Imperial College London

Lecture 1

Introduction to Circuits and Systems

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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

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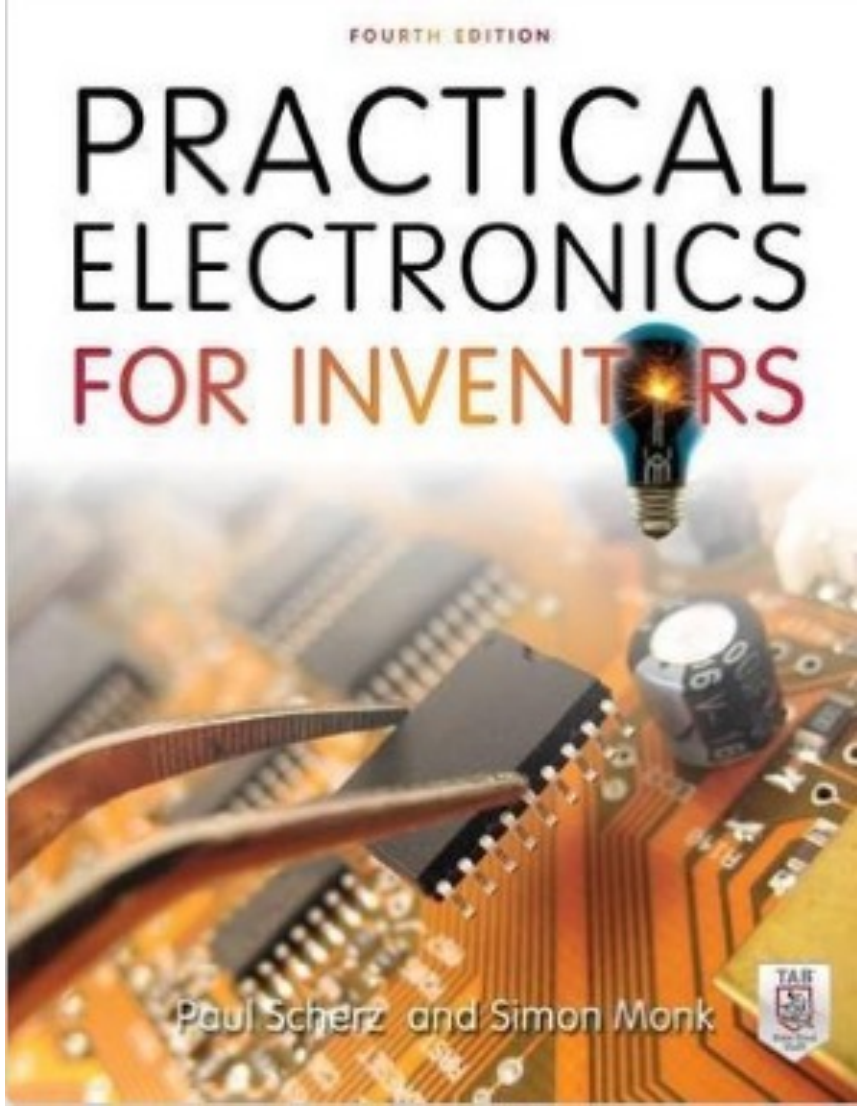
Buy this book!



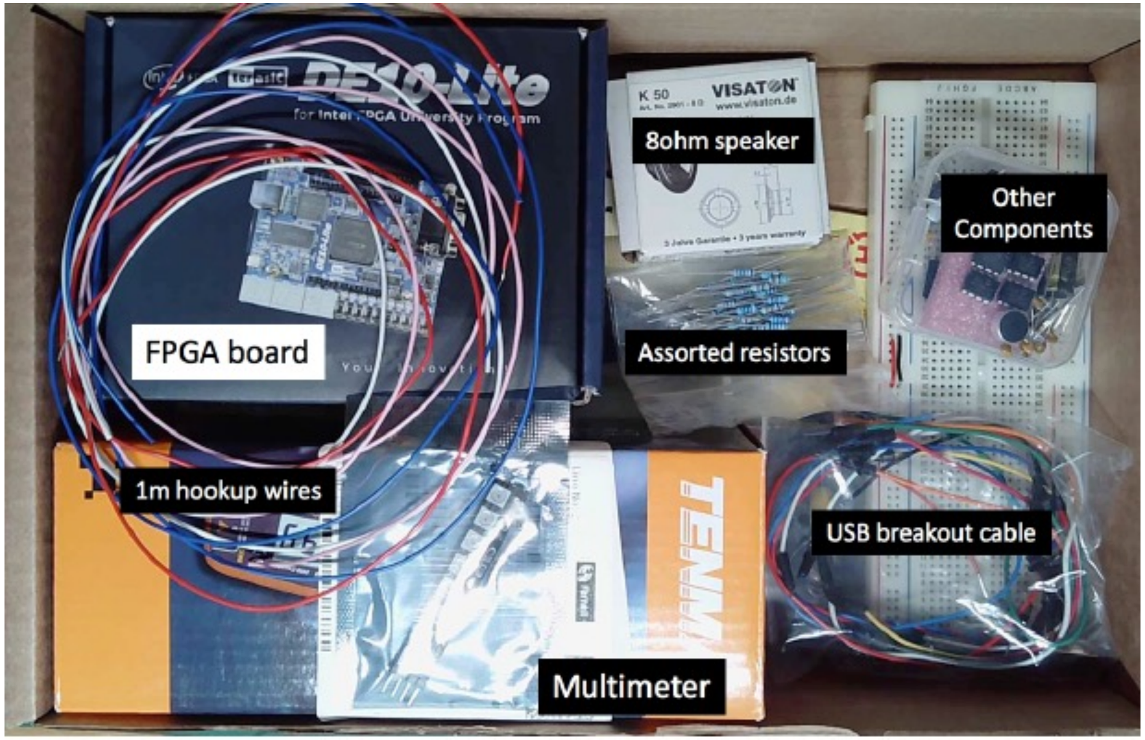
- Recommended book:
  Practical Electronics for Inventors,
  Paul Scherz & Simon Mon

- 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!

