EE 435

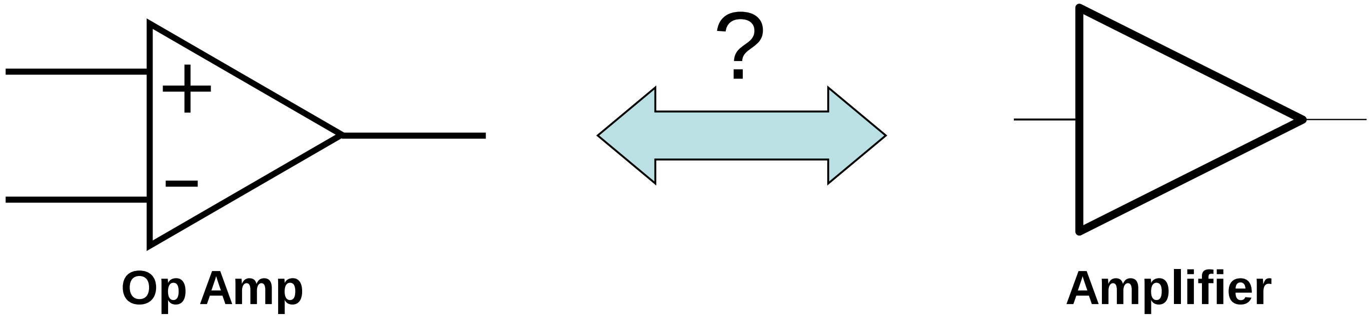
Lecture 2:

Basic Op Amp Design

- Single Stage Low Gain Op Amps

Review from last lecture:

How does an amplifier differ from an operational amplifier?

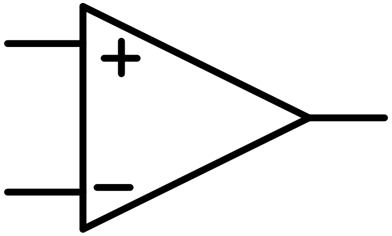


Amplifier used in open-loop applications

Operational Amplifier used in feedback applications

Review from last lecture:

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?

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

1. Very Large Gain

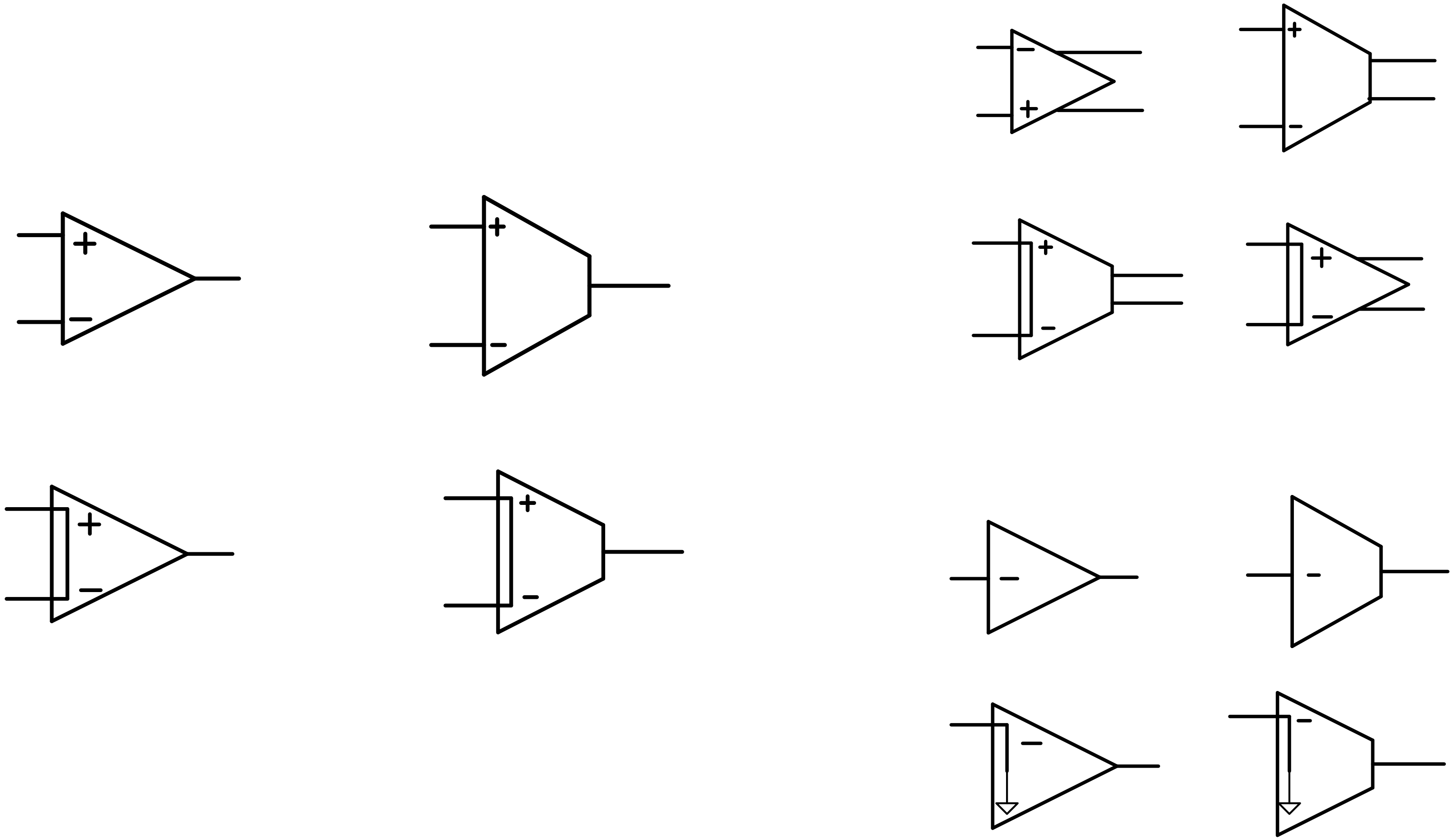
To make A_F (or A_{VF}) insensitive to variations in A

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?

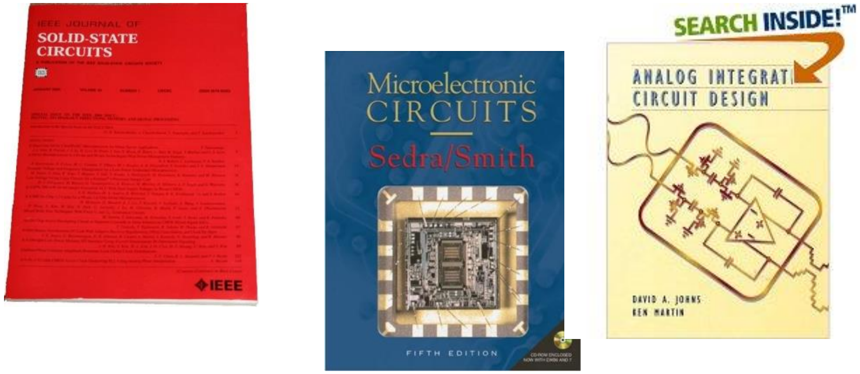
1. Very Large Voltage Gain

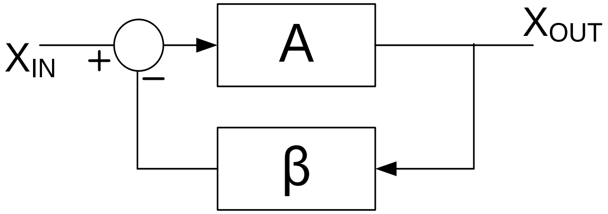
and …

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

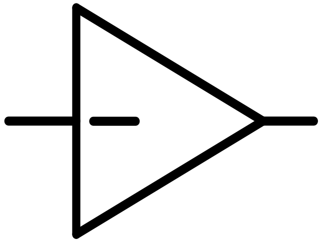
- Keep an open mind about everything that is done and always ask whether the approach others are following is leading you in the right direction

