EE 435

Lecture 2:

Basic Op Amp Design
- Single Stage Low Gain Op Amps
How does an amplifier differ from an operational amplifier?

**Review from last lecture:**

- **Op Amp**: Operational Amplifier used in feedback applications
- **Amplifier**: Amplifier used in open-loop applications

**Operational Amplifier**

Operational Amplifier used in feedback applications

**Amplifier**

Amplifier used in open-loop applications
Review from last lecture:

Conventional Wisdom Does Not Always Provide Correct Perspective – even in some of the most basic or fundamental areas!!

• Just because it’s published doesn’t mean it’s 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 approach others are following is leading you in the right direction
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
Review from last lecture:

What is an Operational Amplifier?

• Amplifier with Very Large Gain
Review from last lecture:

What is an Operational Amplifier?

Textbook Definition:

- Voltage Amplifier with Very Large Gain
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What is an Operational Amplifier?

• Amplifier with Very Large Gain

• Differential Input and Single-Ended Output?
Are differential input and single-ended outputs needed?

Consider Basic Amplifiers

Inverting Amplifier

Noninverting Amplifier

Only single-ended input is needed for Inverting Amplifier!
Many applications only need single-ended inputs!
Basic Inverting Amplifier Using Single-Ended Op Amp

Inverting Amplifier with Single-Ended Op Amp
Fully Differential Amplifier

- Widely (almost exclusively) used in integrated amplifiers
- Seldom available in catalog parts
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 \( \{V_{XQ}, V_{YQ}\} \)

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

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

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

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

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

\[ V_{IN}=V_{INQ}+V_{iSS} \]

Then

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

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

But if A is large, this reduces to

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

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

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

\[ V_O = (-A)(V_1-V_XQ)+V_{YQ} \]

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

Summary:

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

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
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
Review of ss steady-state analysis

Time and $s$-Domain Analysis

- $X(s)$
  - $s$-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

- $X(t)$
  - Time Domain Circuit
  - Circuit Analysis
    - KVL, KCL
  - Set of Differential Equations
  - Solution of Differential Equations
  - $X_{OUT}(t)$
Review of ss steady-state analysis

s- Domain Analysis

\[ x(t) \]

s- Transform

s- Domain Circuit

Circuit Analysis
KVL, KCL

Set of Linear equations in s

Solution of Linear Equations

Inverse s Transform

X_{out}(s)

X_{out}(t)
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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<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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Diagrams for each element type are shown to illustrate their small-signal and dc equivalent circuits.
**Review of ss steady-state analysis**

### Dc and small-signal equivalent elements

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<thead>
<tr>
<th>Element</th>
<th>ss equivalent</th>
<th>dc equivalent</th>
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<tbody>
<tr>
<td>Capacitors</td>
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<td>Inductors</td>
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<td>Diodes</td>
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<td>MOS transistors</td>
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<tr>
<td>Simplified</td>
<td><img src="image" alt="Simplified MOS" /></td>
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</tbody>
</table>

*Diagrams showing equivalent circuits for capacitors, inductors, diodes, and MOS transistors.*
Review of ss steady-state analysis

Dc and small-signal equivalent elements

**Element**

**Bipolar Transistors**

**Dependent Sources**

**ss equivalent**

**dc equivalent**

Simplified
Summary of Sinusoidal Steady-State Analysis Methods for Linear Networks

Time-Domain Circuit \rightarrow \text{Circuit Analysis} \rightarrow \text{Differential Equations} \rightarrow \text{Laplace Transform} \rightarrow V_{\text{OUT}}(s)

\[ V_{\text{OUT}}(s) = T(s)V_{\text{IN}}(s) \]

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

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

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

\[ V_1 \quad G_MV_1 \quad G \quad C_L \quad V_{OUT} \]

\[ A_V = \frac{-G_M}{sC_L + G} \]

\[ A_{V0} = \frac{-G_M}{G} \]

\[ BW = \frac{G}{C_L} \]

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

GB and \( A_{V0} \) are two of the most important parameters in an op amp
Single-stage single-input low-gain op amp

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

\[ A_{v0} = \frac{-g_m}{g_0} \]

\[ BW = \frac{g_0}{C_L} \]

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

The parameters \( g_m \) and \( g_0 \) 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 $\{W_1, L_1 \text{ and } I_{DQ}\}$

Thus there are 3 degrees of freedom.

