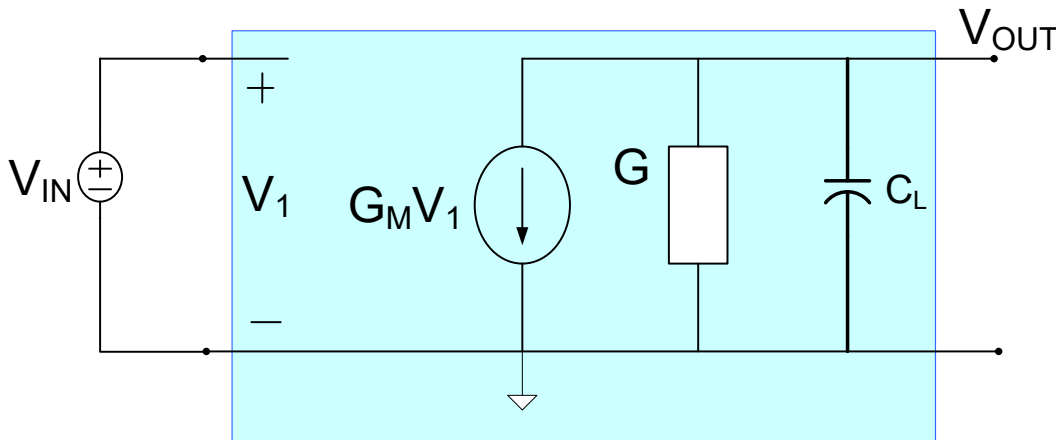


$$A_V = -\frac{G_M}{G}$$

All properties of the circuit are determined by A_V and G

General single-stage single-input low-gain op amp

Small Signal Model of the op amp with C_L (unilateral with $R_{IN}=\infty$)



$$A_V = \frac{-G_M}{sC_L + G}$$

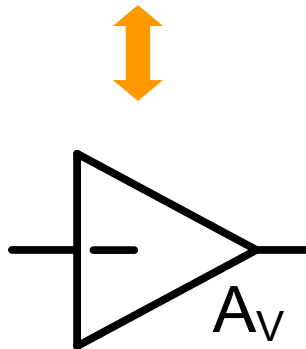
$$A_{V0} = \frac{-G_M}{G}$$

3dB (actually half-power) bandwidth:

$$BW = \frac{G}{C_L}$$

$$GB \stackrel{\text{def}}{=} |A_{V0} \cdot BW|$$

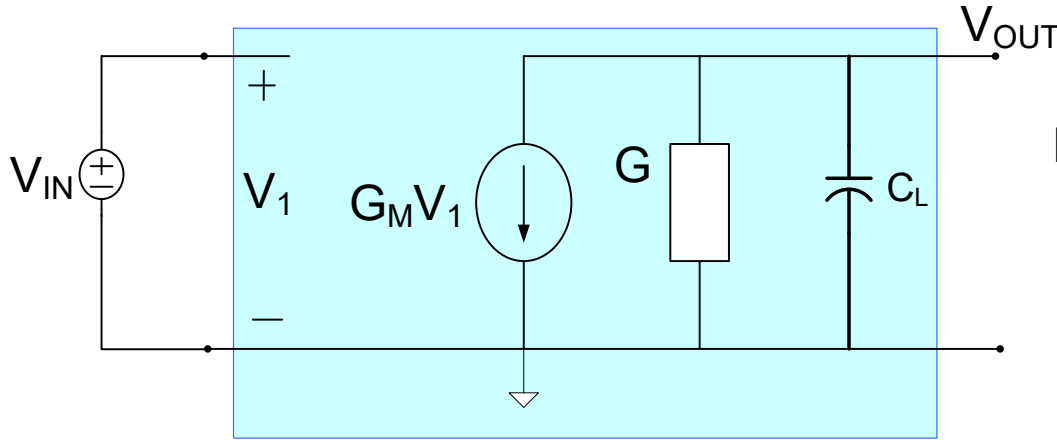
$$GB = \left(\frac{G_M}{G}\right) \left(\frac{G}{C_L}\right) = \frac{G_M}{C_L}$$



