Imperial College London

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

Welcome to this 2nd year module on electronic circuits and systems. The goal of the Circuits and Systems module is to prepare you for elective courses in the third and fourth years. In some cases, it might even help you with third-year industrial placement in the electronics sector.

The emphasis will be on system's view of real-life electronic circuits, the relationship between analogue and digital electronics and the interfacing between the two, the implication of non-ideal behaviour in electronic circuits such as noise and bandwidth limitations, the building blocks for both analogue and digital electronics sub-systems and the method used to design such sub-circuits.

Please note that I do not put my notes on BlackBoard because I always make my notes open-source (i.e. anyone can access them with or without an Imperial College account). Instead, I maintain a course webpage shown in the slide here. This gets updated week-by-week as we progress through the term. Everything I cover: lecture notes, problem sheets, solutions, sample exam paper, experiment instructions, design solutions and useful resources are all included on this page:

www.ee.ic.ac.uk/pcheung/teaching/EE2_CAS/

I strongly recommend that you BOOKMARK this link.

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

You have covered some of the topics in this module last year. For example, you have already done operational amplifiers and basic digital logic. However, these topics in Year 1 were covered with the assumption that the circuits are ideal or perfect.

In this model, we will consider them with their inherent limitations. Last year, analogue circuits and digital circuits were taught separately – they were hardly ever mixed. This year, we will consider how to connect the two types of circuits together.

Most importantly we will take on a higher system-level view of electronic circuits, a **top-down** instead of **bottom-up** approach. This module also integrates together various subjects you learned in Year 1. In this way, you are prepared to elect a number of optional subjects in later years.

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

This module is delivered exclusively in person. Here is a plan which may be adapted depending on how we progress throughout the term.

Week	Lectures & Problem Classes	Lab Experiment
2 7 Oct	**Lecture 1** – Introduction to electronic systems & the Circuits and Systems module	**Lab 0** Pick up and unpacking Lab-in-a-Box & preparations
3 14 Oct	**Lecture 2** – Amplification of electrical signals & operational amplifiers Class 1: Discussion on Lab 1	**Lab 1** Amplication and Op-amps
4 21 Oct	**Lecture 3** – Anatomy of the LM386 audio amplifier Class 2: Discussion Problem sheet 1 part 1 & Lab 2	**Lab 2** Op-amps Applications
5 28 Oct	**Lecture 4** – Application of Op-Amps Class 3: Problem sheet 1 part 2 & discussions on Lab Oral	**Lab 3** Setting up and using DE10-Lite with Quartus
6 4 Nov		Interim Lab Oral (Lab 1 & 2 only)
7 11 Nov	**Lecture 5** – Digital design with FPGAs **Lecture 6** – System Verilog HDL Class 5: Problem sheet 2 and discssion on Lab 4	**Lab 4** FSM design
8 18 Nov	**Lecture 7** – FSM design and SPI interface **Lecture 8** – Timing constraints & timing analysis Class 6: Problem sheet 3 and discuss Lab 5	**Lab 5** SPI interface to DAC & Sinewave generation
9 25 Nov	**Lecture 9** – D-to-A converters **Lecture 10** – A-to-D converters Class 7: Problem sheet 4 and discuss Lab 6	**Lab 6** Echo sythesizer
2 5 Dec	**Lecture 11** – Memory organisation, Address decoding **Lecture 12** - Embedded memory and DSP blocks Class 8: Problem sheet 5 and discuss Open-ended challenges	Open-ended challenges
9 12 Dec	**Lecture 13** – System level design considerations Class 9: Open-ended challenges & Lab 6	Final Lab Oral

Related Courses

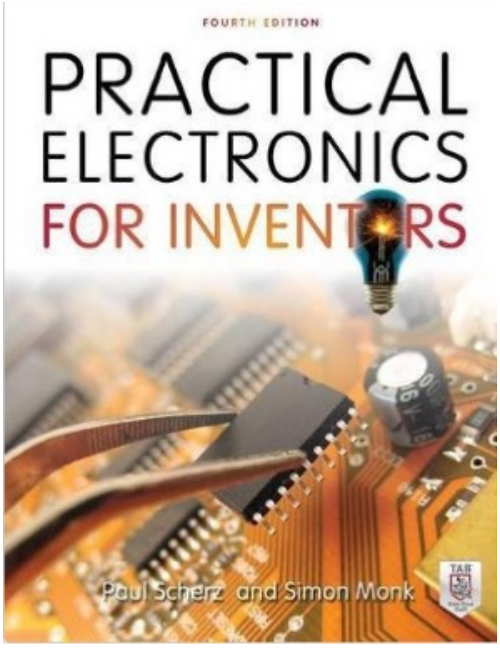
- **Follow on from these Year 1 modules**
  - ELEC40002 Analysis and Design of Circuits
  - ELEC40003 Digital Electronics & Computer Architecture
  - ELEC40004 Programming for Engineers
  - ELEC40006 Electronics design project 1

- **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

This module builds on what you learned in four separate modules from Year 1. It will also help you with many modules in later years. It helps you to transit from theory to practice in both analogue circuits and in reasonably complex digital systems, and to join them together to form a complete systems that processes real analogue signals.

.

Buy this book!