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

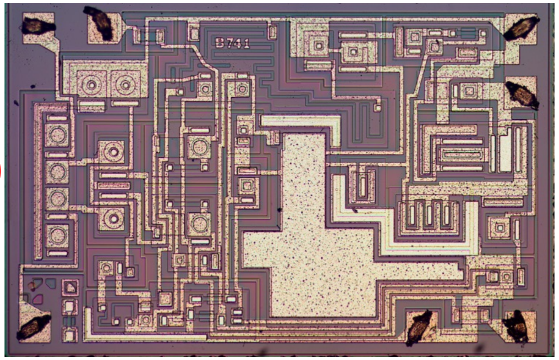
- **Sustainability** – return the measurement equipment and the FPGA board when finished; reuse other components where possible to minimize waste.
- Your final Lab Oral marks will not be issued until you have returned the Lab-in-a-Box to the techinicians in the Level 1 Lab.



History of Microelectronics

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

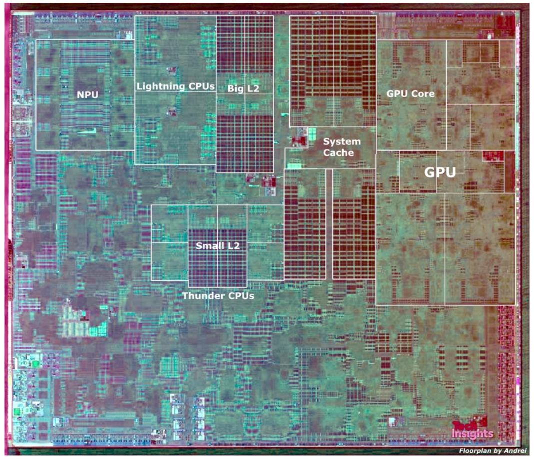
- 1925 – **FET** concept patented (Lilienfeld, Canada)
- 1942 – Effect observed first in *duodiodes* for radar
- 1947 – First **Ge BJT**: Bardeen/Brattain/Shockley (Bell)
- 1954 – First **Silicon BJT**: Teal (TI)
- 1960 – First **MOS Transistor**: Kahng/Atalla (Bell)



741 opamp, 1968

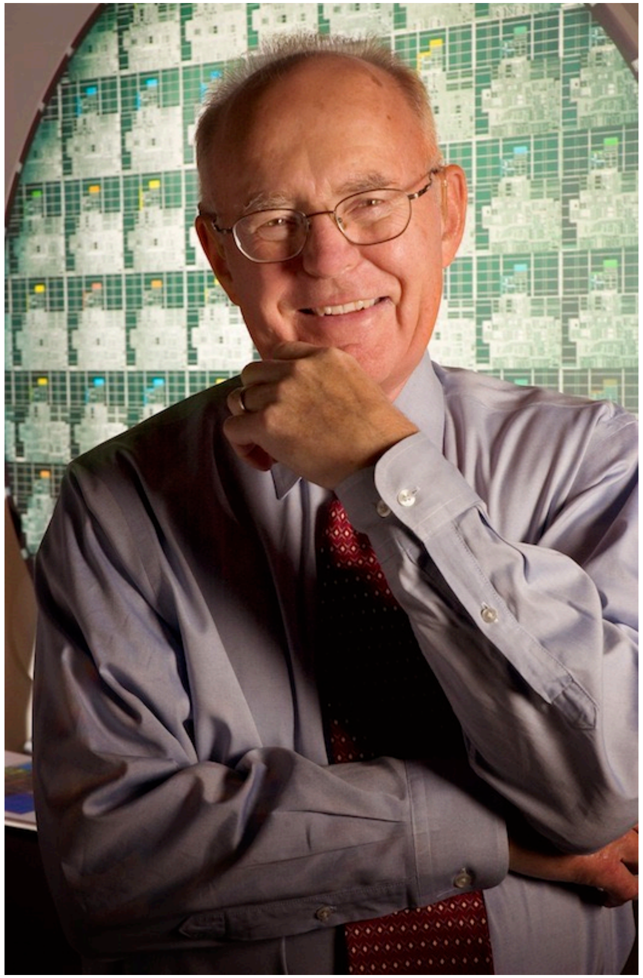
The **Integrated Circuit** (**IC**)