Analysis is general and applies to any single-stage single-input op amp (unilateral with $R_{IN}=\infty$)

GB and A_{V0} are two of the most important parameters in an op amp

Single-stage single-input low-gain op amp



By inspection from General Analysis

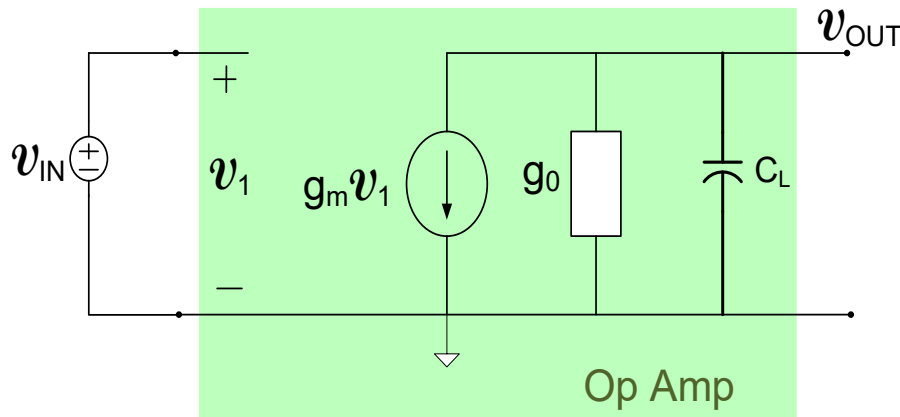
$$A_V = \frac{-g_m}{sC_L + g_o}$$

$$A_{V0} = \frac{-g_m}{g_o}$$

$$BW = \frac{g_o}{C_L}$$

$$GB = \left(\frac{g_m}{g_o} \right) \left(\frac{g_o}{C_L} \right) = \frac{g_m}{C_L}$$

for common-source amplifier



The parameters g_m and g_o give little insight into design

How do we design an amplifier with a given architecture in general or this architecture in particular?

What is the design space?

Generally V_{SS} , V_{DD} , C_L (and possibly V_{OUTQ}) will be fixed

Must determine $\{W_1, L_1, I_{DQ} \text{ and } V_{INQ}\}$

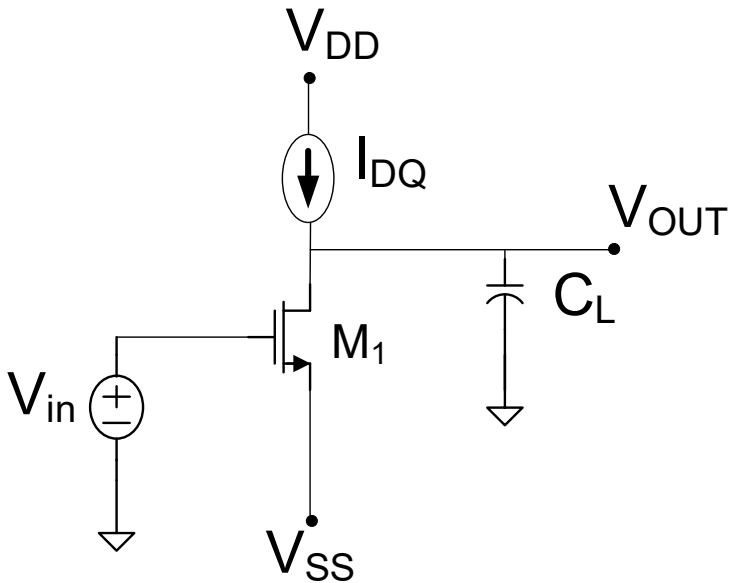
Thus there are 4 design variables

But W_1 and L_1 appear as a ratio in almost all performance characteristics of interest

and I_{DQ} is related to V_{INQ} , W_1 and L_1 (this is a constraint)

$$I_{DQ} = \mu C_{OX} \frac{W}{L} (V_{INQ} - V_{SS} - V_{TH})^2$$

Thus the 3-dimensional design space has only two independent variables (or two degrees of freedom).



How do we design an amplifier with a given architecture in general or this architecture in particular?

What is the design space?