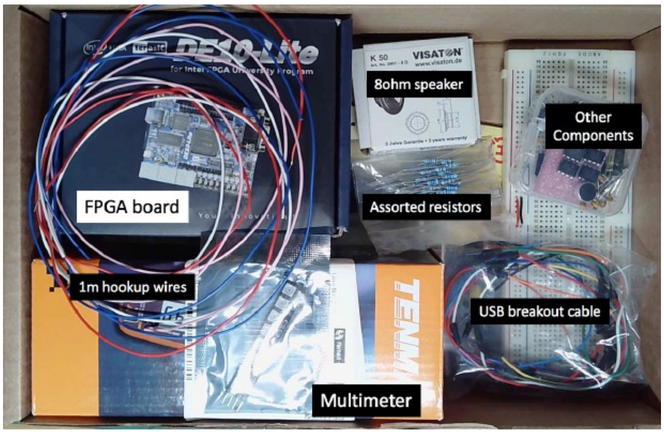
- Recommended book:
  Practical Electronics for Inventors,
  Paul Scherz & Simon Mon
- Useful for analogue part in particular
- Very useful reference for the future when you want to build electronic circuits
- Over 1000 pages for under £30 – a bargain!

I will be providing notes throughout this course. So strictly speaking, you could get away without using any textbooks. However, I recommend only one book – Practical electronics for inventors. This is NOT a conventional textbook, i.e. this is not aimed at preparing you for sitting examinations. Instead this book is particularly suitable for engineers who want to build real circuits that work. It has a good balance between theory and practice, it is relatively low cost in spite of its size (>1000 pages) and it covers everything you need in electronics at sufficient depth.

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.



PYKC 8 Oct 2024 EE2 - Circuits & Systems Lecture 1 Slide 6

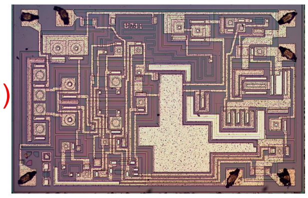
This module will be based on scheduled lectures and practical laboratory experiments. This is achieved through a Lab-in-a-Box that I have prepared for you. You may pick up your person Lab-in-a-Box (with your name on the box) from Level 1 Electronics Lab from Wednesday 12 October 2022 onwards.

We hope that this contains everything you need for this module. However, any missing component can be collected later in the Electronics Lab.

History of Microelectronics

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

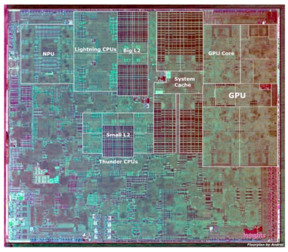
- 1925 – **FET** concept patented (Lilienfeld, Canada)
- 1942 – Effect observed first in *duodiodes* for radar
- 1947 – First **Ge BJT**: Bardeen/Brattain/Shockley (Bell)
- 1954 – First **Silicon BJT**: Teal (TI)
- 1960 – First **MOS Transistor**: Kahng/Atalla (Bell)



741 opamp, 1968

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**



Apple A13, 2019

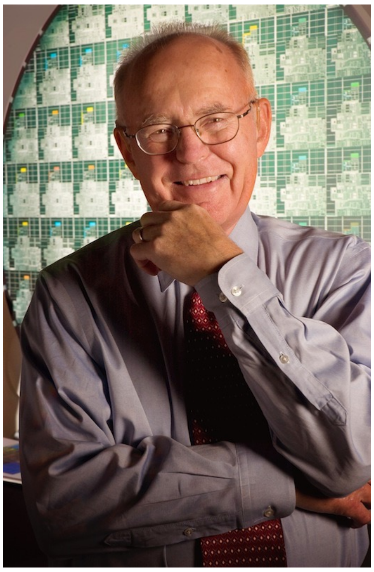
PYKC 8 Oct 2024 EE2 - Circuits & Systems Lecture 1 Slide 7

This slide charts the chronological development of microelectronics from its earliest idea, the invention of the BJT, the integrated circuit to the modern IC. The three milestones highlighted in RED here are particularly relevant to this module.

Without the invention of transistor in 1947, we will not have the field of modern electronics. The analogue portion of this module is based on operational amplifiers, and most popular of which is the 741 introduced by Fairchild in 1968. This chip only has 20 or so transistors. In fact most analogue chips only have relatively small number of transistors even today.

This is in contrast with the Apple A13 chips introduced last year, which is essentially a digital IC with small number of analogue circuits. This chip has over 8.5 brilliant transistors!

Moore's Law

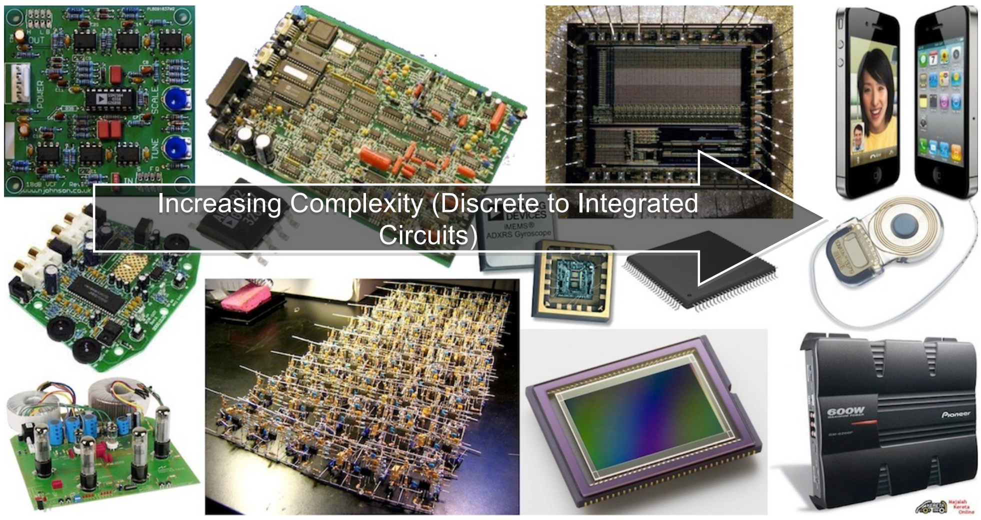


- **Gordon Moore**, co-founder of Intel, observed in 1965 that number of transistors per square inch in ICs doubled every year.
  - In subsequent years, the pace slowed down a bit, but density has **doubled approximately every 18 months**, and this is the current definition of Moore's Law.
  - This trend 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)!

