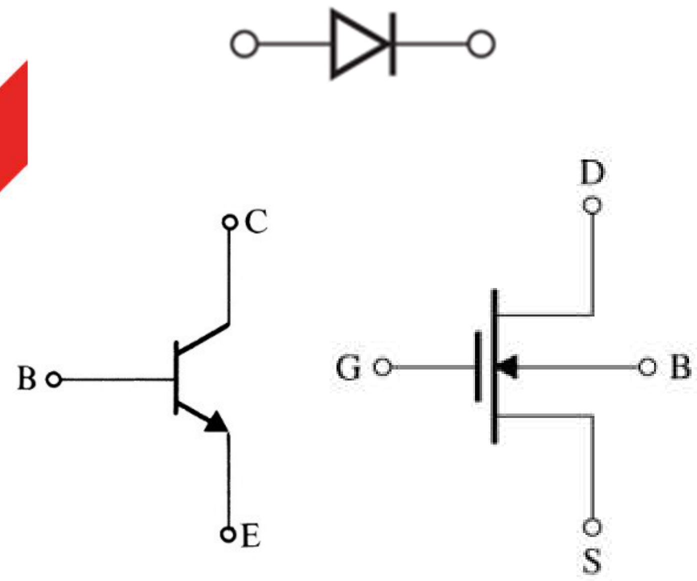
# ELEC2005
# Electrical and Electronic Systems

INTRODUCTION AND PREREQUISITE REVIEW

DAVID PAYNE



MACQUARIE University

# Lecture 1

1. **Unit Overview**
2. Review of fundamental concepts
3. Nonlinearity
4. Amplifiers

# Teaching Staff

**Unit Conveners:**

Dr. David Payne

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Dr. Leonardo Callegaro

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**Tutor:**

Tutors will also be available in the lab sessions and tutorial workshops.

**Please read the unit guide!**

# The Textbook

- These lectures topics are covered in the following textbooks:

Microelectronic Circuits

*Sedra/Smith, 6th Edition*

Power system analysis & design

*Glover/Overbye/Sarma, 6th Edition*

Power electronics: a first course

*Mohan*

# Two Parts to this Unit

**Part 1:** Weeks 1-7 Nonlinear Devices

Diodes, BJTs, MOSFETs

How do they ***work***?

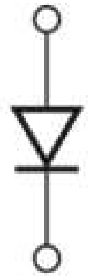
How do we use them in ***circuits***?

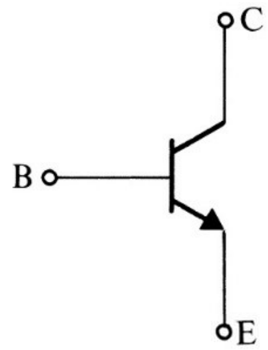
Building circuits to specifications (circuit ***design***)

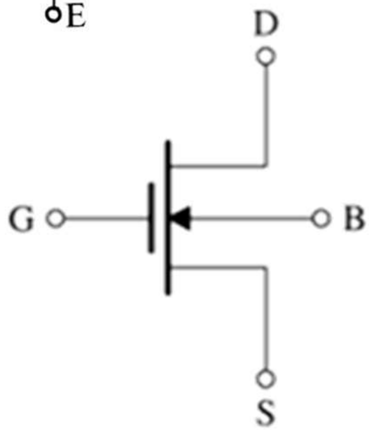
Developing a “library” of ***building blocks*** and…

Building our ***experience***!

**Part 2:** Weeks 8-13
High power systems and components, energy generation/conversion/storage





# Weekly plan, part 1

| Week | Lecture date Tuesday | Lecture Topics | Staff | Book chapters | Assignment | Laboratory/workshop session | Lab/ workshop location |
|---|---|---|---|---|---|---|---|
| 1 | 25/07/23 | Unit overview, prereq review,<br>circuit analysis and amplifiers. | DP | Sedra Ch. 1.1-1.5, 2 | | No laboratory or workshop session | 44 Waterloo Rd, Room G65 |
| 2 | 01/08/23 | Non-linearity,<br>Diodes, diode models and circuits | DP | Sedra Ch. 3 | | Lab 1: Introduction to LTspice and Analog Discovery Kits | 44 Waterloo Rd, Room G65 |
| 3 | 08/08/23 | BJT concepts, models.<br>Intro theory | DP | Sedra Ch. 4 | Assign 1 posted | Lab 2: Diode Circuits | 44 Waterloo Rd, Room G65 |
| 4 | 15/08/23 Submit Assign 1 | BJT large-signal and small-signal analysis | DP | Sedra Ch. 4 | | Tutorial Workshop 1: Diodes and BJTs | 44 Waterloo Rd, Room G65 |
| 5 | 22/08/23 | MOSFET concepts, models. Intro theory | DP | Sedra Ch. 5 | Assign 1 due | Lab 3: BJT Amplifier | 44 Waterloo Rd, Room G65 |
| 6 | 29/08/23 Submit Assign 2 | MOSFET Circuits, large-signal and small-signal analysis | DP | Sedra Ch. 5 | Assign 2 posted | Lab 4: MOSFET Amplifier | 44 Waterloo Rd, Room G65 |
| 7 | 05/09/23 | Power Semiconductors, Thyristors, IGBT | DP | Mohan Ch.2.1-2.4 | | Tutorial Workshop 2: MOSFETS and Power Semiconductors | 44 Waterloo Rd, Room G65 |

**Available for download from iLearn**

# Weekly plan, part 2

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 8 | 26/09/23 | AC circuits review, PFC: Ohm's law, KCL, KVL, series, parallel, time-domain AC power, phasors, impedance, power factor, power triangle, power factor correction (PFC) | LC | Lecture slides, Glover Ch. 2 | Assign 2 due | Lab 5: Single-phase ac circuits | 44 Waterloo Rd, Room G18 |
| 9 | 03/10/23 | Three-phase systems: 3ϕ power, star and delta connections, balanced and unbalanced 3ϕ systems | LC | Lecture slides, Glover Ch. 2 | Assign 3 posted | Lab 6: Power factor correction | 44 Waterloo Rd, Room G18 |
| 10 | 10/10/23 | Magnetics and transformer: Review of magnetic circuits, inductance calculation, power transformer principles | LC | Lecture slides, Mohan Ch. 7, Glover Ch. 3 | Assign 3 due | Tutorial Workshop 3: Single and three-phase ac circuits, power calculation, power factor correction | 44 Waterloo Rd, Room G18 |
| 11 | 17/10/23 | Principles of renewable-energy based power systems: renewables, PV energy & power conversion | LC | Lecture slides, (Masters Ch. 8 -) | Assign 4 posted | Lab 7: Single-phase transformer | 44 Waterloo Rd, Room G18 |
| 12 | 24/10/23 | Principles of battery energy storage and electric vehicles | LC | Lecture slides, (Masters Ch. 9 -; LabVolt Battery Manual) | | Lab 8: Three-phase circuits | 44 Waterloo Rd, Room G18 |
| 13 | 31/10/23 | Review Lecture | LC | | Assign 4 due | Tutorial Workshop 4: Magnetics, solar energy conversion, battery storage | 44 Waterloo Rd, Room G18 |

# Learning Outcomes

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**1.** Distinguish the main technical features of electrical and electronic technologies used in renewable energy and storage, electrical transportation, robotics and autonomous systems

**2.** Identify operational characteristics of typical power converters and electrical machines for a range of industrial applications

**3.** Demonstrate fundamental knowledge in power computations in AC systems

**4.** Explain the working principles of key nonlinear devices such as transistors and power semiconductors

**5.** Design, simulate, and perform hardware evaluation of circuits with one or more nonlinear components

Main Focus of Part 1

# Learning Outcome 4

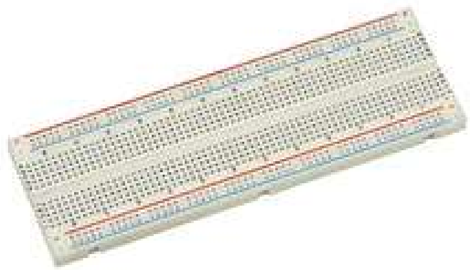
**4.** Explain the working principles of key nonlinear devices such as transistors and power semiconductors

- Building on prerequisite knowledge (ELEC2070)
- Learn the properties and characteristics of non-linear devices including diodes and transistors
- Learn how these devices work at the circuit level to modify current and voltage
- Use equivalent circuit models to simplify complex linear and nonlinear circuits
- In most cases, such models can enable linearization of the circuit within the limits of interest

# Learning Outcome 5

**5.** Design, simulate, and perform hardware evaluation of circuits with one or more nonlinear components

- Throughout the unit you will use LTSpice circuit simulation tools to help build your understanding of non-linear devices and circuits
- This learning outcome will be assessed in the laboratory sessions. Lab 1 will include an introduction to circuit simulation with LTSpice
- To work through the Part 1 lab worksheets you will build and analyse physical electronic circuits
- You will learn how to rapidly prototype non-linear circuits and how to measure the response (steady state and frequency response)



# Assessment

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- Assessment will be split across pre-lecture mini-quizzes, laboratory sessions, online assignments, and a final exam
- Weekly schedule gives details of relevant timings and deadlines
- Further details will be available through iLearn

| Assessment Type | Assessment Weightings (%) |
|---|---|
| Pre-lecture mini quizzes | 10 |
| Laboratories | 25 |
| Assignments | 30 |
| Final Exam | 35 |

# Pre-Lecture Mini Quizzes

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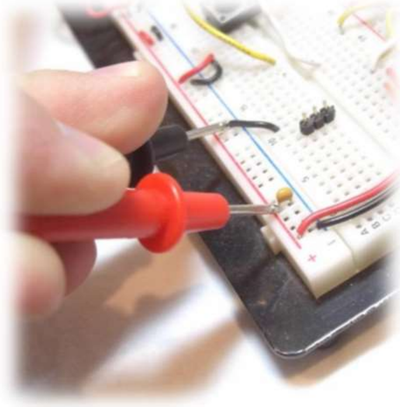
- A short ilearn quiz will be made available in the week prior to each lecture
- Lecture slides and additional learning content for that week will also be available on iLearn
- You will use these resources to answer the mini-quiz **before** coming to the lecture (The quiz will close at the lecture start time!)
- This is to encourage active student engagement and better understanding during the lectures
- These quiz questions will be short and simple. They will total 10% of the overall assessment for the unit.

# Laboratories and Workshops

Aligned with learning outcomes.

1. Laboratory sessions for simulating, constructing and measuring circuits.
2. Problem solving workshops for practicing for tests.