Must determine $\{W_1, L_1, I_{DQ} \text{ and } V_{INQ}\}$

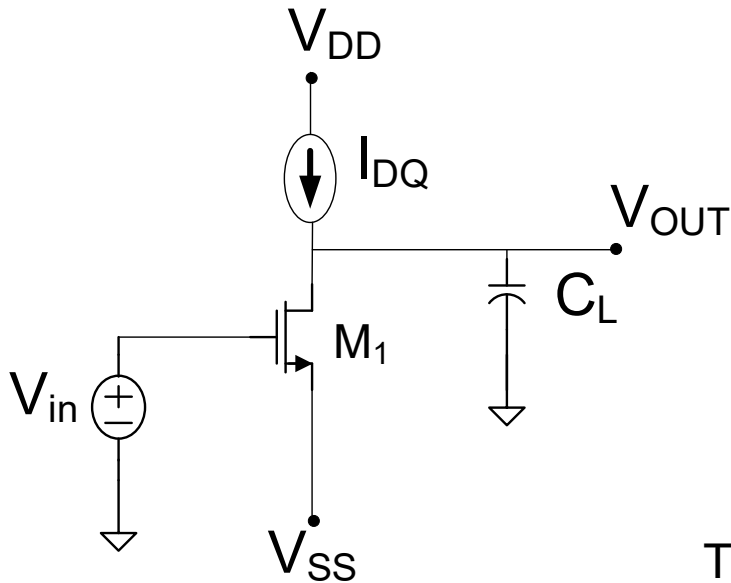
Thus the 3-dimensional design space has one constraint (and hence 2 degrees of freedom):

Design Space: $\left\{ \frac{W_1}{L_1}, I_{DQ} \text{ and } V_{INQ} \right\}$

Constraint: $I_{DQ} = \mu C_{OX} \frac{W}{L} (V_{INQ} - V_{SS} - V_{TH})^2$

Thus design or “synthesis” with this architecture involves exploring the two-dimensional design space (using any 2 of the 3 variables). Practically:

$$\left\{ \frac{W_1}{L_1}, I_{DQ} \right\}$$



How do we design an amplifier with a given architecture in general or this architecture in particular?

What is the design space?

Generally V_{SS} , V_{DD} , C_L (and possibly V_{OUTQ}) will be fixed

1. Determine the design space

Must determine $\{W_1, L_1, I_{DQ} \text{ and } V_{INQ}\}$

2. Identify the constraints

Thus there are 4 design variables

But W_1 and L_1 appear as a ratio in almost all performance characteristics of interest

3. Determine the entire set of unknown variables and the Degrees of Freedom

and I_{DQ} is related to V_{INQ} , W_1 and L_1

4. Determine an appropriate parameter domain

Thus the design space generally has only two independent variables or **two degrees of freedom**

(Parameter domains for characterizing the design space are not unique!)

$$\left\{ \frac{W_1}{L_1}, I_{DQ} \right\}$$

Thus design or “synthesis” with this architecture involves exploring the two-dimensional design space

5. Explore the resultant design space with the identified number of Degrees of Freedom

$$\left\{ \frac{W_1}{L_1}, I_{DQ} \right\}$$

How do we design an amplifier with a given architecture ?

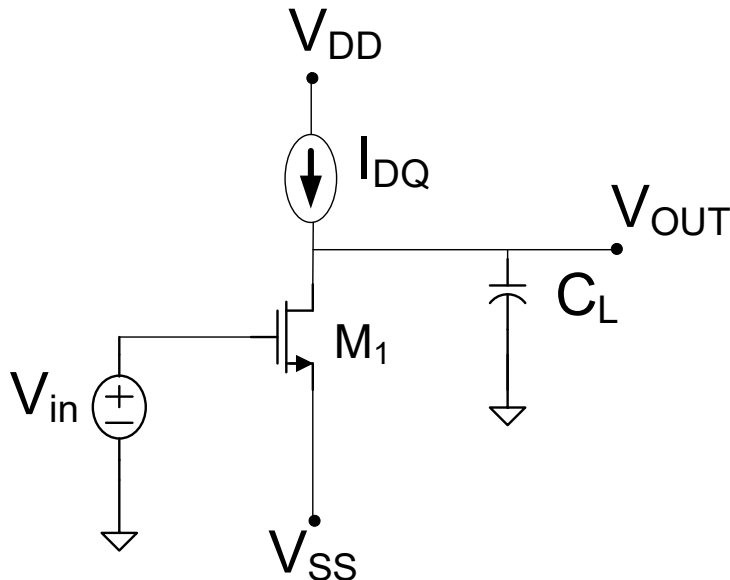
1. Determine the design space
2. Identify the constraints
3. Determine the entire set of unknown variables and the Degrees of Freedom
4. Determine an appropriate parameter domain
5. Explore the resultant design space with the identified number of Degrees of Freedom