I am sure I don't have to say too much about this slide. Gordon Moore famously predicted a long time ago that integrated circuit will grow in complexity exponentially (doubling every 18 months or so). This prediction is best illustrated by one of the latest chip in 2020, again by Apple Computer.

The Apple M1 chip that is used in the latest Apple products has 16 billion transistors. **That is, there are more transistors in this one chip than human beings alive today**!

What does electronic system look like?

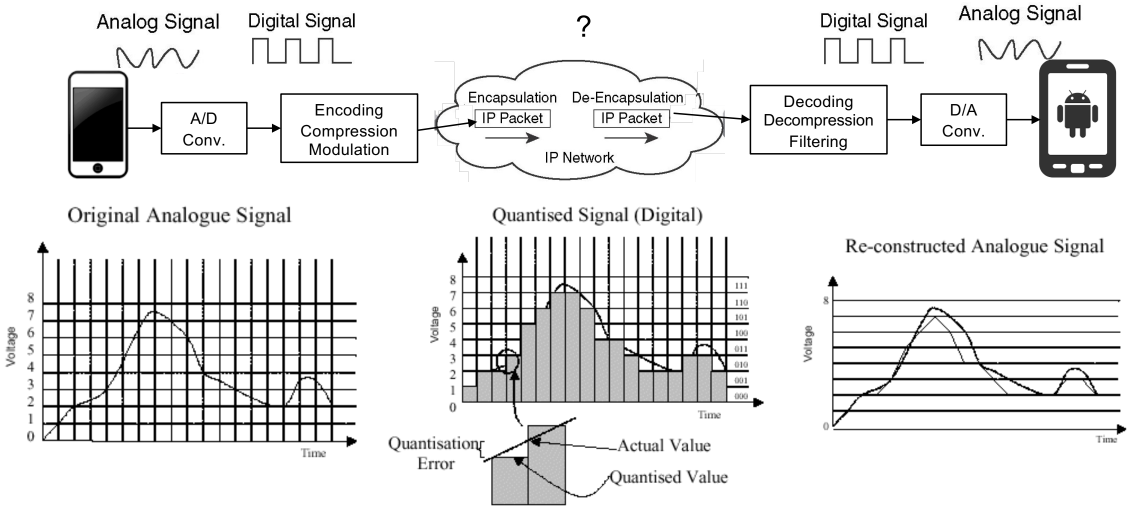


PYKC 8 Oct 2024 EE2 - Circuits & Systems Lecture 1 Slide 9

This slides shows how electronic circuits have, over the past few decades, have moved from discrete components and small ICs to highly complete systems such as a modern mobile phone. This march of miniaturization will continue into the foreseeable future.

Even today, a typical modern high-end phone may have over 200 billion transistors. It is estimated that the number of human beings ever lived in the history of mankind total around 107 billion!

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.

It is important for you to appreciate the high-level view of an electronic system, end-to-end. Shown here is a mobile phone linked to another mobile phone. The speech signal, like many electrical signal in the physical world, are analogue in nature. That is, the signal varies continuously in time and in amplitude. A modern electronic system converts the analogue signal into digital form in two steps. It **samples** the data into discrete time, a process known as "**sampling**". It then **digitize** each sample into discrete levels, a process known as "**quantization**".

You will learn in the Signals and System module this year that the sampling processing does NOT destroy information. We know how to recover the original signal without loosing any information. However, quantization will always loose information – we will only have an approximation of the original signal.

Once the speech is in digital form, it goes through many digital circuits which compresses the speech signal so that you try to send as little information as possible, these are then turn into electrical signals that are suitable for transmission through air, cable or optical fibre. This process is called modulation.

For modern phones, the transmission could very well be via the internet (known as Voice over IP or VoIP).

At the receiving end, the reverse happens.

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

While it is true that digital electronics often grabs the headlines, our analogue professors always come out defending their patch. Here are number of common misconceptions that I "borrowed" from Tim Constandinou when he was leading the analogue electronics 2 module in previous years.

Most important message here is that digital electronics will NOT work without analogue. Indeed any digital circuit running at the limit of its operating frequency, even when the output signal is digital, behaves like an analogue circuit.

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

Here are a number of reasons why designing analogue circuits is difficult.

Analogue design is viewed by some a ”black magic” or “black art”. The gap between theory (this ought to work) and practice (but it doesn’t) is often quite wide.

One way to overcome the difficulty of designing analogue circuit is to use building blocks. Operational amplifier (or op-amp) is one of the most useful analogue building blocks. Therefore this module will be focused on using real-life op-amps to achieve different goals.