- 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**



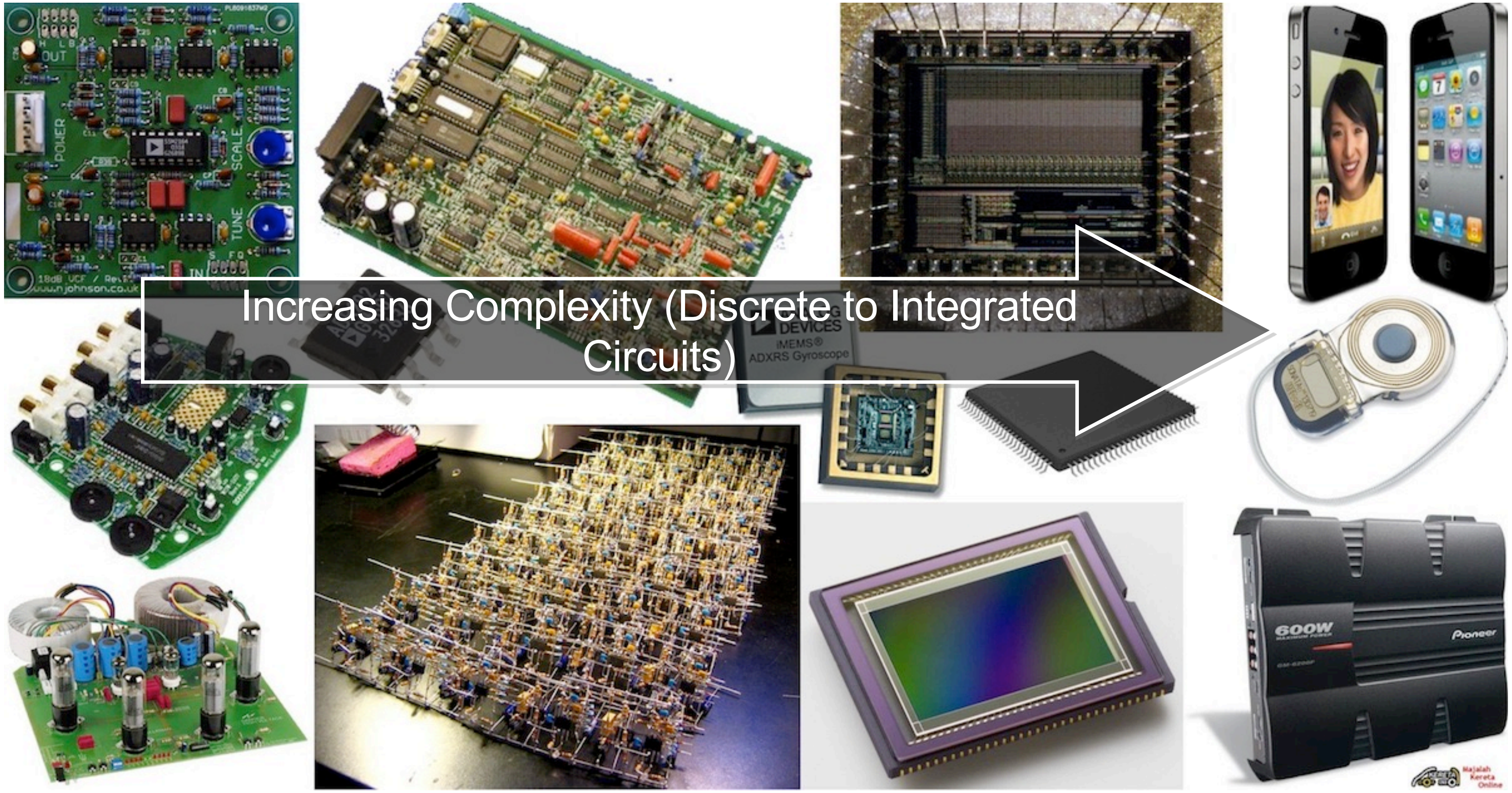
Apple A13, 2019

Moore's Law

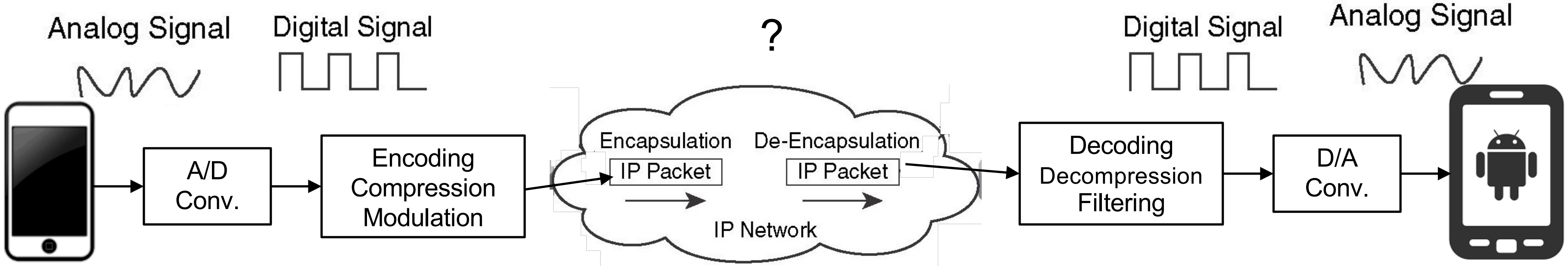


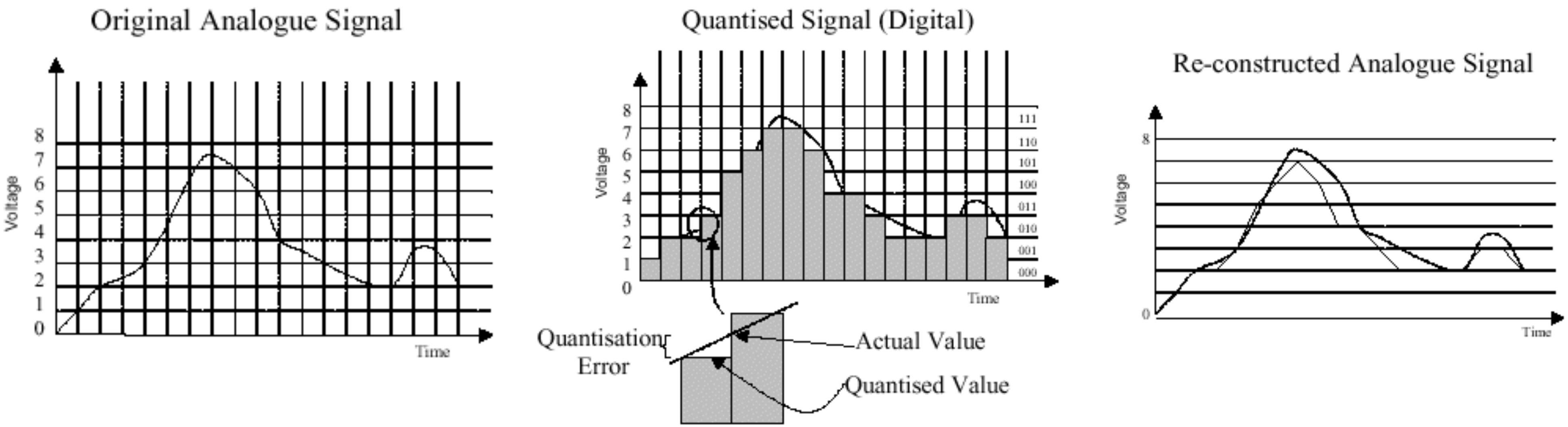
- **Gordon Moore**, co-founder of Intel, observed in 1965 that number of transistors per square inch in ICs doubled every year.
  - In subsequent years, the pace slowed down a bit, but density has **doubled approximately every 18 months**, and this is the current definition of Moore's Law.
  - This trend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

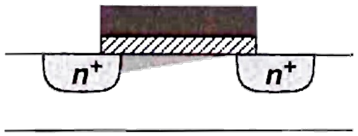
- Analogue circuits deal with multi-dimensional **tradeoff** of **speed**, **power**, **gain**, **precision**, **supply**, …
- Analogue circuits are much more sensitive to:
  - **Noise**, **crosstalk**, and other interferers, **second-order device effects**
