Lecture 1

Introduction to Circuits and Systems

Prof Peter YK Cheung Imperial College London

URL: www.ee.ic.ac.uk/pcheung/teaching/EE2_CAS/ E-mail: p.cheung@imperial.ac.uk

Course Aims & Objective

- Designing Analogue Circuits
 - Real-life operational amplifier, single rail supply
 - Limitation of real op-amps
 - Applications of op-amps
- Designing Digital Circuits
 - Field Programmable Gate Arrays
 - Design methods & constraints
 - SystemVerilog Hardware Description Language
- Systems view of electronic circuits
 - Partitioning between analogue & digital parts in a system
 - Interface between analogue & digital parts

Organization and Schedule

- Course structure
 - 2-hours lecture session on Tuesday @ 14.00 16.00
 - 1-hour "**Problem Class**" on Thursday @ 16.00 17.00
 - Two 2-hour **laboratory** session on Monday & Tuesday @ 09.00 11.00
- ✤ 16 lectures will be supported by:
 - 6 lab experiments and "open-ended" challenges which will be assessed through two individual Lab Oral sessions
 - 6 problem sheets to help apply what you have learned to answer questions
- ✤ Assessment:
 - **2-hour written paper** in Summer Term (60%)
 - Mid-term Lab Oral (15%)
 - End of Term Lab Oral (25%)
- Please consult the "EE2 Circuits and Systems Module Description and Planning" document

Related Courses

Follow on from these Year 1 modules

- ELEC40002 Analysis and Design of Circuits
- ELEC40003 Digital Electronics & Computer Architecture
- ELEC40004 Programming for Engineers
- ELEC40006 Electronics design project 1

Relevant to these Year 3 and 4 modules

- EE3.01 Analogue Integrated Circuits and Systems
- EE3.02 Instrumentation
- EE3.05 Digital System Design
- EE3.21 Biomedical Electronics
- EE3.24 Embedded Systems
- EE4.16 Analogue Signal Processing
- EE4.17 High Performance Analogue Electronics
- EE4.20 Full-Custom Integrated Circuit Design
- EE4.71 Hardware and Software Verification

Imperial College London

Buy this book!

FOURTH EDITION

PRACTICAL ELECTRONICS FOR INVENTIONS

aul Scherz and Simon Monk

- Recommended book:
 Practical Electronics for Inventors, Paul Scherz & Simon Mon
- Useful for analogue part in particular
- Very useful reference for the future when you want to build electronic circuits
- Over 1000 pages for under £30 a bargain!



Lab-in-a-Box

- Equipment on loan to you to support this module:
 - Oscilloscope (USB based) and multimeter
 - DE10-Lite FPGA board with prototype shield
 - Prototyping breadboard
 - Other electronics components to support the Lab Experiments
- Sustainability return the measurement equipment and the FPGA board when finished; reuse other components where possible to minimize waste.
- Your final Lab Oral marks will not be issued until you have returned the Lab-in-a-Box to the techinicians in the Level 1 Lab.



History of Microelectronics

The **Transistor** (term came from **"Transfer Resistor**")

- > 1925 **FET** concept patented (Lilienfeld, Canada)
- > 1942 Effect observed first in *duodiodes* for radar
- > 1947 First Ge BJT: Bardeen/Brattain/Shockley (Bell)
- > 1954 First Silicon BJT: Teal (TI)
- > 1960 First MOS Transistor: Kahng/Atalla (Bell)

The Integrated Circuit (IC)

- > 1952 IC concept published by Dummer (UK MoD)
- > 1958 **First IC**: Dilby (TI) and Noyce (Fairchild/Intel)
- > 1960 **MSI** (100s of devices integrated per chip)
- > 1968 20 transistors: 741 opamp
- > 1970 LSI (1000s of devices integrated per chip)
- > 1989 1m+ transistors on single chip: Intel 80486
- > 2008 1.7b+ transistors on single chip: Intel Itanium
- > 2019 8.5b+ transistors on single chip: Apple A13



741 opamp, 1968



Apple A13, 2019

Moore's Law



- Gordon Moore, co-founder of Intel, observed in 1965 that number of transistors per square inch in ICs doubled every year.
 - In subsequent years, the pace slowed down a bit, but density has doubled approximately every 18 months, and this is the current definition of Moore's Law.
 - This trend has been driving the microelectronics industry – technology target
 - Most experts, including Moore himself, expect Moore's Law to hold for at least another decade.
- In 2020, Apple's M1 chip has more transistors (16 billion transistors using 5nm technology) than people alive today (around 7.8 billion)!

What does electronic system look like?



Analogue vs Digital



- Most physical phenomena are in the analogue domain.
- Most modern electronics systems operate in the digital domain.
- Analogue-to-Digital (A/D) converters, and Digital-to-Analogue (D/A) converters links the two worlds together.

Common Misconceptions (A vs. D)

- "Analogue electronics is no longer needed its all done in digital nowadays"
 - All electronics are fundamentally ANALOGUE! Therefore analogue will ALWAYS be needed
- "Digital is better quality than analogue"
 - No, digital is just more tolerant to interference than analogue
- "Digital is lower power than analogue"
 - No, in fact in the most demanding applications analogue is always the more energy efficient
- "There is no future for an Analogue Design Engineer"
 - There is generally a great shortage of analogue design engineers therefore there are excellent employment opportunities
 - True there are more jobs in digital than analogue, as there are more job in software than hardware
 - All digital circuits, at some frequency, are really analogue

Why is analogue design challenging?