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**

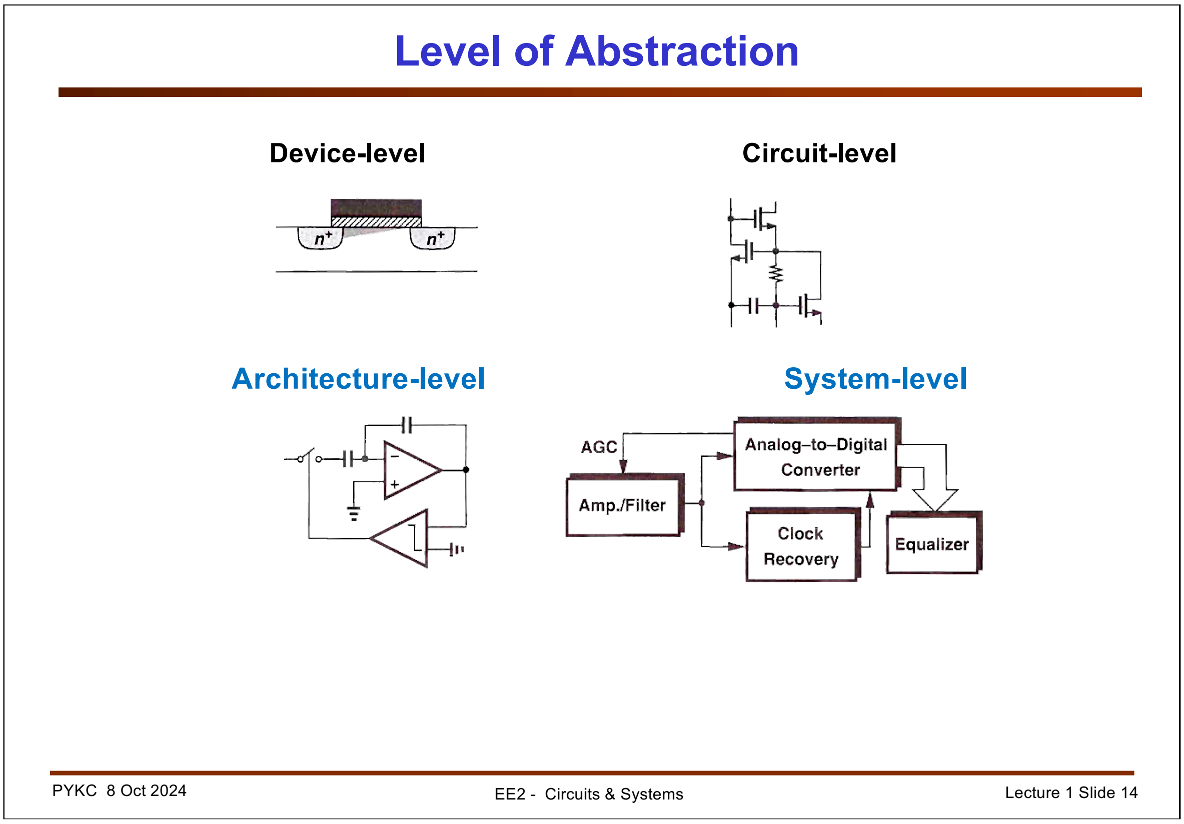
Designing digital circuits is also not that easy. The problem is dominated by the issue of complexity. Even a modest digital block would have hundreds to thousands of transistors.

Digital circuits of high complexity (e.g. a microprocessor) is not easy to specify. Drawing the schematic for a few tens of gates is already a challenge. Digital circuits are generally too complex to prototype on breadboard. If this is the case, how can one verify whether one's design is working correctly or not?

Once a digital chip is made, the next challenge is to test that it does behave as expected at the correct clock frequency. Testing a complex digital IC is really difficult and costly.

There are many other issues such as timing closure (which means that when you connect different parts of the digital circuit together, you need to optimize it so that it will run at the desired clock frequency without error), partitioning a large IC into smaller parts so that the design task can be divided among many engineers.

On top of all that, digital circuits also suffer the same problem as analogue circuits but to a less extend.



One important concept of electronic circuit, as shared with programming and software, is levels of abstraction. You have learned in Year 1 low level view of electronics, starting with devices with electrons and holes, diffusion regions, inversion layers etc. You also learn about electronics as interconnecting transistors (part 2 of Analysis and Design of Circuits). However for this module we will limit ourselves to higher level of abstraction, either at architectural or building block level, and at system level (i.e. interconnection of various blocks and sub-systems).

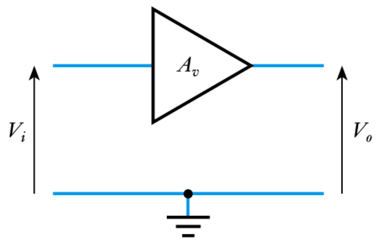
Electronic Amplifiers

- 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

$$\text{Voltage Gain } (A_v) = \frac{V_o}{V_i} \text{ or } 20\log_{10}\frac{V_o}{V_i}\text{ dB}$$

$$\text{Current Gain } (A_i) = \frac{I_o}{I_i} \text{ or } 20\log_{10}\frac{I_o}{I_i}\text{ dB}$$

$$\text{Power Gain } (A_p) = \frac{P_o}{P_i} \text{ or } 10\log_{10}\frac{P_o}{P_i}\text{ dB}$$



The next few slides serve as a quick revision of something you have learned in the First Year. The concept is amplification.