Start in **Week 2** (check weekly plan)



| | | | |
|---|---|---|---|
| To maximize benefit, arrive on time to scheduled sessions and use your time efficiently | Revise lecture notes and online learning content to prepare | You can work on labs or tutorials in your own time, during the timetabled session, or both! | Upload your lab worksheet questions to iLearn for grading. |

# Flexible Practical Learning

- Part 1 Laboratory modules are in a worksheet format
- You will be provided with portable 'lunch-box lab kits'
- You can progress through the worksheets on your own schedule, in the location of your choice
- During scheduled lab timeslots we will provide support
- It is strongly recommended that you attend these sessions
- You should at least carry out the 'pre-lab' section of the worksheet before attending scheduled lab session
- Worksheet answers will be submitted via an ilearn quiz
  **Deadline is 11:55pm on the day of the scheduled lab session (unless stated otherwise)**



**Collect kits this week! See iLearn for instructions**

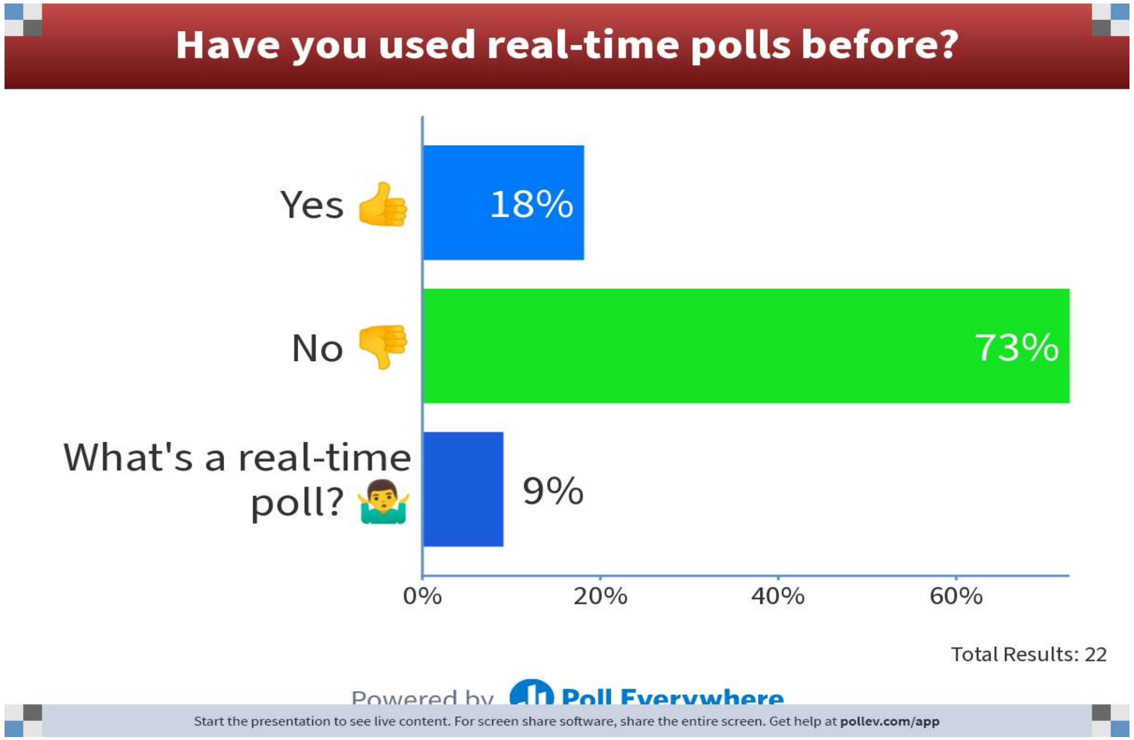
# Assignments

- Assignment questions will be in the form of iLearn quizzes.
- Questions will have randomised component values (answers will vary – Do not copy each other!)
- Your marks and the correct answers will be posted < 2 weeks after the submission date
- You will have at least 10 days to complete each assignment! Late submissions will only be accepted through formal special consideration requests with evidence.
- Worked solutions will not be provided be default. If one of your answers is marked incorrect, you are encouraged to re-work the problem to try to find the error and get to the correct answer
- The conveners and tutors are here to help if needed, we will happily work through it with you

# Interactive Feedback

## Poll Everywhere

- We use Poll Everywhere for real-time feedback and polling during lectures
- Use your browser in smartphone/computer or install the Poll Everywhere App




Timer Bar (2 mins) :

Go to **PollEv.com/davidpayne187** on your mobile or laptop to vote

# Lecture 1

1. Unit Overview
2. **Review of fundamental concepts**
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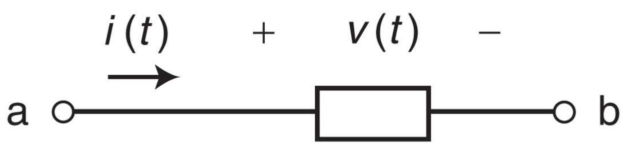
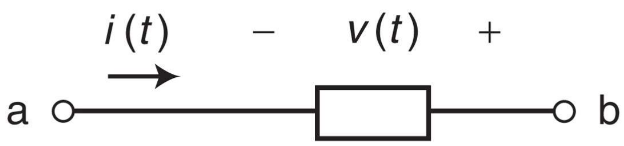
# Review of Fundamentals

## POLARITY, RESISTANCE




(a)




(b)

(a) **Passive:** Cannot introduce net energy into the circuit (for example a resistor).

(b) **Active:** Relies on a source of energy – can usually inject power to the circuit (for example a battery).

**We are going to use resistors in their linear region**

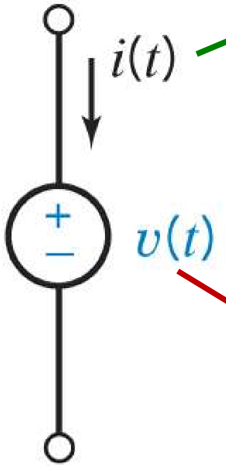
$$v = Ri$$

→ Mathematical model of an ideal (linear) resistor

# Review of Fundamentals

## IDEAL INDEPENDENT SOURCES

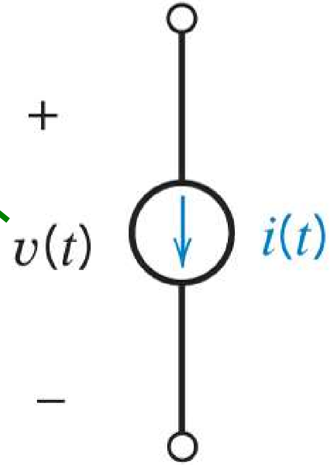
These are unknown values until we calculate in a circuit (they can be any value if ideal source)




This is the set value (known)

(a)

Symbol of ideal independent voltage source



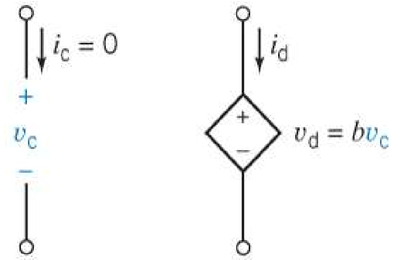

This is the set value (known)

(b)

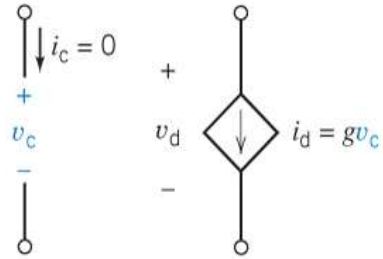
Symbol of ideal independent current source

# Review of Fundamentals

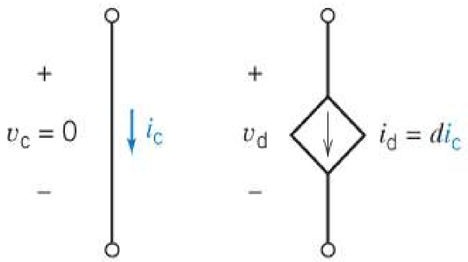
## DEPENDENT SOURCES



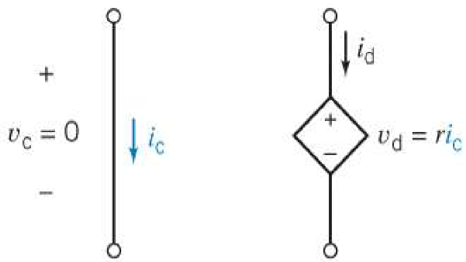

Voltage-Controlled
Voltage Source (VCVS)




Voltage-Controlled
Current Source (VCCS)




Current-Controlled
Current Source (CCCS)



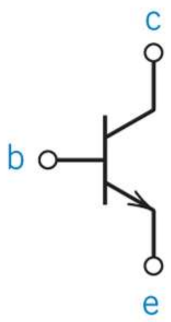

Current-Controlled
Voltage Source (CCVS)

**There are no simple dependent sources in practice!**
But they are useful for modelling transistors, amplifiers etc.

# Review of Fundamentals

## DEPENDENT SOURCE EXAMPLE

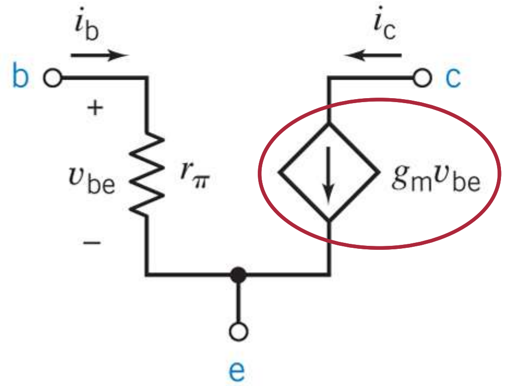
Transistor action:
Current between **c** and **e** depends on voltage between **b** and **e**



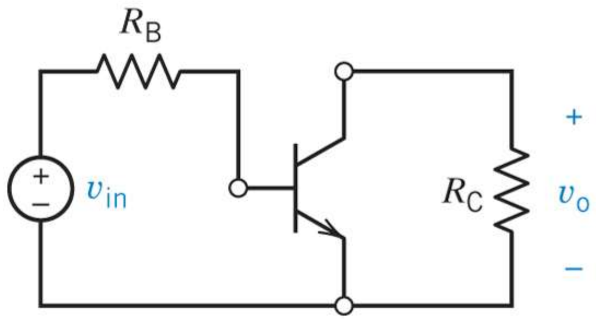

(a)