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

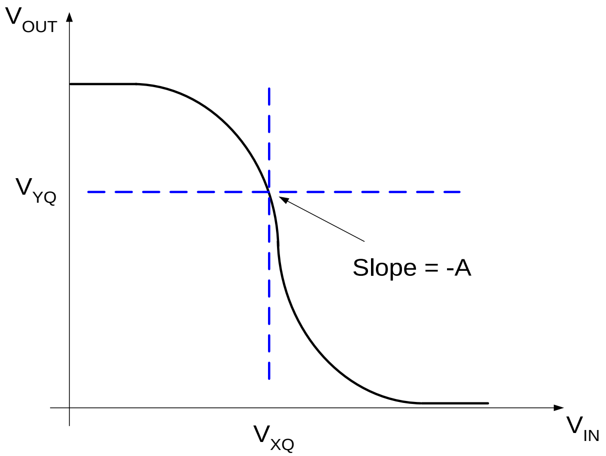


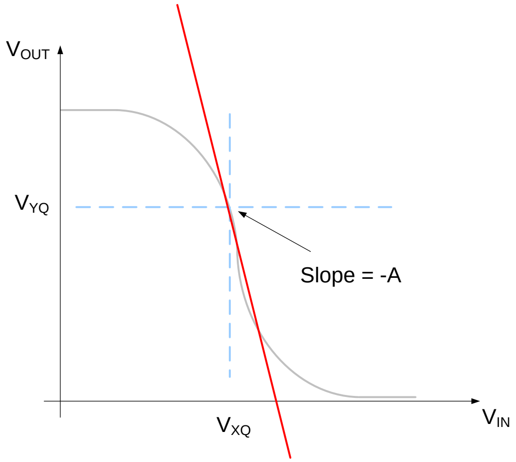
- Differential Input

(Symbol not intended to distinguish between different amplifier types)

Single-ended Op Amp Inverting Amplifier

Consider:





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

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

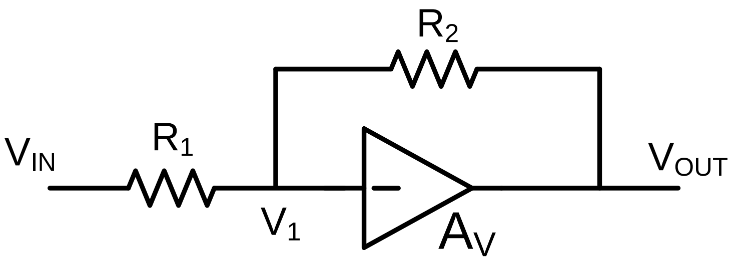
$$V_{OUT} \cong (-A)(V_{IN} - V_{XQ}) + V_{YQ}$$

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

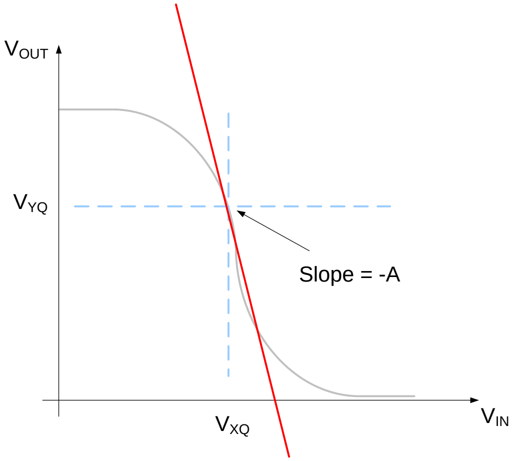
If the gain of the amplifier is large, V_{XQ} is a characteristic of the amplifier

Single-ended Op Amp Inverting Amplifier

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



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



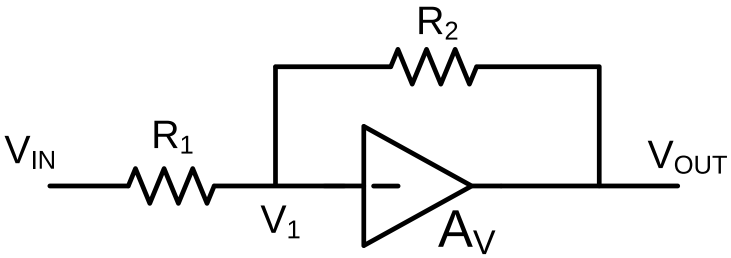
Eliminating V_1 we obtain:

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

If we define V_{iSS} 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

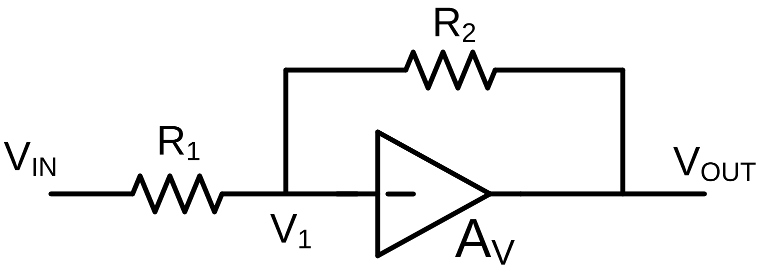
$$V_O = -\frac{R_2}{R_1}V_{inss}+V_{XQ}+\frac{R_2}{R_1}\left(V_{XQ}-V_{inQ}\right)$$

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

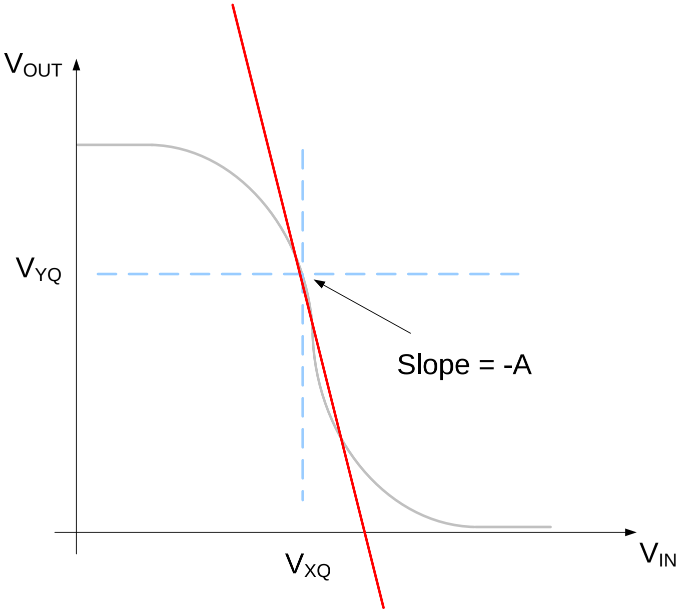
$$V_O \cong -\frac{R_2}{R_1}V_{inss}+V_{XQ}$$

Single-ended Op Amp Inverting Amplifier

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



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

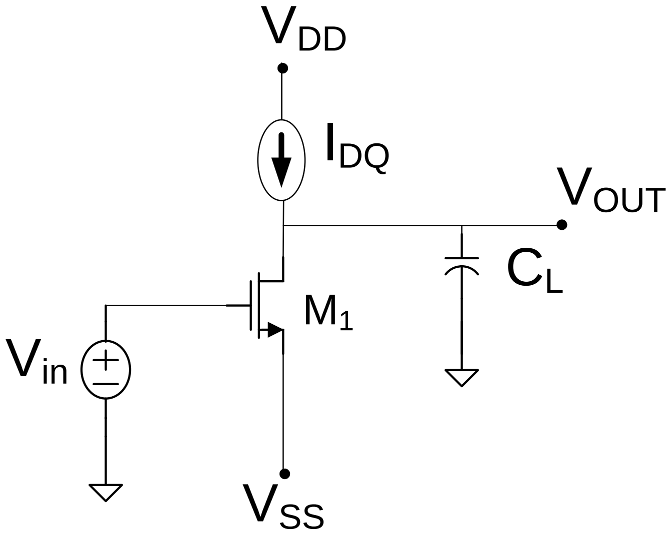


Summary:

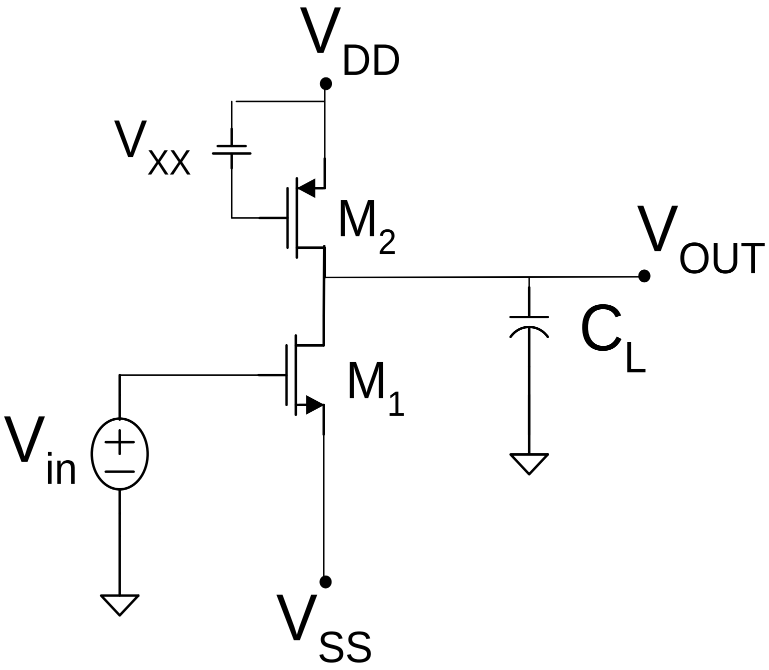
$$V_O = -\frac{R_2}{R_1} V_{inss} + V_{XQ} + \frac{R_2}{R_1}\left(V_{XQ} - V_{inQ}\right)$$

What type of circuits have the transfer characteristic shown?