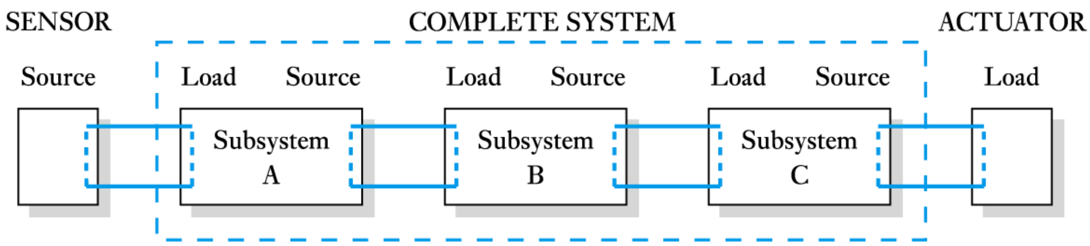
Here is a symbol we normal use to represent an electronic amplifier, which is connected to an external power source.

Amplification is characterised by its gains, which is the ratio of output to input. The ratio or gain can be in voltage, current or power.

Remember that gain is often expressed in dB. For voltage and current, the gain in dB is 20 times log of the ratio. For power, the multiplying factor is 10 instead of 20.

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**



In electronic systems, there can be a number of amplification stages connected in series (also known as cascade). In the system shown here, a sensor may produce the **source** of the electrical signal. This could be passed through three stages to drive an actuator, which is the final **load**.

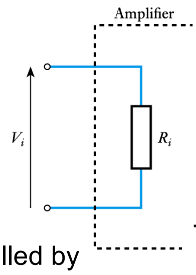
In an ideal amplifier, the source would have zero source impedance and the load would have infinite load impedance. In which case, the voltage gain would be independent of the source and load.

In practical systems, both source impedance and load impedance would be non-zero and not infinite. In which case, both source and load will affect the actual voltage gain as we will see later.

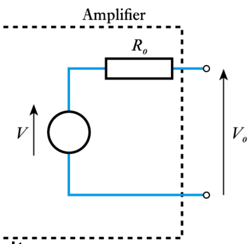
The concept of non-ideal source and non-ideal load is important in electronics.

Modelling Sources and Loads

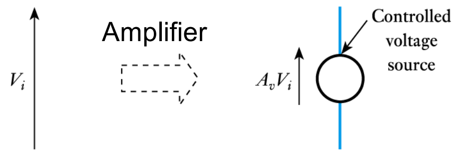
- **Modelling the input of an amplifier**
  - the input can often be adequately modelled by a simple resistor
  - the **input resistance**



- **Modelling the output of an amplifier**
  - Similarly, the output of an amplifier can be modelled by an ideal voltage source and an output resistance.
  - This is an example of a **Thévenin equivalent circuit**



- **Modelling the gain of an amplifier**
  - can be modelled by a controlled voltage source
  - the voltage produced by the source is determined by the input voltage to the circuit



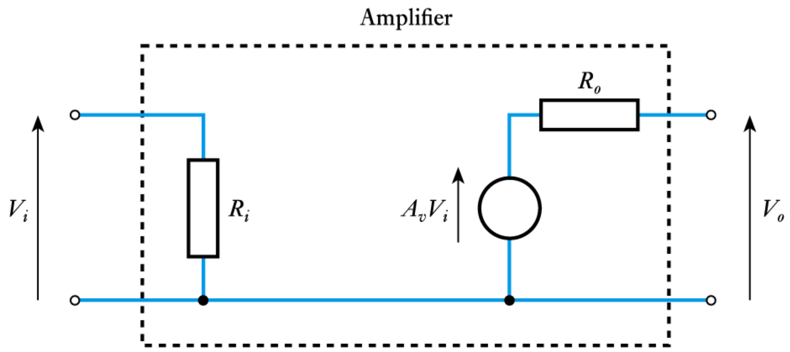
Consider an actual input of an amplifier. Its input can be modelled as an **input resistance** R_i as shown in the figure here. In an ideal amplifier, $R_i = \infty$. In real amplifier R_i is large but finite.

The output of an actual amplifier can be modelled by an ideal voltage source *v* in series with an **output resistance** R_O as shown. For an ideal amplifier $R_O = 0$. In a real amplifier, R_O is non-zero but usually small.

Finally, the voltage gain of an amplifier is modelled by a **dependent voltage source**. The voltage is dependent on the input voltage and the multiplication factor is A_V, the voltage gain.

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



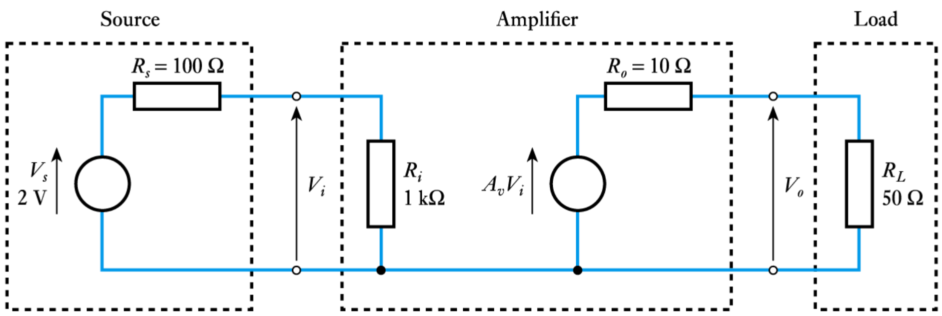
Putting these three elements together, we have a model of an amplifier. This is quite universal.

Please satisfy yourself that this model of an amplifier is linear: it obeys both the principles of **proportionality** and **superposition**.

