EE 330
Lecture 28

Comparison of MOS and BJT performance
Basic amplifier architectures
Engineering Trends and Study Abroad Options
Welcome

Welcome to the Journal of Engineering Education (JEE), the research journal for engineering education. The journal of choice for over 8,500 subscribers in nearly 80 countries!

The Journal of Engineering Education (JEE) is a peer-reviewed international journal published quarterly by the American Society for Engineering Education (ASEE) in partnership with a global community of engineering education societies and associations.
Getting the Numbers Right: International Engineering Education in the United States, China, and India

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companies, their employees, and policymakers. Just as globalization has redefined the economic logic in traditional industries, it is now reshaping knowledge-intensive fields like electronics and information technology (IT).

While the offshoring of manufacturing jobs has been documented for decades, there is fresh debate over the relocation of service-related jobs in sectors like banking, IT, and engineering. Today, multinational corporations (MNCs) are reorganizing their global research and development (R&D) networks to lower costs and increase efficiency, while expanding their operations abroad—especially in the developing world (Goldbrunner, Doz, Wilson, and Veldhoen, 2006; Hart, 2006). These new business structures
Figure 1. Production of engineering and technology Bachelor's Degrees in the United States, China, and India.
English-language ability was a concern for both countries, but while it was only minor concern for Indian engineers, it remains a major concern for Chinese engineers (Farrell, Laboissière, Rosenfeld, Stürze, and Umezawa, 2005).

Multinational corporations like those surveyed by McKinsey represent a small percentage of the overall employment opportunities for engineers in India and China, nor are they the only players in the market for globally competitive engineers. Hundreds of thousands of Chinese and Indian engineers will find gainful employment working for domestic firms.
Vivek Wadhwa is a visiting scholar at University of California at Berkeley, director for research at the Pratt School of Engineering at Duke University, and senior research associate at Harvard Law School.
Watch out, Silicon Valley: China and India aren't just graduating bad engineers and stealing intellectual property anymore. They're fostering innovations that will shake the world.

BY VIVEK WADHWAN | DECEMBER 28, 2010
over 20% of the articles on this search are now in non-English venues
### Table 5.14
S&E articles in all fields, by country/economy: 1996 and 2007

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Figure 2-26
Thousands

- China
- United States
- Japan
- South Korea
- UK
- Germany
Figure 3-48
Estimated number of researchers in selected regions/countries/economies: 1995–2007
Thousands

EU = European Union
Engineers educated today will be under increasing pressure to be able to communicate with, supervise, work with, and work for Asian engineers that may or may not have good English communication skills and must understand the culture of engineers around the world to be effective.

This is not something that may happen in the future but rather is something that is already occurring and WILL become increasingly critical in the next decade.
Study Abroad Opportunities in Asia

Two Opportunities in Taiwan

The increasing role Asia is playing in both the engineering field and the world’s economy is unlike anything we have seen in many decades.

All indicators suggest that this role will become even more significant in the future.

Both opportunities and expectations in the field will invariable show increased alignment with business and engineering in a global economy.

Understanding the culture and the environment of engineers working in Asia will offer substantial benefits for many/most engineers in the short-term and will likely be expected of many/most engineers within a decade.
Taipei 101 – The tallest building in the world!
Landmark Architecture – The Grand Hotel in Taipei
The two schools in Taipei Taiwan with exchange programs with ISU College of Engineering

**Tatung University**

**National Taiwan University of Science and Technology (NTUST)**

- Both good schools with strong engineering programs
- Ongoing interactions between faculty and students
- Strong ties with industry in Taiwan
- Interactions expected to expand in years to come
Exchange program principles:

• Both schools will offer selected courses to ISU students in English

• Courses pre-approved so that progress towards graduation is not delayed

• Approximately revenue neutral exchange (often costs less than spending the time in Ames)

• Internship opportunity often provided
Introduction to
College of Electrical Engineering and Computer Science (CEECS)

120 full-time faculty members:
42 Professors,
35 Associate Professors,
38 Assistant Professors,
5 Instructors.

2,645 students:
(1,386 undergraduates,
1,020 Master candidates,
239 Doctoral candidates).

Founded in 1998

College of Electrical Engineering & Computer Science

Department of Electronic Engineering

Department of Electrical Engineering

Deptartment of Computer Science & Information

Graduate Institute of Opto-Electronic Engineering
Introduction to Electronic Engineering Dept.