Parameter Domains for Characterizing Amplifier Performance

- Should give insight into design
- Variables should be independent
- Should be of minimal size
- Should result in simple design expressions
- **Most authors give little consideration to either the parameter domain or the degrees of freedom that constrain the designer**

Parameter Domains for Characterizing Amplifier Performance

Consider this basic op amp structure



$$A_v = \frac{-g_m}{sC_L + g_0}$$

$$A_{v0} = \frac{-g_m}{g_0}$$

$$GB = \frac{g_m}{C_L}$$

Small signal parameter domain :

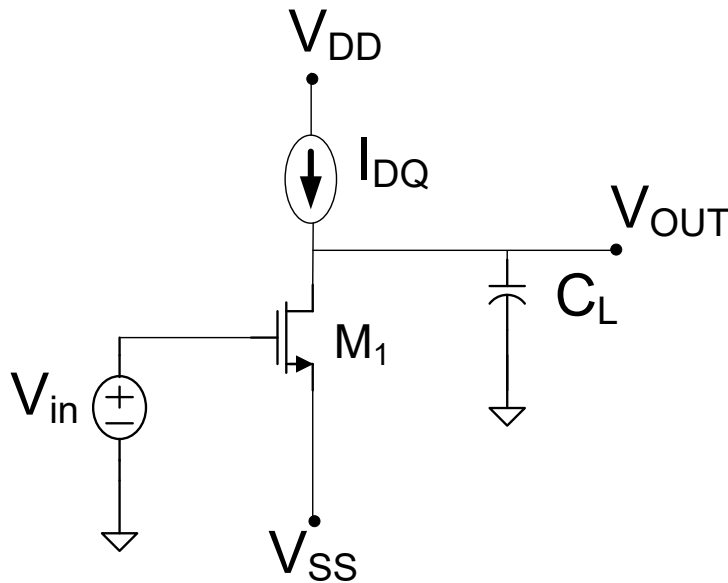
$$\{g_m, g_0\}$$

Degrees of Freedom: 2

Small signal parameter domain
obscures implementation issues

Parameter Domains for Characterizing Amplifier Performance

Consider basic op amp structure



$$A_v = \frac{-g_m}{sC_L + g_0}$$

$$A_{v0} = \frac{-g_m}{g_0}$$

$$GB = \frac{g_m}{C_L}$$

What parameters does the designer really have to work with?

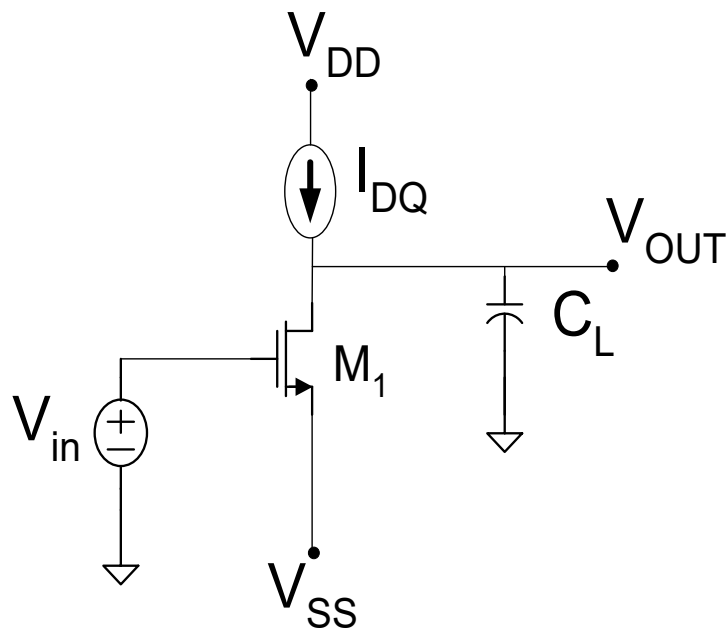
$$\left\{ \frac{W}{L}, I_{DQ} \right\}$$