An example (1)

- An amplifier has a voltage gain of 10, an input resistance of 1 kΩ 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:



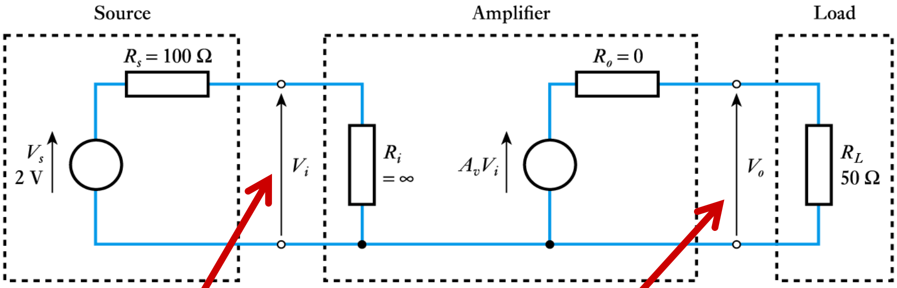
Let us now consider an example. We assume that source voltage is a 2V battery with a 100W source resistance R_S. This source signal is applied to the input of an amplifier V_I with a 1kW input resistance, a gain of 10 and a 10W output resistance. The output of the amplifier V_O is driving a 50W load.

This can be modelled as shown in the diagram here.

The question is: what is the output voltage of the amplifier?

An ideal voltage amplifier

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



- If $R_i = \infty$, then

$$\frac{R_i}{R_S + R_i} \approx \frac{R_i}{R_i} = 1$$

- and,

$$V_i = \frac{R_i}{R_s + R_i} V_s \approx V_s = 2\ \text{V}$$

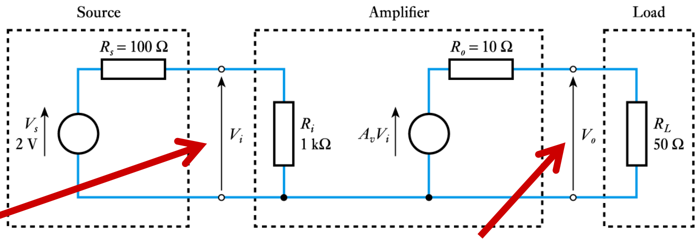
$$V_o = A_v V_i \frac{R_L}{R_o + R_L} = 10\, V_i \frac{50\ \Omega}{0\ \Omega + 50\ \Omega} = 10 \times 2 \frac{50\ \Omega}{50\ \Omega} = 20\ \text{V}$$

If the amplifier is ideal, loading the source or the amplifier output will not affect the system gain. The gain will remain to be 10.

An example (2)

- From this we calculate the output voltage:

$$V_i = \frac{R_i}{R_s + R_i} V_s = \frac{1\ \text{k}\Omega}{100\ \Omega + 1\ \text{k}\Omega} \times 2\ \text{V} = 1.82\ \text{V}$$



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

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

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

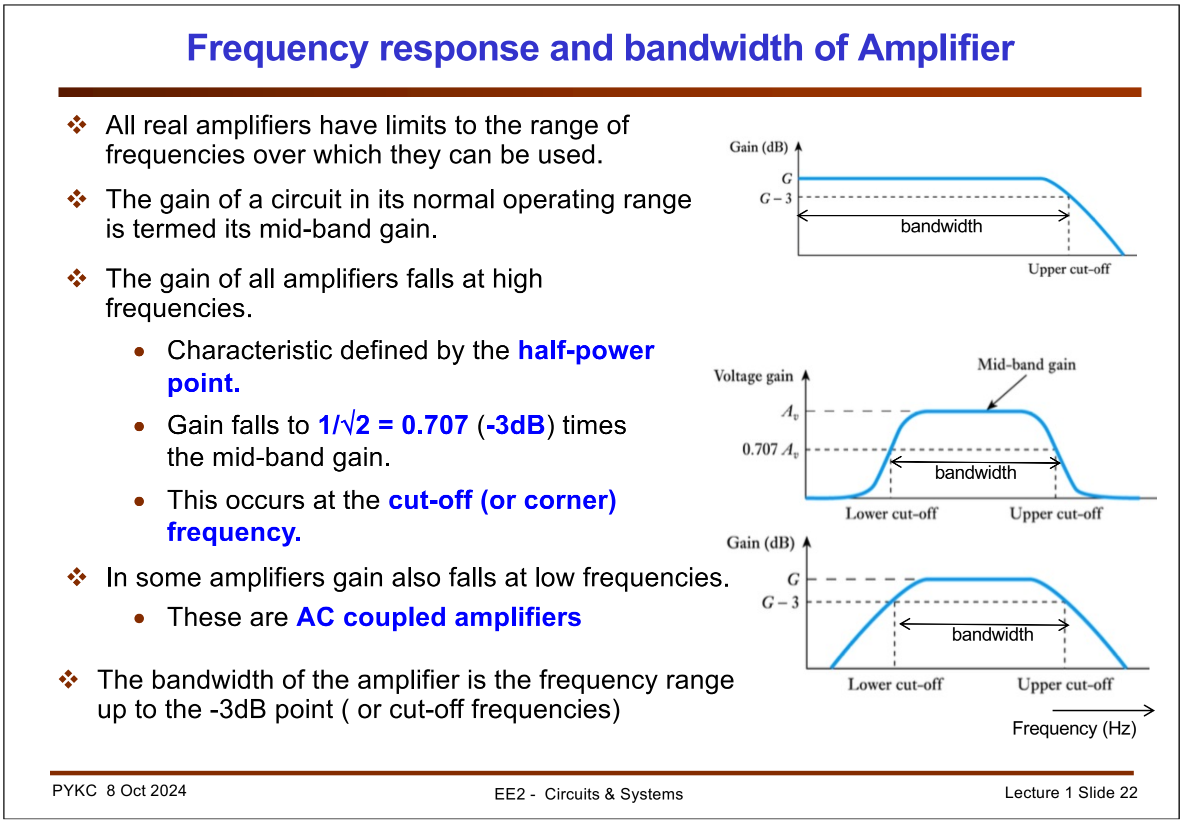
- The reduction of the voltage gain is due to **loading effects**.
- The original gain of the amplifier in isolation was 10. It is the **unloaded** gain.