Founded in 1974.
Faculty Members: 54 active members.
Teaching and research are categorized into three major groups:

The Computer Engineering Group
features parallel and distributed processing, multimedia processing, embedded system and FPGA design, computer architecture, and VLSI design.

The Electronic System Group
focuses on broadband networks, communication systems, digital signal and image processing, microwave engineering, and power electronics.

The Optoelectronics and Semiconductor Group
emphasizes on semiconductor materials and devices, optoelectronics, fiber-optic modules and systems, display technology, lighting,
Research Achievements of Electronic Engineering Dept.

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Industry and Academia Cooperation

- To realize the advanced technologies for industrial applications.
- The industry and academia cooperation is strongly encouraged.
- The department seeks to build up strong links with the industry.
- This elegantly balances the focus between theory and practice.
- In the past few years, the department has achieved excellence in the fields of embedded systems, IC chip design, wireless and broadband networks, optical communications, image display, nano-photonic materials and devices, bio-medical technologies and solid-state lighting.
Research Areas of Electrical Engineering Dept.

- Power and Energy
- Power Electronics
- System Engineering
- Integrated Circuits and Systems
- Computer and Network
- Communication and Electromagnetic Engineering
- Communication and Electromagnetic Technology Center
- Power Electronics Technology Center
- Building Energy Efficiency and Renewable Energy Center
Founded in 1999

- 22 full-time faculty members:

Research in fields such as:

1. Multi-media Systems
2. Information security
3. Artificial intelligence
4. Communication network

Research areas in *Multi-media Systems* include:

- Image processing, video and data compression
- Machine vision
- Augmented reality
- Voice synthesis, song synthesis, and related machine audio processing
Research areas in *Communication network* include:

- Mobile computing
- Wireless network
- Wireless sensor network
- Multi-media network
- Voice over Internet Protocol (VoIP)
- High-speed network
- Network performance analysis
- Queuing theory
- Network communication protocol
Study Abroad Opportunities in Asia

Both are good schools and both should provide a good study abroad opportunity

If interested in either program contact:

Tatung University

Prof. Morris Chang (ISU coordinator) or
Prof. Randy Geiger

National Taiwan University of Science and Technology

Prof. Randy Geiger (ISU coordinator)
Graphical Analysis and Interpretation

Device Model (family of curves)

\[ I_{dq} = \frac{\mu C_{ox} W}{2L} (V_{gs} - V_T)^2 (1 + \lambda V_{ds}) \]

- Linear signal swing region smaller than saturation region
- Modest nonlinear distortion provided saturation region operation maintained
- Symmetric swing about Q-point
- Signal swing can be maximized by judicious location of Q-point
Further Model Extensions

Existing model does not depend upon the bulk voltage!

Observe that changing the bulk voltage will change the electric field in the channel region!

Changing the bulk voltage will change the thickness of the inversion layer

Changing the bulk voltage will change the threshold voltage of the device

\[ V_T = V_{T0} + \gamma \left( \sqrt{\phi - V_{BS}} - \sqrt{\phi} \right) \]
Review from Last Lecture

Typical Effects of Bulk on Threshold Voltage for n-channel Device

\[ V_T = V_{T0} + \gamma \left( \sqrt{\phi} - V_{BS} - \sqrt{\phi} \right) \]

\[ \gamma \approx 0.4V^{\frac{1}{2}} \quad \phi \approx 0.6V \]

Bulk-Diffusion Generally Reverse Biased \((V_{BS} < 0)\) for n-channel
Shift in threshold voltage with bulk voltage can be substantial
Often \(V_{BS}=0\)
Model Extension Summary

\( I_G = 0 \)

\( I_B = 0 \)

\[
I_d = \begin{cases} 
0 & \text{for } V_{GS} \leq V_T \\
\mu C_{ox} \frac{W}{L} \left( V_{GS} - V_T - \frac{V_{DS}}{2} \right) V_{DS} & \text{for } V_{GS} \geq V_T, V_{DS} < V_{GS} - V_T \\
\mu C_{ox} \frac{W}{2L} \left( V_{GS} - V_T \right)^2 \cdot (1 + \lambda V_{DS}) & \text{for } V_{GS} \geq V_T, V_{DS} \geq V_{GS} - V_T 
\end{cases}
\]

\( V_T = V_{T0} + \gamma \left( \sqrt{\phi - V_{BS}} - \sqrt{\phi} \right) \)