- High performance analog circuit design can 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?

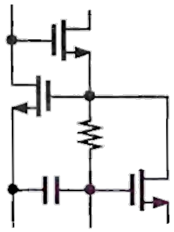
- Digital circuits deal primarily with **complexity**, **performance** and **speed/power** trade-off
- Complexity leads to many problems:
  - Difficult to **specify**
  - Impossible to breadboard and **prototype**
  - Hard to **verify** design
  - Hard to **test** chip once manufactured
  - **Timing 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

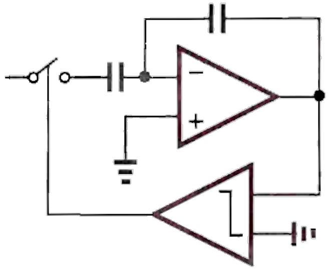
Device-level



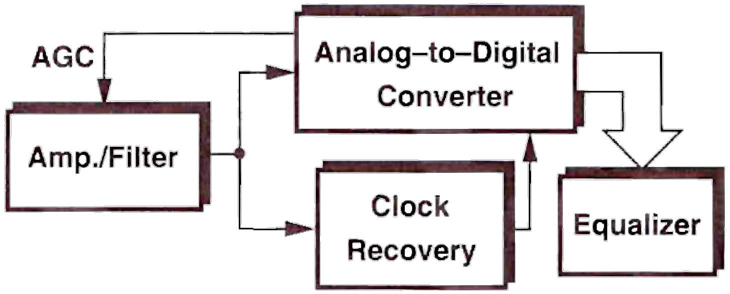
Circuit-level



Architecture-level



System-level



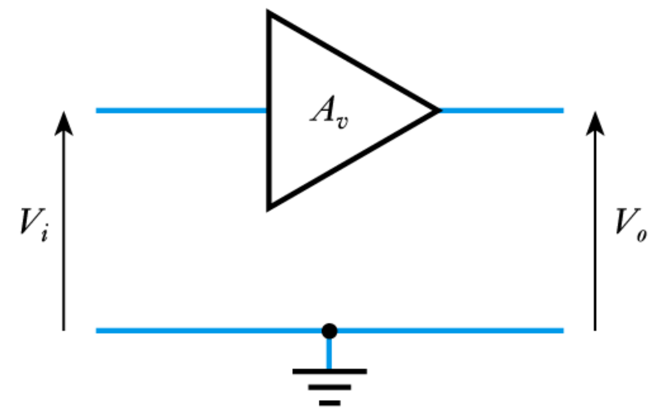
Electronic Amplifiers

- 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

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

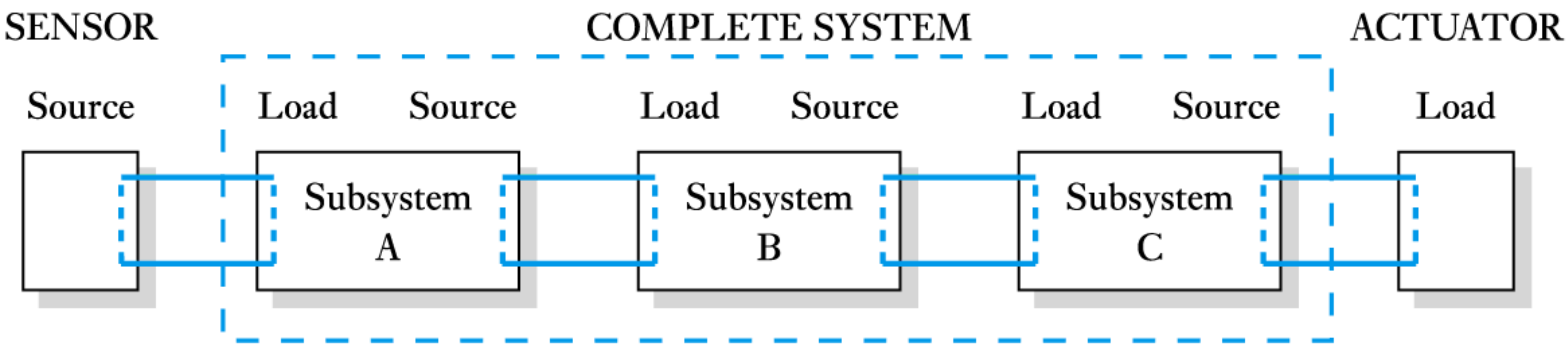
$$\text{Current Gain } (A_i) = \frac{I_o}{I_i} \text{ or } 20 \log_{10} \frac{I_o}{I_i} \text{ dB}$$