PYKC 8 Oct 2024 EE2 - Circuits & Systems Lecture 1 Slide 21

However, both the source and input of the amplifier are non-ideal. Therefore the input of the amplifier has a loading effect on the source voltage. V_I is derived from V_S according the voltage divider circuit as shown here. Instead of 2V, the amplifier input only sees a 1.82V due to the loading effect of the amplifier on the source.

Similar, the output load R_L has a loading effect on the amplifier output, which is now modelled with the Thevein equivalent circuit. Similar this is acting as a voltage divider. The output voltage is 15.2V, which is considerably smaller than the 20V as expected with an ideal amplifier (which would have infinite input resistance and zero output resistance).

The effective voltage gain is now only x 8.25 instead of x10.



In the previous example, the source signal is a dc voltage at 2V. In general, the source signal can be of any frequency. DC voltage is only a special case where the frequency is 0.

In real amplifiers, the gain of the amplifier is NOT constant for ALL frequencies. Most amplifier will have a gain that drops offer at some upper frequency. We call this the cut-off frequency or **corner frequency**. It is so called because beyond this frequency, the output signal starts to fall (hence cutting off signal components at this and high frequencies).

The cut-off frequency is defined as the frequency at which the power is reduced by half. Since voltage is proportional to square root of power, the half-power frequency corresponds to that where the voltage gain is reduced by a factor of **1/√2** or **-3dB**.

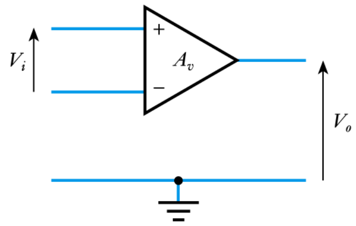
The gain at the "normal operating frequency" is known as the **mid-band gain**.

Amplifier can also discriminate (i.e. suppress) signals at lower frequencies such as DC. We call this an AC coupled amplifier because it only passes AC signals.

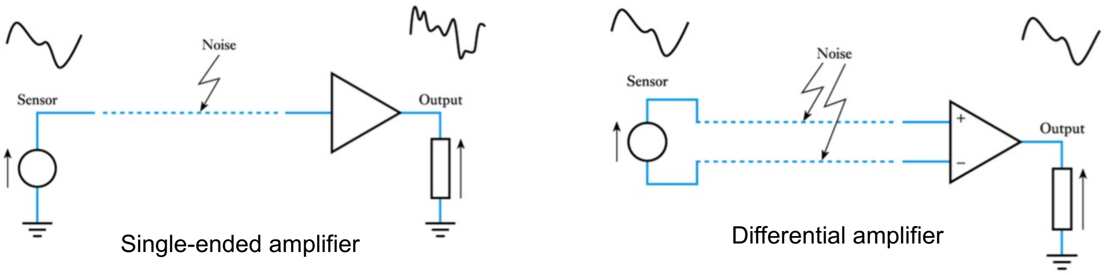
The bandwidth of an amplifier is the frequency range from 0 to the upper -3dB frequency for a DC coupled amplifier, or between lower and upper -3dB frequencies for an AC coupled amplifier.

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:



PYKC 8 Oct 2024 EE2 - Circuits & Systems Lecture 1 Slide 23

So far, we have only considered amplifiers that takes an input signal with one terminal, which is always referenced to GROUND. We call this a **single-ended** signal. The amplifier is known as a single-ended amplifier.

Single-ended amplifier is susceptible to picking up unwanted noise signal.

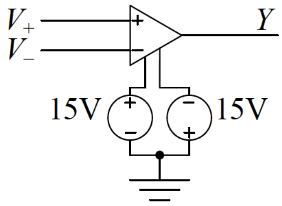
Another type of amplifier has two input signals, labelled +ve and –ve inputs. The amplification is provided on the difference between V^+ and V^- input (i.e. $V_O = A_V \times (V^+ - V^-)$).

The advantage of a **differential amplifier** is that any noise picked up by the two input signal wires are cancelled out if the noise signals on both wires are identical. The (noise) signal that is common to both inputs is known as "common-mode" signal. The signal that is difference between the two inputs is known as "differential signal". A differential amplifier only provides amplification to the differential signal. The common-mode signal is complete suppressed or rejected.

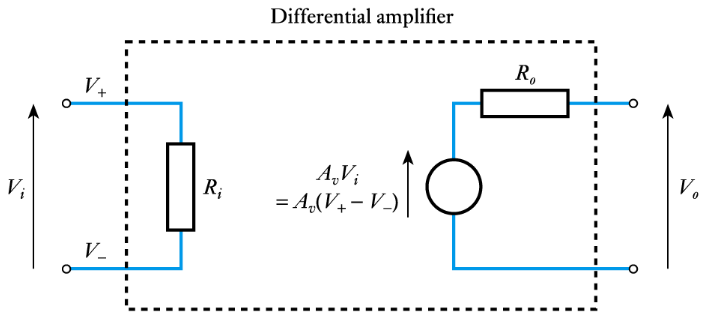
We can find such a differential amplifier everywhere. For example, the land line in your home uses a differential signal and the phone has a differential amplifier. In that way, your phone conversation is still clear even if someone is vacuuming the carpet! In order to ensure that the noise pick-up on both signal wires are the same, the phone wire is twisted together, so that both wire on average is of the same distance to the noise source.