Model Parameters : \( \{ \mu, C_{ox}, V_{T0}, \phi, \gamma, \lambda \} \)

Design Parameters : \( \{ W, L \} \) but only one degree of freedom \( W/L \)
Large and Small Signal Model Summary

Large Signal Model

\[ I_D = \begin{cases} 
0 & V_{GS} \leq V_T \\
\mu C_{OX} \frac{W}{L} \left( V_{GS} - V_T - \frac{V_{DS}}{2} \right) V_{DS} & V_{GS} \geq V_T, V_{DS} < V_{GS} - V_T \\
\mu C_{OX} \frac{W}{2L} \left( V_{GS} - V_T \right)^2 \cdot \left( 1 + \lambda V_{DS} \right) & V_{GS} \geq V_T, V_{DS} \geq V_{GS} - V_T 
\end{cases} \]

\[ V_T = V_{T0} + \gamma \left( \sqrt{\phi - V_{BS}} - \sqrt{\phi} \right) \]

Small Signal Model

\[ i_g = 0 \]
\[ i_b = 0 \]
\[ i_d = g_m v_{gs} + g_{mb} v_{bs} + g_o v_{ds} \]

where
\[ g_m = \frac{\mu C_{OX} W}{L} V_{EBQ} \]
\[ g_{mb} = g_m \left( \frac{\gamma}{2\sqrt{\phi - V_{BSQ}}} \right) \]
\[ g_o = \lambda I_{DQ} \]
\[ g_{mb} < g_m \quad g_o << g_m, g_{mb} \]
Review from Last Time

Example: Obtain the small signal model of the following circuit. Assume MOSFET is operating in the saturation region.
Example

Obtain the small signal model of the following circuit. Assume MOSFET is operating in the saturation region

Solution:

\[ V \left(g_m + g_0\right) = I \]

\[ R_{EQ} = \frac{1}{g_m + g_0} \approx \frac{1}{g_m} \]
Relative Magnitude of Small Signal Parameters

\[
g_m = \frac{I_{CQ}}{V_t} \quad g_\pi = \frac{I_{CQ}}{\beta V_t} \quad g_o \approx \frac{I_{CQ}}{V_{AF}}
\]

\[
\begin{align*}
g_m &= \frac{I_Q}{V_t} \\
g_{\pi} &= \frac{I_Q}{\beta V_t} = \beta \\
g_o &= \frac{I_Q}{V_{AF}} \approx \frac{200V}{100 \cdot 26mV} = 77
\end{align*}
\]

\[g_m \gg g_\pi \gg g_o\]

Often the go term can be neglected in the small signal model because it is so small.
Small Signal Model Simplifications for the MOSFET and BJT

Often simplifications of the small signal model are adequate for a given application.

These simplifications will be discussed next.
Small Signal MOSFET Model Summary

An equivalent Circuit:

\[ g_m = \frac{\mu C_{OX} W}{L} (V_{GSQ} - V_T) \]

\[ g_o = \lambda I_{DQ} \]

\[ g_{mb} = g_m \left( \frac{\gamma}{2\sqrt{\phi - V_{BSQ}}} \right) \]

Alternate equivalent representations for \( g_m \)

\[ g_m = \sqrt{2\mu C_{OX} W} \sqrt{I_{DQ}} \]

\[ g_m = \frac{2I_{DQ}}{V_{GSQ} - V_T} = \frac{2I_{DQ}}{V_{EBQ}} \]

\[ g_{mb} < g_m \]

\[ g_o << g_m, g_{mb} \]
Small Signal Model Simplifications

Simplification that is often adequate
Small Signal Model Simplifications

Even further simplification that is often adequate
Small Signal BJT Model Summary

An equivalent circuit

\[ g_m = \frac{I_{CQ}}{V_t} \]

\[ g_\pi = \frac{I_{CQ}}{\beta V_t} \]

\[ g_o \approx \frac{I_{CQ}}{V_{AF}} \]

\[ g_m >> g_\pi >> g_o \]

This contains absolutely no more information than the set of small-signal model equations
Small Signal BJT Model Simplifications

Simplification that is often adequate
Gains for MOSFET and BJT Circuits

For both circuits
\[ A_v = -g_m R \]

Gains vary linearly with small signal parameter \( g_m \)

Power is often a key resource in the design of an integrated circuit

In both circuits, power is proportional to \( I_{CQ}, I_{DQ} \)
How does $g_m$ vary with $I_{DQ}$?

$$g_m = \sqrt{\frac{2\mu C_{Ox} W}{L}} \sqrt{I_{DQ}}$$

Varies with the square root of $I_{DQ}$

$$g_m = \frac{2I_{DQ}}{V_{GSQ} - V_T} = \frac{2I_{DQ}}{V_{EBQ}}$$

Varies linearly with $I_{DQ}$

$$g_m = \frac{\mu C_{Ox} W}{L} (V_{GSQ} - V_T)$$

Doesn’t vary with $I_{DQ}$
How does $g_m$ vary with $I_{DQ}$?