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

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

$$\left\{\frac{W_1}{L_1}, I_{DQ}\right\}$$
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Thus the design space generally has only two independent variables or two degrees of freedom:

\[
\begin{bmatrix}
W_1 \\
L_1 \\
I_{DQ}
\end{bmatrix}
\]

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

\[
\begin{bmatrix}
W_1 \\
L_1 \\
I_{DQ}
\end{bmatrix}
\]

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

Parameter domains for characterizing the design space are not unique!

5. Determine an appropriate parameter domain
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

\[
\begin{aligned}
&W, I_{DQ} \\
\end{aligned}
\]

\[\text{GB} = \frac{g_m}{C_L}\]

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

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

\[
\begin{aligned}
g_m &= \frac{2I_{DQ}}{V_{EB}} = \frac{\mu C_{OX} W}{L} \\
V_{EB} &= \sqrt{\frac{\mu C_{OX} W}{L}} \sqrt{I_{DQ}} \\
g_o &= \lambda I_{DQ}
\end{aligned}
\]
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:

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

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

- 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
End of Lecture 2
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:

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

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

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

Alternate parameter domain:

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

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

Degrees of Freedom: 2

Small signal parameter domain:

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

Natural design parameter domain:

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

Alternate parameter domain:

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

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

Alternate parameter domain:

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

Architecture Dependent
Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

Small signal parameter domain:

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

Natural design parameter domain:

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

Alternate parameter domain:

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

- Alternate parameter domain gives considerable insight into design
- Alternate parameter domain provides modest parameter decoupling
- Term in box figure of merit for comparing architectures
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: \( \{P, V_{EB}\} \)

\[ W = ? \]
\[ L = ? \]
\[ I_{DQ} = ? \]
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:** \( \{\frac{W}{L}, I_{DQ}\} \)

\[
I_{DQ} = \frac{P}{V_{DD}} \\
\frac{W}{L} = \frac{P}{V_{DD} \mu C_{OX} V_{EB}^2}
\]
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
Design With the Basic Amplifier Structure

Consider basic op amp structure

\[ V_{\text{DD}} \]

\[ I_{\text{DQ}} \]

\[ V_{\text{OUT}} \]

\[ V_{\text{SS}} \]

\[ V_{\text{in}} \]

\[ M_1 \]

\[ C_L \]

Alternate Parameter Domain

\[ \{ P, V_{EB} \} \]

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

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

Degrees of Freedom: 2

But, does the designer really have 2 degrees of freedom?

From circuit interconnection constraint we have

\[ V_{EB} = -V_{SS} - V_T \]
Design With the Basic Amplifier Structure

Consider basic op amp structure

Alternate Parameter Domain

\[ \{ P, V_{EB} \} \]

\[ A_{V0} = \begin{bmatrix} \frac{2}{\lambda} \end{bmatrix} \begin{bmatrix} 1 \end{bmatrix} \]

\[ GB = \begin{bmatrix} 2 \end{bmatrix} \begin{bmatrix} 0 \end{bmatrix} \]

Mathematical Degrees of Freedom: 2

\[ V_{EB} = -V_{SS} - V_T \]

Constraints: 1

Design Degrees of Freedom:

MDoF – Constraints = 1
Design With the Basic Amplifier Structure

Consider basic op amp structure

\[ \begin{align*}
V_{\text{DD}} & \quad I_{\text{DQ}} & \quad V_{\text{OUT}} \\
M_1 & \quad C_L &
\end{align*} \]

Alternate Parameter Domain

\[ \{ P, V_{EB} \} \]

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

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

Design Degrees of Freedom: 1

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

Luck or Can’t
Design With the Basic Amplifier Structure

Consider basic op amp structure

Alternate Parameter Domain

\[ \{ P, V_{EB} \} \]

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

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

What do you do if you can’t meet the performance requirements?