$i_c = g_m v_{be}$

constant

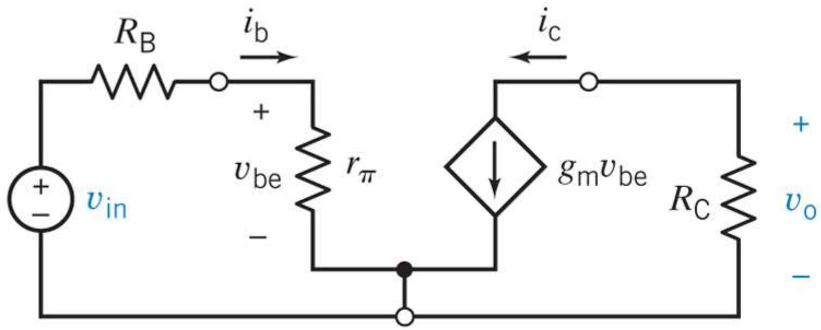



(b)




(c)

**Actual circuit**




(d)

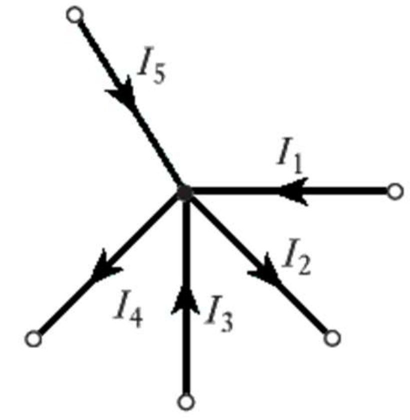
**Equivalent circuit**

- easier to analyze
- describes behavior of original circuit

# Review of Fundamentals

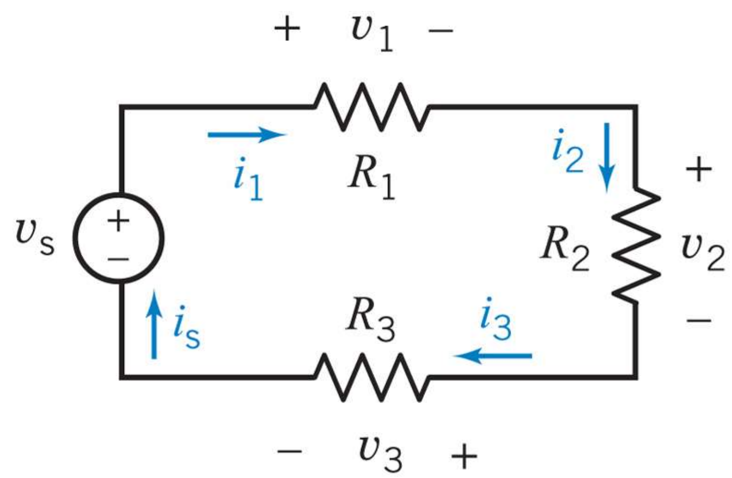
## KIRCHOFFS LAWS

The algebraic sum of all **currents entering or leaving a node is zero** at any time instant




$$I_1 - I_2 + I_3 - I_4 + I_5 = 0$$

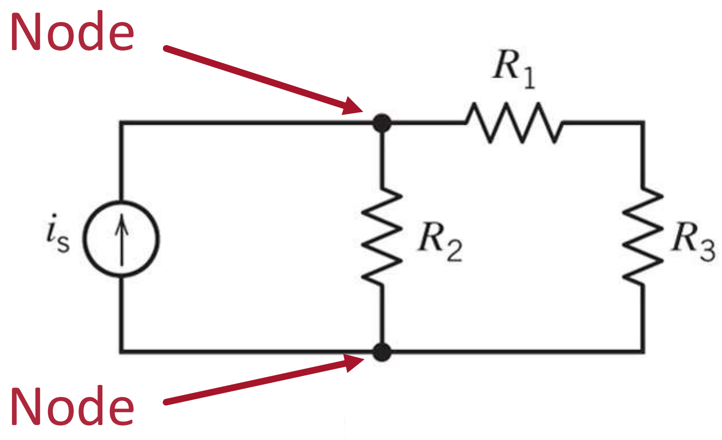
The algebraic sum of all **voltages around a loop is zero** at any time instant

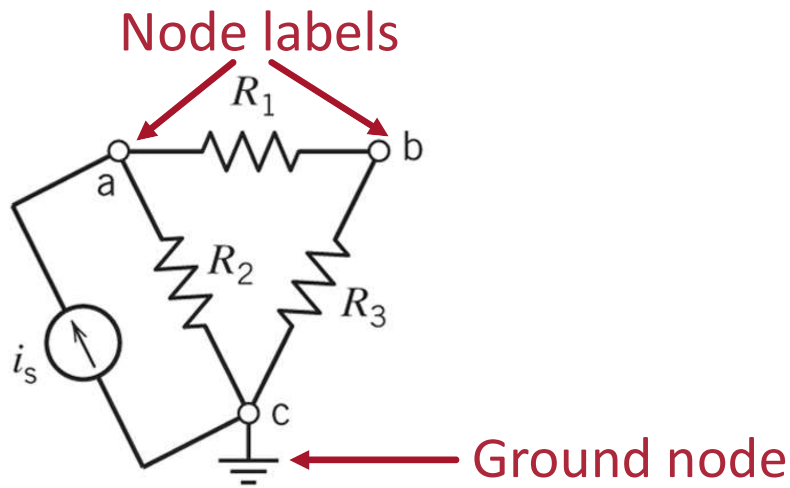



$$v_1 + v_2 + v_3 - v_s = 0$$

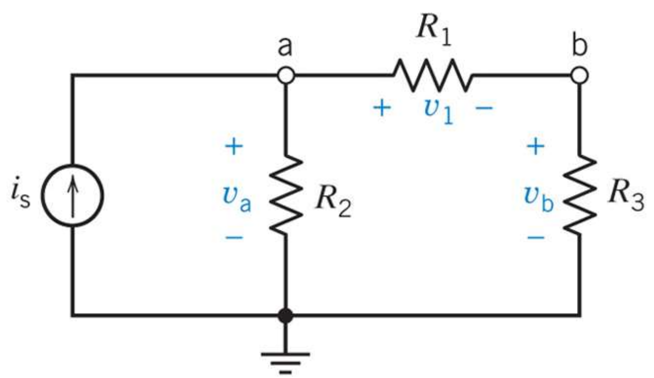
# Review of Fundamentals

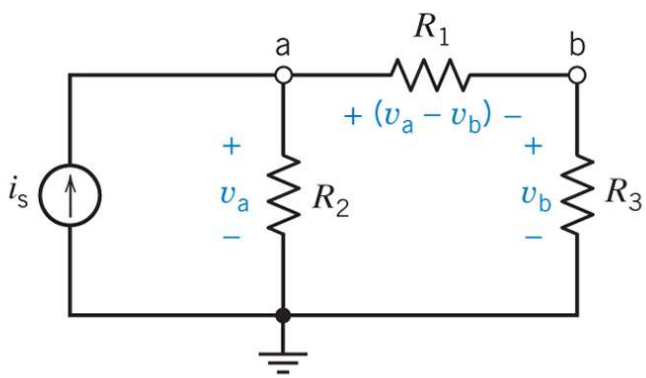
## NODES



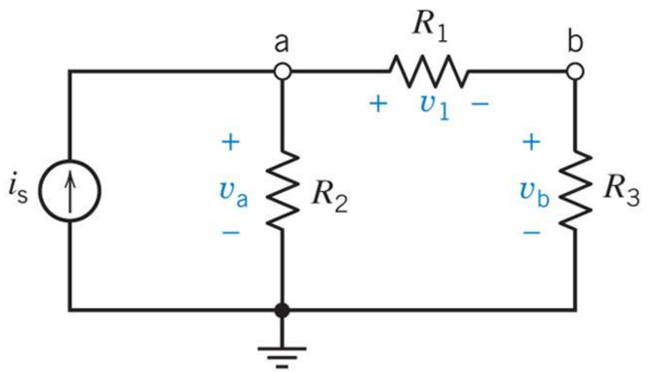

Ground node potential is zero volts.
All other nodes can be measured relative to ground.
Each node corresponds to a unique voltage (relative to ground).



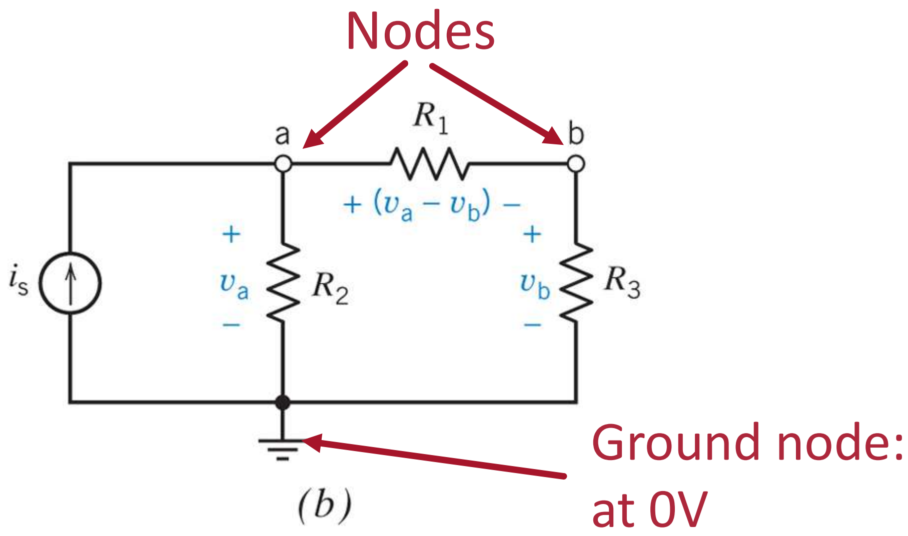



# Review of Fundamentals

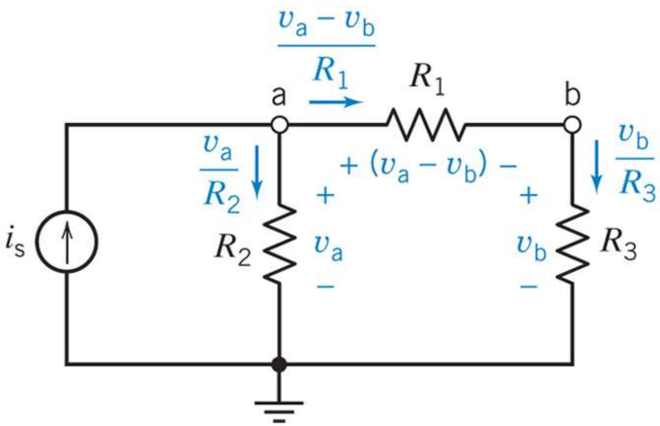
## NODE VOLTAGE ANALYSIS: STEP 1




(a)




(b)




(c)

1. First, write element currents in terms of node voltages:

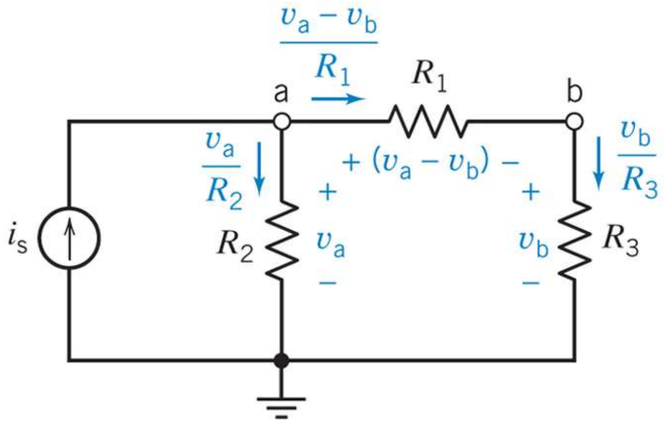
$$i_1 = \frac{v_a - v_b}{R_1} \qquad i_2 = \frac{v_a}{R_2} \qquad i_3 = \frac{v_b}{R_3}$$

Pay attention to the direction of current!