Degrees of Freedom: 2

Call this the natural parameter domain

Parameter Domains for Characterizing Amplifier Performance

Consider basic op amp structure (not generic !)



Natural parameter domain

$$\left\{ \frac{W}{L}, I_{DQ} \right\}$$

$$GB = \frac{g_m}{C_L}$$

$$A_{v0} = \frac{-g_m}{g_o}$$

How do performance metrics A_{v0} and GB relate to the natural domain parameters?

$$g_m = \frac{2I_{DQ}}{V_{EB}} = \frac{\mu C_{OX} W}{L} V_{EB} = \sqrt{2\mu C_{OX} \frac{W}{L} I_{DQ}}$$

$$g_o = \lambda I_{DQ}$$

Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

$$A_v = \frac{-g_m}{sC_L + g_0}$$

Small signal parameter domain : $\{g_m, g_0\}$

$$A_{v0} = \frac{-g_m}{g_0} \quad GB = \frac{g_m}{C_L}$$

Natural design parameter domain: $\left\{ \frac{W}{L}, I_{DQ} \right\}$

$$A_{v0} = \frac{\sqrt{2\mu C_{OX} \frac{W}{L}}}{\lambda \sqrt{I_{DQ}}} \quad GB = \frac{\sqrt{2\mu C_{OX} \frac{W}{L}} \sqrt{I_{DQ}}}{C_L}$$

- Expressions very complicated
- Both A_{v0} and GB depend upon both design parameters
- Natural parameter domain gives little insight into design and has complicated expressions

How do we design an amplifier with a given architecture ?

1. Determine the design space
2. Identify the constraints
3. Determine the entire set of unknown variables and the Degrees of Freedom $\text{DOF}=2$
4. Determine an appropriate parameter domain $\left\{ \frac{W}{L}, I_{DQ} \right\}$
5. Explore the resultant design space with the identified number of Degrees of Freedom

In natural parameter domain explore how $\frac{W}{L}$ and I_{DQ} affect desired performance

Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

Small signal parameter domain :

$$\{g_m, g_0\}$$

$$A_{v0} = \frac{-g_m}{g_0}$$

$$GB = \frac{g_m}{C_L}$$

Natural design parameter domain:

$$\left\{ \frac{W}{L}, I_{DQ} \right\}$$

$$A_{v0} = \left[\frac{\sqrt{2\mu C_{OX}}}{\lambda} \right] \left[\frac{\sqrt{\frac{W}{L}}}{\sqrt{I_{DQ}}} \right]$$

$$GB = \left[\frac{\sqrt{2\mu C_{OX}}}{C_L} \right] \left[\sqrt{\frac{W}{L}} \sqrt{I_{DQ}} \right]$$

Process
Dependent

Architecture
Dependent

Process
Dependent

Architecture
Dependent

Key Observation !

Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

Small signal parameter domain : $\{g_m, g_0\}$

$$A_{v0} = \frac{-g_m}{g_0} \quad GB = \frac{g_m}{C_L}$$

Natural design parameter domain:

$$\left\{ \frac{W}{L}, I_{DQ} \right\}$$

$$A_{v0} = \left[\frac{\sqrt{2\mu C_{OX}}}{\lambda} \right] \left[\frac{\sqrt{\frac{W}{L}}}{\sqrt{I_{DQ}}} \right] \quad GB = \left[\frac{\sqrt{2\mu C_{OX}}}{C_L} \right] \left[\sqrt{\frac{W}{L}} \sqrt{I_{DQ}} \right]$$