Single-stage single-input low-gain op amp



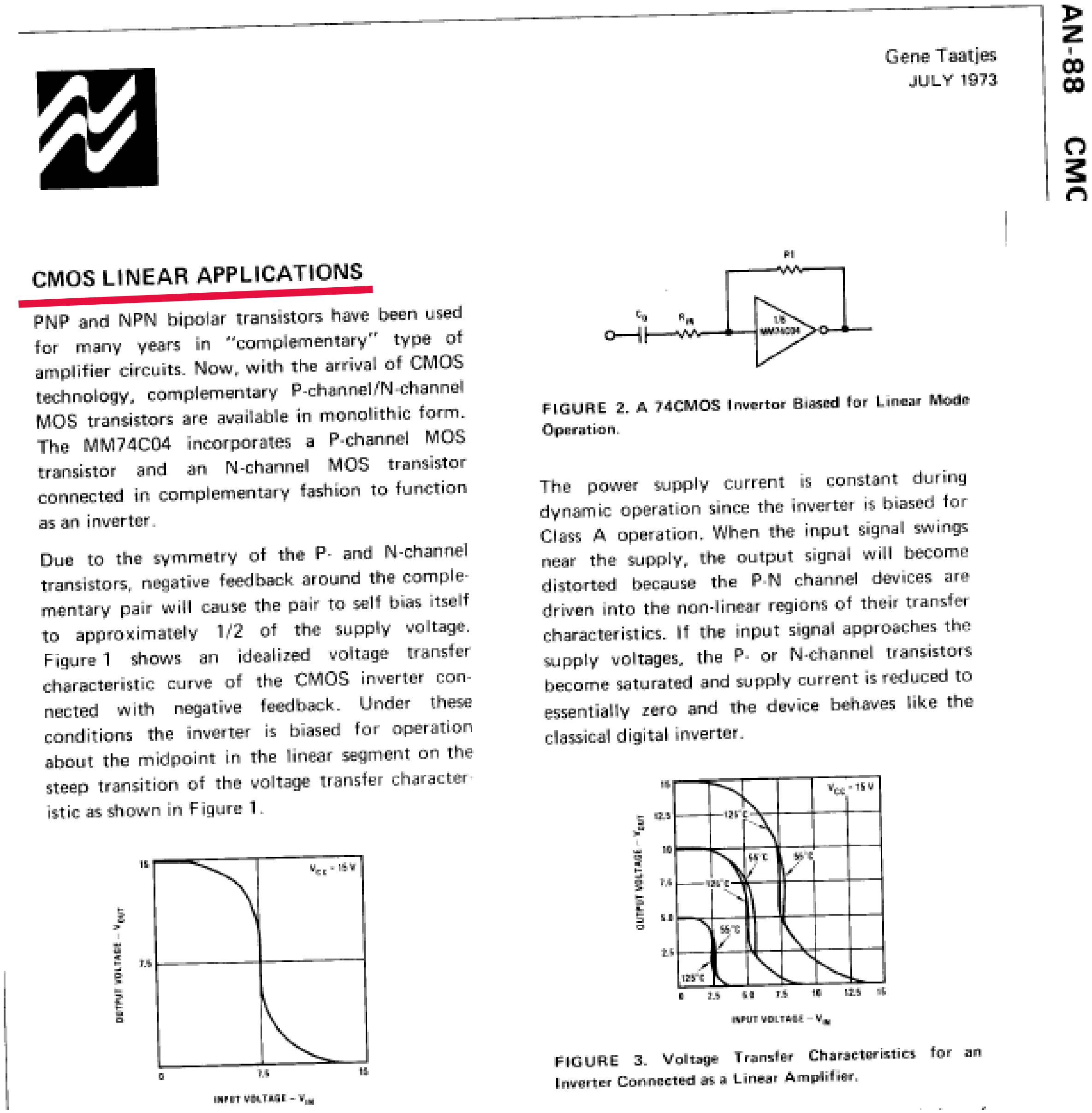
Basic Structure



Practical Implementation

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

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.

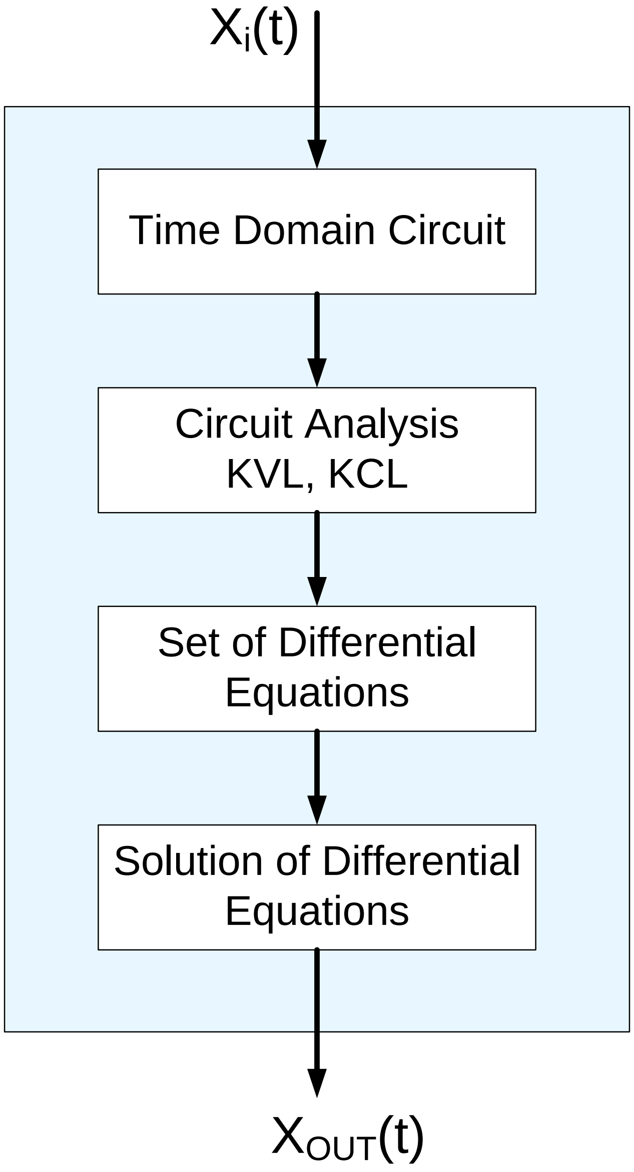
FIGURE 2. A 74CMOS Invertor Biased for Linear Mode Operation.

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 Approach to Circuit Analysis