Look for a different architecture that either has more favorable performance characteristics or more design degrees of freedom.
Design With the Basic Amplifier Structure

Consider basic op amp structure

\[ \{ P, V_{EB} \} \]

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

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

So, what performance can the designer really get with this circuit?

\[ V_{EB} = -V_{SS} - V_T \]

Designer really has no control of \( V_{EB} \) with this circuit so

- Gain is fixed by the architecture
- \( P \) can be used to determine \( GB \)

If gain is adequate, designer got “lucky” but \( GB \) can be engineered.
Design With the Basic Amplifier Structure

Consider basic op amp structure

\[ V_{EB} = -V_{SS} - V_T \]

GB varies linearly with P!
GB is very costly!

If gain is adequate, designer got “lucky” but
GB can be engineered
Architectural Modification of the Basic Amplifier Structure

\( \{P, V_{EB}, V_{XX}\} \)

Mathematical Degrees of Freedom : 3

\[ V_{EB} = V_{XX} - V_{SS} - V_T \]

Circuit Constraints: 1

Effective Design Degrees of Freedom: 2

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

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

- \( V_{EB} \) used to determine the gain (\( P \) does not affect gain!)
- \( P \) used to determine GB (but \( V_{EB} \) does affect \( P \) needed for a given GB)
Consider the modified single-stage op amp

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

\[
GB = \frac{g_m}{C_L}
\]

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

Question: How does the GB of the modified single-stage amplifier change with bias current?

\[ GB = \frac{g_m}{C_L} \]

GB increases linearly with \( I_{DQ} \)

\[ GB = \left[ \frac{2}{C_L} \right] \left[ \frac{I_{DQ}}{V_{EB}} \right] \]
Design Space Exploration

Question: How does the GB of the modified single-stage amplifier change with bias current?

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

GB increases with the square root of \( I_{DQ} \)

![Graph showing GB vs I_{DQ}](image-url)
Design Space Exploration

Question: How does the GB of the modified single-stage amplifier change with bias current?

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

GB independent of \( I_{DQ} \)
Design Space Exploration

Question: How does the GB of the modified single-stage amplifier change with bias current?

$$GB = \frac{1}{\sqrt{I_{DQ}}} \frac{P}{C_L} \sqrt{\frac{2\mu C_{OX} W}{L}}$$

GB decreases with the reciprocal of the square root of $I_{DQ}$
Design Space Exploration

Question: How does the GB of the modified single-stage amplifier change with bias current?

\[ GB = \sqrt{\frac{2\mu C_{OX} WP^3}{LV_{DD}}} \frac{I_{DQ} C_L}{I_{DQ}} \]

GB decreases with the reciprocal of \( I_{DQ} \)
Design Space Exploration

Question: How does the GB of the modified single-stage amplifier change with bias current?

GB = \left[ \frac{2}{C_L} \right] \left[ \frac{I_{DQ}}{V_{EB}} \right]

Increases Linearly

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

Increases Quadratically

Independent of \( I_{DQ} \)

GB = \frac{1}{\sqrt{I_{DQ}}} \frac{P}{C_L} \frac{\sqrt{2\mu C_{OX} W}}{L} \frac{2\mu C_{OX} W P^3}{\sqrt{L V_{DD}}} \frac{L V_{DD}}{I_{Q C_L}}

Decreases Quadratically

Decreases Linearly

It depends upon how the design space is explored !!!
Design Space Exploration

Different trajectories through a design space
Design Space Exploration

Issue becomes more involved for amplifiers or circuits with more than one transistor

Choice of design parameters can have major impact on insight into design

Size of parameter domain should agree with the number of degrees of freedom

Affects of any parameter on performance whether it be in the identified parameter domain or not is strongly dependent on how design space is explored

Small signal and natural parameter domains give little insight into design or performance
Single-Stage Low-Gain Op Amps

- Single-ended input

Basic single-stage op amp

\[ V_{DD} \]
\[ I_{DQ} \]
\[ V_{OUT} \]
\[ V_{SS} \]
\[ C_L \]
\[ V_{in} \]
\[ V_{XX} \]
Single-Stage Low-Gain Op Amps

• Single-ended input

Observations:

• This circuit often known as a common source amplifier
• Gain in the 30dB to 45dB range
• Inherently a transconductance amplifier since output impedance is high
• Voltage gain is ratio of transconductance gain to output conductance
• Critical to know degrees of freedom in design and know how to systematically explore design space
• Alternative parameter domain much more useful for design than small-signal domain or natural domain
• Performance of differential circuits will be obtained by inspection from those of the single-ended structures