All of the above are true – but with qualification

$g_m$ is a function of more than one variable ($I_{DQ}$) and how it varies depends upon how the remaining variables are constrained.
Comparison of BJT and MOSFET

How do the small signal models of the MOSFET and BJT compare?
The transconductance of the BJT is typically much larger than that of the MOSFET (and larger is better!) This is due to the exponential rather than quadratic output/input relationship.
Comparison of MOSFET and BJT

The output conductances are comparable but that of the BJT is usually modestly smaller (and smaller is better!)
Comparison of MOSFET and BJT

$g_\pi = \frac{I_{CQ}}{\beta V_t}$

$g_\pi = 0$

$g_\pi$ is the reciprocal of the input impedance

$g_\pi$ of a MOSFET is much smaller than that of a BJT (and smaller is better!)
Review of Small-Signal Analysis Approach

In the next few slides we will summarize the results obtained for doing small-signal analysis and explicitly review the simplified models used for Q-point analysis.
Standard Approach to small-signal analysis of nonlinear networks

Nonlinear Network

dc Equivalent Network

Q-point

Values for small-signal parameters

Small-signal equivalent network

Small-signal output

Total output

(good approximation)
Systematic Approach to Small-Signal Circuit Analysis

- Obtain dc equivalent circuit by replacing all elements with large-signal (dc) equivalent circuits
- Obtain dc operating points (Q-point)
- Obtain ac equivalent circuit by replacing all elements with small-signal equivalent circuits
- Analyze linear small-signal equivalent circuit
Recall

Dc and small-signal equivalent elements

<table>
<thead>
<tr>
<th>Element</th>
<th>ss equivalent</th>
<th>dc equivalent</th>
</tr>
</thead>
</table>

**MOS Transistors**

**Bipolar Transistors**

Simplified

Simplified

Simplified
The simplified large signal models for the MOSFET and the BJT

Simplified large-signal models (sometimes termed dc equivalent models) are usually adequate for determining operating point in practical MOS and Bipolar circuits.

Can create circuits where the simplified models are not adequate but these are often not practical circuits.

Will discuss only for npn and n-channel but similar models for pnp and p-channel devices.
Square-Law Model

\[ I_G = 0 \]
\[ I_B = 0 \]

\[ I_d = \begin{cases} 0 & \text{if } V_{GS} \leq V_T \\ \mu C_{ox} \frac{W}{L} \left( V_{GS} - V_T - \frac{V_{DS}}{2} \right) V_{DS} & \text{if } V_{GS} > V_T, V_{DS} < V_{GS} - V_T \\ \mu C_{ox} \frac{W}{2L} \left( V_{GS} - V_T \right)^2 \cdot (1 + \lambda V_{DS}) & \text{if } V_{GS} > V_T, V_{DS} \geq V_{GS} - V_T \end{cases} \]

\[ V_T = V_{T0} + \gamma \left( \sqrt{\phi - V_{BS}} - \sqrt{\phi} \right) \]
Simplified MOS Model for Q-point Analysis

\[ I_G = 0 \]
\[ I_B = 0 \]
\[ I_D = \mu C_{ox} \frac{W}{2L} (V_{GS} - V_T)^2 \]

Simplified dc equivalent circuit

\[ G \rightarrow \quad \frac{\mu C_{ox} W}{2L} (V_{GS} - V_T)^2 \]
\[ S \]
dc BJT model

\[ I_C = \beta I_B \left( 1 + \frac{V_{CE}}{V_{AF}} \right) \]
\[ I_B = \frac{J_S A_E}{\beta} e^{\frac{V_{BE}}{V_t}} \]
\[ V_t = \frac{kT}{q} \]

- **Forward Active**
  - \( V_{BE} > 0.4V \)
  - \( V_{BC} < 0 \)