# Review of Fundamentals

## NODE VOLTAGE ANALYSIS: STEP 2

2. Apply Kirchhoff's **Current** Law at each node, except for the ground node:




(c)

Node a: $i_s = i_1 + i_2$

$$\boxed{i_s = \frac{v_a - v_b}{R_1} + \frac{v_a}{R_2}}$$

Node b: $i_1 = i_3$

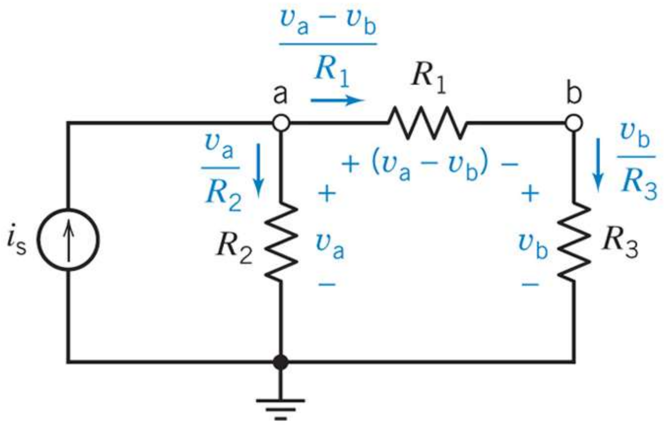
$$\boxed{\frac{v_a - v_b}{R_1} = \frac{v_b}{R_3}}$$

The variables $i_1$ and $i_2$ are not needed if we want to find only the node voltages. The source current $i_s$ is normally given.

# Review of Fundamentals

## NODE VOLTAGE ANALYSIS: STEP 3

3. Order the equations with respect to the unknowns (such as you would do for the matrix method) and solve them:



(c)

Node a:

$$i_s = \frac{v_a - v_b}{R_1} + \frac{v_a}{R_2}$$

$$i_s = \left(\frac{1}{R_1} + \frac{1}{R_2}\right) v_a - \frac{1}{R_1} v_b$$

Node b:

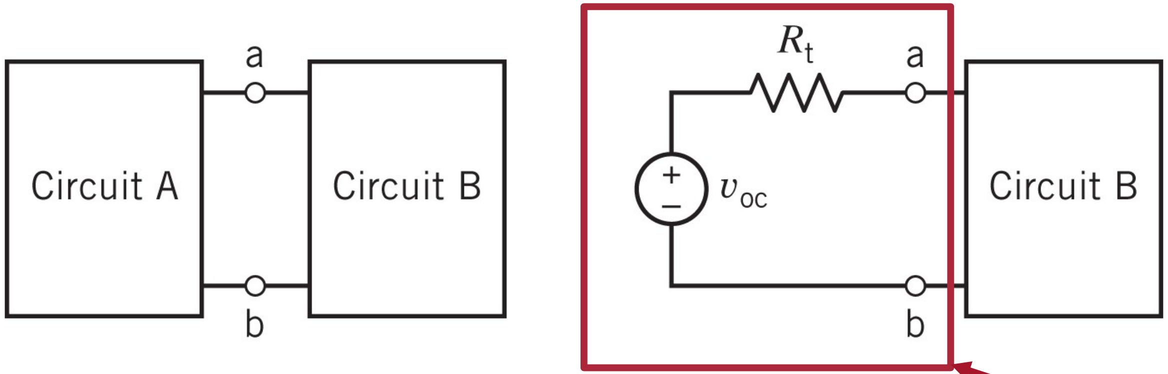
$$\frac{v_a - v_b}{R_1} = \frac{v_b}{R_3}$$

$$0 = \left(\frac{1}{R_1} + \frac{1}{R_3}\right) v_b - \frac{1}{R_1} v_a$$

# Review of Fundamentals

## THÉVENIN'S THEOREM

*"Any combination of voltage sources and resistors with two terminals can be replaced by a single voltage source and a single series resistor."*



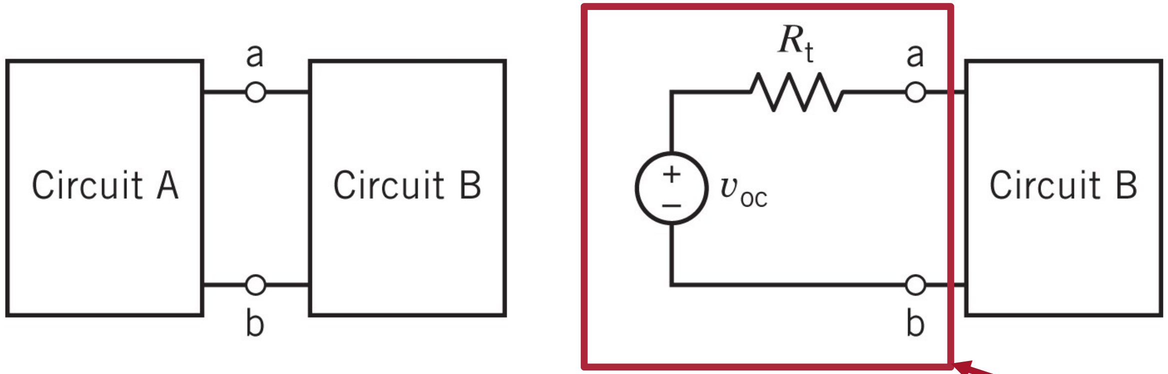

Léon Charles Thévenin
1857 - 1926

Thévenin equivalent circuit

Circuit A can be replaced with a simpler Thévenin equivalent circuit.

# Review of Fundamentals

## THÉVENIN'S THEOREM




Thévenin equivalent circuit

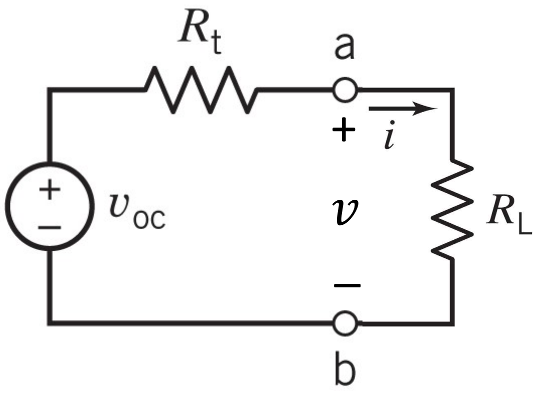
Thévenin equivalent circuit of Circuit A:

1. Calculate the **open-circuit voltage** and the **short-circuit current** of Circuit A.
2. Then calculate Thévenin resistance as: $$R_t = \frac{v_{oc}}{i_{sc}}$$

This method works well for calculations but may not be good in practice.
For example: if you short circuit a battery, you will discharge it.

# Review of Fundamentals

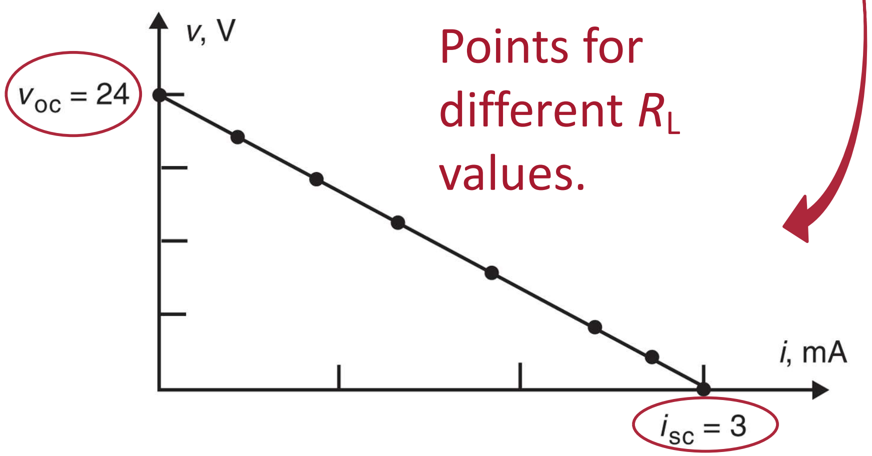
## GRAPHICAL ANALYSIS TO DETERMINE THÉVENIN EQUIVALENT




From KVL we have

$$v = v_{oc} - R_t i$$

Only $v_{oc}$ and one $R_L$ measurement is needed to make a linear graph. This is easy.




Points for different $R_L$ values.

A plot of terminal voltage and currents.

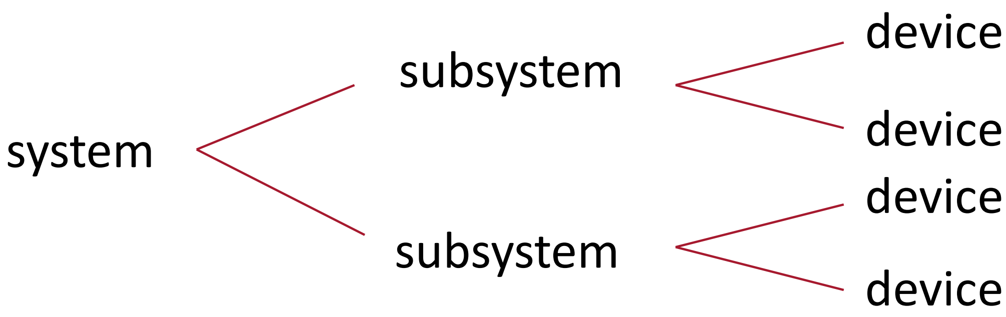
Useful method for when we are in the lab!

