EE 435

Lecture 2:

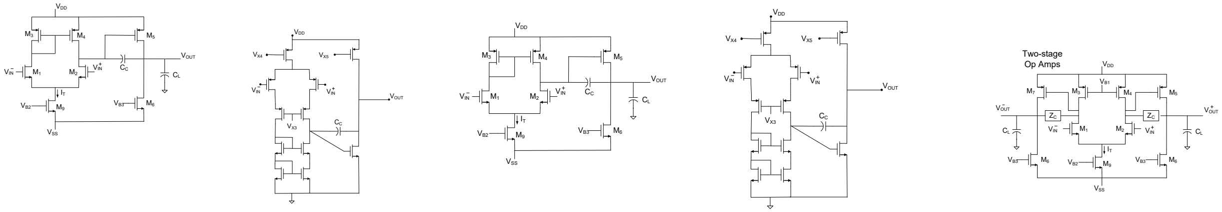
Basic Op Amp Design

- Single Stage Low Gain Op Amps

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

Understand

Synthesize



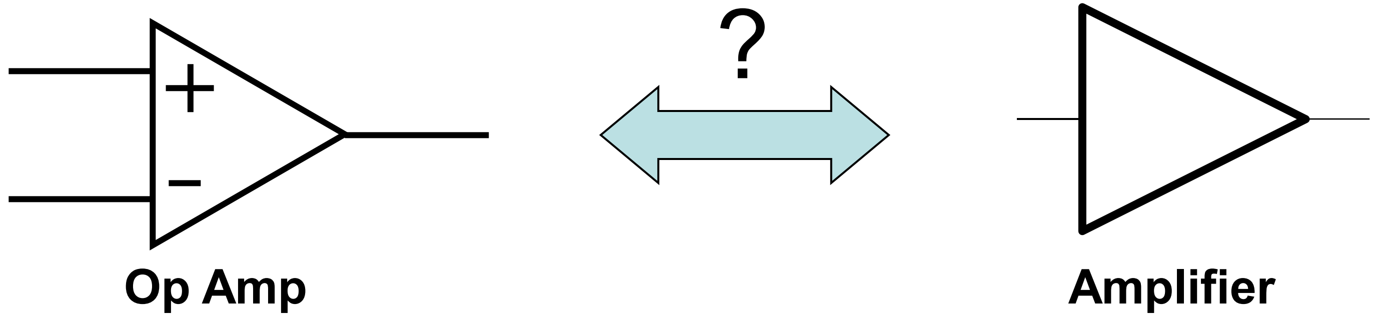
Analyze **(if not available from the Understand step)**

Modify, Extend, and Create

Simulate and Verify

Review from last lecture:

How does an amplifier differ from an operational amplifier?

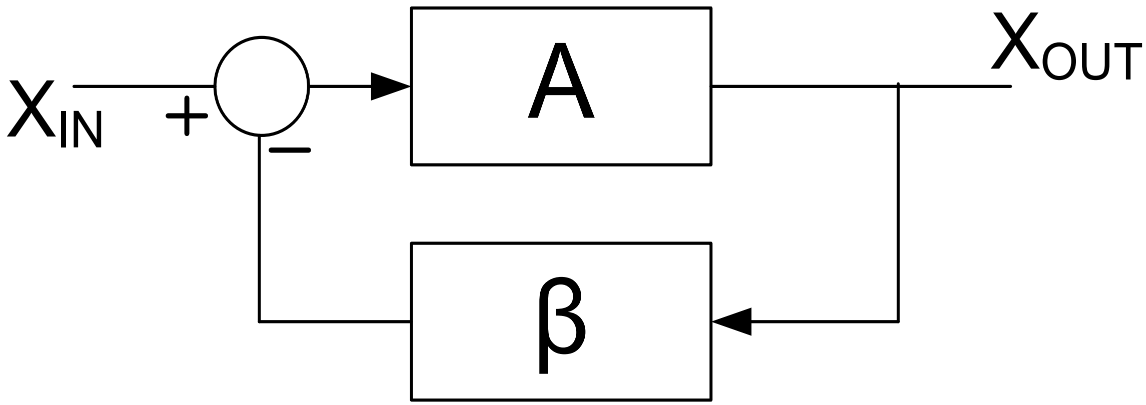


Amplifier used in open-loop applications

Operational Amplifier used in feedback applications

Review from last lecture:

Why are Operational Amplifiers Used?



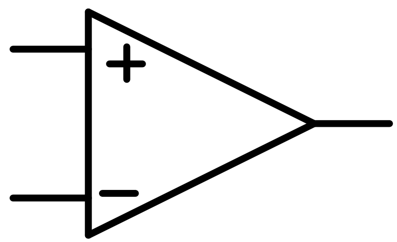
Input and Output Variables intentionally designated as "X" instead of "V"

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

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:

What Characteristics are Really Needed for Op Amps?

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

1. Very Large Gain

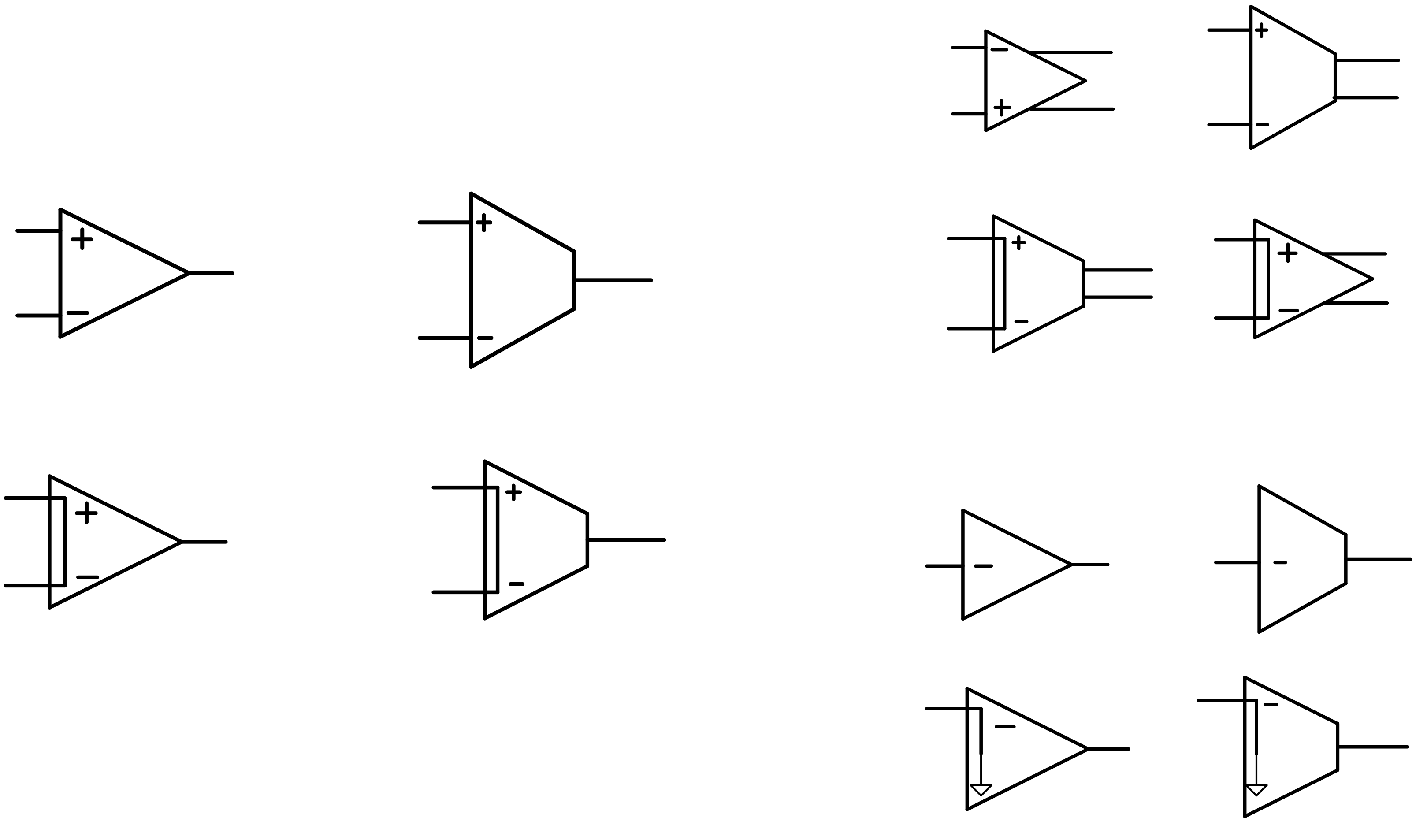
To make A_F (or A_{VF}) insensitive to variations in A

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?

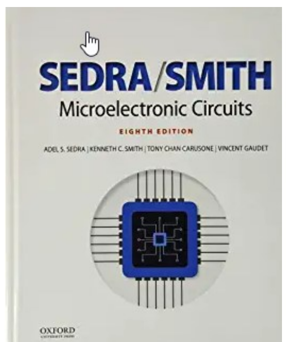
1. Very Large Voltage Gain

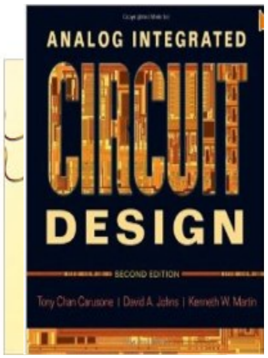
and …

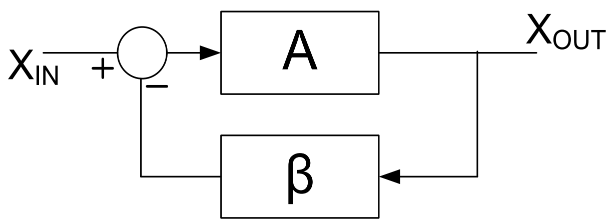
2. Low Output Impedance
3. High Input Impedance
4. Large Output Swing
3. Large Input Range
4. Good High-frequency Performance
5. Fast Settling
6. Adequate Phase Margin
7. Good CMRR
8. Good PSRR
9. Low Power Dissipation
10. Reasonable Linearity
11. . . .

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 !!

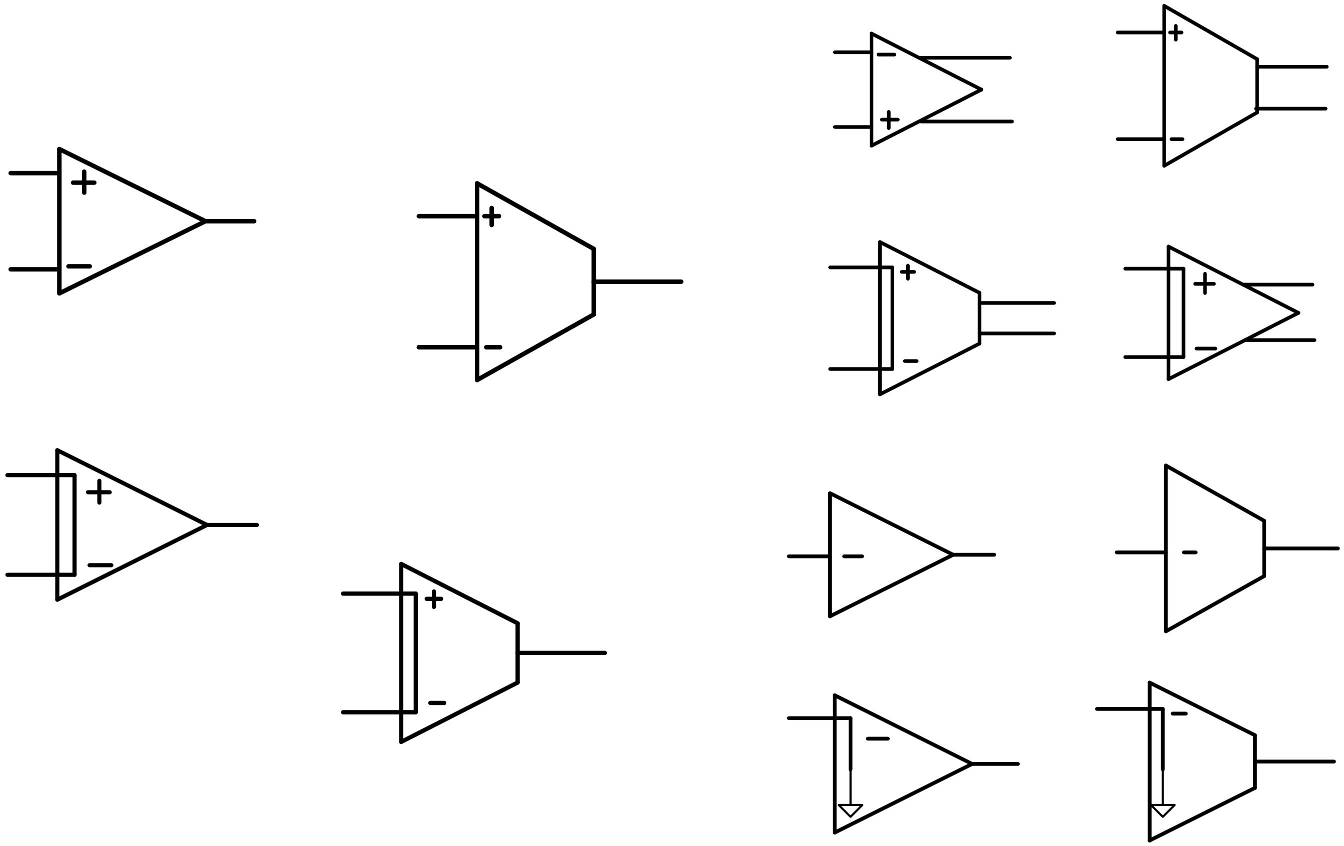
- Just because its published doesn’t mean its correct