$X_i(t)$

Time Domain Circuit

Circuit Analysis
KVL, KCL

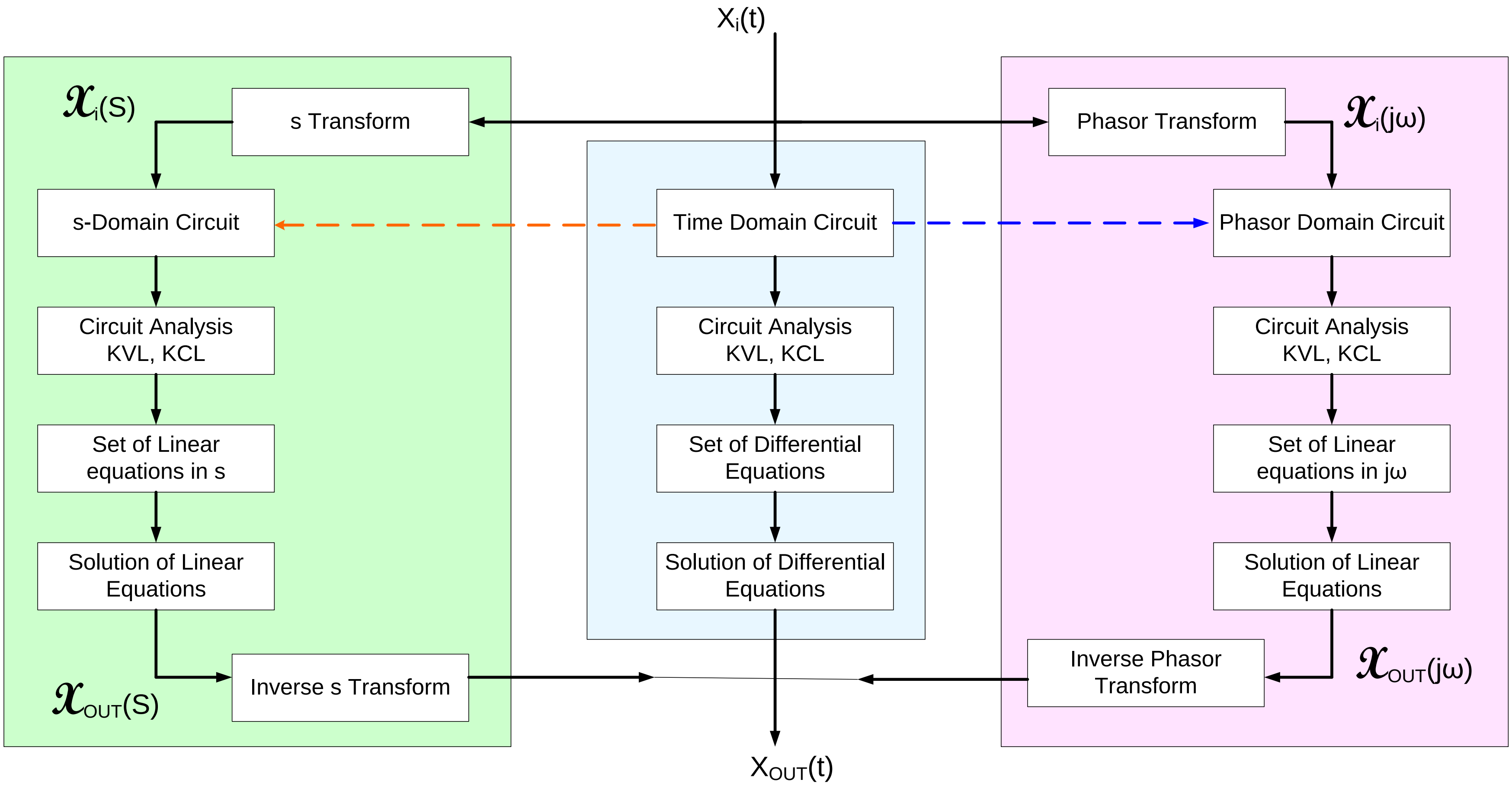
Set of Differential
Equations

Solution of Differential
Equations

$X_{OUT}(t)$

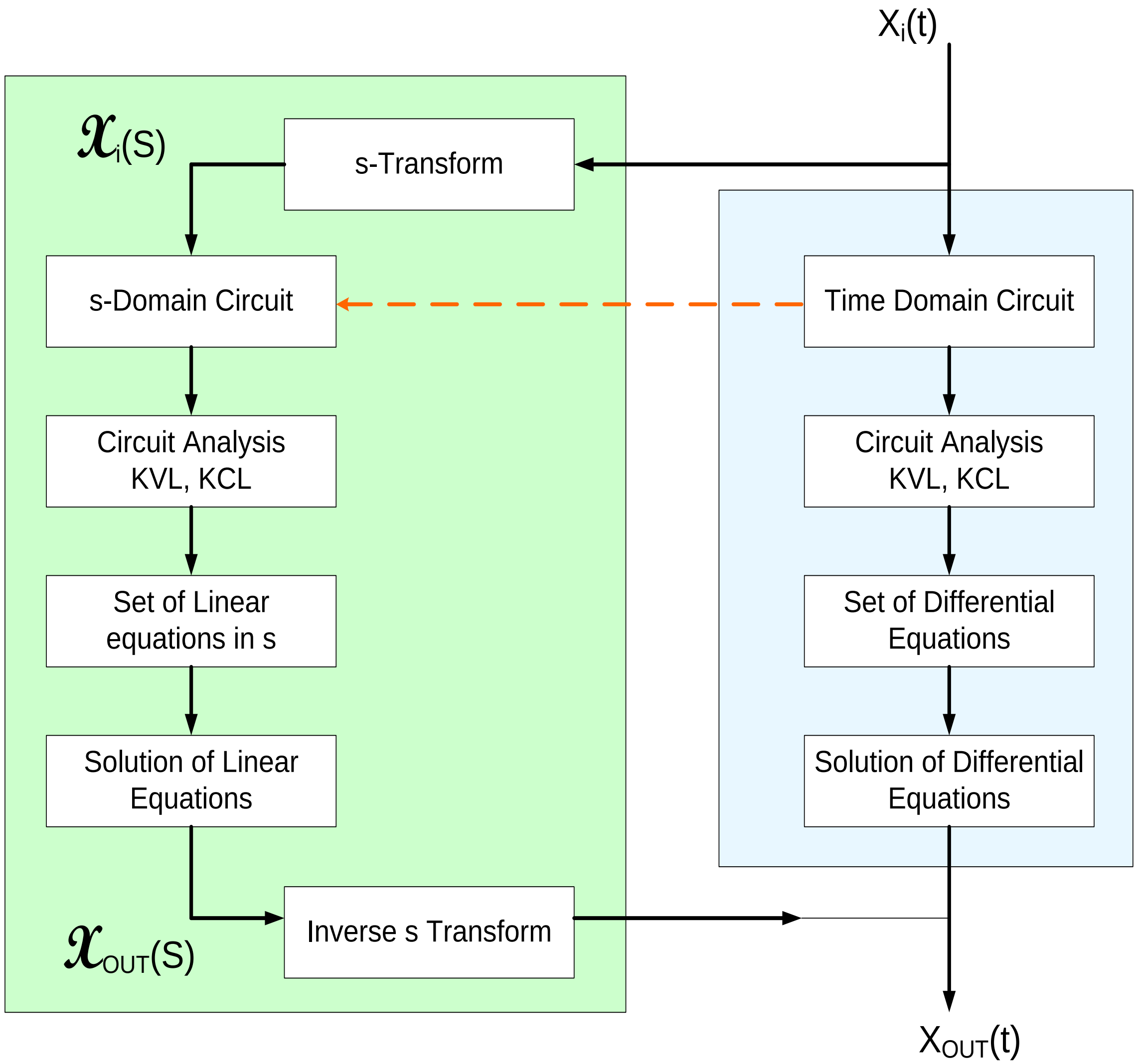
Review of ss steady-state analysis

Time, Phasor, and s- Domain Analysis



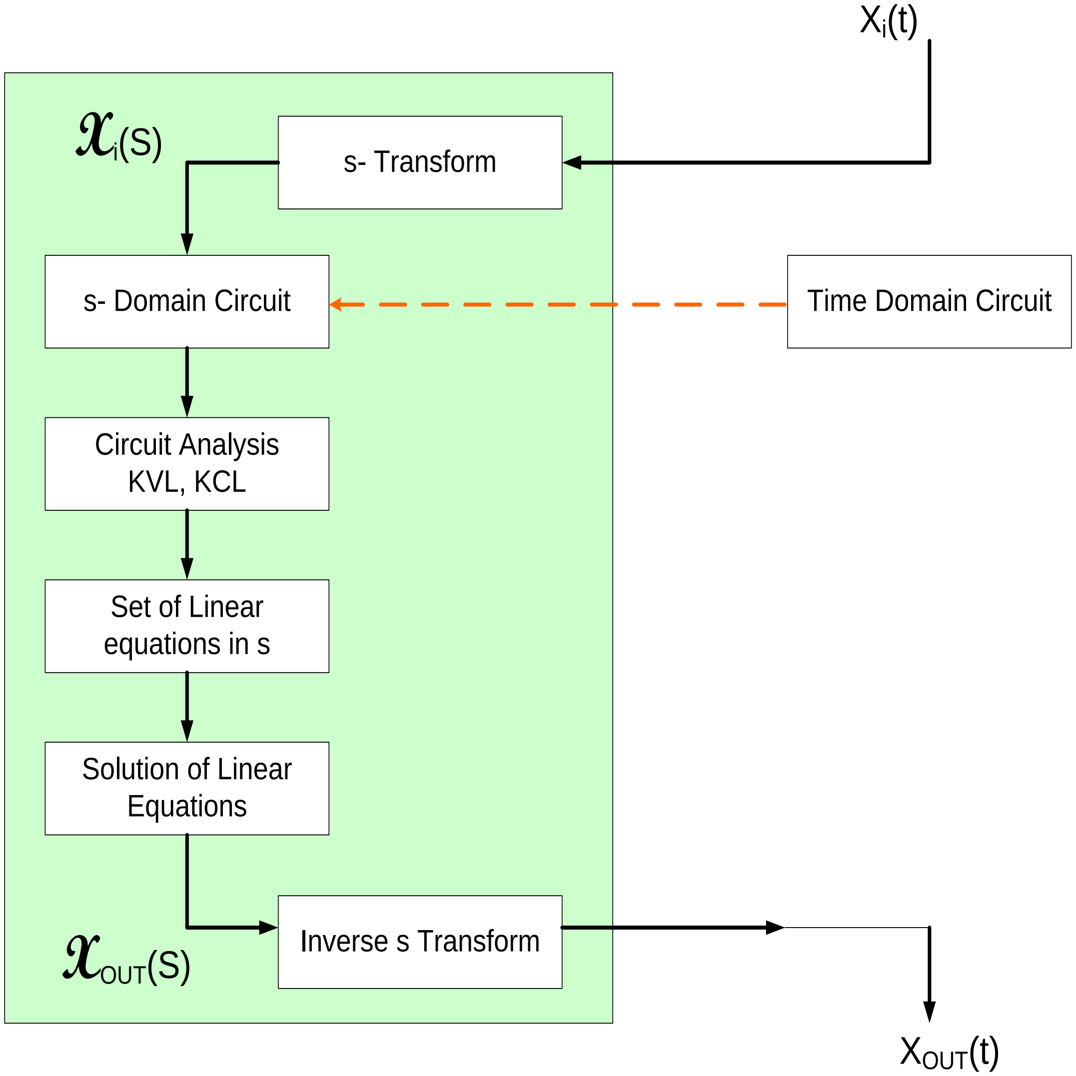
Review of ss steady-state analysis

Time and s- Domain Analysis



Review of ss steady-state analysis

s- Domain Analysis



$X_i(t)$

$\mathcal{X}_i(S)$

s- Transform

s- Domain Circuit

Time Domain Circuit

Circuit Analysis
KVL, KCL

Set of Linear
equations in s

Solution of Linear
Equations

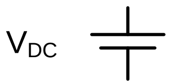
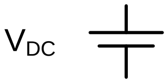