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



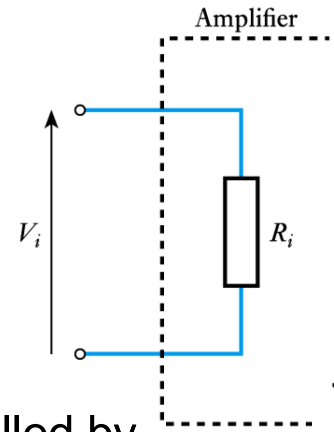
Sources and Loads

- 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**

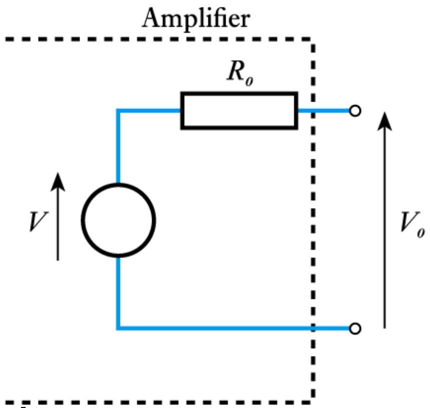


Modelling Sources and Loads

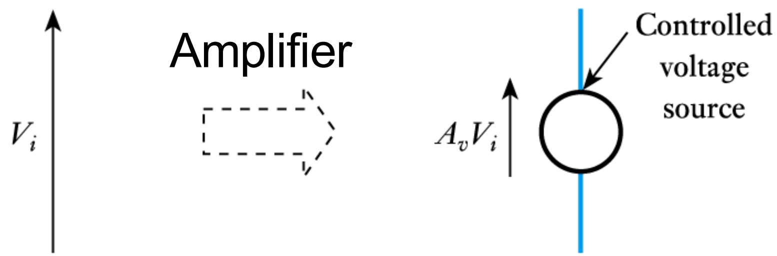
- **Modelling the input of an amplifier**
  - the input can often be adequately modelled by a simple resistor
  - the **input resistance**



- **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**

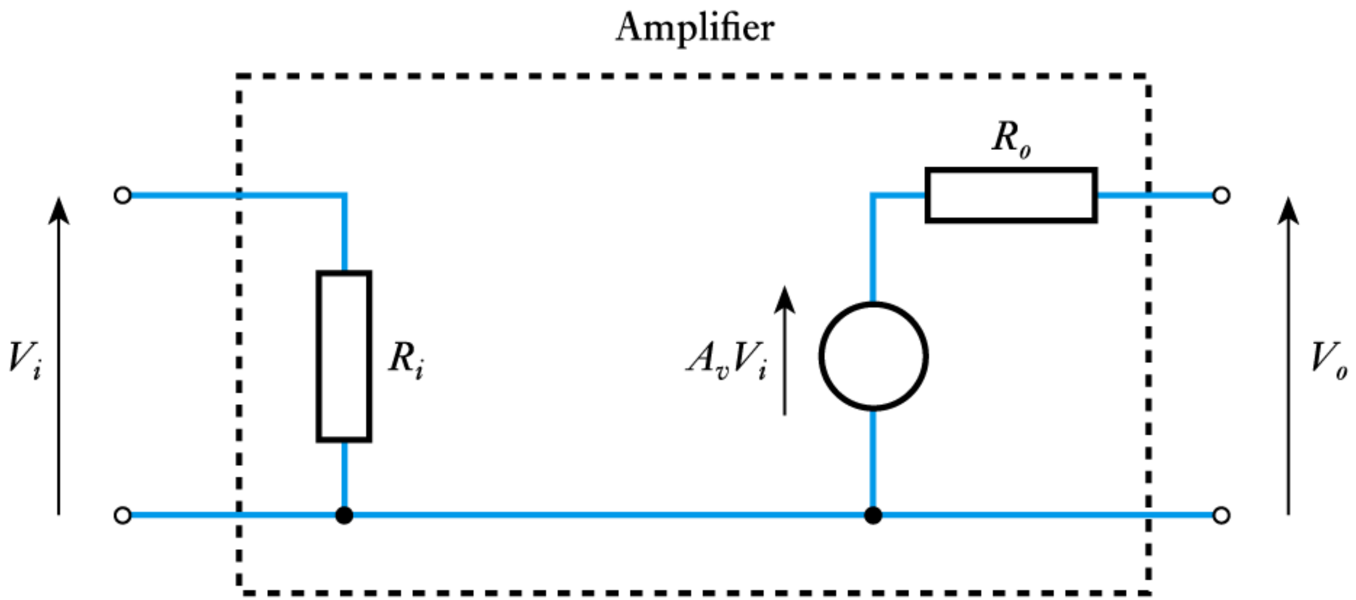


- **Modelling the gain of an amplifier**
  - can be modelled by a controlled voltage source
  - the voltage produced by the source is determined by the input voltage to the circuit