- 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

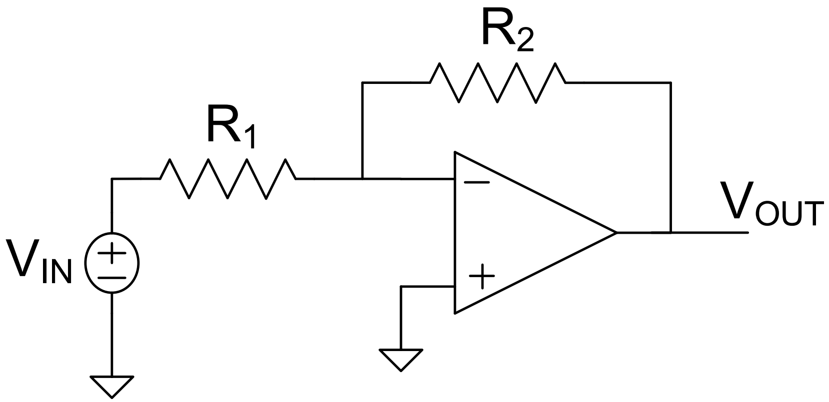


Operational Amplifiers

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

Consider Op Amp with GB=1MHz, $A_{00}=10^5$, $R_2=100K$, $R_1=2K$, $V_{IN}=0.1\sin(2\pi\bullet5000t)$

Ideally $A_{VFB} = -50$ $V_{OUT}=5\sin(2\pi\bullet5000t)$



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

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

Operational Amplifiers

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

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

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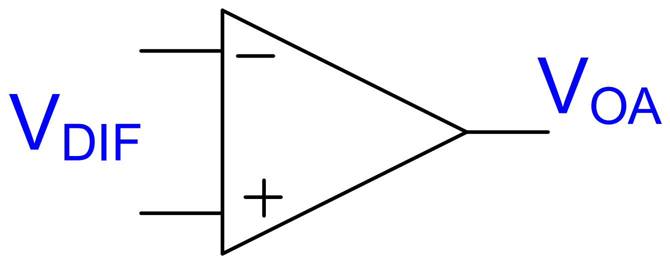


$$A_{OA}(s)=\frac{A_o p}{s+p}=\frac{GB}{s+p}$$

p=10 rad/sec

At f=5KHz

$$A_{OA}(j2\pi\bullet 5000)=\frac{10^6}{j2\pi\bullet 5000+10}$$

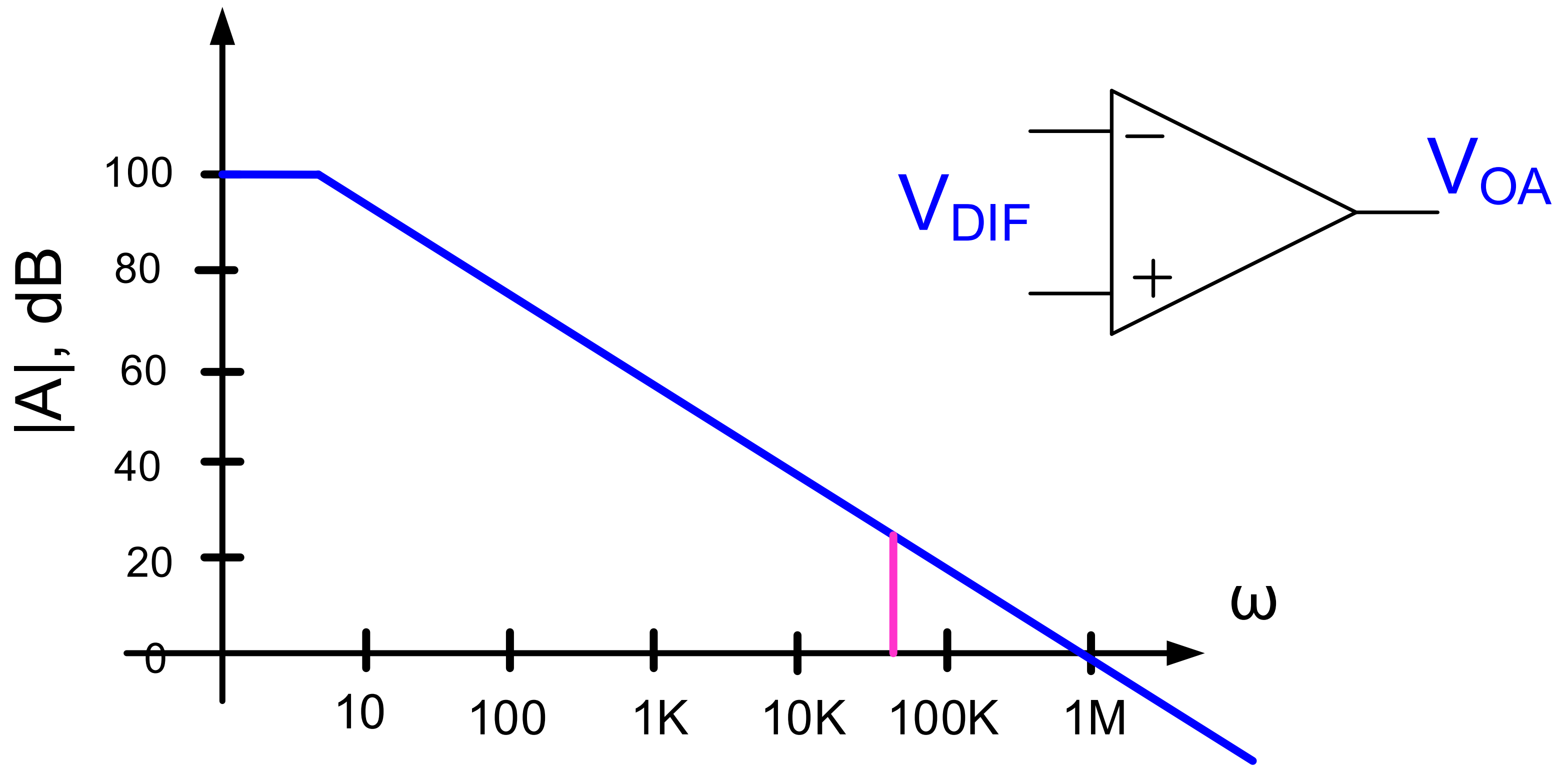
$$\left|A_{OA}(j2\pi\bullet 5000)\right|=\left|\frac{10^6}{\sqrt{(2\pi\bullet 5000)^2+100}}\right|\simeq\frac{10^6}{2\pi\bullet 5000}=31.8$$

The gain of this operational amplifier at the operating frequency is only 31.8

Operational Amplifiers

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

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



At ω=2π•5K rad/sec |A|=31.8

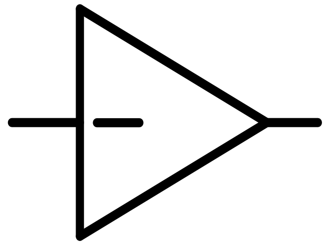
So will now investigate amplifiers that have varying “large” gains

Basic Op Amp Design Outline

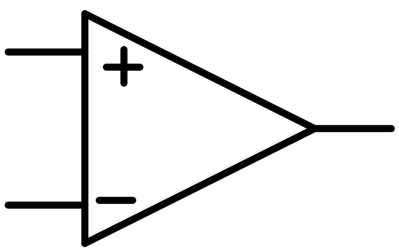
- Fundamental Amplifier Design Issues
- Single-Stage Low Gain Op Amps
- Single-Stage High Gain Op Amps
- Two-Stage Op Amp
- Other Basic Gain Enhancement Approaches

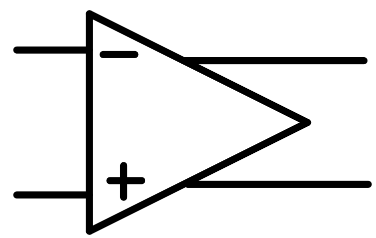
Single-Stage Low-Gain Op Amps

- Single-ended input



- Differential Input

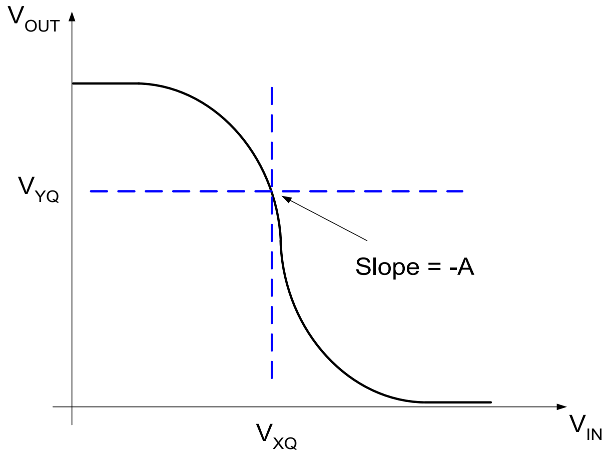


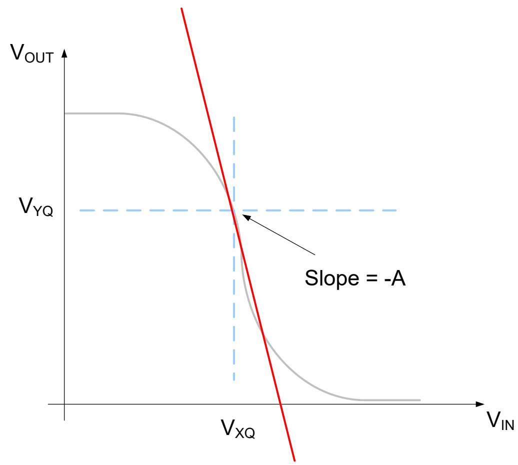


(Symbol not intended to distinguish between different amplifier types)

Single-ended Op Amp (Inverting Amplifier)

Consider:





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

$$\mathbf{V_{OUT} = f(V_{IN})}$$

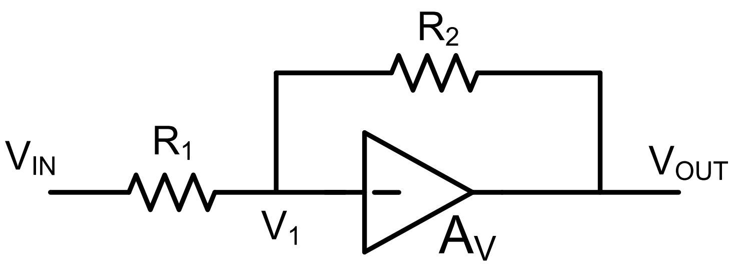
$$V_{OUT} \cong (-A)(V_{IN} - V_{XQ}) + V_{YQ}$$