Alternate parameter domain:

$$\{P, V_{EB}\}$$

$$P = \text{Power} = V_{DD} I_{DQ}$$

$$V_{EB} = \text{excess bias} = V_{GSQ} - V_T$$

$$A_{v0} = -\frac{g_M}{g_0} = -\left(\frac{2I_{DQ}}{V_{EB}} \right) \left(\frac{1}{\lambda I_{DQ}} \right) = -\frac{2}{\lambda V_{EB}} \quad GB = \frac{g_M}{C_L} = \left(\frac{2I_{DQ}}{V_{EB}} \right) \frac{1}{C_L} = \left[\frac{2}{V_{DD} C_L} \right] \frac{P}{V_{EB}}$$

Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

Small signal parameter domain : $\{g_m, g_0\}$

$$A_{V0} = \frac{-g_m}{g_0} \quad GB = \frac{g_m}{C_L}$$

Natural design parameter domain: $\left\{ \frac{W}{L}, I_{DQ} \right\}$

$$A_{V0} = \left[\frac{\sqrt{2\mu C_{OX}}}{\lambda} \right] \left[\frac{\sqrt{\frac{W}{L}}}{\sqrt{I_{DQ}}} \right] \quad GB = \left[\frac{\sqrt{2\mu C_{OX}}}{C_L} \right] \left[\sqrt{\frac{W}{L}} \sqrt{I_{DQ}} \right]$$

Alternate parameter domain: $\{P, V_{EB}\}$

$$A_{V0} = \left[\frac{2}{\lambda} \right] \left[\frac{1}{V_{EB}} \right] \quad GB = \left[\frac{2}{V_{DD} C_L} \right] \left[\frac{P}{V_{EB}} \right]$$



Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

Small signal parameter domain : $\{g_m, g_0\}$

$$A_{v0} = \frac{-g_m}{g_0} \qquad GB = \frac{g_m}{C_L}$$

Natural design parameter domain: $\left\{ \frac{W}{L}, I_{DQ} \right\}$

$$A_{v0} = \left[\frac{\sqrt{2\mu C_{OX}}}{\lambda} \right] \frac{\sqrt{\frac{W}{L}}}{\sqrt{I_{DQ}}} \qquad GB = \left[\frac{\sqrt{2\mu C_{OX}}}{C_L} \right] \sqrt{\frac{W}{L}} \sqrt{I_{DQ}}$$

Alternate parameter domain:

$\{P, V_{EB}\}$

$$A_{v0} = \left[\frac{2}{\lambda} \right] \left[\frac{1}{V_{EB}} \right] \qquad GB = \left[\frac{2}{V_{DD} C_L} \right] \left[\frac{P}{V_{EB}} \right]$$



Architecture Dependent

Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

Small signal parameter domain : $\{g_m, g_0\}$

$$A_{V0} = \frac{-g_m}{g_0} \qquad GB = \frac{g_m}{C_L}$$

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Alternate parameter domain: $\{P, V_{EB}\}$

$$A_{V0} = \left[\frac{2}{\lambda} \right] \left[\frac{1}{V_{EB}} \right] \qquad GB = \left[\frac{2}{V_{DD} C_L} \right] \left[\frac{P}{V_{EB}} \right]$$

- Alternate parameter domain gives considerable insight into design
- Easy to map from alternate parameter domain to natural parameter domain
- Alternate parameter domain provides modest parameter decoupling
- $A_{V0} \left[\frac{\lambda}{2} \right]$ and $GB \left[\frac{V_{DD} C_L}{2} \right]$ figures of merit for comparing different architectures

How do we design an amplifier with a given architecture ?