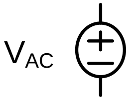
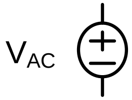
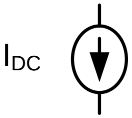
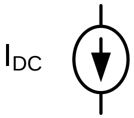
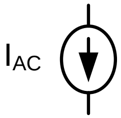
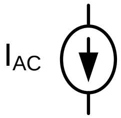
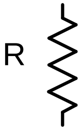
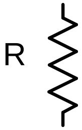
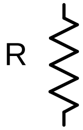
$\mathcal{X}_{OUT}(S)$

Inverse s Transform

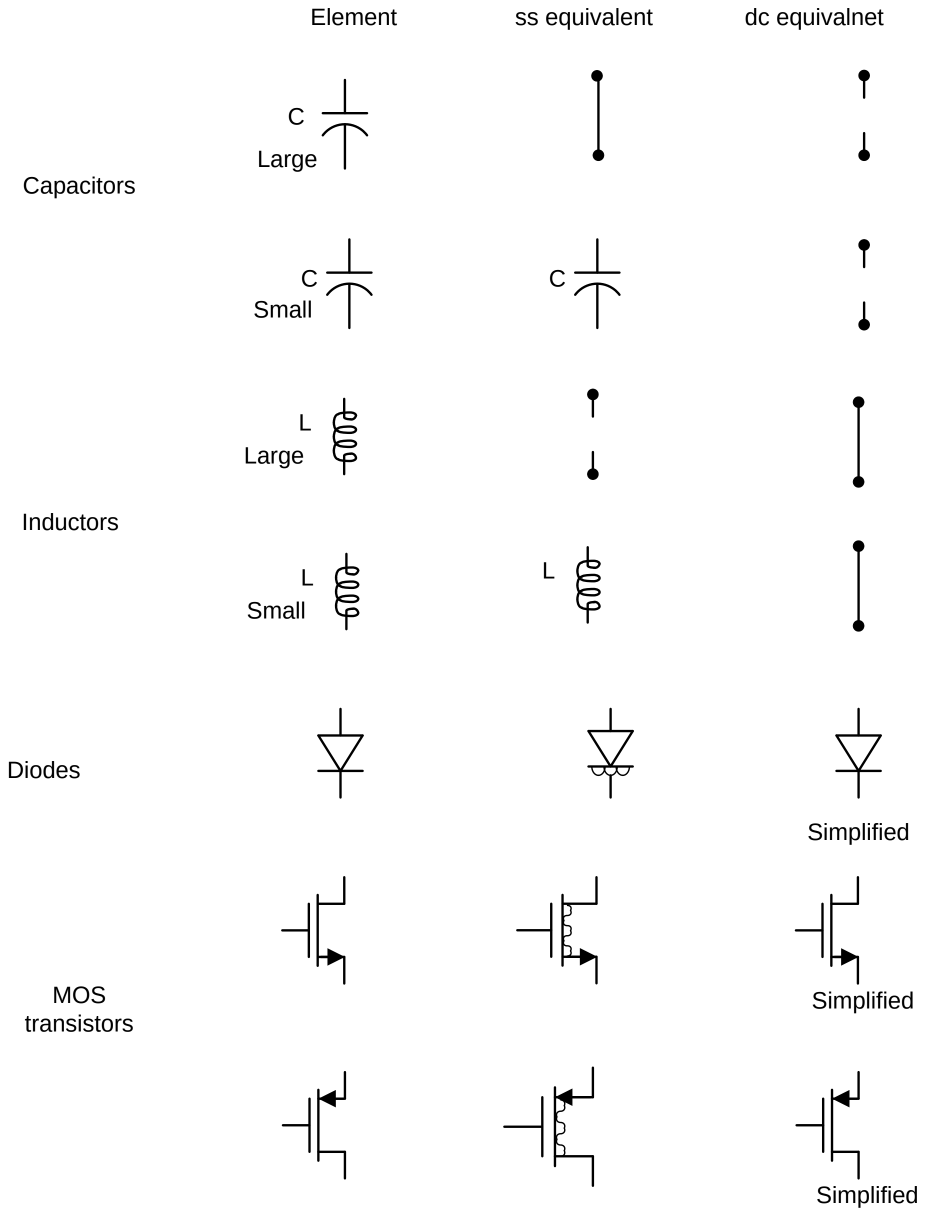
$X_{OUT}(t)$

Review of ss steady-state analysis

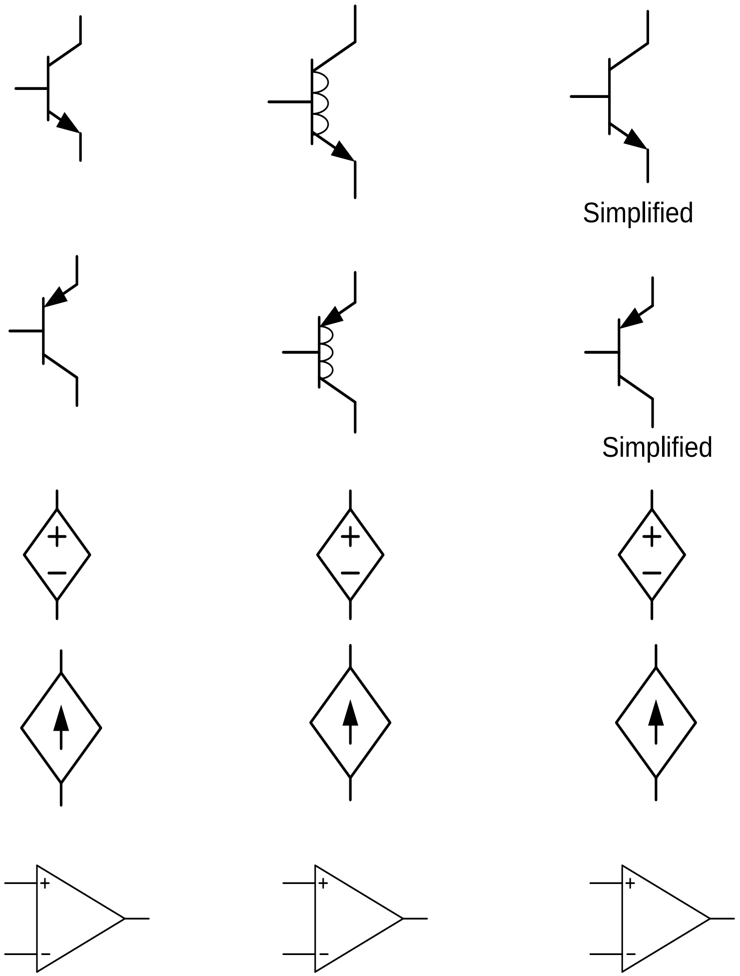
Dc and small-signal equivalent elements

	Element	ss equivalent	dc equivalvalnet
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