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

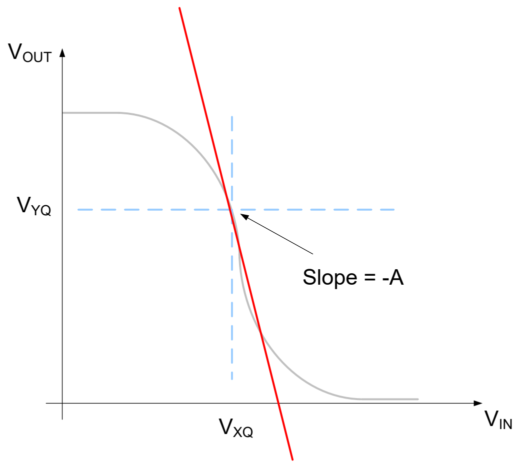
If the gain of the amplifier is large, V_{XQ} is a characteristic of the amplifier

Single-ended Op Amp (Inverting Amplifier)

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



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



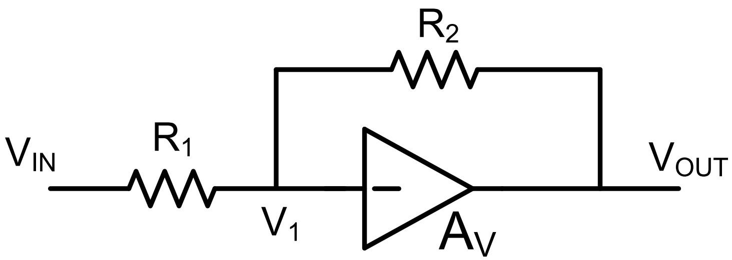
Eliminating V_1 we obtain:

$$V_0 = (-A)\left(\frac{R_1}{R_1+R_2}V_0 + \frac{R_2}{R_1+R_2}V_{IN} - V_{XQ}\right) + V_{YQ}$$

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

$$V_0 = \left(\frac{-A\left(\frac{R_2}{R_1+R_2}\right)}{1+A\left(\frac{R_1}{R_1+R_2}\right)}\right)\left(V_{iSS}+V_{INQ}\right) + \left(\frac{A}{1+A\left(\frac{R_1}{R_1+R_2}\right)}\right)V_{XQ} + \left(\frac{1}{1+A\left(\frac{R_1}{R_1+R_2}\right)}\right)V_{YQ}$$

Single-ended Op Amp Inverting Amplifier



$$V_0 = \left(\frac{-A\left(\frac{R_2}{R_1+R_2}\right)}{1+A\left(\frac{R_1}{R_1+R_2}\right)} \right)\left(V_{iSS} + V_{INQ}\right) + \left(\frac{A}{1+A\left(\frac{R_1}{R_1+R_2}\right)} \right) V_{XQ} + \left(\frac{1}{1+A\left(\frac{R_1}{R_1+R_2}\right)} \right) V_{YQ}$$

But if A is large, this reduces to

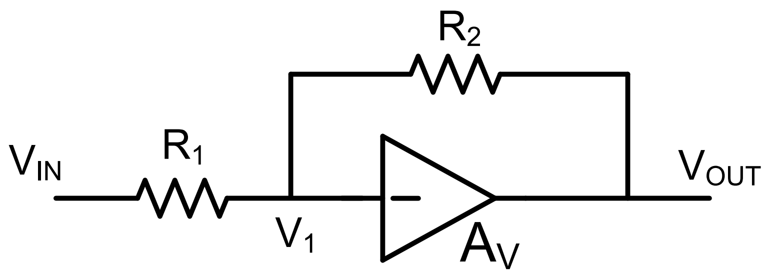
$$V_O = -\frac{R_2}{R_1} V_{iss} + V_{XQ} + \frac{R_2}{R_1}\left(V_{XQ} - V_{INQ}\right)$$

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

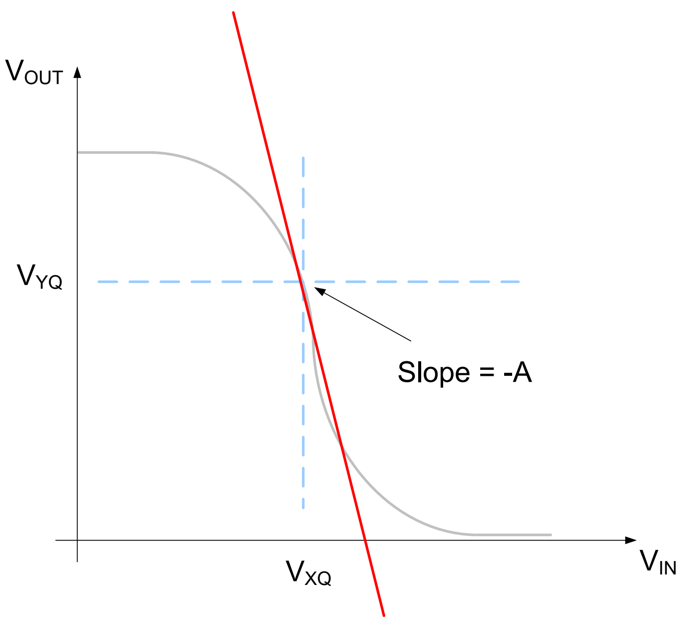
$$V_O \cong -\frac{R_2}{R_1} V_{iss} + V_{XQ}$$

Single-ended Op Amp Inverting Amplifier

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



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

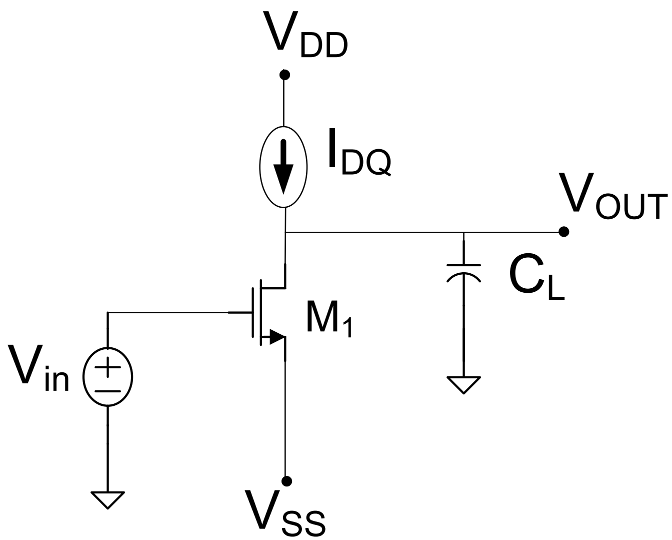


Summary:

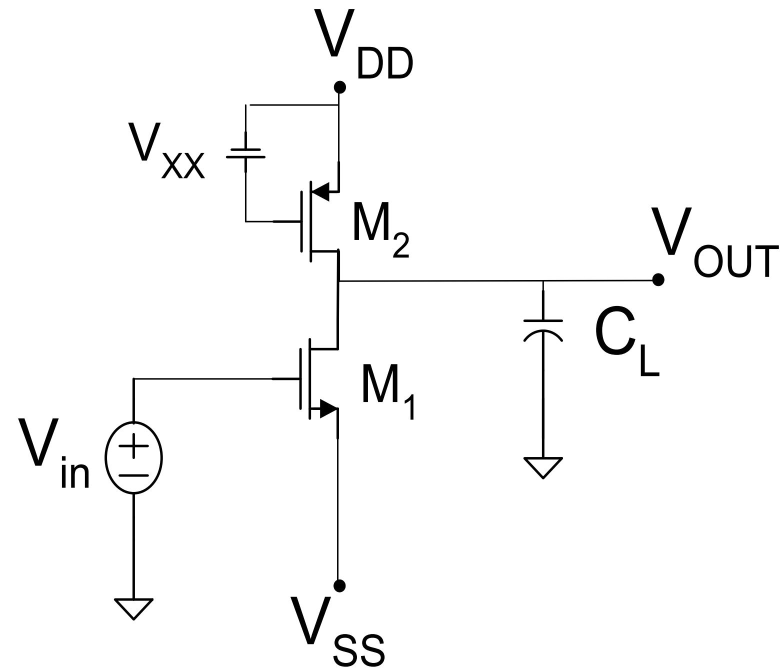
$$V_O = -\frac{R_2}{R_1} V_{iss} + V_{XQ} + \frac{R_2}{R_1}\left(V_{XQ} - V_{inQ}\right)$$

What type of circuits have the transfer characteristic shown?

Single-stage single-input <u>low-gain</u> op amp



Basic Structure



Practical Implementation

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

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

This is not a new idea !

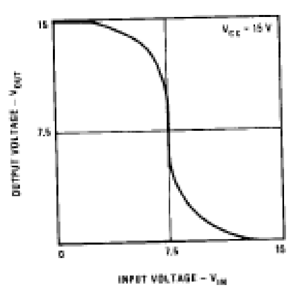
AN-88 CMC

Gene Taatjes
JULY 1973

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.



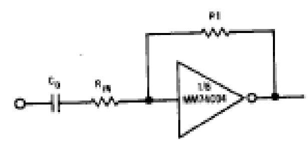


FIGURE 2. A 74CMOS Invertor Biased for Linear Mode Operation.

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.

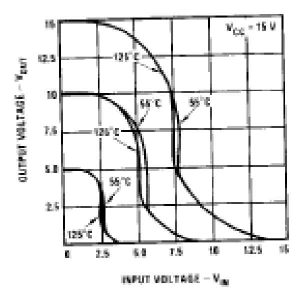
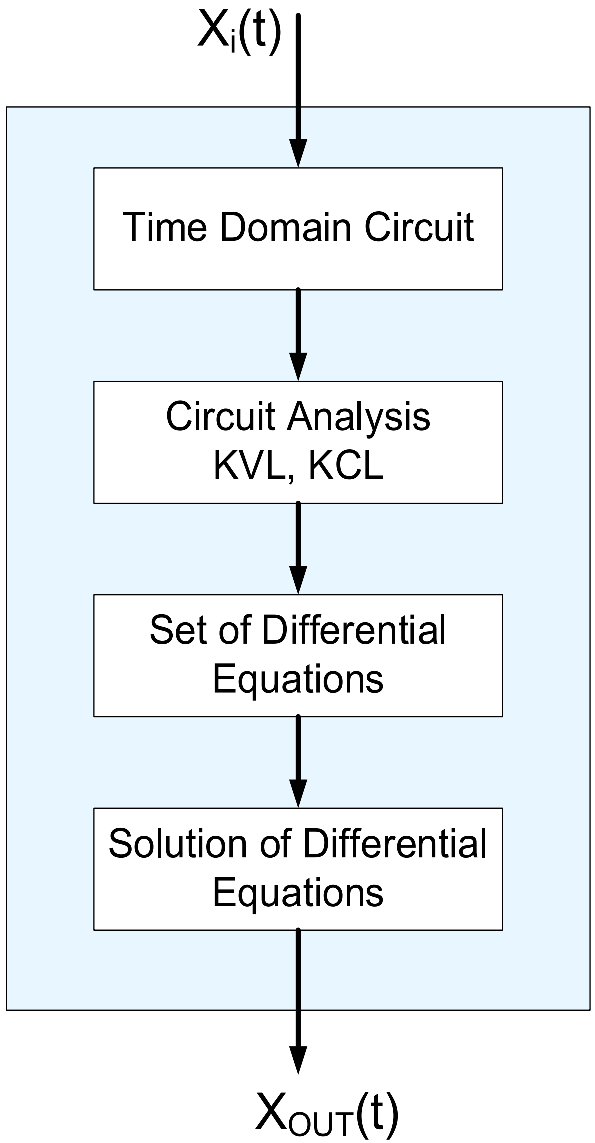