1. Determine the design space
2. Identify the constraints
3. Determine the entire set of unknown variables and the Degrees of Freedom $\text{DOF}=2$
4. Determine an appropriate parameter domain $\{P, V_{EB}\}$
5. Explore the resultant design space with the identified number of Degrees of Freedom

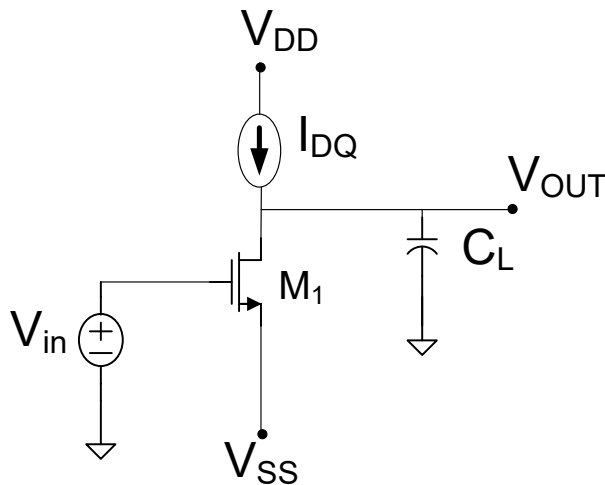
In practical parameter domain explore how P and V_{EB} affect desired performance

Parameter Domains for Characterizing Amplifier Performance

- Design often easier if approached in the alternate parameter domain
- **How does one really get the design done, though? That is, how does one get back from the alternate parameter domain to the natural parameter domain?**

Alternate parameter domain:

$$\{P, V_{EB}\}$$



$$W = ?$$

$$L = ?$$

$$I_{DQ} = ?$$

$$V_{INQ} = ?$$

Parameter Domains for Characterizing Amplifier Performance

- Design often easier if approached in the alternate parameter domain
- **How does one really get the design done, though? That is, how does one get back from the alternate parameter domain to the natural parameter domain?**

Alternate parameter domain: $\{P, V_{EB}\}$

Natural design parameter domain: $\left\{\frac{W}{L}, I_{DQ}\right\}$

$$I_{DQ} = \frac{P}{V_{DD} - V_{SS}} \quad \frac{W}{L} = \frac{P}{(V_{DD} - V_{SS}) \mu C_{OX} V_{EB}^2}$$

To complete design:

Arbitrarily pick W or L

Satisfy constraint -

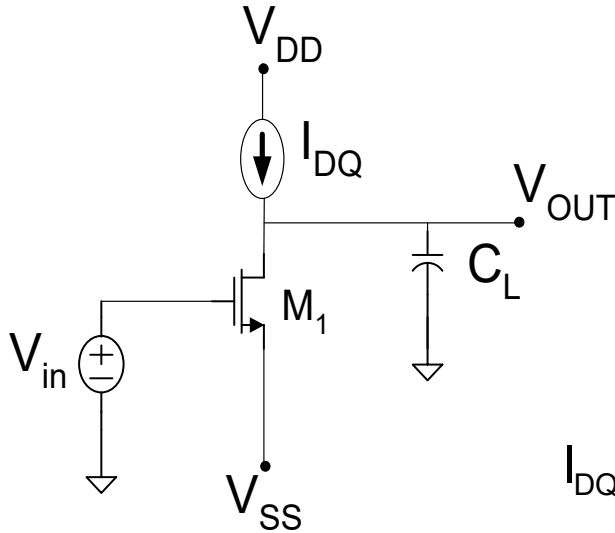
$$V_{INQ} = V_{SS} + V_T + \sqrt{I_{DQ} \frac{2}{\mu C_{OX}} \frac{L}{W}}$$

Design With the Basic Amplifier Structure

Consider basic op amp structure

Alternate parameter domain: $\{P, V_{EB}\}$

Degrees of Freedom: 2



$$A_{V0} = \left[\frac{2}{\lambda} \right] \left[\frac{1}{V_{EB}} \right]$$

$$GB = \left[\frac{2}{V_{DD} C_L} \right] \left[\frac{P}{V_{EB}} \right]$$

$$I_{DQ} = \frac{P}{V_{DD} - V_{SS}}$$

$$\frac{W}{L} = \frac{2P}{V_{DD} \mu C_{OX} V_{EB}^2}$$

$$V_{INQ} = V_{SS} + V_T + \sqrt{I_{DQ} \frac{2}{\mu C_{OX}} \frac{L}{W}}$$

What are the design requirements?