Equivalent circuit of an amplifier

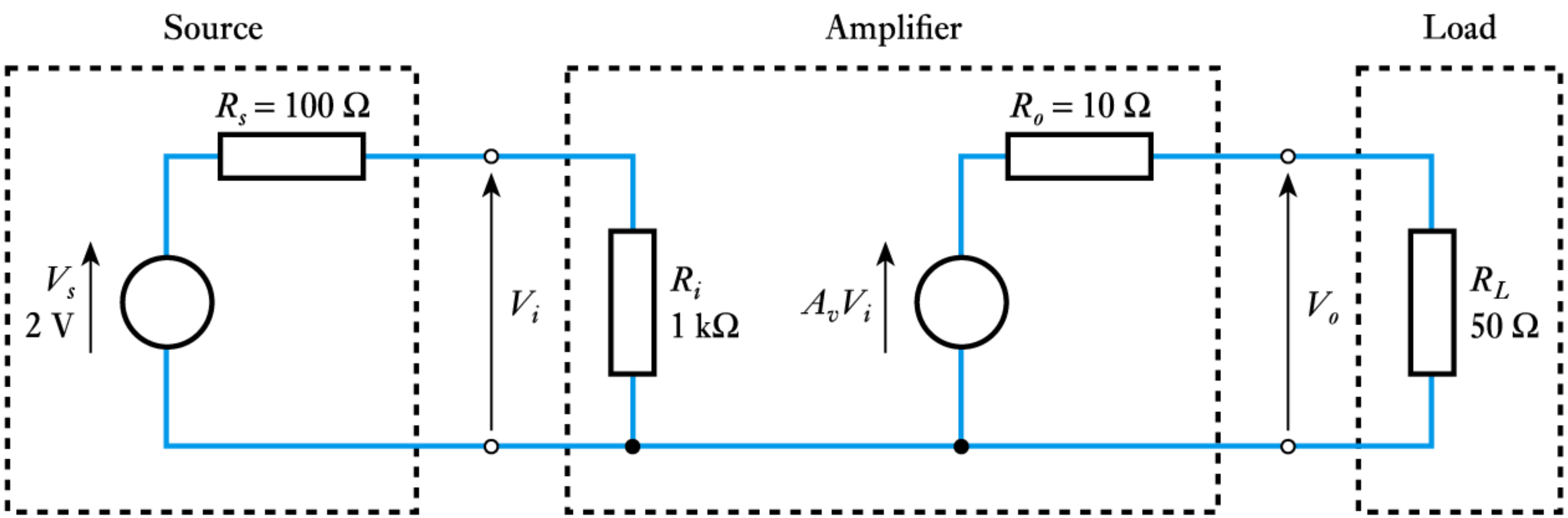
- We can put together the models for input, output and gain, to form a model of the entire amplifier as shown here



An example (1)

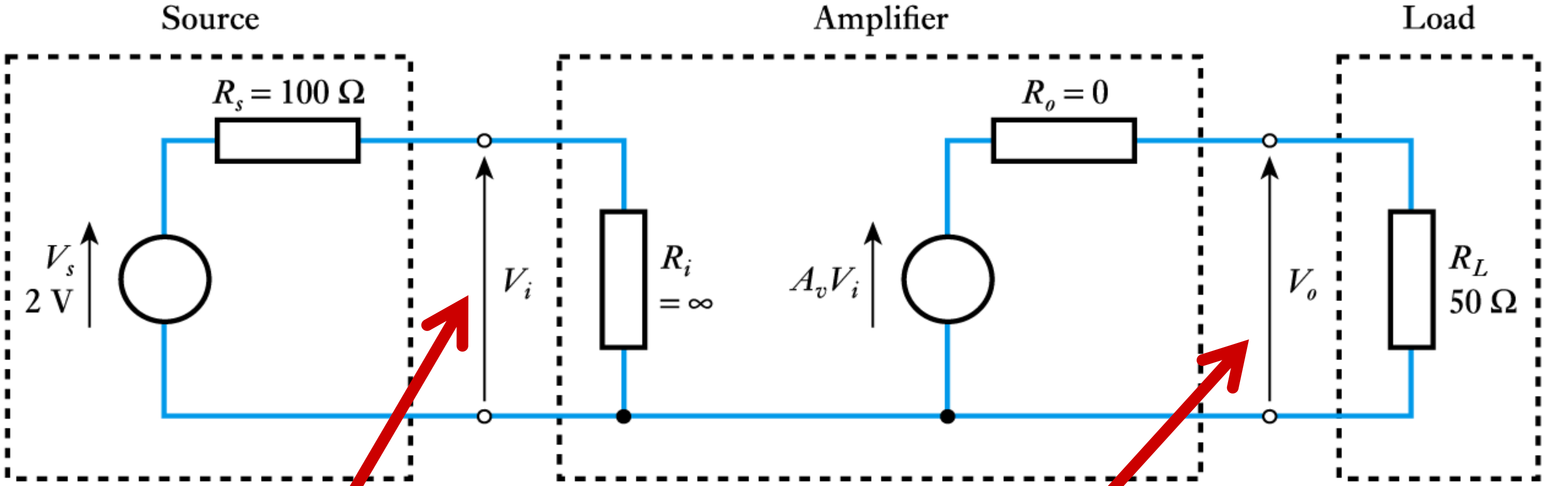
- An amplifier has a voltage gain of 10, an input resistance of 1 kΩ and an output resistance of 10 Ω.
- The amplifier is connected to a sensor that produces a voltage of 2 V and has an output resistance of 100 Ω, and to a load of 50 Ω.
- What will be the output voltage of the amplifier (that is, the voltage across the load resistance)?