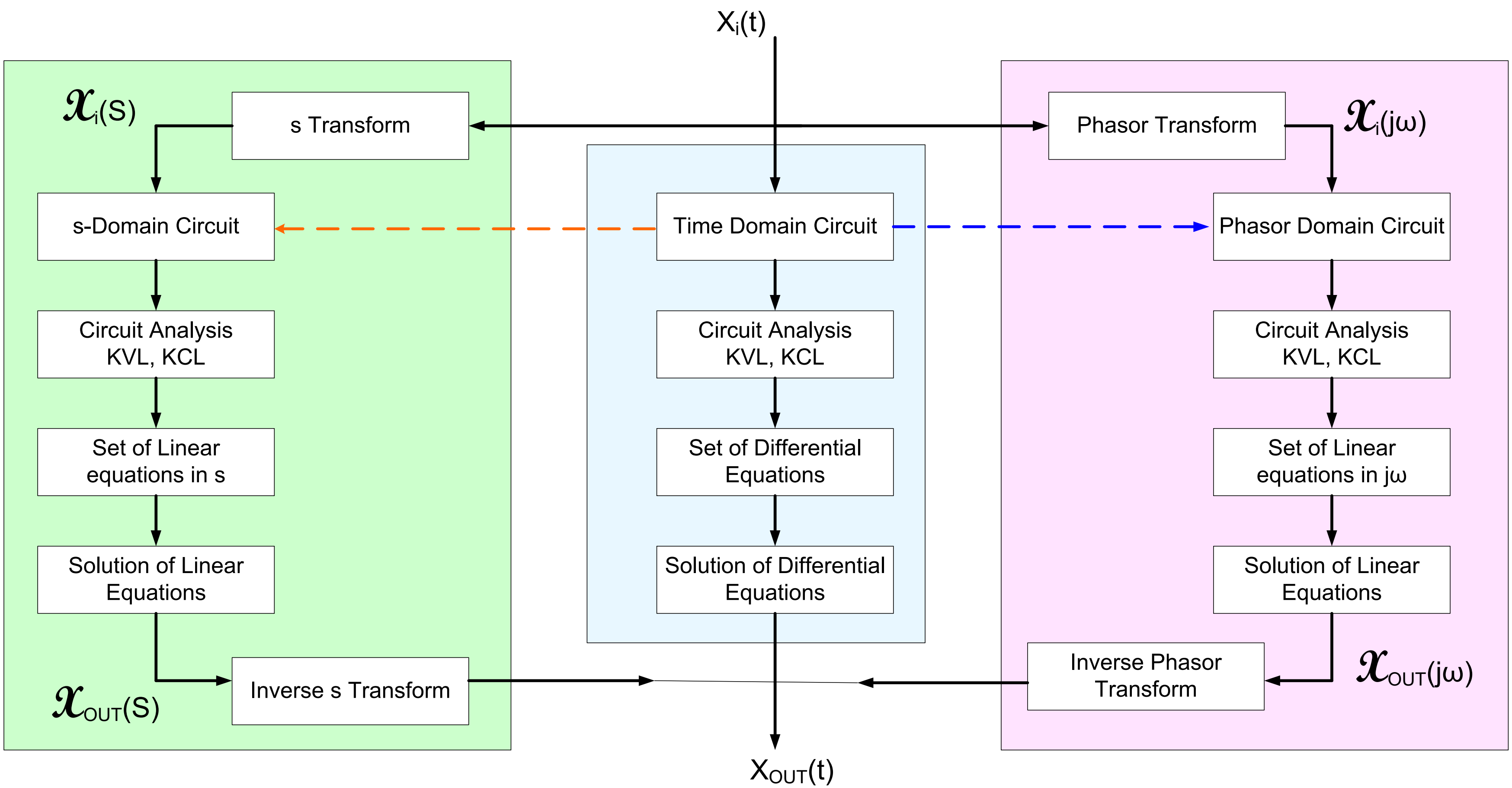
FIGURE 3. Voltage Transfer Characteristics for an Inverter Connected as a Linear Amplifier.

Review of ss steady-state analysis

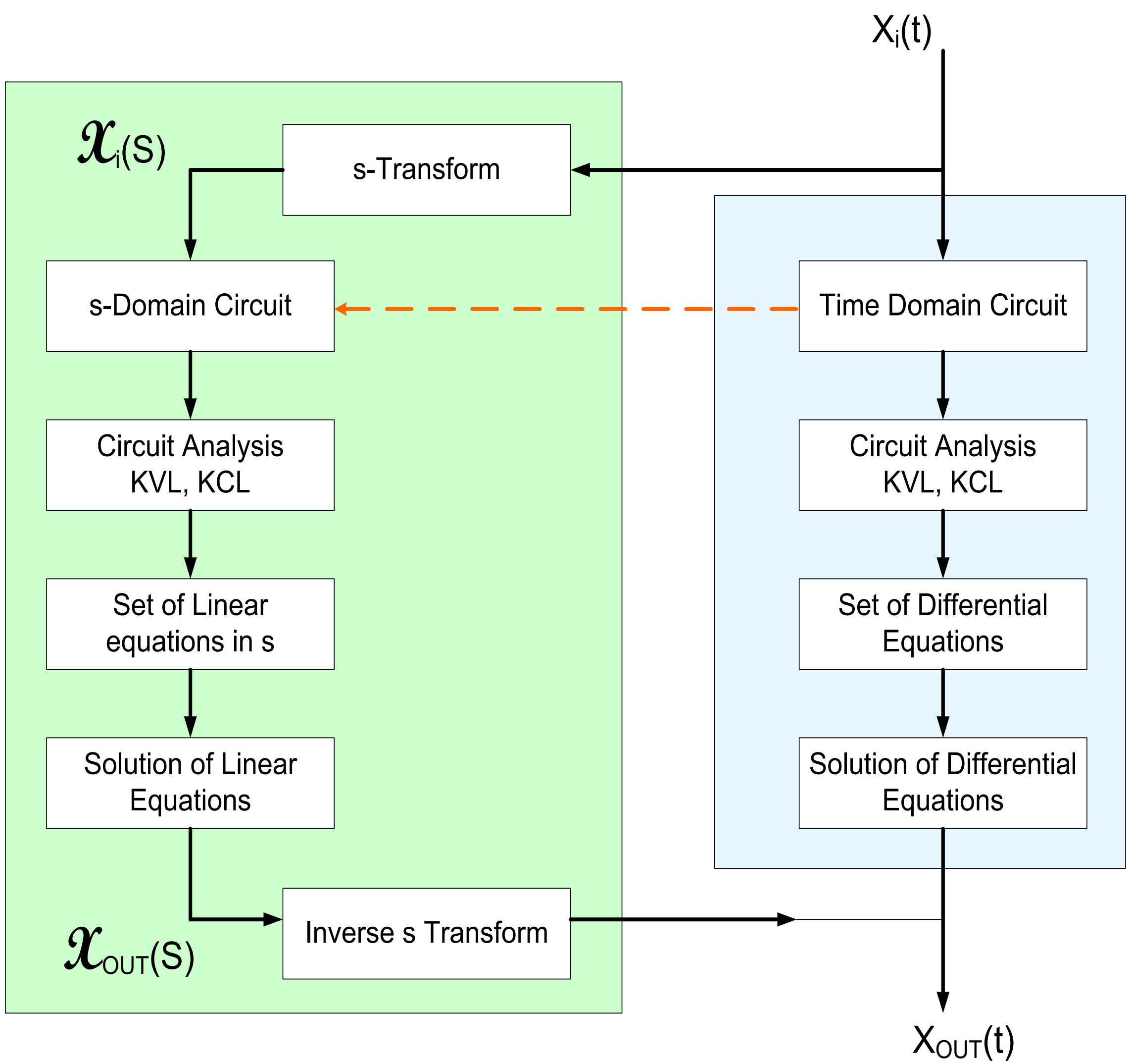
Standard Formal Approach to Circuit Analysis