Dc and small-signal equivalent elements



Dc and small-signal equivalent elements



Element

ss equivalent

dc equivalnet

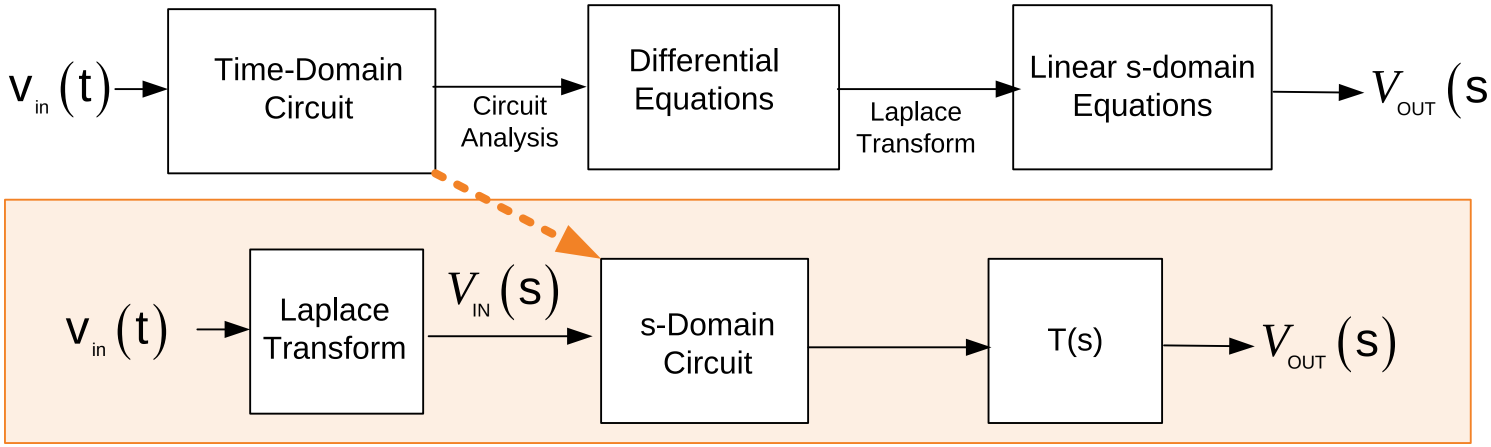
Bipolar
Transistors

Simplified

Simplified

Dependent
Sources

Summary of Sinusoidal Steady-State Analysis Methods for Linear Networks



$V_{in}(t)$ → Time-Domain Circuit → Circuit Analysis → Differential Equations → Laplace Transform → Linear s-domain Equations → $V_{OUT}(s)$

$V_{in}(t)$ → Laplace Transform → $V_{IN}(s)$ → s-Domain Circuit → T(s) → $V_{OUT}(s)$

Transfer Function of Time-Domain Circuit:

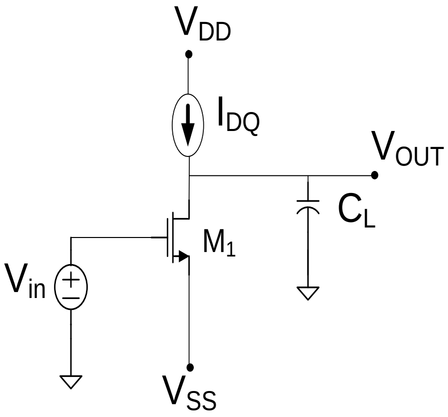
$$T(s)=\frac{V_{OUT}(s)}{V_{IN}(s)}$$

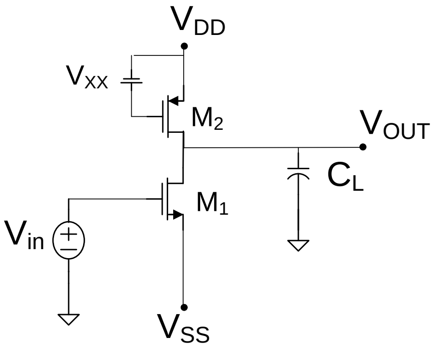
Key Theorem:

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

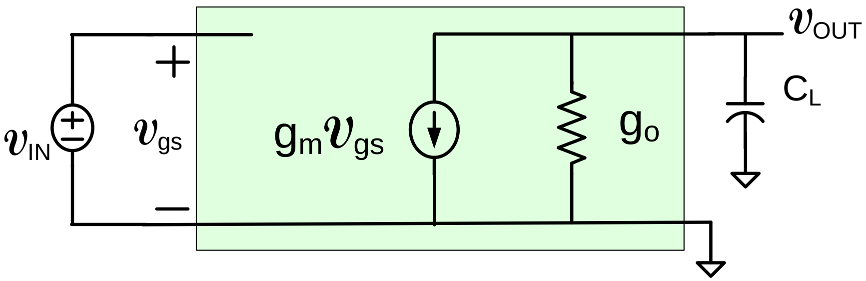
$$v_{out}(t)=V_M\left|T(j\omega)\right|\sin\left(\omega t+\theta+\angle T(j\omega)\right)$$

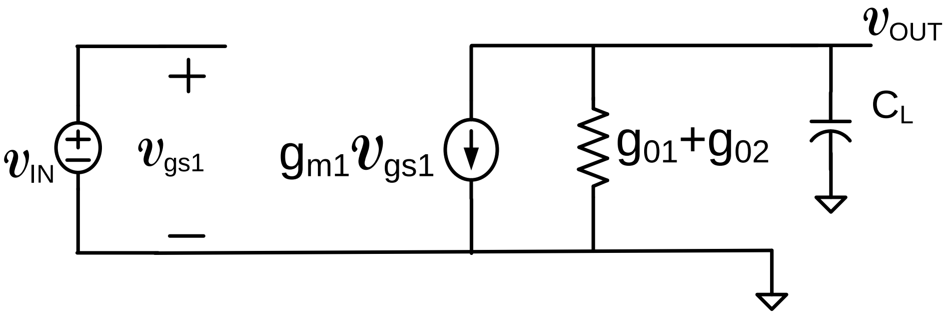
Single-stage single-input low-gain op amp





Small Signal Models



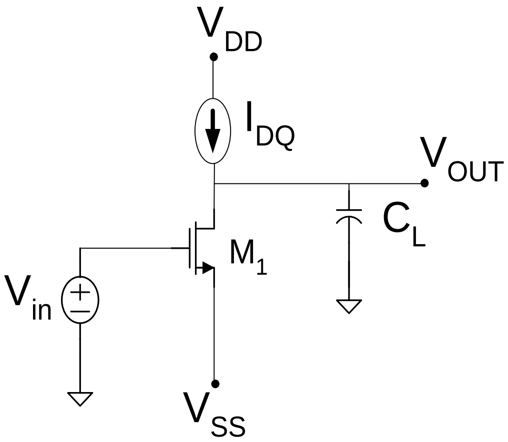


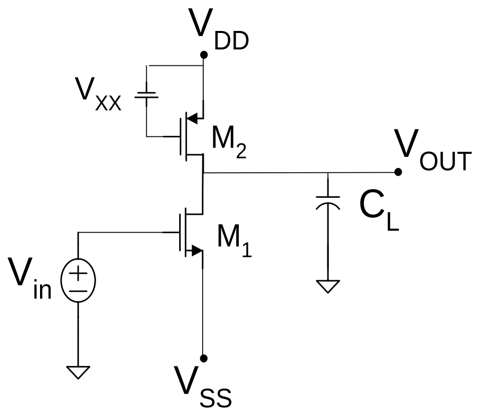
$$A_V = \frac{-g_m}{sC_L + g_o}$$

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

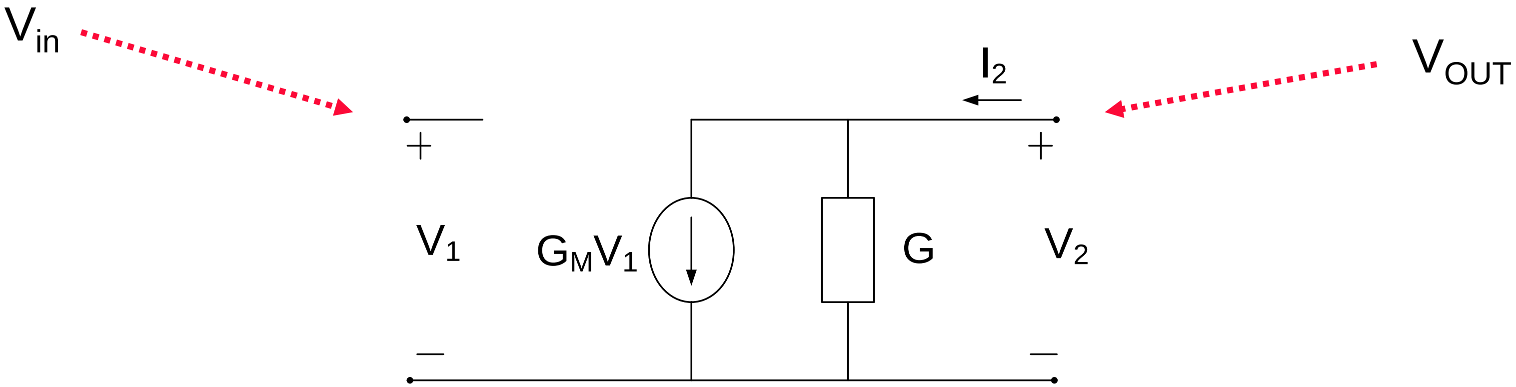
dc Voltage gain is ratio of overall transconductance gain to output conductance