Equivalent circuit of a differential amplifier

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



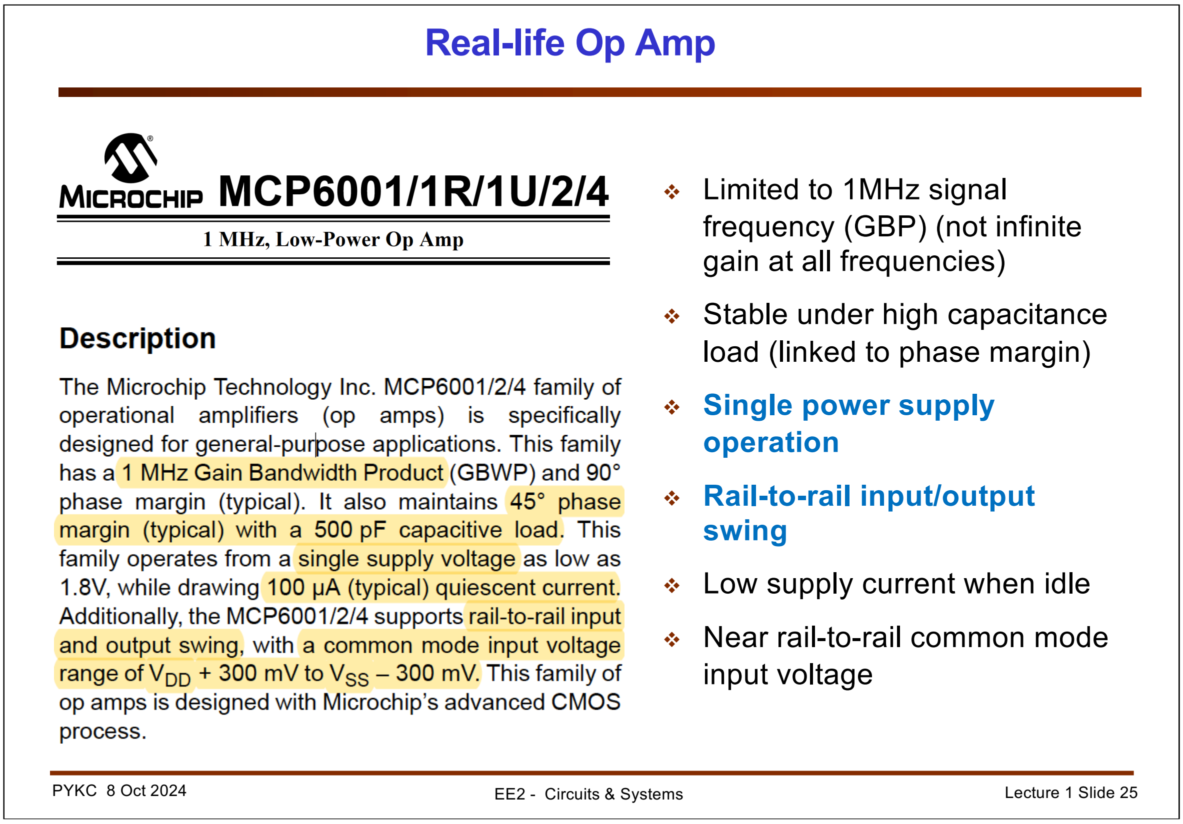
- The equivalent circuit of such a differential amplifier is:



Operational amplifier is the most common type of differential amplifier. Here is diagram taken from last year's notes (Lecture 9, slide 4). It shows a differential amplifier with ±15V power supply.

Show here is the equivalent circuit for such a differential amplifier. An ideal amplifier will have infinite Ri, infinite Av at all frequencies and zero Ro.

In real systems, you often find that your circuit has to work with a single power rail because it is powered by a battery. True, one could use circuits that generates negative voltage source from a positive voltage battery. Such circuits are often expensive and power hungry. Therefore in this module, we will only use op-amps that uses single power supply. We will also consider how to make such an amplifier work when you cannot use the ground potential (earth) as the reference voltage. Where is the "virtual earth"?



You will be starting Lab 1 soon when you will build amplifier circuits with the MCP6002 op-amp (this has two op-amps in a single 8-pin package).

Unlike an ideal op-amp, this has limitations. Many of these are shown as features.

1. This op-amp cannot operate above 1MHz (its gain falls to 1, and therefore it does not behave like an amplifier)
2. It is designed to be stable under all negative feedback conditions, even when a large capacitor load is connected. The output resistance Ro and the load capacitor Co together introduces a delay. This could result in instability in the circuit with feedback. You will learn more about feedback and instability in the 2nd year Feedback Control module.
3. Single power supply is a must in modern portable electronic systems.
4. Rail-to-rail swing is extremely important. Battery operating devices usually have limited supply voltage (3.7V or 5V). With single supply, it is important that the output can reach nearly the extreme voltages allowed. The outdated 741 cannot do this.
5. Portable devices demand low current drain from battery when idle.
6. Why is near rail-to-rail common mode input voltage important? I will leave you to ponder this feature and consider its implication. It will be a very good discussion point at the problem class with your class tutor.