# Lecture 1

1. Unit Overview
2. Review of fundamental concepts
3. **Nonlinearity**
4. Amplifiers

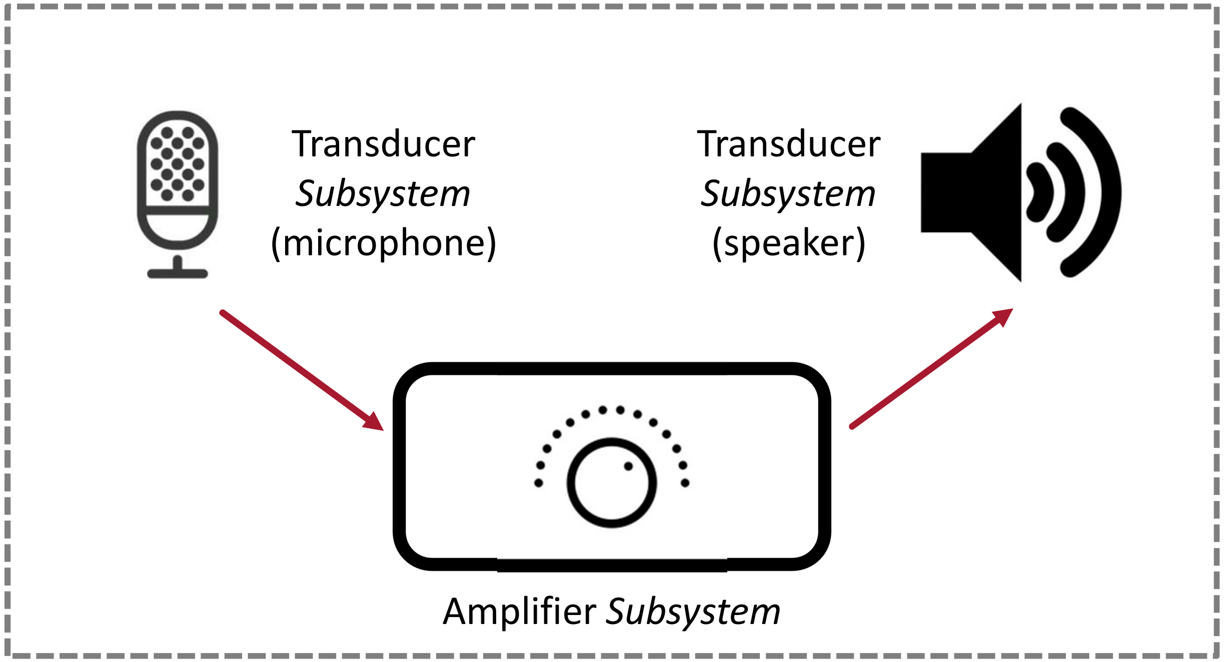
# Intro to Nonlinear Devices

## DEVICES



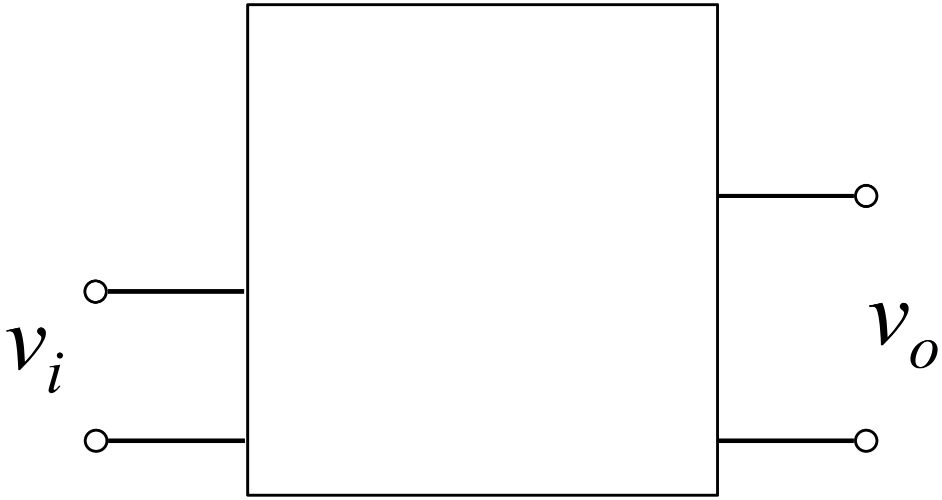

Example case:

Audio *System*



# Intro to Nonlinear Devices

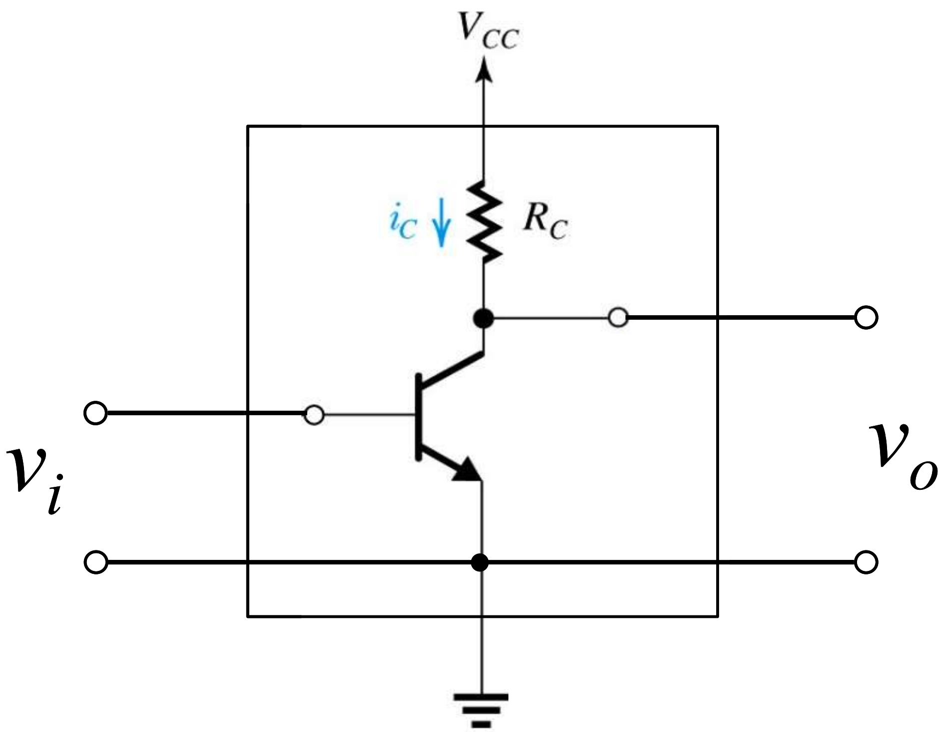
## Devices




Amplifier *subsystem*

# Intro to Nonlinear Devices

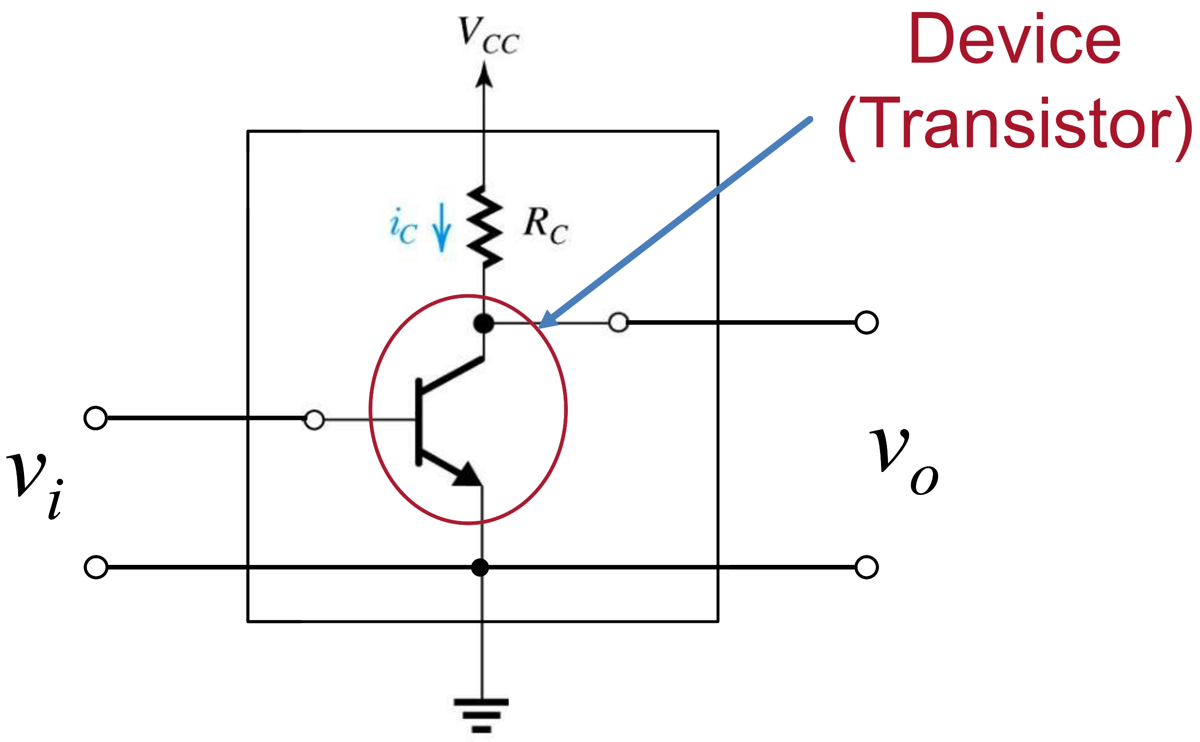
## Devices




Amplifier *subsystem*

# Intro to Nonlinear Devices

## Devices

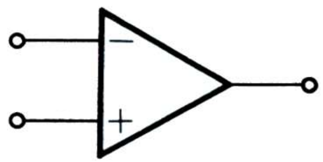



Amplifier *subsystem*

# Intro to Nonlinear Devices

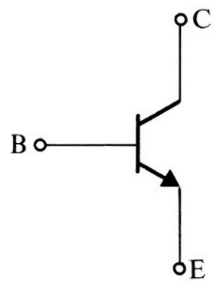
## WHAT IS A NONLINEAR DEVICE/CIRCUIT?