Single-stage single-input low-gain op amp





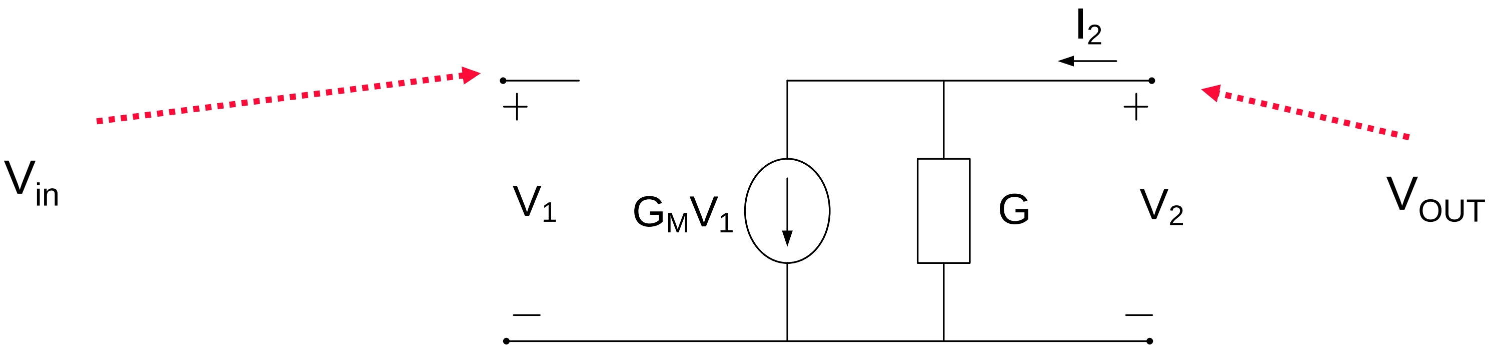
Observe in either case the small signal equivalent circuit is a two-port of the form:



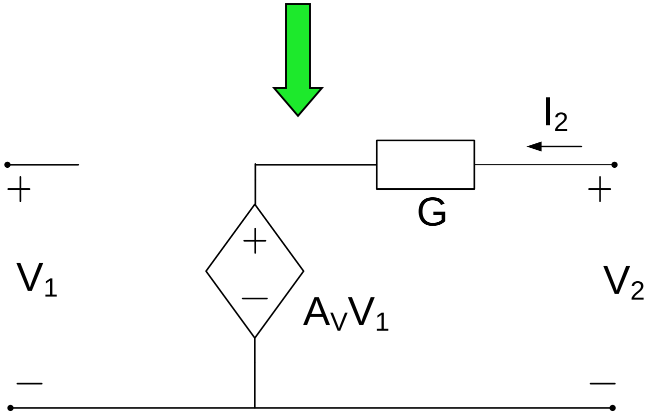
All properties of the circuit are determined by G_M and G

Single-stage single-input low-gain op amp

Small Signal Model of the op amp



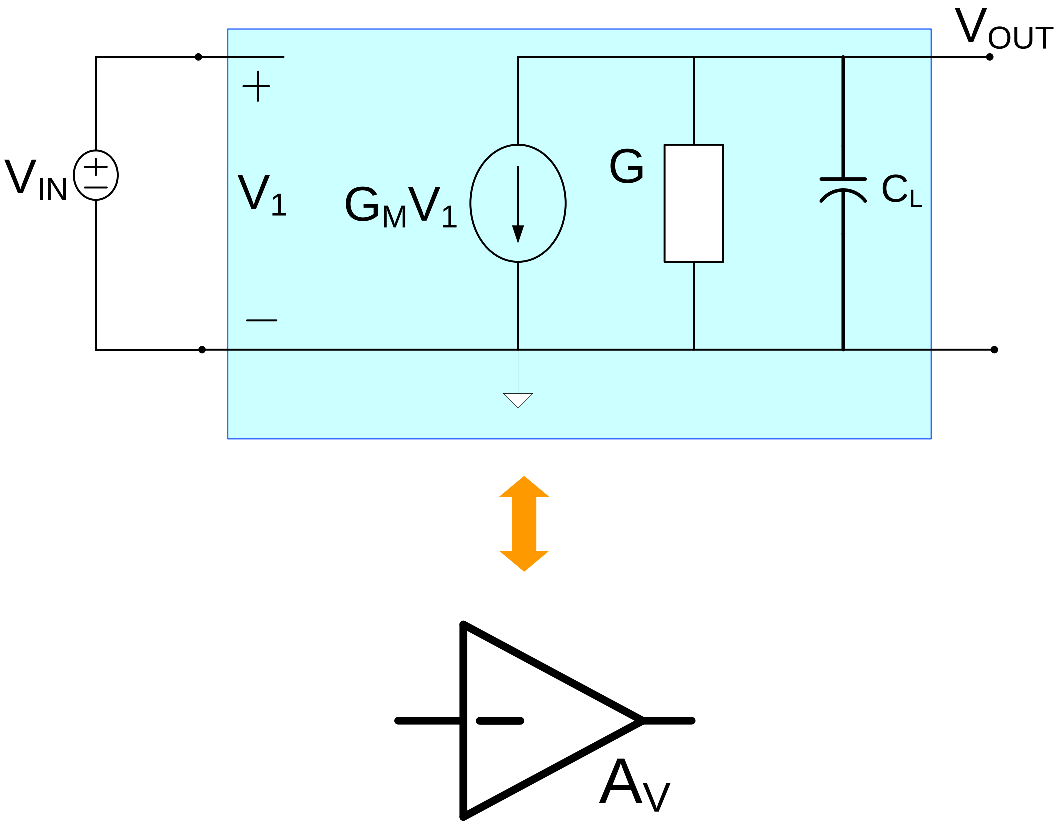
Alternate equivalent small signal model obtained by Norton to Thevenin transformation



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

All properties of the circuit are determined by A_V and G

Single-stage single-input low-gain op amp



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

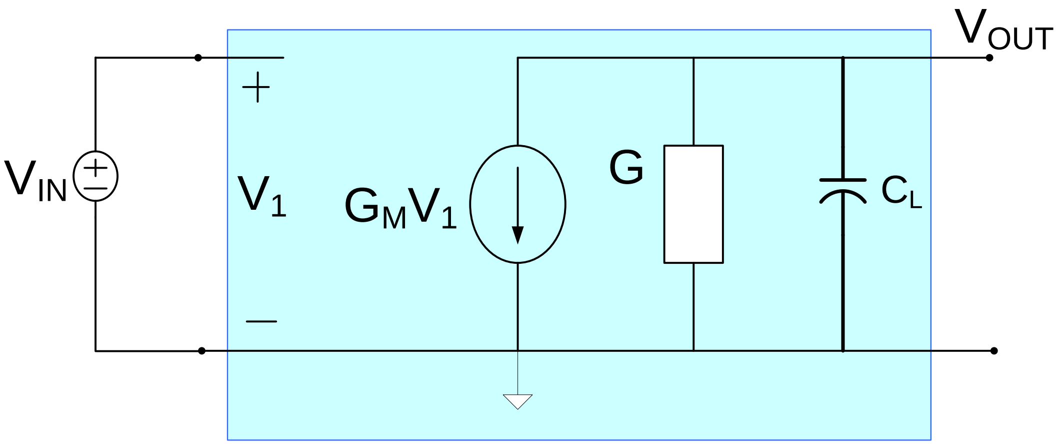
$$A_{V0} = \frac{-G_M}{G}$$

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

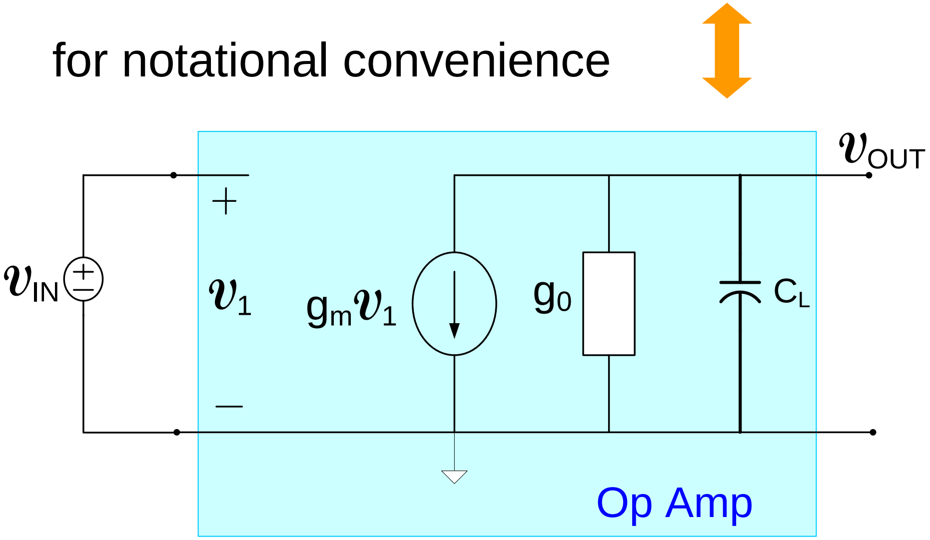
$$GB = \left(\frac{G_M}{G}\right)\left(\frac{G}{C_L}\right) = \frac{G_M}{C_L}$$

