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:

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 approach others are following is leading you in the right direction
What is an Operational Amplifier?

Review from last lecture:

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
Are differential input and single-ended outputs needed?

Consider Basic Amplifiers

![Inverting Amplifier Diagram]

![Noninverting Amplifier Diagram]

Only single-ended input is needed for Inverting Amplifier!
Many applications only need single-ended inputs!
Review from last lecture:

Basic Inverting Amplifier Using Single-Ended Op Amp

Inverting Amplifier with Single-Ended Op Amp
Review from last lecture:

Fully Differential Amplifier

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

\[
V_{OUT} = f(V_{IN})
\]

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

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 \( V_{IN} = V_{INQ} + V_{iSS} \)

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

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

But if A is large, this reduces to

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

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

\[
V_O \approx -\frac{R_2}{R_1} V_{\text{ISS}} + V_{\text{XQ}}
\]
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:

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

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.

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

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

\[ \mathcal{X}_i(S) \]  
\hline 
<table>
<thead>
<tr>
<th>s Transform</th>
<th>s-Domain Circuit</th>
<th>Circuit Analysis KVL, KCL</th>
<th>Set of Linear equations in s</th>
<th>Solution of Linear Equations</th>
<th>[ \mathcal{X}_{\text{OUT}}(S) ]</th>
</tr>
</thead>
</table>

\[ X_i(t) \]  
\hline 
| Phasor Transform | \[ \mathcal{X}_i(j\omega) \] |

\[ \mathcal{X}_{\text{OUT}}(S) \]  
\hline 
| Inverse s Transform | X_{\text{OUT}}(t) |

\[ \mathcal{X}_{\text{OUT}}(j\omega) \]  
\hline 
| Phasor Domain Circuit | \[ \mathcal{X}_{\text{OUT}}(j\omega) \] |

\[ X_{\text{OUT}}(t) \]  
\hline 
| Circuit Analysis KVL, KCL | Set of Linear equations in j\omega | Solution of Linear Equations | Inverse Phasor Transform |

\[ X_{\text{OUT}}(t) \]  
\hline 
| Circuit Analysis KVL, KCL | Set of Linear equations in j\omega | Solution of Linear Equations | Inverse Phasor Transform |

\[ X_{\text{OUT}}(t) \]  
\hline 
| Circuit Analysis KVL, KCL | Set of Linear equations in j\omega | Solution of Linear Equations | Inverse Phasor Transform |
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

Inverse s Transform

\[ X_{OUT}(S) \]

\[ X_i(t) \]

Time Domain Circuit

Circuit Analysis
KVL, KCL

Set of Differential Equations

Solution of Differential Equations

\[ X_{OUT}(t) \]
Review of ss steady-state analysis

s- Domain Analysis

\[ X_i(t) \]

\[ X_i(S) \]

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>
</tr>
</thead>
<tbody>
<tr>
<td>dc Voltage Source</td>
<td>$V_{DC}$</td>
<td>$V_{DC}$</td>
</tr>
<tr>
<td>ac Voltage Source</td>
<td>$V_{AC}$</td>
<td>$V_{AC}$</td>
</tr>
<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>
</tr>
<tr>
<td>Resistor</td>
<td>$R$</td>
<td>$R$</td>
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</table>

The table above lists the steady-state (ss) and direct current (dc) equivalents for various electrical elements. Diagrams are provided to illustrate the symbols for each type of source and the resistor.
Review of ss steady-state analysis

Dc and small-signal equivalent elements

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<thead>
<tr>
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<tr>
<td>Capacitors</td>
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<tr>
<td>Large C</td>
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<tr>
<td>Small C</td>
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<td>Large L</td>
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<td>Small L</td>
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<td>Inductors</td>
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<td>Small L</td>
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<td>Diodes</td>
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<tr>
<td>Simplified</td>
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<tr>
<td>MOS transistors</td>
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<td>Simplified</td>
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### Dc and small-signal equivalent elements

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<tr>
<td>Bipolar Transistors</td>
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<td></td>
</tr>
<tr>
<td>Dependent Sources</td>
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</tbody>
</table>

- **Simplified** diagrams for various elements in both steady-state and small-signal equivalent representations.
Summary of Sinusoidal Steady-State Analysis Methods for Linear Networks

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

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

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

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

dc Voltage gain is ratio of overall transconductance gain to output conductance
Observe in either case the small signal equivalent circuit is a two-port of the form:

\[
\begin{align*}
V_{\text{in}} & \quad V_{\text{out}} \\
V_{1} & \quad G_{M}V_{1} \\
V_{2} & \quad G
\end{align*}
\]

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

All properties of the circuit are determined by $A_V$ and $G$
Single-stage single-input low-gain op amp

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

\[ AV_0 = \frac{-G_M}{G} \]

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

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

GB and \( AV_0 \) 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 $V_{OUT}$) 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

$$\left\{ \frac{W_1}{L_1}, I_{DQ} \right\}$$
How do we design an amplifier with a given architecture in general or this architecture in particular?