- Many systems/subsystems involve complex nonlinear circuits with multiple nonlinear devices
- Four of the most common nonlinear devices are shown here, diodes and transistors and the circuits constructed with them are the focus of part 1 of this unit
- For each of these, the relationship between their output and input characteristics is not linear

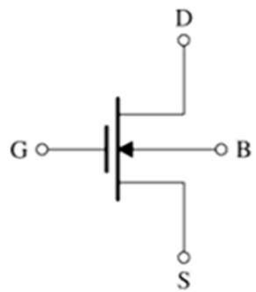



Opamp

Diode




Bipolar Junction Transitor



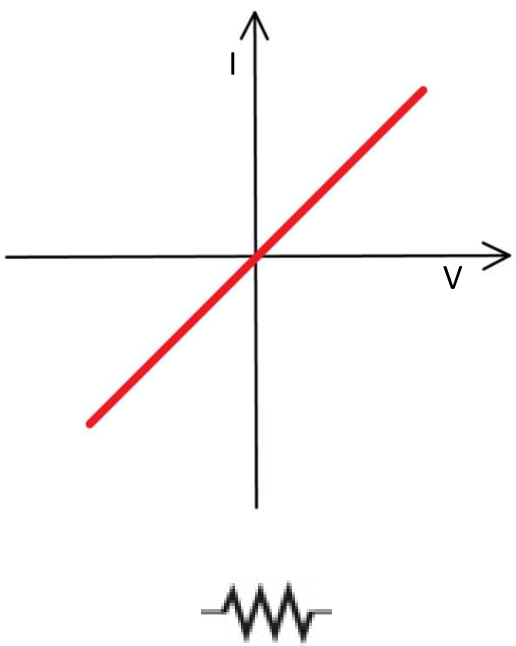

Field Effect Transitor

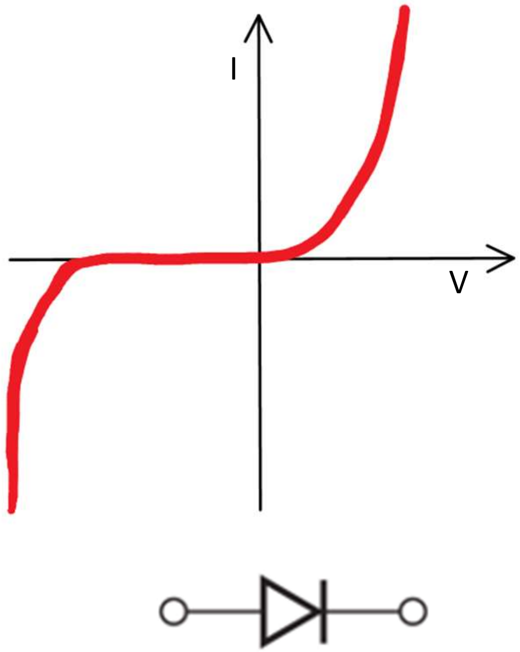
# Intro to Nonlinear Devices

WHAT IS A NONLINEAR DEVICE/CIRCUIT?

- Devices such as *ideal* resistors, capacitors and inductors have a output characteristics that are a linear function of input.

- Diodes and transistors have a more complex relationship between input and output
  - Though they have regions of linearity

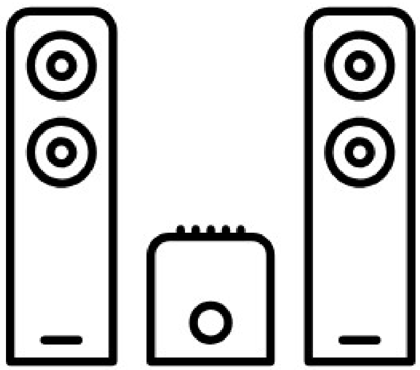


# Intro to Nonlinear Devices

## WHY ARE NONLINEAR DEVICES IMPORTANT?

- Much of modern electronics now involves digital signal processing and logic circuits
- However, digital electronics need to interface with the real world
- Nonlinear devices and circuits are required for this, particularly for signal amplification and initial filtering



# Lecture 1

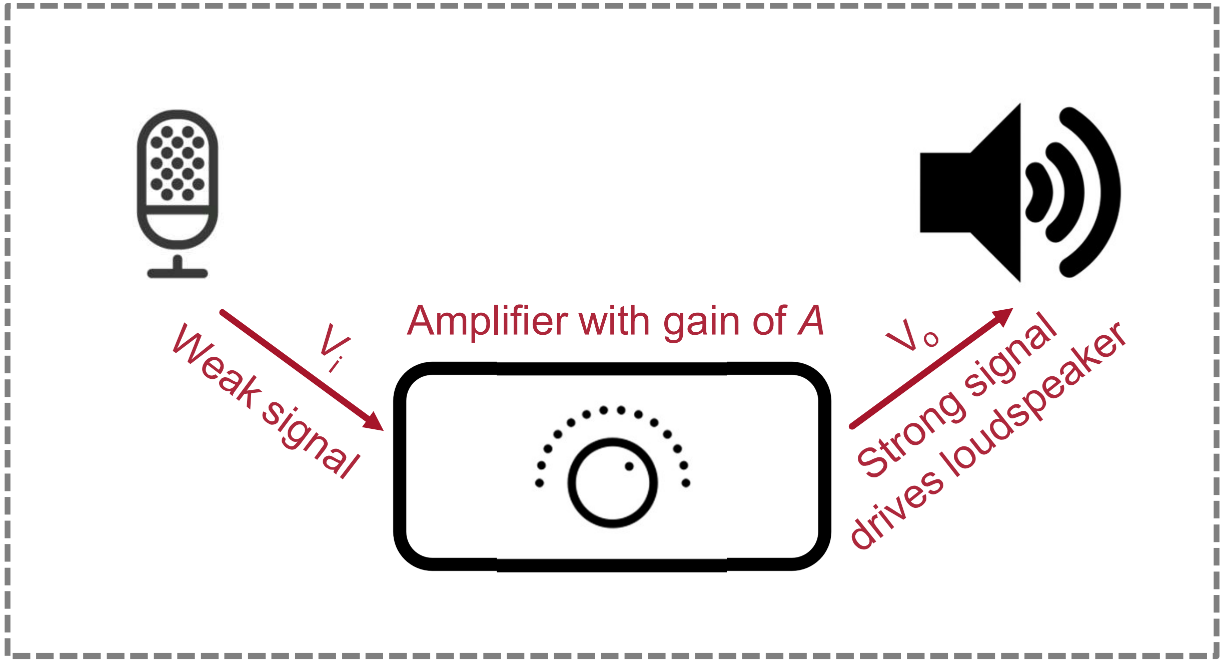
1. Unit Overview
2. Review of fundamental concepts
3. Nonlinearity
4. **Amplifiers**

# Amplifiers

## WHY DO WE NEED THEM AND WHAT DO THEY DO?

- Most transducers produce very weak signals (uV – mV range).
- We need to strengthen these signals whilst maintaining the information
  - Need linear gain, though non linearity here can also be useful

Audio System

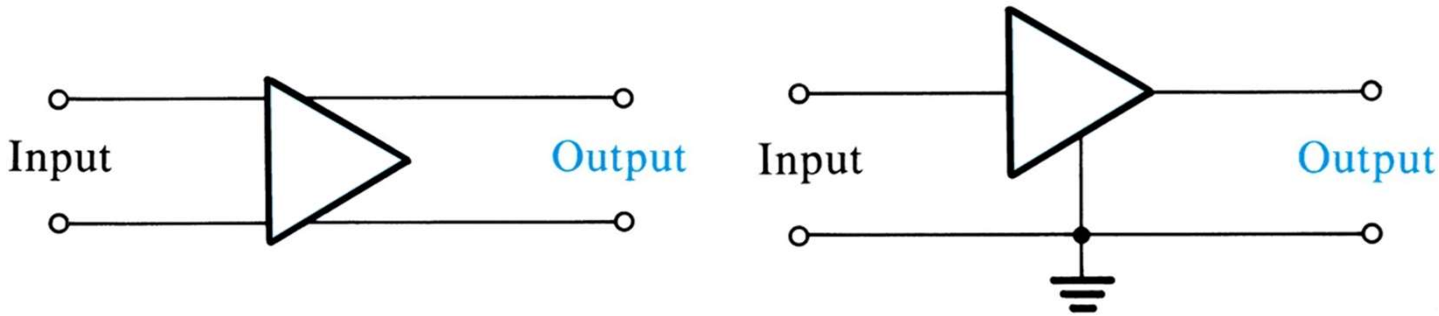



The output is the input, scaled by *A* (the *gain*)

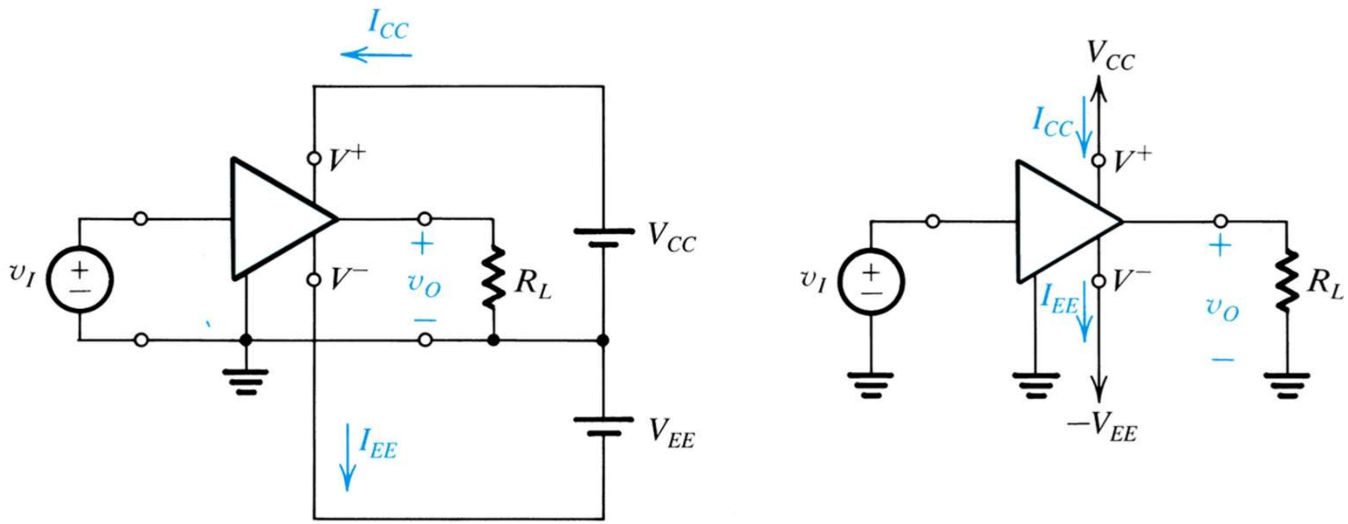
$$V_o(t) = AV_i(t)$$

# Amplifiers

## CIRCUIT SYMBOL



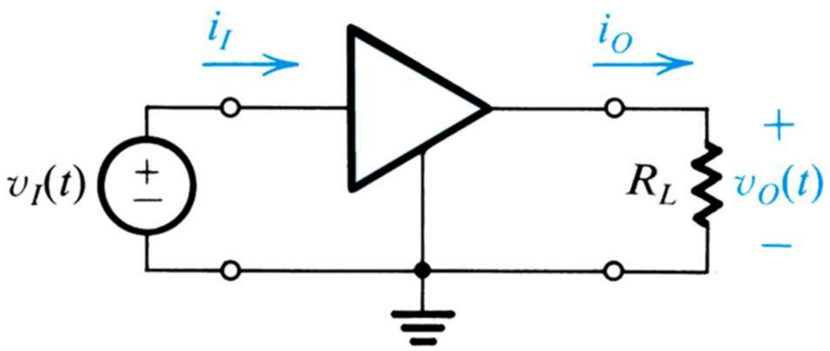

- A two port circuit, shown as a triangle indicating the direction of signal flow
- Typically there is a common terminal – a reference point (*ground*)
- In reality, the amp also has a power supply (often not explicitly shown)