- We start by constructing an equivalent circuit of the amplifier, the source and the load:



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,

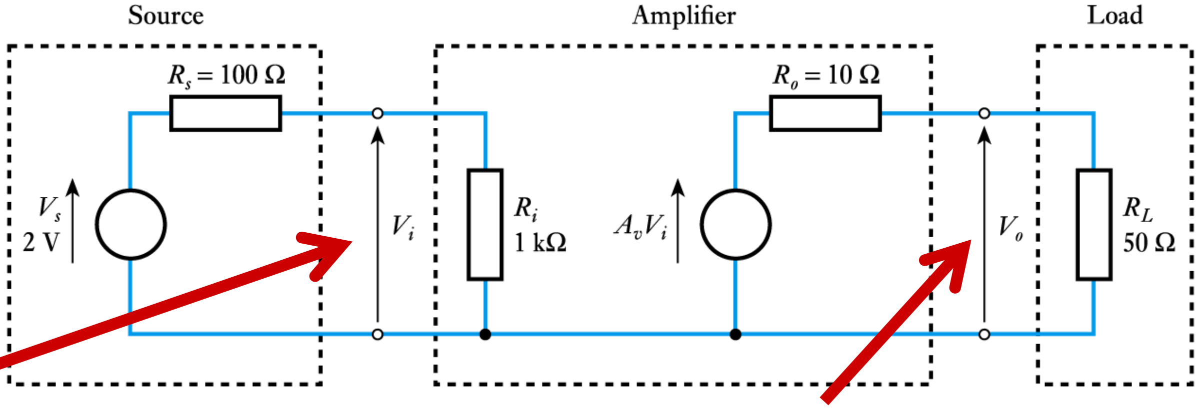
$$V_i = \frac{R_i}{R_s + R_i} V_s \approx V_s = 2\ \text{V}$$

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

An example (2)

- From this we calculate the output voltage:

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



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

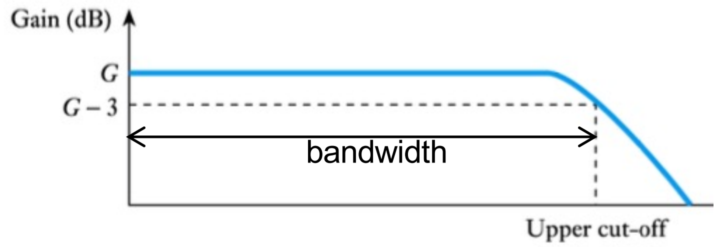
- Although the amplifier has a gain of 10 when it is NOT connected to anything, when used in the system, the actual gain is:

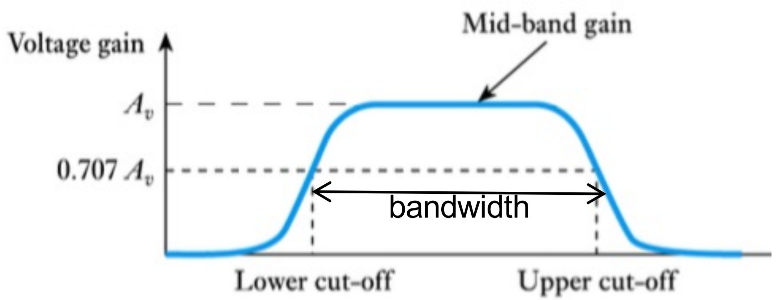
$$\text{Voltage Gain } (A_V) = \frac{V_O}{V_i} = \frac{15.2}{1.82} = 8.35$$

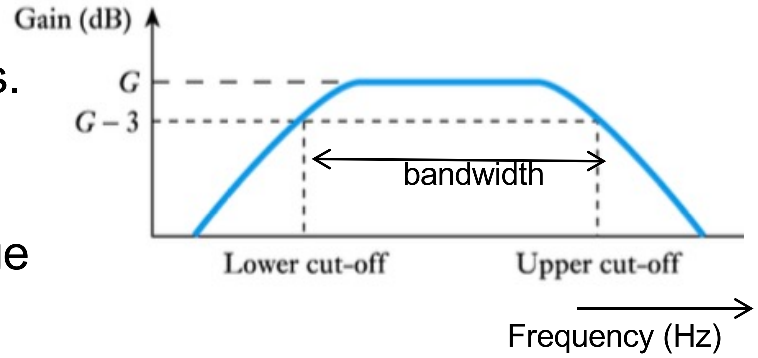
- The reduction of the voltage gain is due to **loading effects**.
- The original gain of the amplifier in isolation was 10. It is the **unloaded** gain.