- **Saturation**
  - \( V_{BE} = 0.7V \)
  - \( V_{CE} = 0.2V \)
  - \( I_C < \beta I_B \)

- **Cutoff**
  - \( I_C = I_B = 0 \)
  - \( V_{BE} < 0 \)
  - \( V_{BC} < 0 \)

A small portion of the operating region is missed with this model but seldom operate in the missing region.
Simplified dc BJT model for Q-point Analysis

\[ I_C = \beta I_B \]

\[ I_B = \frac{J_S A_E}{\beta} e^{\frac{V_{BE}}{V_t}} \]

\[ V_{BE} = 0.6V \]

Simplified dc equivalent circuit
Examples

Not convenient to have multiple dc power supplies
$V_{\text{OUTQ}}$ very sensitive to $V_{\text{EE}}$
Examples

Not convenient to have multiple dc power supplies
\( V_{OUTQ} \) very sensitive to \( V_{EE} \)

Compare the small-signal equivalent circuits of these two structures
Examples

Compare the small-signal equivalent circuits of these two structures

Since Thevenin equivalent circuit in red circle is $V_{IN}$, both circuits have same voltage gain
Examples

Determine $V_{OUTQ}$, $A_V$, $R_{IN}$
Determine $v_{OUT}$ and $V_{OUT}(t)$ if $v_{IN} = .002\sin(400t)$
Examples

(biasing components: $C$, $R_B$, $V_{CC}$ in this case, all disappear in small-signal gain circuit)

Several different biasing circuits can be used
Examples

Biasing Circuit

Determine \( V_{OUTQ} \) and the SS voltage gain, assume \( \beta = 100 \).
Examples

\[ R_1 = 2K \]
\[ Q_1 \]
\[ V_{OUT} \]
\[ V_{CC} = 12V \]
\[ R_B = 500K \]
\[ C = 1\mu F \]
\[ V_{IN(t)} \]
\[ \beta = 100 \]

Determine \( V_{OUT Q} \)

\[ V_{CC} = 12V \]
\[ R_{B1} = 500K \]
\[ R_2 = 2K \]
\[ V_{OUT Q} \]
\[ I_B \]
\[ 0.6V \]
\[ \beta I_B \]

\[ I_{CQ} = \beta I_{BQ} = 100 \left( \frac{12V-0.6V}{500K} \right) = 2.3mA \]

\[ V_{OUT Q} = 12V - I_{CQ} R_1 = 12V - 2.3mA \cdot 2K = 7.4V \]
Examples

Determine the SS voltage gain

\[ V_{CC} = 12\, V \]
\[ R_B = 500\, K \]
\[ C = 1\, \mu F \]
\[ R_1 = 2\, K \]
\[ \beta = 100 \]

**ss equivalent circuit**

\[ V_{IN} \rightarrow R_B \rightarrow Q_1 \rightarrow R_1 \rightarrow V_{OUT} \]

\[ V_{IN} = V_{BE} \]

\[ V_{OUT} = -g_m V_{BE} R_1 \]

\[ A_v = -R_1 g_m \]

\[ A_v \approx -\frac{I_{CQ} R_1}{V_t} \approx -\frac{2.3\, mA \cdot 2K}{26\, mV} \approx -177 \]

This basic amplifier structure is widely used and repeated analysis serves no useful purpose

Have seen this circuit before but will repeat for review purposes
Examples

\[ V_{CC} = 12V \]
\[ R_B = 500K \]
\[ R_1 = 2K \]
\[ C = 1 \mu F \]
\[ V_{IN}(t) \]
\[ \beta = 100 \]

Determine the \( R_{IN} \)

\[ R_{in} = \frac{V_{IN}}{i_{IN}} \]

Usually \( R_B \gg r_\pi \)

\[ R_{in} = R_B \parallel r_\pi \approx r_\pi \]

\[ R_{in} \approx r_\pi = \frac{I_{CQ}}{\beta V_t} \]
Examples

Determine $V_{OUT}$ and $V_{OUT}(t)$ if $V_{IN} = .002\sin(400t)$

\[ V_{OUT} \approx V_{OUTQ} + A_v V_{IN} \]

\[ V_{OUT} \approx 7.4V - 177 \cdot .002 \cdot \sin(400t) \]

\[ V_{OUT} \approx 7.4V - .35 \cdot \sin(400t) \]
End of Lecture 28