# Amplifiers

## GAIN AND TRANSFER CHARACTERISTIC

- Signal gain can be achieved and expressed through voltage, current or power




Voltage gain:

$$A_v \equiv \frac{\upsilon_o}{\upsilon_I}$$

Current gain:

$$A_i \equiv \frac{i_o}{i_I}$$

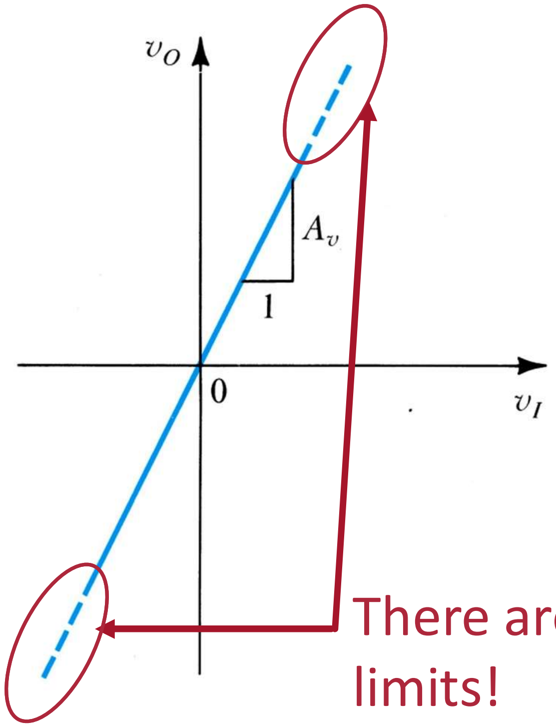
Power gain:

$$A_p \equiv \frac{\upsilon_o i_o}{\upsilon_I i_I} = A_\upsilon A_i$$

Gain is a ratio, expressed as dimensionless, or V/V, A/A etc.
Engineers often express gain logarithmically

$20 \log |A_v|$ dB    $20 \log |A_i|$ dB    $10 \log A_p$ dB

Example transfer characteristic:




There are limits!

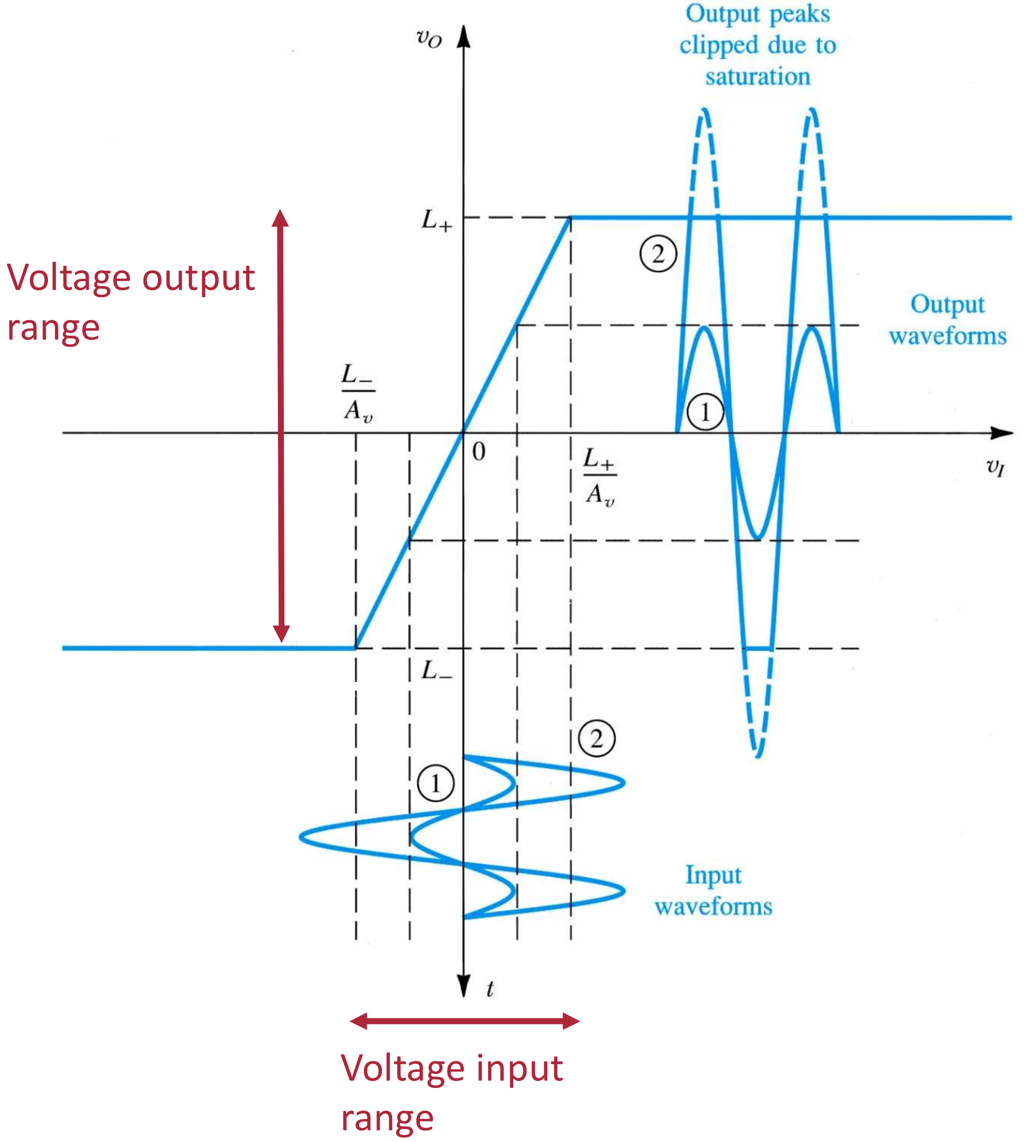
# Amplifiers

## SATURATION

- In reality, gain is limited
- Saturation, or clipping, will occur when the output voltage approaches that of the power supplies
- Output signal becomes distorted

We must design amplifiers to avoid this! Knowledge of the input range is needed.

More realistic transfer characteristic



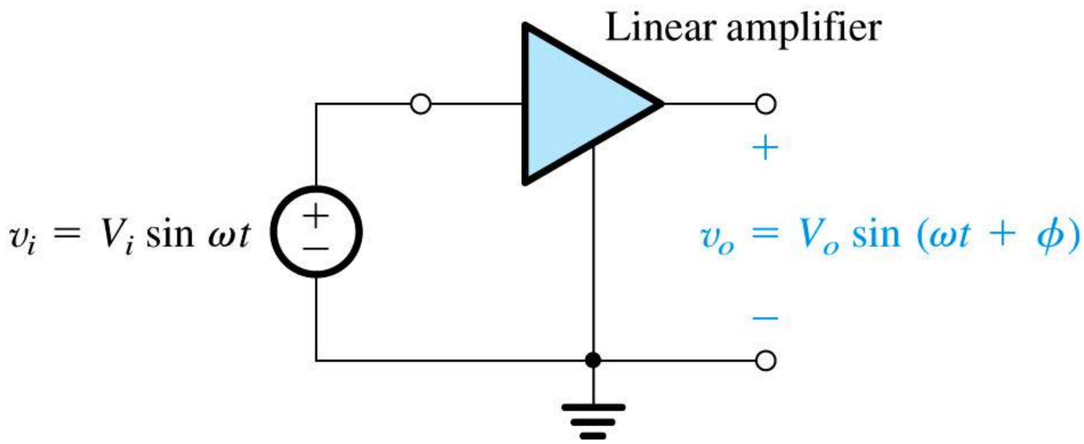
# Amplifiers

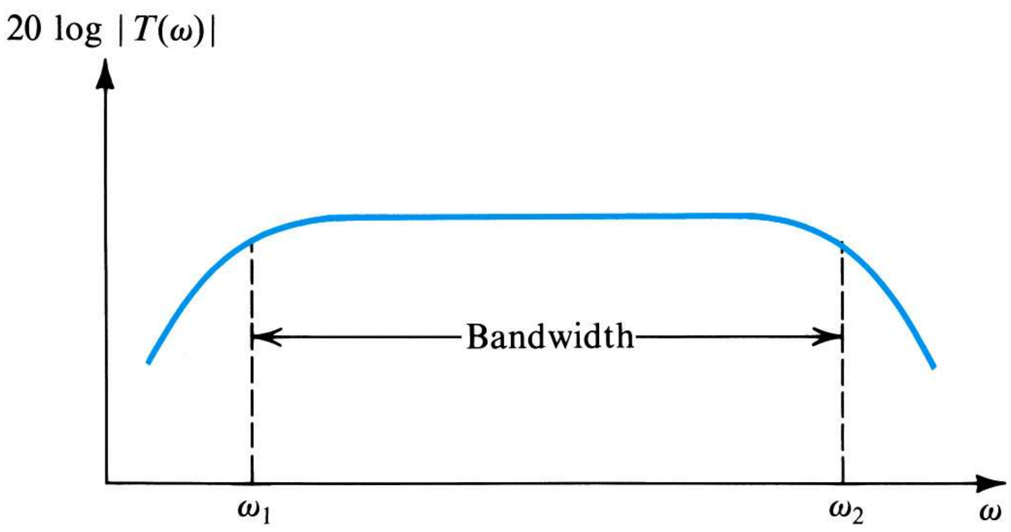
## FREQUENCY RESPONSE AND BANDWIDTH

- Amplifying a sine wave signal can change it's amplitude and phase, but not it's frequency

- Amplifiers typically only have a flat gain response over a specific frequency range, the *bandwidth*

We must design amplifiers to operate correctly over the correct frequency range for our application!

