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
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?
What Characteristics are Really Needed for Op Amps?

\[ A_F = \frac{A}{1 + A\beta} \approx \frac{1}{\beta} \]

\[ A_{VF} = \frac{-A\beta_1}{1 + A\beta} \approx \frac{-\beta_1}{\beta} \]

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)
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
5. Large Input Range
6. Good High-frequency Performance
7. Fast Settling
8. Adequate Phase Margin
9. Good CMRR
10. Good PSRR
11. Low Power Dissipation
12. Reasonable Linearity
13. ...
What is an Operational Amplifier?

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)
Consider:

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

\[
V_{OUT} = f(V_{IN}) \quad V_{OUT} \approx (-A)(V_{IN} - V_{XQ}) + V_{YQ}
\]

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 $V_{OUT}$)

$$V_O = (-A)(V_1 - V_{XQ}) + V_{YQ}$$

$$V_1 = \frac{R_1}{R_1 + R_2} V_O + \frac{R_2}{R_1 + R_2} V_{IN}$$

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 $V_{IN} = V_{INQ} + V_{iSS}$

$$V_0 = \left(-A\left(\frac{R_2}{R_1 + R_2}\right)\right)\left(V_{iSS} + V_{INQ}\right) + \left(\frac{A}{1+A}\left(\frac{R_1}{R_1 + R_2}\right)\right)V_{XQ} + \left(\frac{1}{1 + A}\left(\frac{R_1}{R_1 + R_2}\right)\right)V_{YQ}$$
Single-ended Op Amp Inverting Amplifier

\[ V_0 = \left( -\frac{A}{1+ A \left( \frac{R_1}{R_1 + R_2} \right)} \right) \left( V_{\text{iss}} + V_{\text{inQ}} \right) + \left( \frac{A}{1 + A \left( \frac{R_1}{R_1 + R_2} \right)} \right) V_{XQ} + \left( \frac{1}{1 + A \left( \frac{R_1}{R_1 + R_2} \right)} \right) V_{YQ} \]

But if \( A \) is large, this reduces to

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

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

\[ V_O \approx -\frac{R_2}{R_1} V_{\text{iss}} + V_{XQ} \]
Single-ended Op Amp Inverting Amplifier

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

\[ V_O = (-A)(V_1 - V_{XQ}) + V_{YQ} \]
\[ V_1 = \frac{R_1}{R_1 + R_2} V_O + \frac{R_2}{R_1 + R_2} V_{IN} \]

Summary:

\[ V_O = -\frac{R_2}{R_1} V_{inss} + V_{XQ} + \frac{R_2}{R_1} (V_{XQ} - V_{inQ}) \]

What type of circuits have the transfer characteristic shown?
Single-stage single-input **low-gain** op amp

**Basic Structure**

**Practical Implementation**

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

\[ \mathbf{X}_i(S) \]
- s-Transform
- s-Domain Circuit
  - Circuit Analysis
    - KVL, KCL
  - Set of Linear equations in s
  - Solution of Linear Equations
- Inverse s-Transform

\[ \mathbf{X}_{\text{OUT}}(S) \]

\[ \mathbf{X}_i(t) \]

\[ \mathbf{X}(j\omega) \]
- Phasor Transform
- Phasor Domain Circuit
  - Circuit Analysis
    - KVL, KCL
  - Set of Linear equations in j\omega
  - Solution of Linear Equations
- Inverse Phasor Transform

\[ \mathbf{X}_{\text{OUT}}(j\omega) \]

\[ \mathbf{X}_{\text{OUT}}(t) \]
Review of ss steady-state analysis

Time and s-Domain Analysis

\[ X_i(S) \]

s-Transform

s-Domain Circuit

Circuit Analysis KVL, KCL

Set of Linear equations in s

Solution of Linear Equations

\[ X_{OUT}(S) \]

Inverse s Transform

Time Domain Circuit

Circuit Analysis KVL, KCL

Set of Differential Equations

Solution of Differential Equations

\[ X_i(t) \]

\[ X_{OUT}(t) \]
s- Domain Analysis

\[ X_i(S) \rightarrow \text{s- Domain Circuit} \rightarrow \text{Circuit Analysis} \rightarrow \text{Set of Linear equations in } s \rightarrow \text{Solution of Linear Equations} \rightarrow \chi_{\text{OUT}}(S) \rightarrow \text{Inverse s Transform} \rightarrow X_{\text{OUT}}(t) \]

\[ X_i(t) \rightarrow \text{Time Domain Circuit} \]

Review of ss steady-state analysis
**Review of ss steady-state analysis**

**Dc and small-signal equivalent elements**

<table>
<thead>
<tr>
<th>Element</th>
<th>ss equivalent</th>
<th>dc equivalent</th>
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</thead>
<tbody>
<tr>
<td>dc Voltage Source</td>
<td>$V_{DC}$</td>
<td>$V_{DC}$</td>
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<tr>
<td>ac Voltage Source</td>
<td>$V_{AC}$</td>
<td>$V_{AC}$</td>
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<tr>
<td>dc Current Source</td>
<td>$I_{DC}$</td>
<td>$I_{DC}$</td>
</tr>
<tr>
<td>ac Current Source</td>
<td>$I_{AC}$</td>
<td>$I_{AC}$</td>
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<tr>
<td>Resistor</td>
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## Review of ss steady-state analysis