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

Single-stage single-input low-gain op amp



for notational convenience



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

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

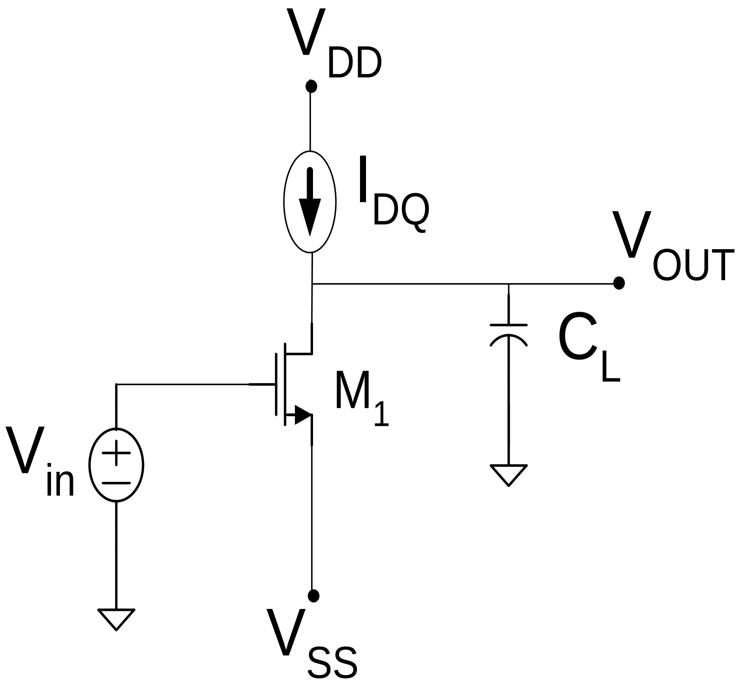
$$BW = \frac{g_0}{C_L}$$

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

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

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)

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

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

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

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

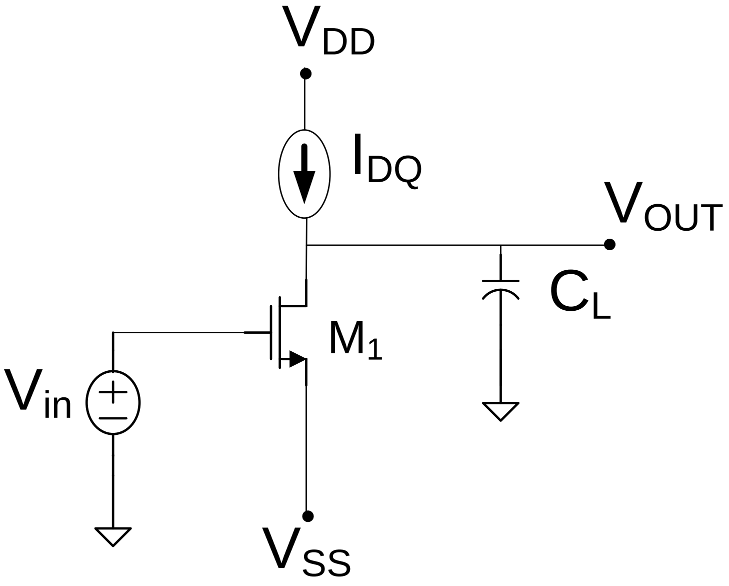
5. Explore the resultant design space with the identified number of Degrees of Freedom

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 :

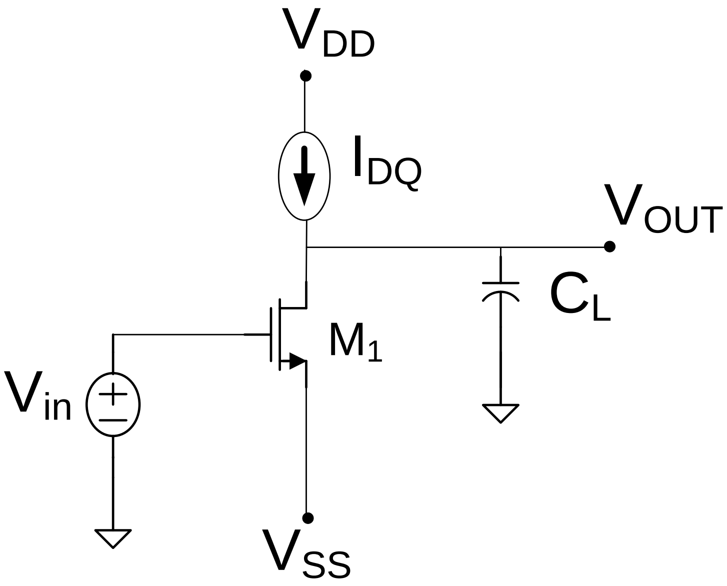
$$\{g_m, g_0\}$$

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?

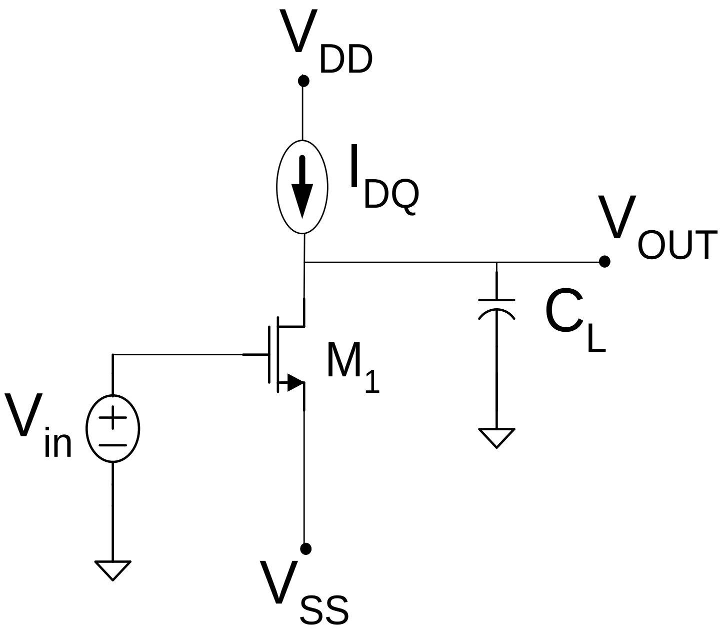
$$\left\{\frac{W}{L}, I_{DQ}\right\}$$

Degrees of Freedom: 2

Call this the natural parameter domain

Parameter Domains for Characterizing Amplifier Performance

Consider basic op amp structure



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?

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

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

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

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

- **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**

Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

Small signal parameter domain :

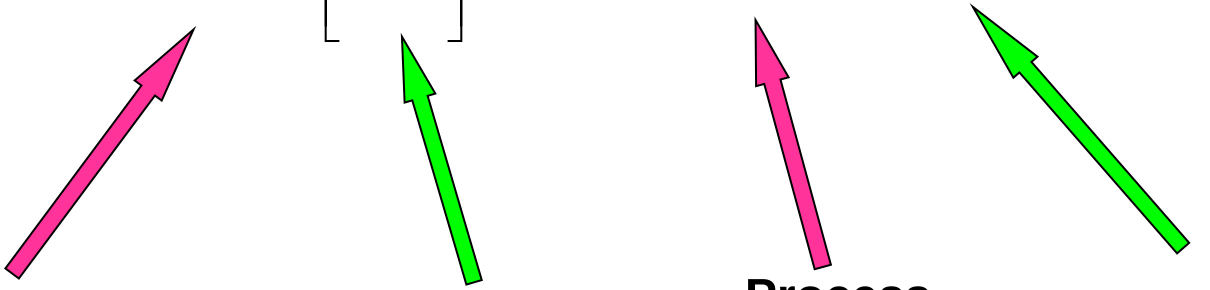
$\{g_m, g_0\}$

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

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

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

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

Process Dependent

Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

Small signal parameter domain :

$$\{g_m, g_0\}$$

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

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

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

Alternate parameter domain:

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

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

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:

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

Alternate parameter domain:

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

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

- **Alternate parameter domain gives considerable insight into design**
- **Alternate parameter domain provides modest parameter decoupling**
- **Term in box figure of merit for comparing architectures**

End of Lecture 2