- Analogue circuits deal with multi-dimensional tradeoff of speed, power, gain, precision, supply, …
- Analogue circuits are much more sensitive to:
 - Noise, crosstalk, and other interferers, second-order device effects
- ✤ High performance analog circuit design can rarely be automated
 - Typically require hand-crafted design and layout
 - Modeling and simulation requires **experience** and **intuition**
- Economic forces require the development of analogue circuits in mainstream digital processes (i.e. CMOS technology)
 - Integration of **analogue** and **digital** functions onto a **single substrate**
- Many levels of abstraction are required

Why is digital design challenging?

- Digital circuits deal primarily with complexity and speed/power trade-off
- Complexity leads to many problems:
 - Difficult to **specify**
 - Impossible to breadboard and **prototype**
 - Hard to **verify** design
 - Hard to **test** chip once manufactured
 - **Timing closure** how to ensure circuit runs reliably at required clock frequency
 - Partitioning how to successfully combine many designer's effort to make a chip
 - Similar issues as in analogue such as cross-talk, clock distribution and signal integrity

Level of Abstraction



Electronic Amplifiers

- Revisit electronic amplifiers (covered last year in Holmes/Mitcheson module on analysis of circuits, L9)
 - take power from a power supply
 - amplification described by gain

Voltage Gain
$$(A_v) = \frac{V_o}{V_i}$$
 or $20 \log_{10} \frac{V_o}{V_i} dB$
Current Gain $(A_i) = \frac{I_o}{I_i}$ or $20 \log_{10} \frac{I_o}{I_i} dB$
Power Gain $(A_p) = \frac{P_o}{P_i}$ or $10 \log_{10} \frac{P_o}{P_i} dB$

Sources and Loads

- An *ideal* voltage amplifier would produce an output determined only by the input voltage and its gain.
 - irrespective of the nature of the source and the load
 - in real amplifiers this is not the case
 - the output voltage is affected by **loading**



Modelling Sources and Loads



Equivalent circuit of an amplifier

 We can put together the models for input, output and gain, to form a model of the entire amplifier as shown here



An example (1)

- An amplifier has a voltage gain of 10, an input resistance of 1 k Ω and an output resistance of 10 Ω .
- The amplifier is connected to a sensor that produces a voltage of 2 V and has an output resistance of 100 Ω , and to a load of 50 Ω .
- What will be the output voltage of the amplifier (that is, the voltage across the load resistance)?
- We start by constructing an equivalent circuit of the amplifier, the source and the load:



An ideal voltage amplifier

- An ideal voltage amplifier would not suffer from loading
 - it would have $R_i = \infty$ and $R_o = 0$



An example (2)



 Although the amplifier has a gain of 10 when it is NOT connected to anything, when used in the system, the actual gain is:

Voltage Gain
$$(A_V) = \frac{V_O}{V_i} = \frac{15.2}{1.82} = 8.35$$

$$\begin{aligned} V_o &= A_v V_i \frac{R_L}{R_o + R_L} \\ &= 10 \, V_i \frac{50 \, \Omega}{10 \, \Omega + 50 \, \Omega} \\ &= 10 \times 1.82 \, \frac{50 \, \Omega}{10 \, \Omega + 50 \, \Omega} = 15.2 \, \text{V} \end{aligned}$$

- The reduction of the voltage gain is due to loading effects.
- The original gain of the amplifier in isolation was 10. It is the unloaded gain.

Frequency response and bandwidth of Amplifier

- All real amplifiers have limits to the range of frequencies over which they can be used.
- The gain of a circuit in its normal operating range is termed its mid-band gain.
- The gain of all amplifiers falls at high frequencies.
 - Characteristic defined by the half-power point.
 - Gain falls to $1/\sqrt{2} = 0.707$ (-3dB) times the mid-band gain.
 - This occurs at the **cut-off (or corner) frequency**.
- In some amplifiers gain also falls at low frequencies.
 - These are **AC coupled amplifiers**
- The bandwidth of the amplifier is the frequency range up to the -3dB point (or cut-off frequencies)





Differential amplifiers

- Differential amplifiers have two inputs and amplify the voltage difference between them.
 - non-inverting input (labelled +) and inverting input (labelled –)



✤ An example of the use of a differential amplifier:



Equivalent circuit of a differential amplifier

Operational Amplifier is a type of differential amplifier (from last year L9S4):



The equivalent circuit of such a differential amplifier is:



Real-life Op Amp

Міскоснір MCP6001/1R/1U/2/4

1 MHz, Low-Power Op Amp

Description

The Microchip Technology Inc. MCP6001/2/4 family of operational amplifiers (op amps) is specifically designed for general-purpose applications. This family has a 1 MHz Gain Bandwidth Product (GBWP) and 90° phase margin (typical). It also maintains 45° phase margin (typical) with a 500 pF capacitive load. This family operates from a single supply voltage as low as 1.8V, while drawing 100 μ A (typical) quiescent current. Additionally, the MCP6001/2/4 supports rail-to-rail input and output swing, with a common mode input voltage range of V_{DD} + 300 mV to V_{SS} – 300 mV. This family of op amps is designed with Microchip's advanced CMOS process.

- Limited to 1MHz signal frequency (GBP) (not infinite gain at all frequencies)
- Stable under high capacitance load (linked to phase margin)
- Single power supply operation
- Rail-to-rail input/output swing
- Low supply current when idle
- Near rail-to-rail common mode input voltage