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)

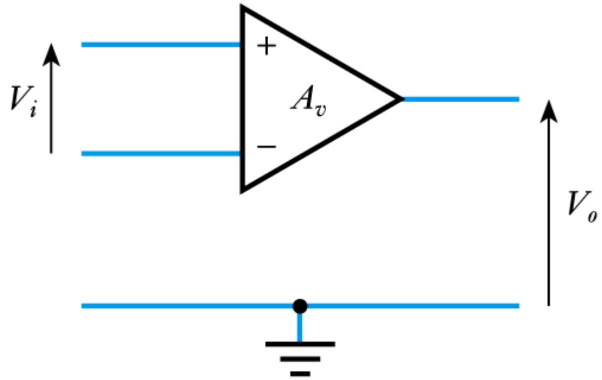




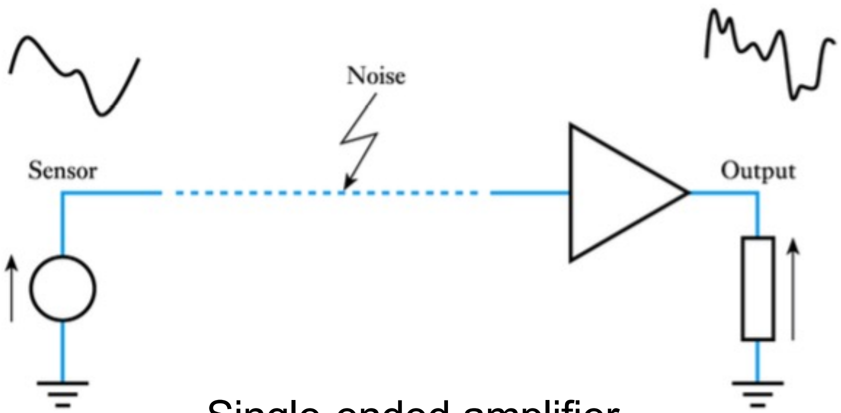


Differential amplifiers

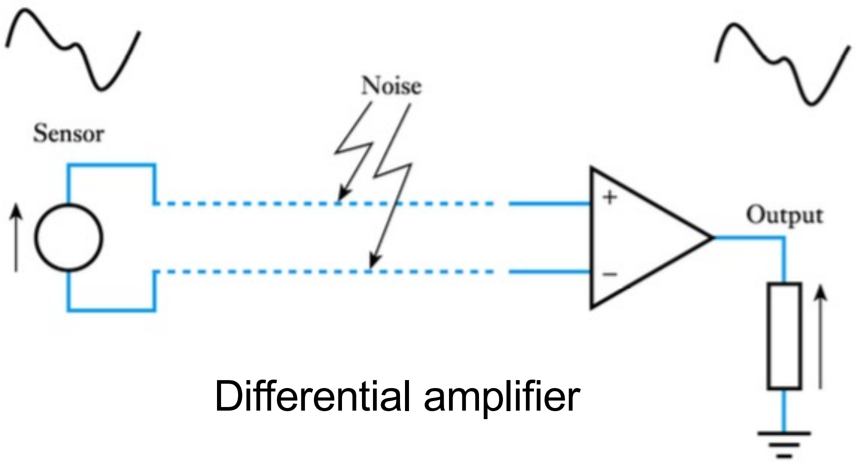
- Differential amplifiers have two inputs and amplify the voltage difference between them.
  - **non-inverting input** (labelled +) and **inverting input** (labelled –)



- An example of the use of a differential amplifier:



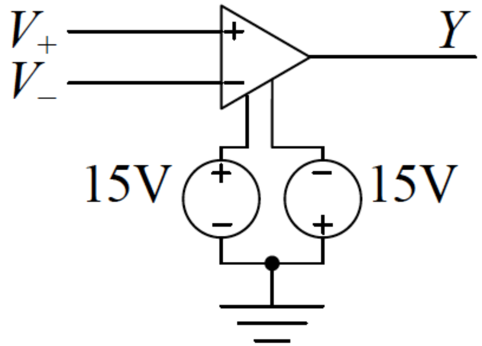
Single-ended amplifier



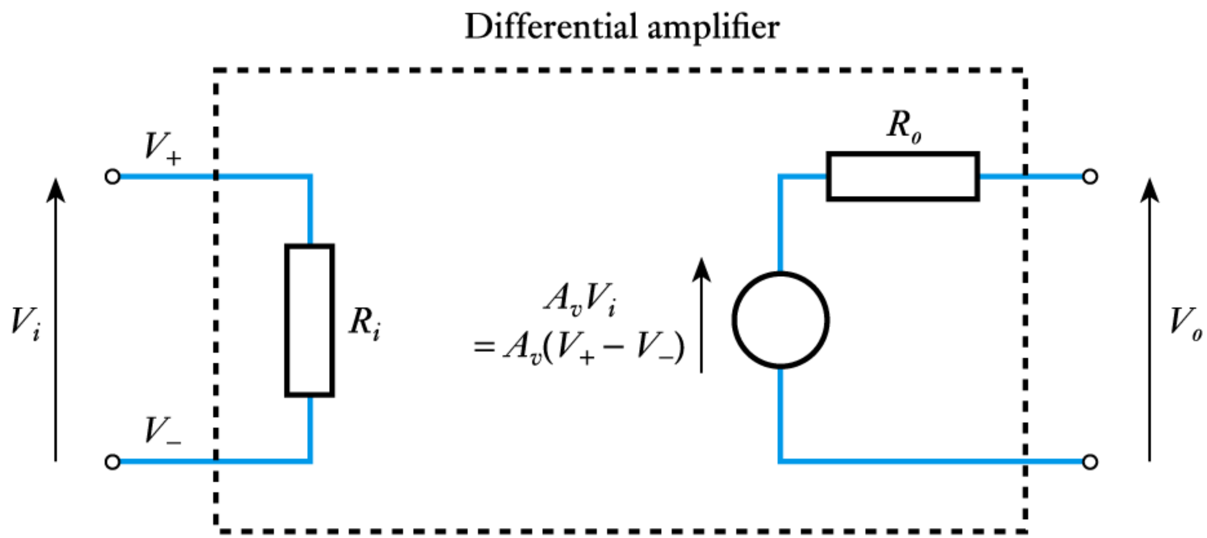
Differential amplifier

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

MICROCHIP **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 µA (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