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

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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?

\[ \left\{ \frac{W}{L}, I_{\text{DQ}} \right\} \]

Degrees of Freedom: 2

Call this the natural parameter domain
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 \(A_{V0}\) and \(GB\) relate to the natural domain parameters?

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

\[
g_o = \lambda I_{DQ}
\]
Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

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

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

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

Natural design parameter domain:

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

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

- 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:

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

Process Dependent

Architecture Dependent

Process Dependent

Architecture Dependent
Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

Small signal parameter domain:

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

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

Natural design parameter domain:

\[ A_{V0} = \left[ \frac{\sqrt{2\mu C_{OX}}}{\lambda} \right] \left[ \frac{W}{\sqrt{L}} \right] \left[ \frac{1}{\sqrt{W_{DQ}}} \right] \]

\[ G_B = \left[ \frac{\sqrt{2\mu C_{OX}}}{C_L} \right] \left[ \frac{W}{L} \right] \left[ \frac{1}{\sqrt{W_{DQ}}} \right] \]

Alternate parameter domain:

\[ P = \text{power} = V_{DD} I_{DQ} \]

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

\[ A_{V0} = \frac{g_M}{g_0} = \left( \frac{2 I_{DQ}}{V_{EB}} \right) \left( \frac{1}{\lambda I_{DQ}} \right) = \frac{2}{\lambda V_{EB}} \]

\[ G_B = \frac{g_M}{C_L} = \left( \frac{2 I_{DQ}}{V_{EB}} \right) \left[ \frac{1}{C_L} \right] = \left[ \frac{2}{V_{DD} C_L} \right] \frac{P}{V_{EB}} \]
Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

Small signal parameter domain:

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

Natural design parameter domain:

\[ A_{v0} = \left[ \sqrt{\frac{2 \mu_{COX}}{\lambda}} \right] \left[ \frac{W}{\sqrt{L}} \right] \left[ \frac{1}{\sqrt{I_{DQ}}} \right] \quad GB = \left[ \sqrt{\frac{2 \mu_{COX}}{C_L}} \right] \left[ \frac{W}{\sqrt{L}} \right] \left[ \frac{1}{\sqrt{I_{DQ}}} \right] \]

Alternate parameter domain:

\[ A_{v0} = \left[ \frac{2}{\lambda} \right] \left[ \frac{1}{V_{EB}} \right] \quad GB = \left[ \frac{2}{V_{DDCL}} \right] \left[ \frac{P}{V_{EB}} \right] \]

Process Dependent
Parameter Domains for Characterizing Amplifier Performance

Degrees of Freedom: 2

Small signal parameter domain:

{\(g_m, g_0\)}

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

Natural design parameter domain:

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

Alternate parameter domain:

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

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

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

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

\begin{align*}
W &= ? \\
L &= ? \\
I_{DQ} &= ? \\
V_{INQ} &= ?
\end{align*}
Parameter Domains for Characterizing Amplifier Performance

• Design often easier if approached in the alternate parameter domain

• How does one really get the design done, though? That is, how does one get back from the alternate parameter domain to the natural parameter domain?

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

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

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

![Basic Amplifier Diagram]

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

**Degrees of Freedom:** 2

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

\[
GB = \begin{bmatrix} 2 \frac{P}{V_{DD}C_L} \end{bmatrix} \begin{bmatrix} \frac{P}{V_{EB}} \end{bmatrix}
\]

\[
I_{DQ} = \frac{P}{V_{DD}}
\]

\[
W = \frac{P}{V_{DD} \mu C_\text{OX} V_{EB}^2}
\]

\[
V_{\text{INQ}} = V_{SS} + V_T + \sqrt{\frac{2}{\mu C_{OX}}} \frac{L}{W}
\]

But what if the design requirement dictates that \( V_{\text{INQ}} = 0 \)?

- Increase the number of constraints from 2 to 3
- 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

\[
A_{V0} = \begin{bmatrix} 2 \lambda & 1 \end{bmatrix}\begin{bmatrix} V_{EB} \end{bmatrix}
\]

\[
G_B = \begin{bmatrix} 2 & P \\ 1 & V_{EB} \end{bmatrix}
\]

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

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