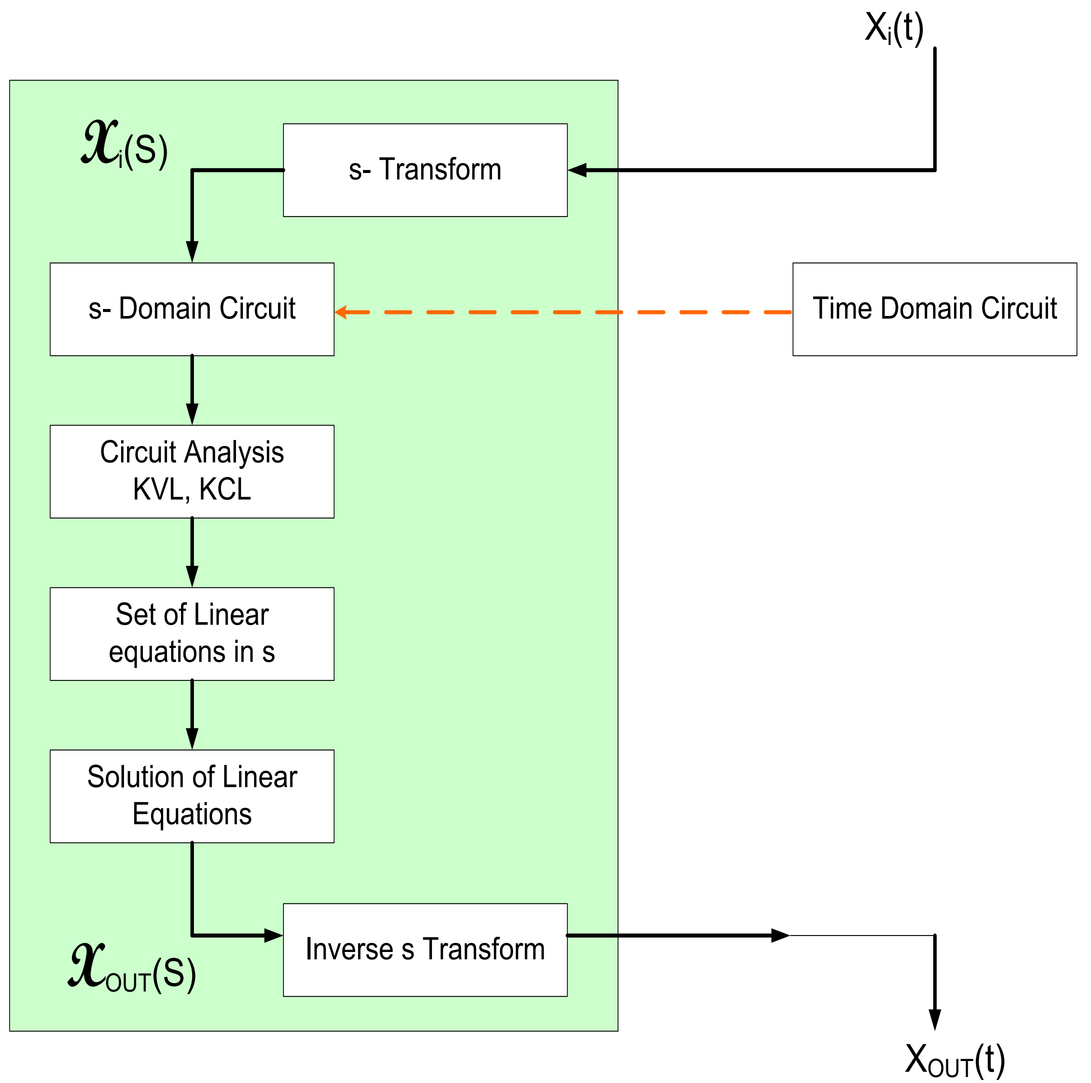
Time, Phasor, and s- Domain Analysis



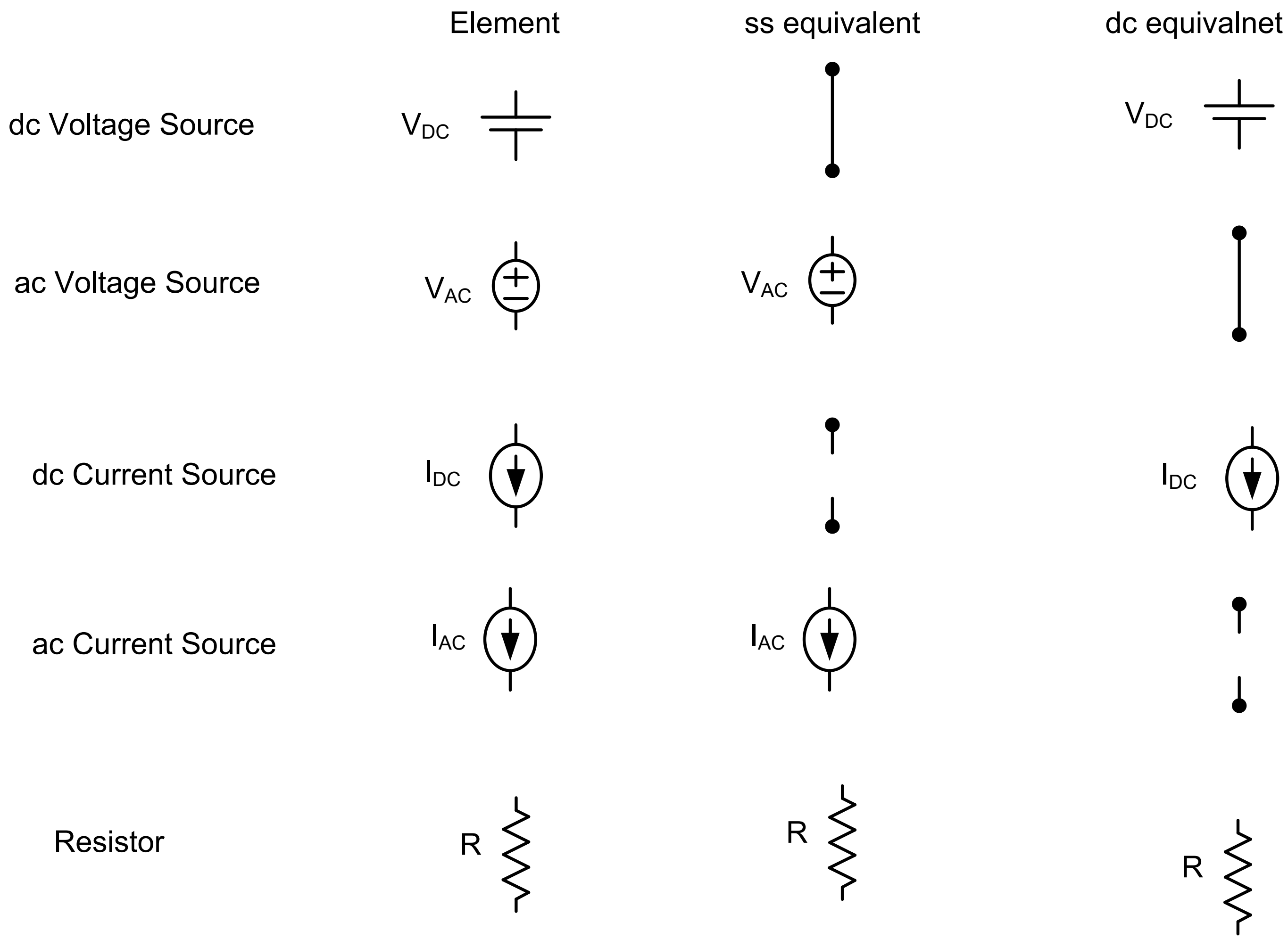
Time and s- Domain Analysis



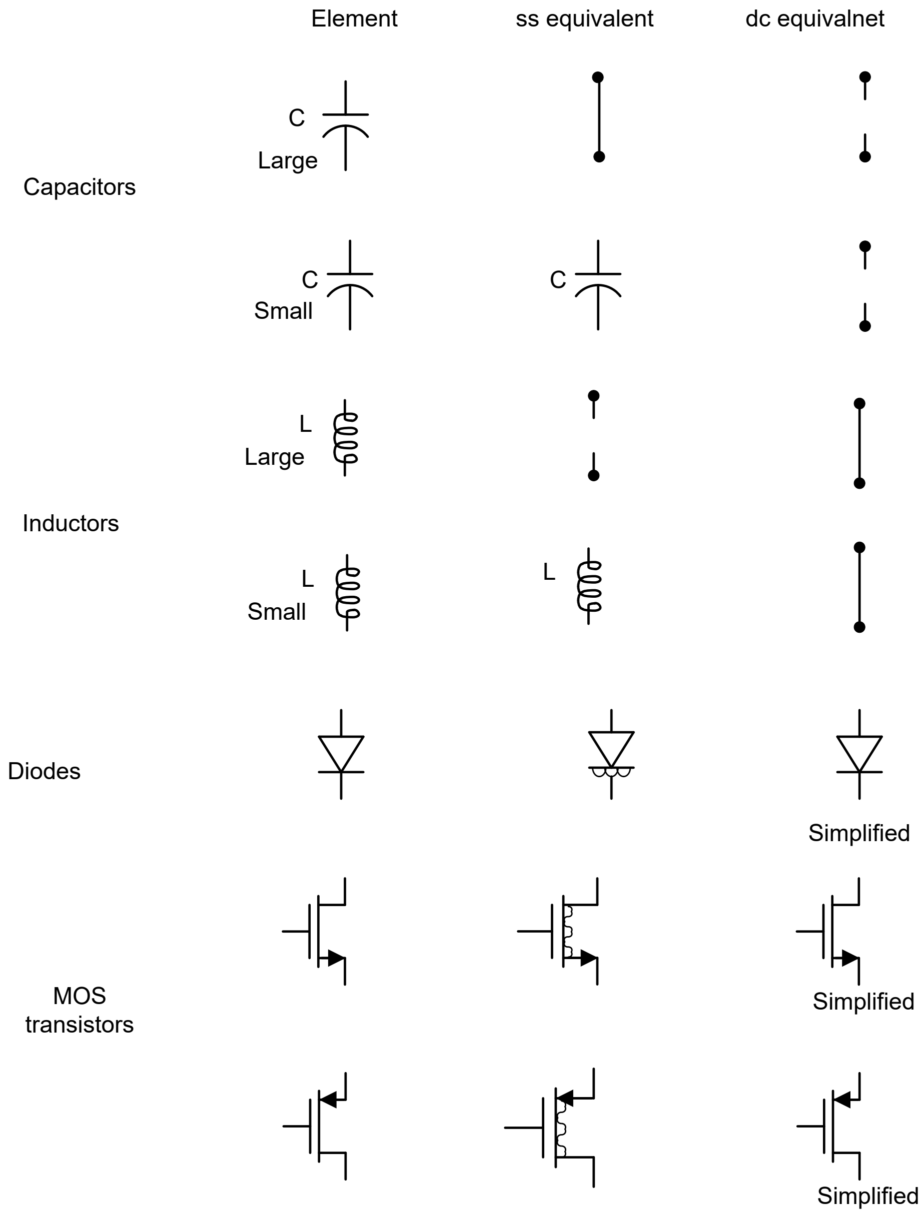
s- Domain Analysis



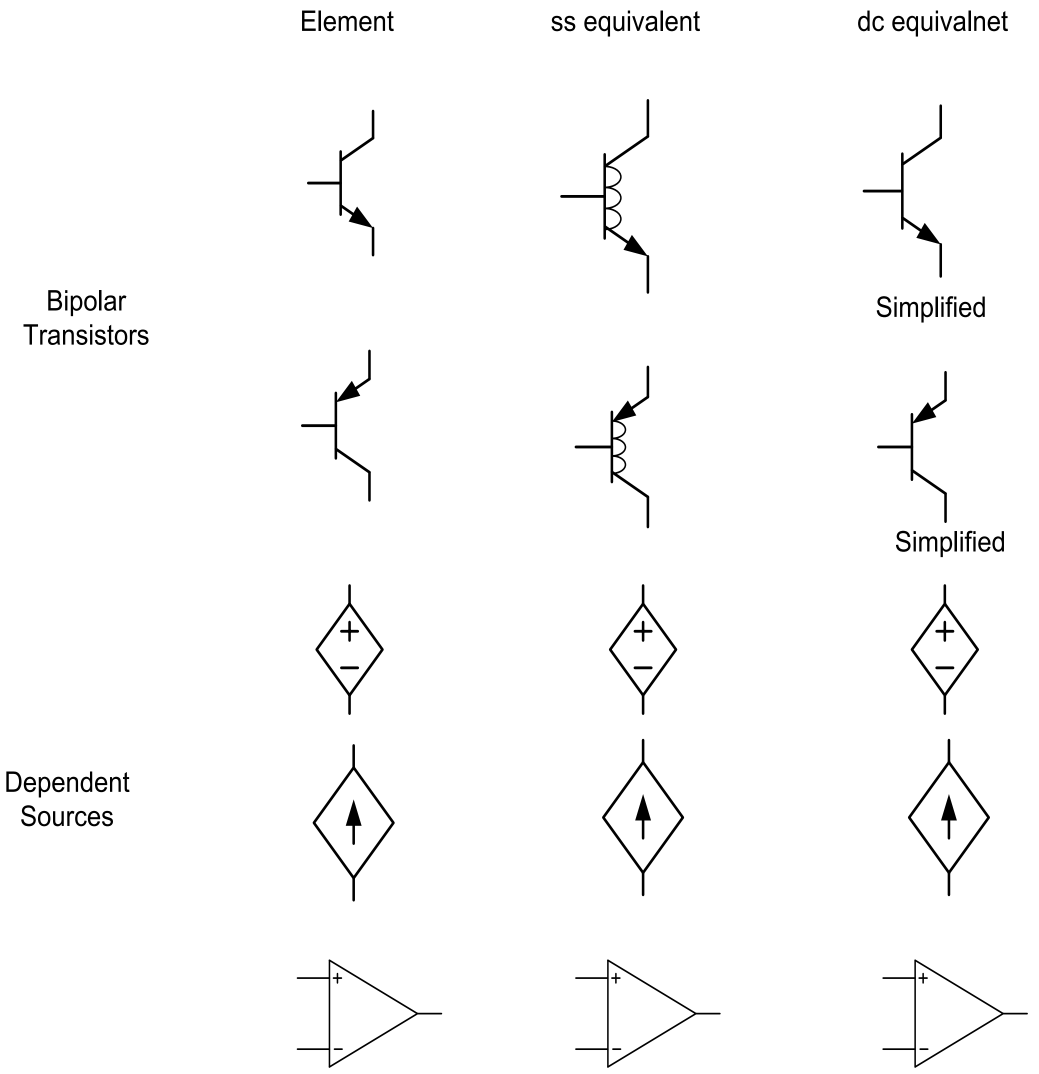
Dc and small-signal equivalent elements



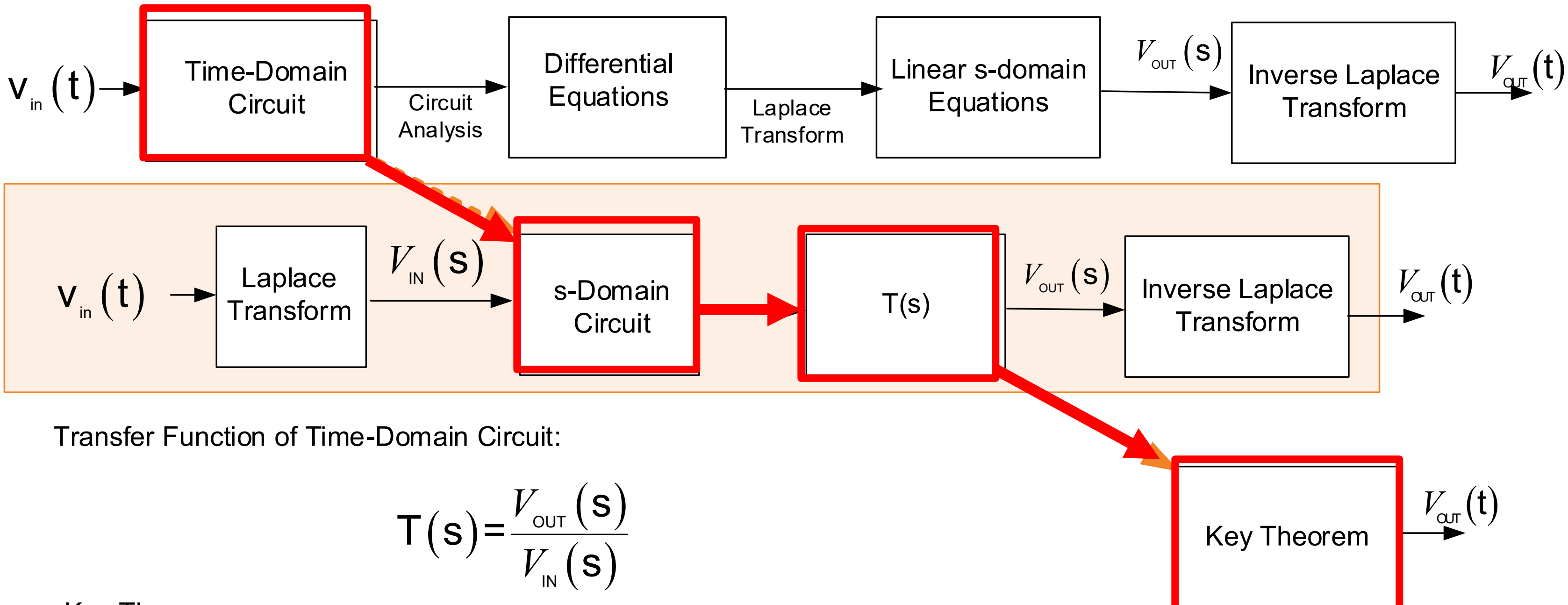
Dc and small-signal equivalent elements



Dc and small-signal equivalent elements



Summary of Sinusoidal Steady-State Analysis Methods for Linear Networks



Transfer Function of Time-Domain Circuit:

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

Key Theorem:

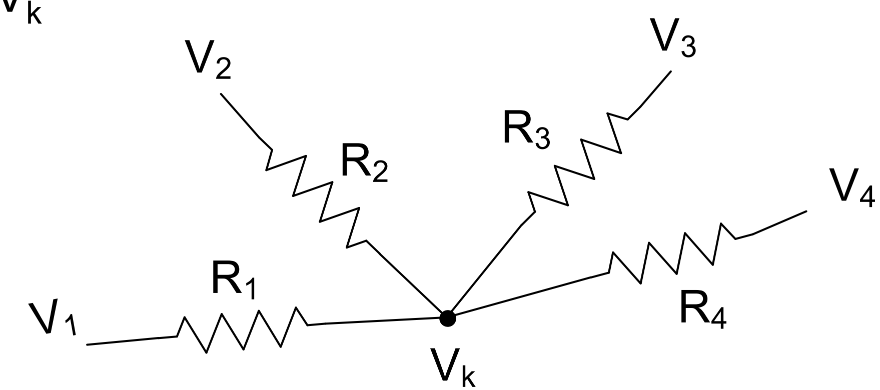
If a sinusoidal input $V_{IN}=V_M\sin(\omega t+\theta)$ is applied to a linear system that has transfer function T(s), then the steady-state output is given by the expression

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

Nodal Analysis (A Brief Review)

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

Example: Determine V_k



From KCL

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

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

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

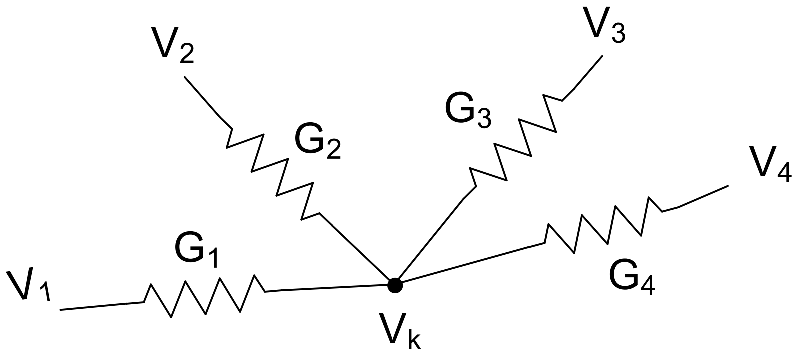
$$V_k = V_1 \frac{R_2R_3R_4}{(R_2R_3R_4 + R_1R_3R_4 + R_2R_1R_4 + R_2R_3R_1)} + V_2 \frac{R_1R_3R_4}{(R_2R_3R_4 + R_1R_3R_4 + R_2R_1R_4 + R_2R_3R_1)} + V_3 \frac{R_2R_1R_4}{(R_2R_3R_4 + R_1R_3R_4 + R_2R_1R_4 + R_2R_3R_1)} + V_4 \frac{R_2R_3R_1}{(R_2R_3R_4 + R_1R_3R_4 + R_2R_1R_4 + R_2R_3R_1)}$$

- 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 $$V_k\left(G_1+G_2+G_3+G_4\right)=G_1V_1+G_2V_2+G_3V_3+G_4V_4$$

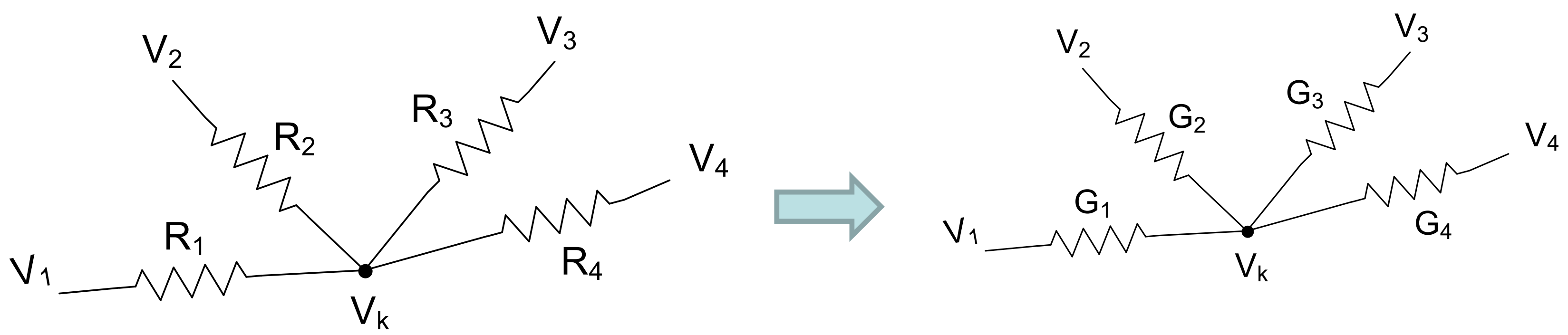
$$V_k=V_1\frac{G_1}{G_1+G_2+G_3+G_4}+V_2\frac{G_2}{G_1+G_2+G_3+G_4}+V_3\frac{G_3}{G_1+G_2+G_3+G_4}+V_4\frac{G_4}{G_1+G_2+G_3+G_4}$$

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)

$$V_k = V_1 \frac{R_2R_3R_4}{(R_2R_3R_4 + R_1R_3R_4 + R_2R_1R_4 + R_2R_3R_1)} + V_2 \frac{R_1R_3R_4}{(R_2R_3R_4 + R_1R_3R_4 + R_2R_1R_4 + R_2R_3R_1)} + V_3 \frac{R_2R_1R_4}{(R_2R_3R_4 + R_1R_3R_4 + R_2R_1R_4 + R_2R_3R_1)} + V_4 \frac{R_2R_3R_1}{(R_2R_3R_4 + R_1R_3R_4 + R_2R_1R_4 + R_2R_3R_1)}$$

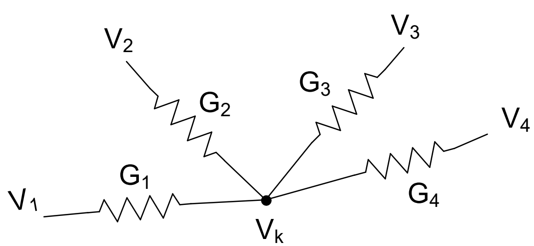
$$V_k = V_1 \frac{G_1}{G_1 + G_2 + G_3 + G_4} + V_2 \frac{G_2}{G_1 + G_2 + G_3 + G_4} + V_3 \frac{G_3}{G_1 + G_2 + G_3 + G_4} + V_4 \frac{G_4}{G_1 + G_2 + G_3 + G_4}$$

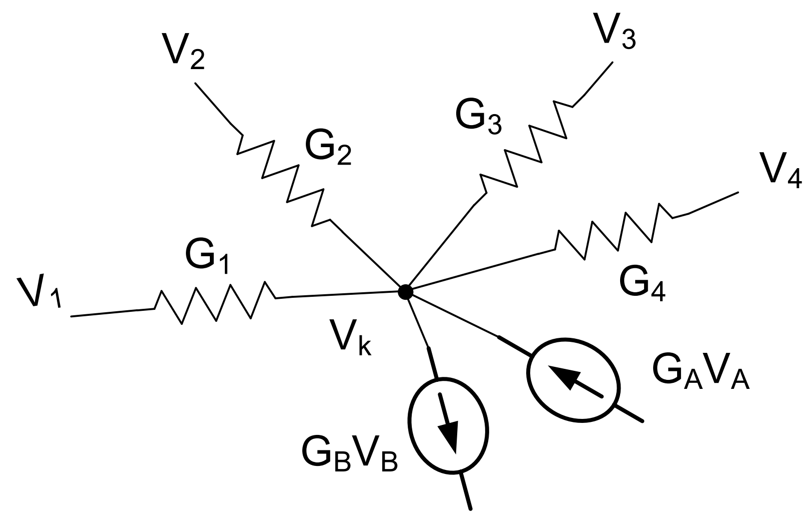
Nodal Analysis (A Brief Review)

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

Example: Determine V_k

Easy to add dependent sources





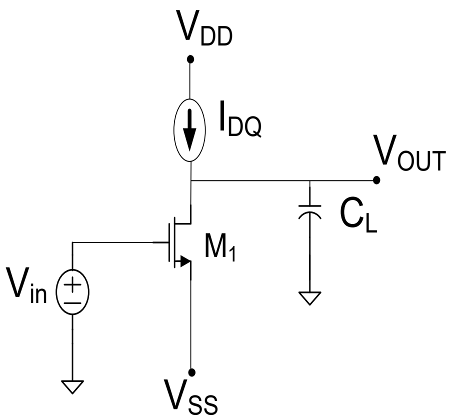
From KCL $$V_k\left(G_1+G_2+G_3+G_4\right)+G_BV_B-G_AV_A=G_1V_1+G_2V_2+G_3V_3+G_4V_4$$

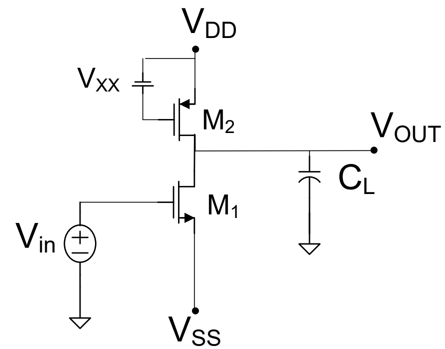
$$V_k=V_1\frac{G_1}{G_1+G_2+G_3+G_4}+V_2\frac{G_2}{G_1+G_2+G_3+G_4}+V_3\frac{G_3}{G_1+G_2+G_3+G_4}+V_4\frac{G_4}{G_1+G_2+G_3+G_4}+V_A\frac{G_A}{G_1+G_2+G_3+G_4}-V_B\frac{G_B}{G_1+G_2+G_3+G_4}$$

Often much simpler to work with conductances than with resistances!

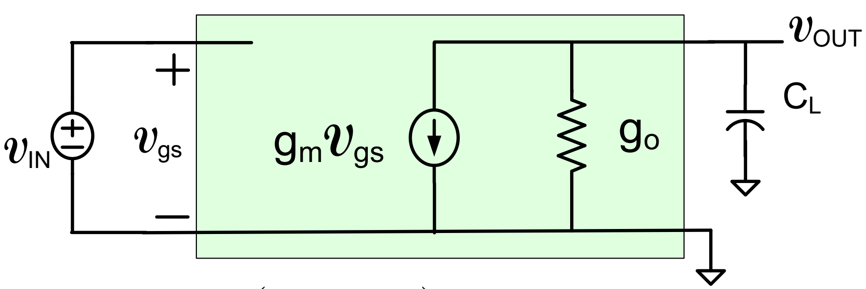
Do we really need the concept of both a resistor and a conductor?