### Dc and small-signal equivalent elements

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<thead>
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<th>dc equivalent</th>
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<tr>
<td>Capacitors</td>
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<td>Inductors</td>
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<tr>
<td>Small L</td>
<td></td>
<td></td>
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<tr>
<td>Diodes</td>
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<tr>
<td>MOS transistors</td>
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Simplified

- Capabilities
Dc and small-signal equivalent elements

Element | ss equivalent | dc equivalent
---|---|---
Bipolar Transistors
Dependent Sources
Summary of Sinusoidal Steady-State Analysis Methods for Linear Networks

Transfer Function of Time-Domain Circuit:

\[ T(s) = \frac{V_{\text{out}}(s)}{V_{\text{in}}(s)} \]

Key Theorem:

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

\[ v_{\text{out}}(t) = V_M |T(j\omega)| \sin(\omega t + \theta + \angle T(j\omega)) \]
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 \( A_{V0} \) are two of the most important parameters in an op amp
The parameters $g_m$ and $g_0$ 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...
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 $\{W_1, L_1, I_{DQ}, V_{INQ}\}$

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.

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

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

\[
\begin{align*}
GB &= \frac{g_m}{C_L} \\
A_{V0} &= \frac{-g_m}{g_0}
\end{align*}
\]

How do performance metrics \( A_{V0} \) and \( GB \) relate to the natural domain parameters?

\[
\begin{align*}
g_m &= \frac{2I_{DQ}}{V_{EB}} = \frac{\mu C_{OX} W}{L} V_{EB} = \sqrt{\mu C_{OX} \frac{W}{L} \sqrt{I_{DQ}}} \\
g_o &= \lambda I_{DQ}
\end{align*}
\]
Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

\[ A_V = \frac{-g_m}{sC_L + g_0} \]

Small signal parameter domain: \( \{g_m, g_0\} \)

\[ A_{V0} = \frac{-g_m}{g_0} \]

GB = \( \frac{g_m}{C_L} \)

Natural design parameter domain:

\[ A_{V0} = \sqrt{\frac{2\mu C_{OX} W}{L \lambda_{DQ}}} \]

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

- 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
Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

Small signal parameter domain:

\[ A_{V0} = \frac{-g_m}{g_0} \quad \text{GB} = \frac{g_m}{C_L} \]

Natural design parameter domain:

\[ A_{V0} = \left[ \frac{\sqrt{2\mu COX}}{\lambda} \right] \left[ \frac{W}{\sqrt{L}} \right] \left[ \frac{1}{\sqrt{I_{DQ}}} \right] \quad \text{GB} = \left[ \frac{\sqrt{2\mu COX}}{C_L} \right] \left[ \frac{W}{L} \sqrt{I_{DQ}} \right] \]
Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

Small signal parameter domain: \( \{g_m, g_0\} \)

\[
A_{V0} = \frac{-g_m}{g_0} \quad \text{GB} = \frac{g_m}{C_L} \quad \left\{ \frac{W}{L}, I_{DQ} \right\}
\]

Natural design parameter domain:

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

Alternate parameter domain: \( \{P, V_{EB}\} \)

\( P = \text{power} = V_{DD}I_{DQ} \quad V_{EB} = \text{excess bias} = V_{GSQ} - V_T \)

\[
A_{V0} = \frac{g_M}{g_0} = \left( \frac{2I_{DQ}}{V_{EB}} \right) \left( \frac{1}{\lambda I_{DQ}} \right) = \frac{2}{\lambda V_{EB}} \quad \text{GB} = \frac{g_M}{C_L} = \left( \frac{2I_{DQ}}{V_{EB}} \right) \frac{1}{C_L} = \frac{2}{V_{DD}C_L} \times \frac{P}{V_{EB}}
\]
Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

Small signal parameter domain:

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

Natural design parameter domain:

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

Alternate parameter domain:

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

Process Dependent
Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

Small signal parameter domain: \( \{g_m, g_0\} \)
\[
A_{v0} = \frac{-g_m}{g_0}
\]

Natural design parameter domain:
\[
A_{v0} = \left[ \frac{\sqrt{2\mu C_{OX}}}{\lambda} \right] \sqrt{\frac{W}{L}} \sqrt{\frac{1}{l_{DQ}}}
\]
\[
GB = \left[ \frac{\sqrt{2\mu C_{OX}}}{C_L} \right] \sqrt{\frac{W}{L}} \sqrt{\frac{1}{l_{DQ}}}
\]

Alternate parameter domain:
\[
A_{v0} = \left[ \frac{2}{\lambda} \right] \left[ \frac{1}{V_{EB}} \right]
\]
\[
GB = \left[ \frac{2}{V_{DD}C_L} \right] \left[ \frac{P}{V_{EB}} \right]
\]

Architecture Dependent
Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

Small signal parameter domain:

\[ A_{V0} = \frac{-g_m}{g_0} \quad \text{GB} = \frac{g_m}{C_L} \]

Natural design parameter domain:

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

Alternate parameter domain:

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

- 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