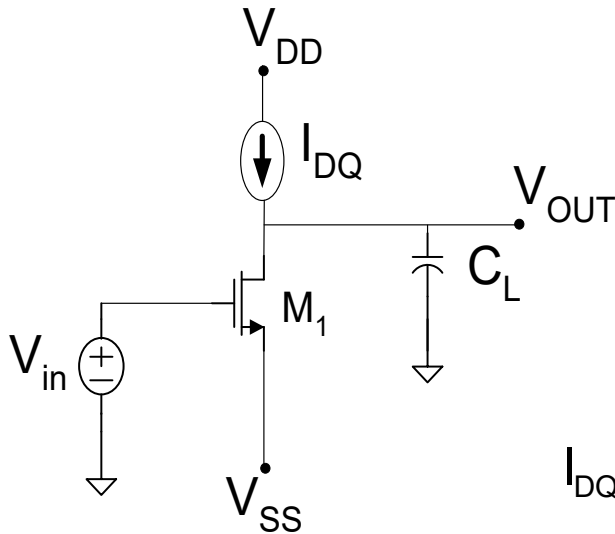
Depends on application !

Design With the Basic Amplifier Structure

Consider basic op amp structure

Alternate parameter domain: $\{P, V_{EB}\}$

Degrees of Freedom: 2



$$A_{V0} = \left[\frac{2}{\lambda} \right] \left[\frac{1}{V_{EB}} \right]$$

$$GB = \left[\frac{2}{V_{DD} C_L} \right] \left[\frac{P}{V_{EB}} \right]$$

$$I_{DQ} = \frac{P}{V_{DD} - V_{SS}}$$

$$\frac{W}{L} = \frac{2P}{V_{DD} \mu C_{OX} V_{EB}^2}$$

$$V_{INQ} = V_{SS} + V_T + \sqrt{I_{DQ} \frac{2}{\mu C_{OX}} \frac{L}{W}}$$

What if the design requirement dictates that $V_{INQ} = 0$?

- Increase the number of constraints from 1 to 2
- Decrease the Degrees of Freedom from 2 to 1

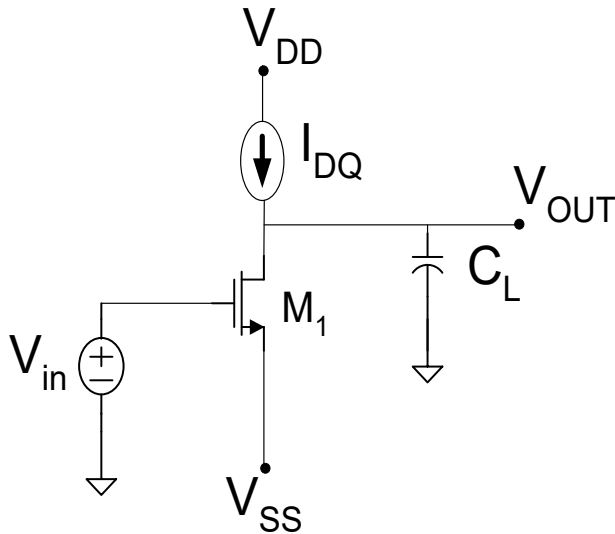
Question: How can one meet two or more performance requirements with one design degree of freedom with this circuit?

Design With the Basic Amplifier Structure

Consider basic op amp structure

Alternate parameter domain: $\{P, V_{EB}\}$

Degrees of Freedom: 2



$$A_{V0} = \left[\frac{2}{\lambda} \right] \left[\frac{1}{V_{EB}} \right]$$

$$GB = \left[\frac{2}{V_{DD} C_L} \right] \left[\frac{P}{V_{EB}} \right]$$

$$I_{DQ} = \frac{P}{V_{DD}}$$

$$\frac{W}{L} = \frac{P}{V_{DD} \mu C_{OX} V_{EB}^2}$$

$$V_{INQ} = V_{SS} + V_T + \sqrt{I_{DQ} \frac{2}{\mu C_{OX}} \frac{L}{W}}$$

But what if the design requirement dictates that $V_{INQ} = 0$?

Question: How can one meet two or more performance requirements with one design degree of freedom with this circuit?

Degrees of Freedom: 1

Luck or Can't



Stay Safe and Stay Healthy !

End of Lecture 2