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



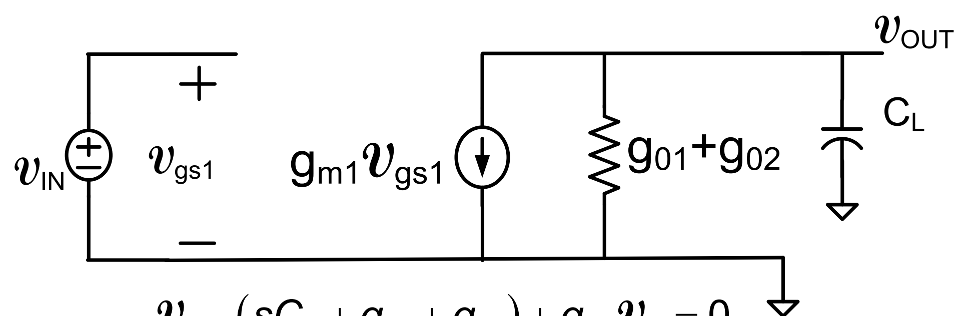


Small Signal Models



$$v_{OUT}\left(sC_L + g_o\right) + g_m v_{IN} = 0$$

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

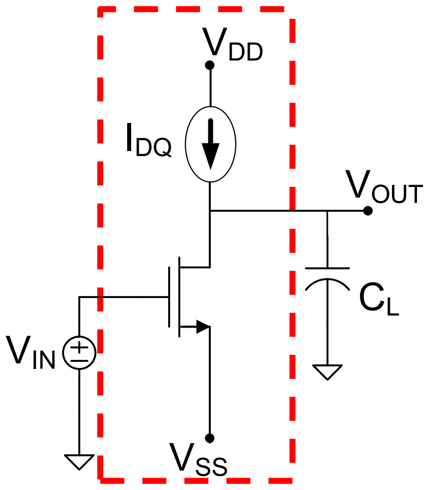


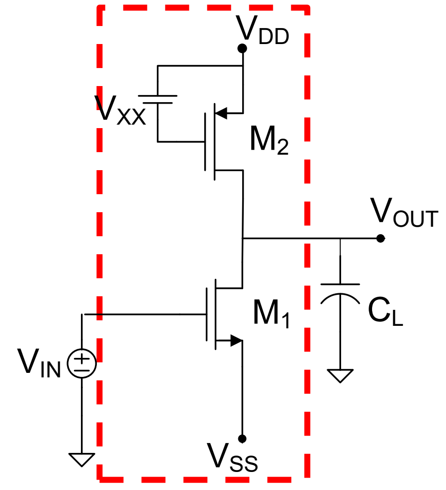
$$v_{OUT}\left(sC_L + g_{o1} + g_{o1}\right) + g_{m1} v_{IN} = 0$$

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

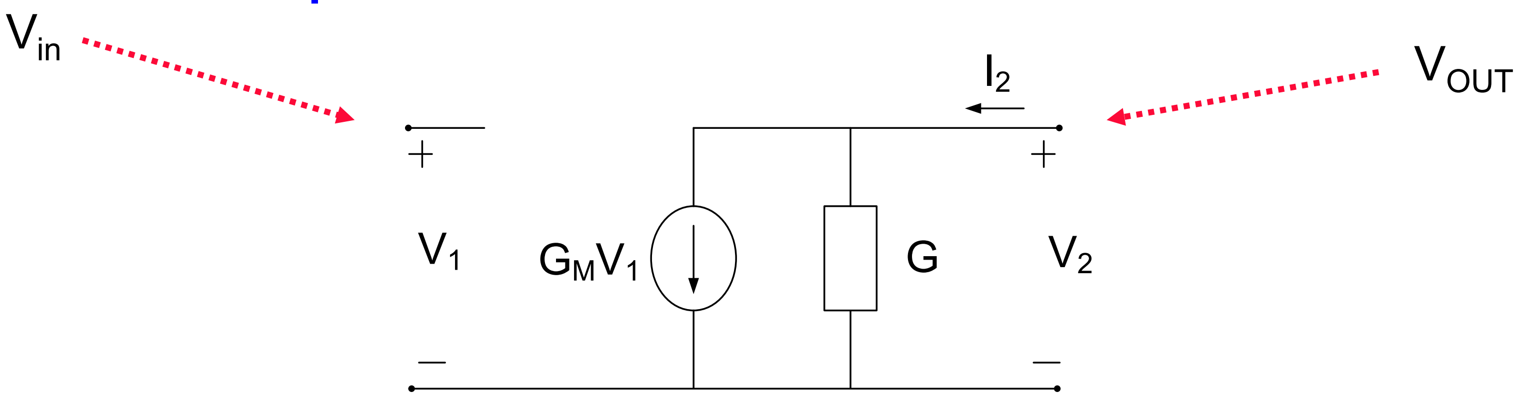
dc Voltage gain is ratio of overall transconductance gain to output conductance

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





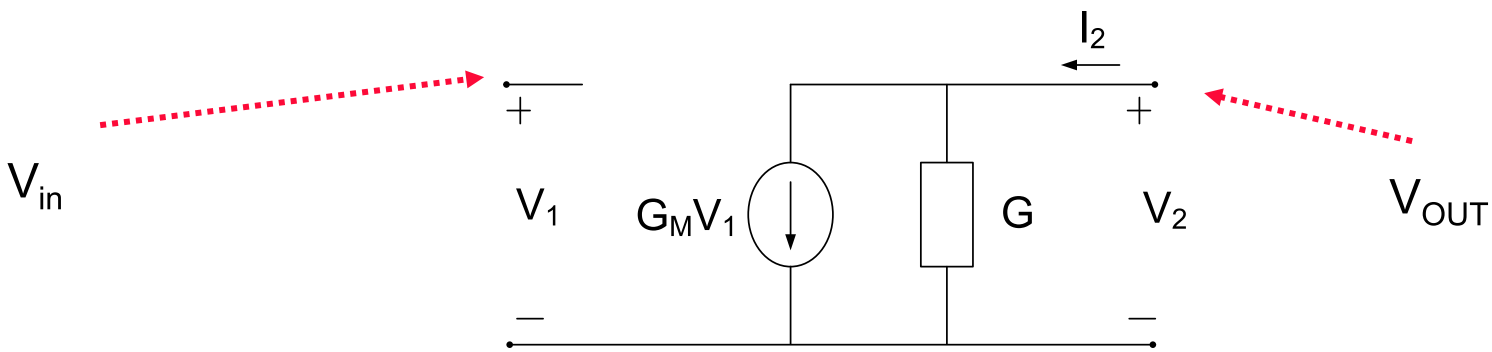
Observe in either case the small signal equivalent circuit is a two-port of the form:



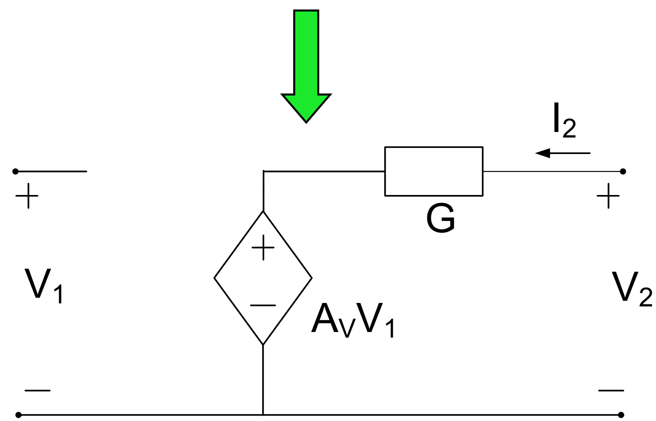
All properties of the circuit are determined by G_M and G

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

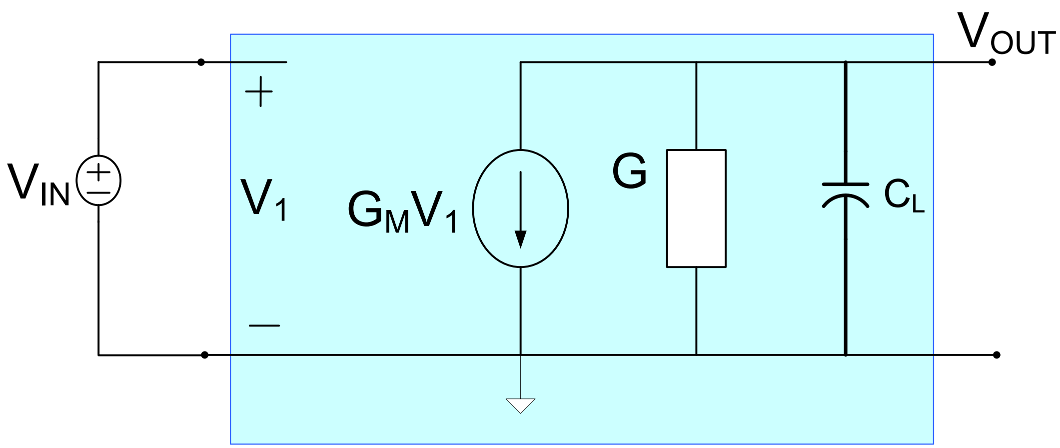


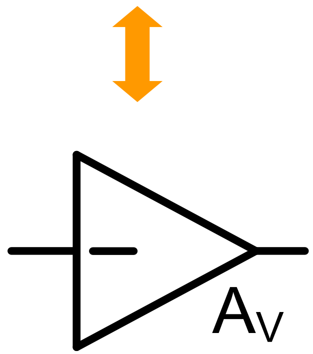
$$A_V = -\frac{G_M}{G}$$

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:

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

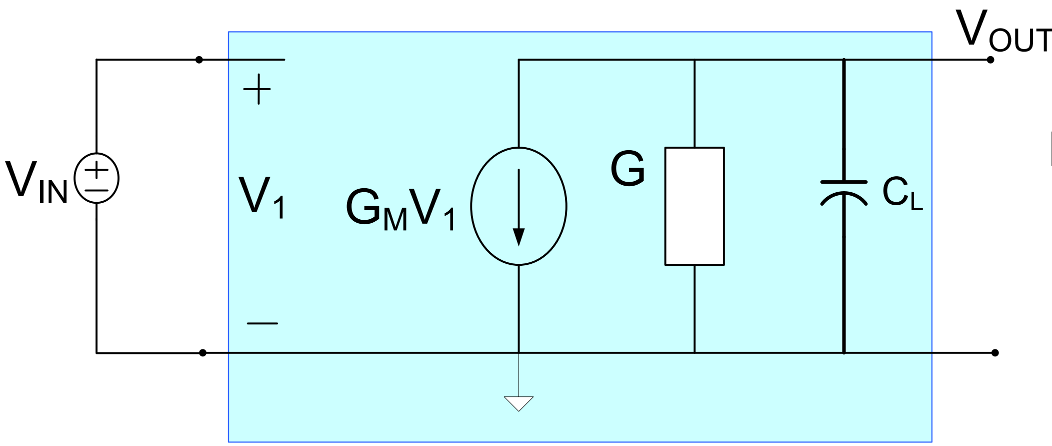
$$GB \underset{def}{=} \left| A_{V0} \bullet BW \right|$$

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

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

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

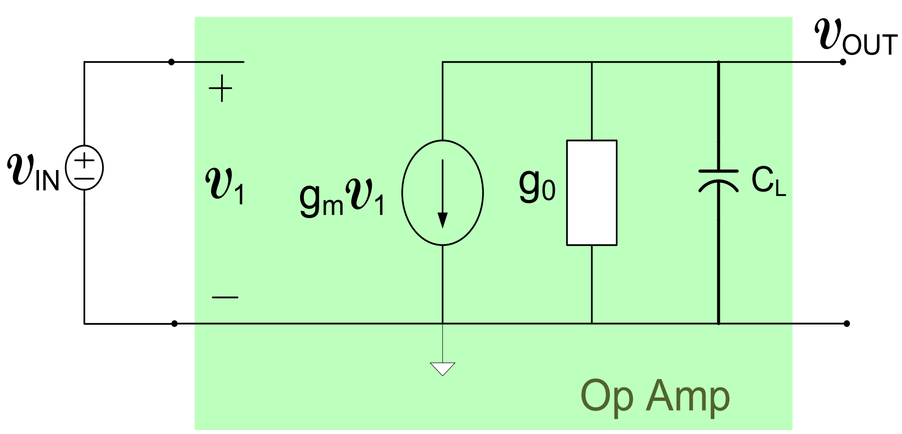
Single-stage single-input low-gain op amp



By inspection from General Analysis

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

for common-source amplifier



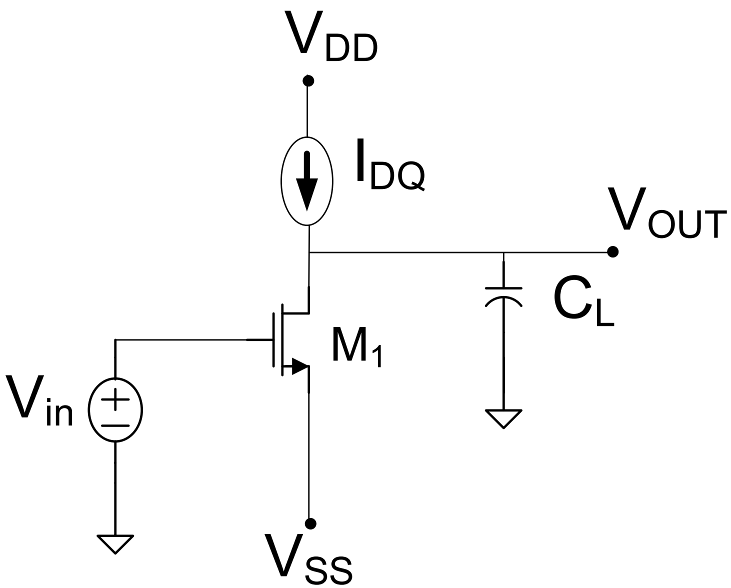
$$A_{V0} = \frac{-g_m}{g_0}$$

$$BW = \frac{g_0}{C_L}$$

$$GB = \left(\frac{g_m}{g_0}\right)\left(\frac{g_0}{C_L}\right) = \frac{g_m}{C_L}$$

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

Thus the 3-dimensional design space generally has only two independent variables (or two degrees of freedom), so can consider any two

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

Thus design or "synthesis" with this architecture involves exploring the two-dimensional design space $\left\{\frac{W_1}{L_1}, I_{DQ}\right\}$

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

Must determine { W_1, L_1, I_{DQ} 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

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

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

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

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

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

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

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

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

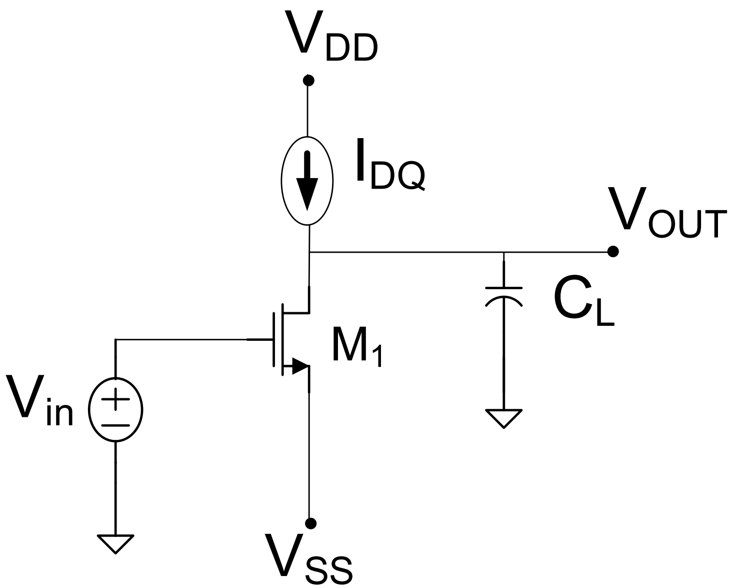
5. Explore the resultant design space with the identified number of Degrees of Freedom

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 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 :

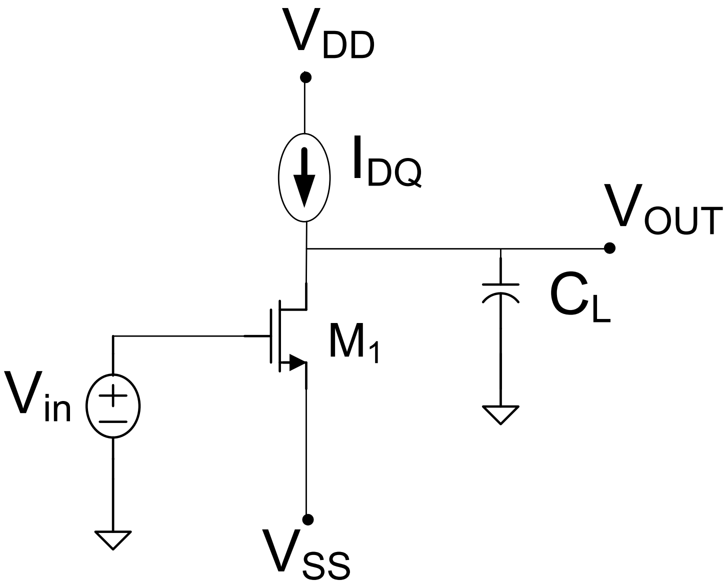
$$\{g_m, g_0\}$$

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?

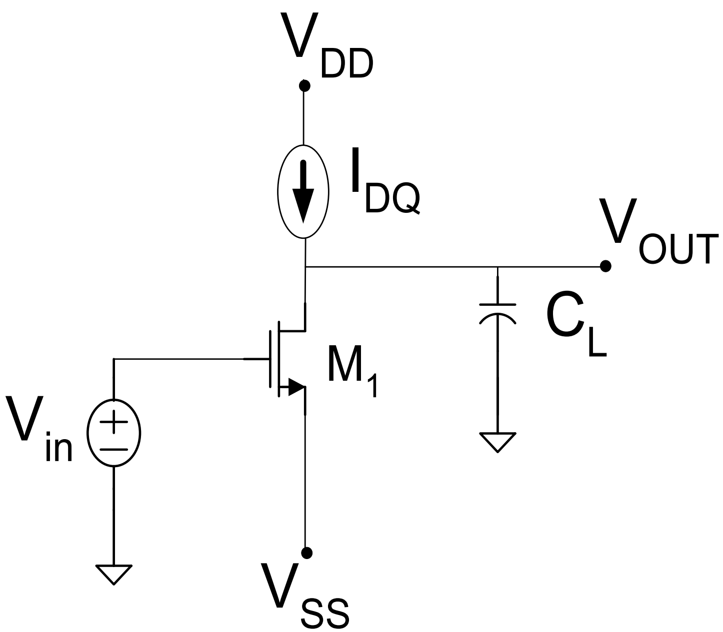
$$\left\{\frac{W}{L}, I_{DQ}\right\}$$

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

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

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

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

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

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

Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

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

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

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

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

$$A_{V0} = \frac{\sqrt{2\mu C_{OX}\frac{W}{L}}}{\lambda\sqrt{I_{DQ}}} \qquad GB = \frac{\sqrt{2\mu C_{OX}\frac{W}{L}}\sqrt{I_{DQ}}}{C_L}$$

- **Expressions very complicated**
- **Both A_{V0} and GB depend upon both design paramaters**
- **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 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 : $\{g_m, g_0\}$

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

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

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

Process Dependent | **Architecture Dependent** | **Process Dependent** | **Architecture Dependent**

Key Observation !

Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

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

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

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

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

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

P=Power=$V_{DD}I_{DQ}$ $\qquad$ V_{EB}=excess bias =$V_{GSQ}-V_T$

$$A_{V0} = -\frac{g_M}{g_0} = -\left(\frac{2I_{DQ}}{V_{EB}}\right)\left(\frac{1}{\lambda I_{DQ}}\right) = -\frac{2}{\lambda V_{EB}} \qquad GB = \frac{g_M}{C_L} = \left(\frac{2I_{DQ}}{V_{EB}}\right)\frac{1}{C_L} = \left[\frac{2}{V_{DD}C_L}\right]\frac{P}{V_{EB}}$$

Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

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

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

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

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

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

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

Process Dependent

Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

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

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

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

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

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 : $\{g_m, g_0\}$

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

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

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

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

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

- **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 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

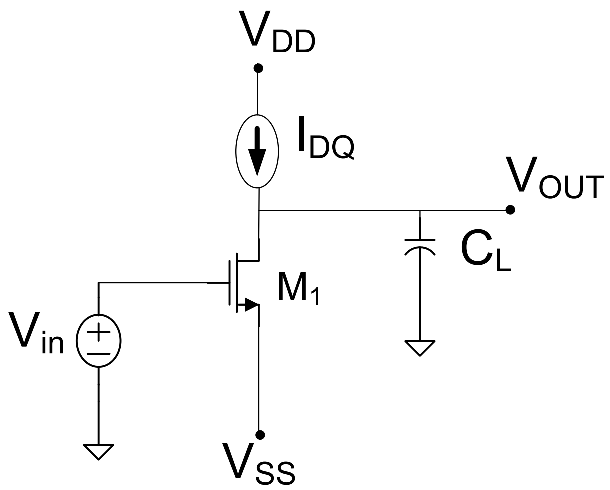
In practical parameter domain explore how P and V_{EB} affect desired performance

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: $\left\{P, V_{EB}\right\}$

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

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

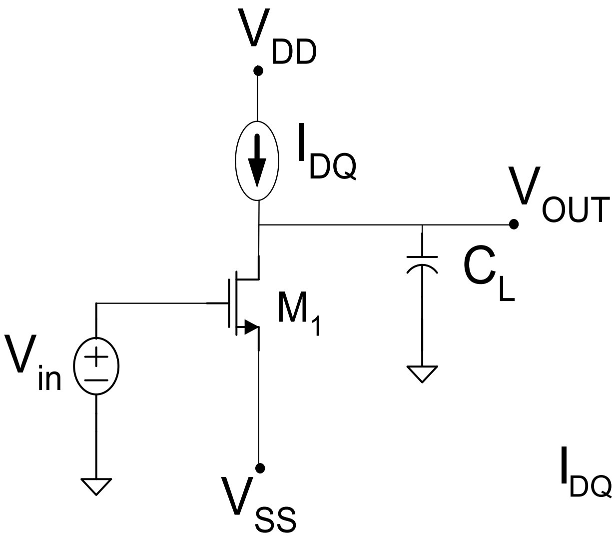
To complete design:

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

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

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

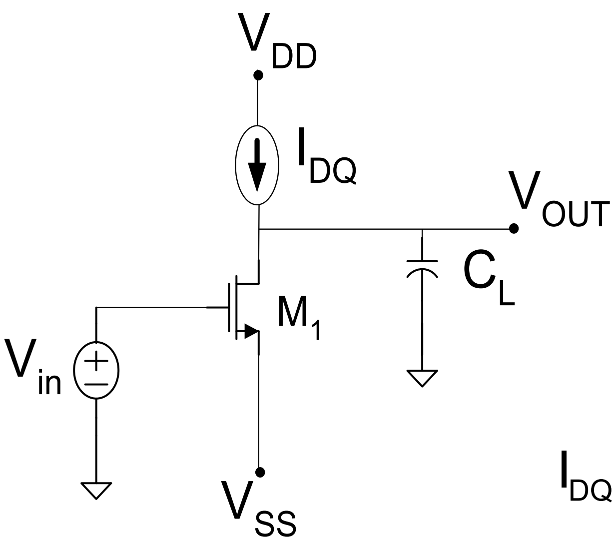
$$I_{DQ} = \frac{P}{V_{DD} - V_{SS}} \qquad \frac{W}{L} = \frac{2P}{V_{DD}\mu C_{OX}V_{EB}^2} \qquad V_{INQ} = V_{SS} + V_T + \sqrt{I_{DQ}\frac{2}{\mu C_{OX}}\frac{L}{W}}$$

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

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

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

$$I_{DQ} = \frac{P}{V_{DD} - V_{SS}} \qquad \frac{W}{L} = \frac{2P}{V_{DD}\mu C_{OX} V_{EB}^2} \qquad V_{INQ} = V_{SS} + V_T + \sqrt{I_{DQ}\frac{2}{\mu C_{OX}}\frac{L}{W}}$$

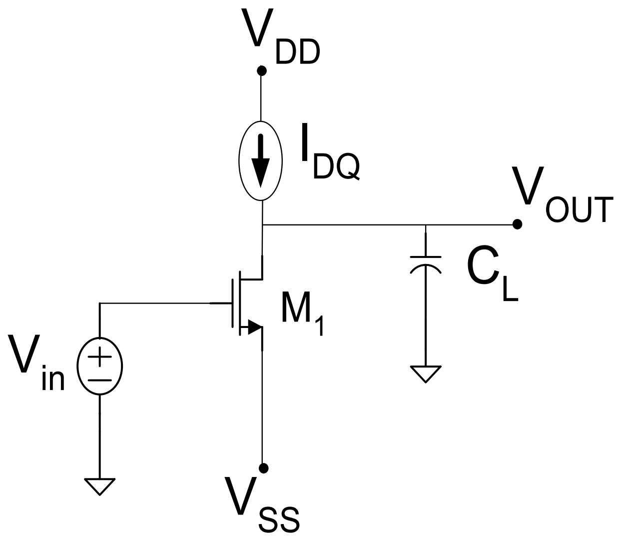
What if the design requirement dictates that $V_{INQ}=0$?

- 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

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

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

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

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