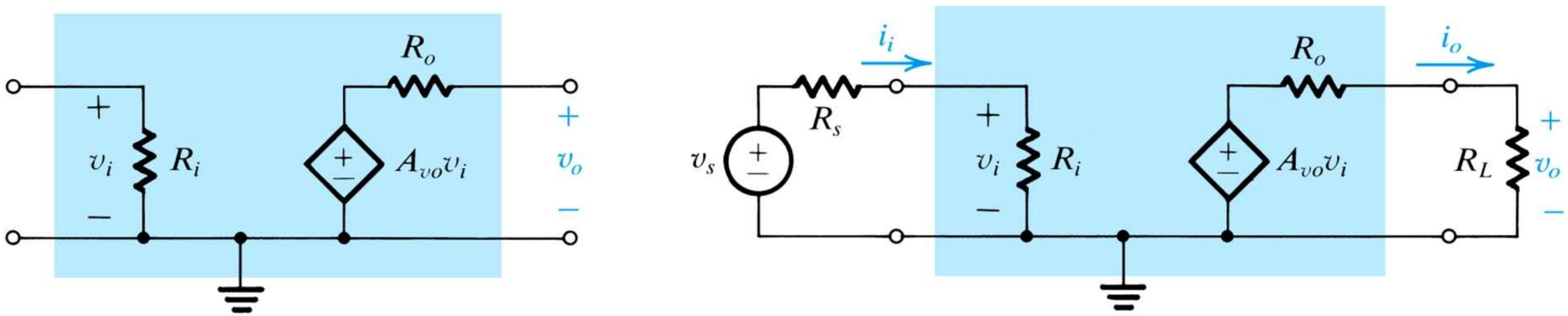


# Amplifiers

## CIRCUIT MODELS

- Used to model terminal behaviour of amp (simplified to a building block)
- Example for a voltage amplifier




$$\upsilon_0 = i_0 R_L = A_{\upsilon o}\upsilon_i R_L / (R_o + R_L) = A_{\upsilon o}\upsilon_i \frac{R_L}{R_L + R_O}$$

Open circuit voltage gain:

$$A_{\upsilon o} = \frac{\upsilon_o}{\upsilon_i}$$

$$\upsilon_i = \upsilon_s \frac{R_i}{R_i + R_s}$$

Overall voltage gain: $$\frac{\upsilon_o}{\upsilon_s} = A_{\upsilon o} \frac{R_i}{R_i + R_s} \frac{R_L}{R_L + R_o}$$

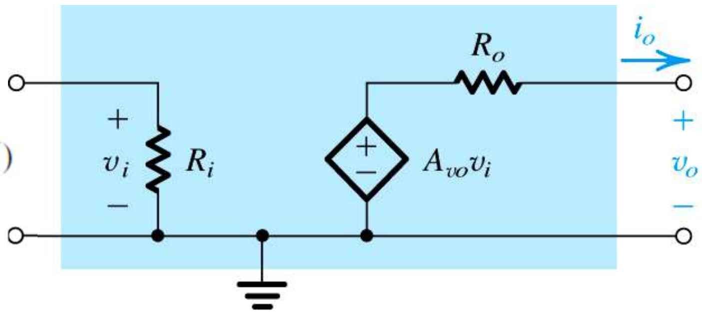
# Amplifiers

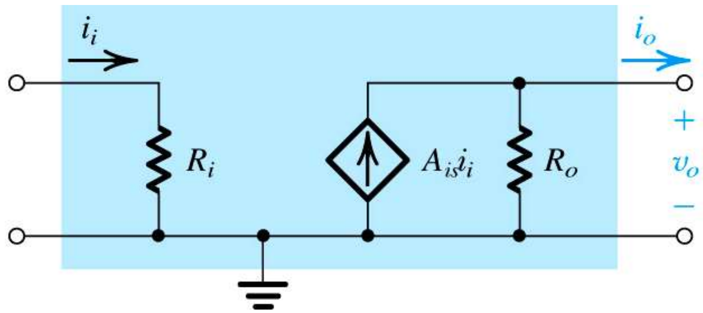
## THE FOUR TYPES OF AMPLIFIER

- Signal of interest (at input or output) may be current or voltage
- Voltage amplifier is most popular but other models can be used

Voltage Amp

$$A_{vo} \equiv \left.\frac{v_o}{v_i}\right|_{i_o=0} \text{ (V/V)}$$



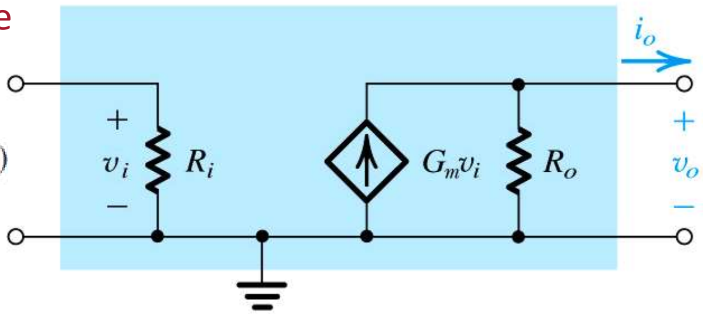



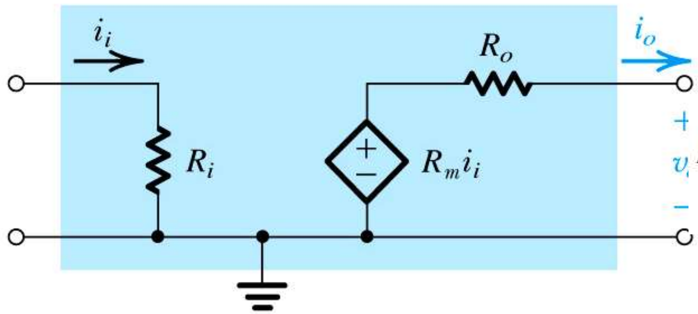

Current Amp

$$A_{is} \equiv \left.\frac{i_o}{i_i}\right|_{v_o=0} \text{ (A/A)}$$

Transconductance Amp

$$G_m \equiv \left.\frac{i_o}{v_i}\right|_{v_o=0} \text{ (A/V)}$$



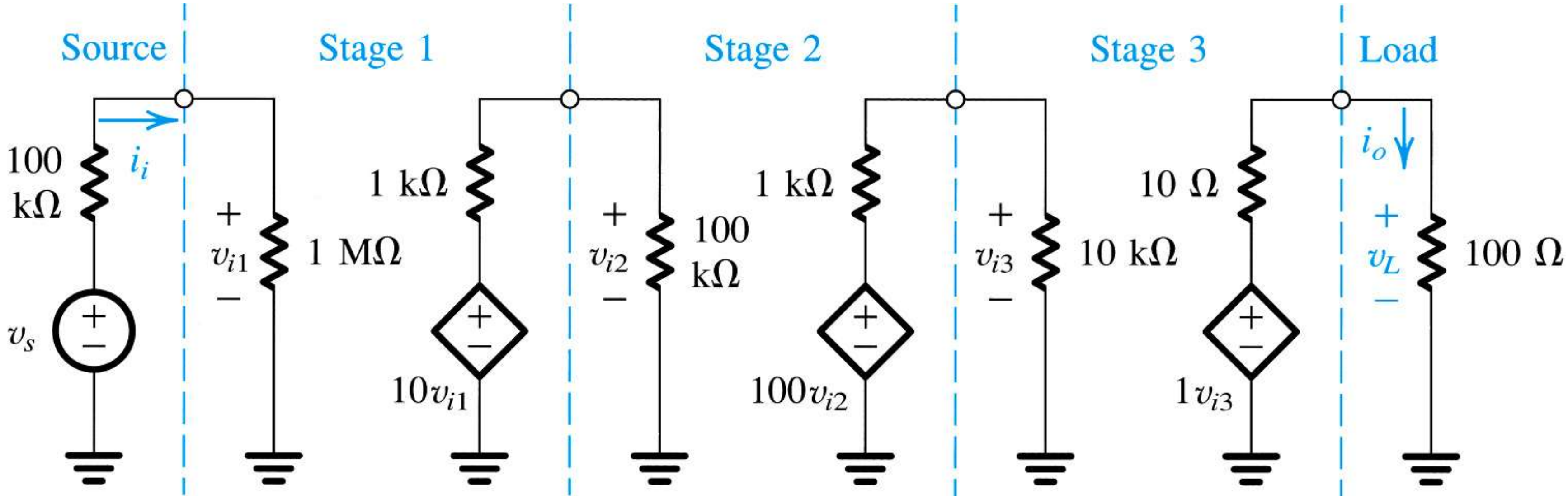




Transresistance Amp

$$R_m \equiv \left.\frac{v_o}{i_i}\right|_{i_o=0} \text{ (V/A)}$$

# Class Example

## CALCULATE THE GAIN OF A 3 STAGE AMPLIFIER

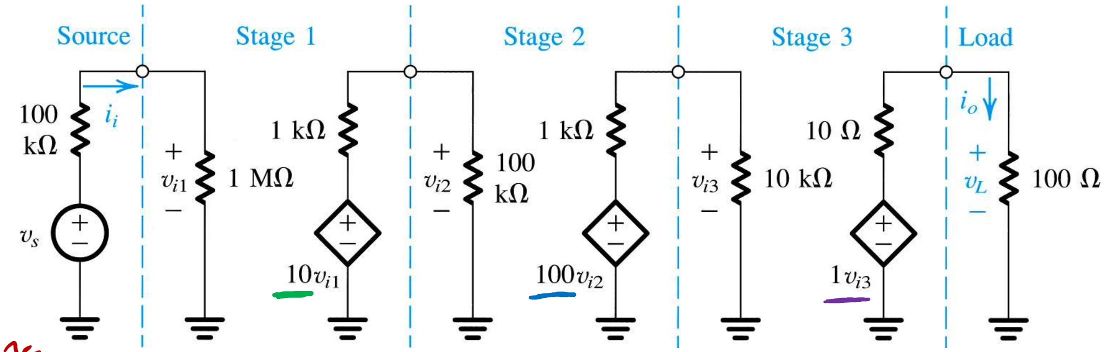


# Class Example

MACQUARIE University

## CALCULATE THE GAIN OF A 3 STAGE AMPLIFIER

- just several potential dividers!
  - solve one at a time
- we want the gain $\frac{V_L}{V_s}$ so need to calculate $V_L$ in terms of $V_s$.




Start with $v_{i1}$

$$v_{i1} = v_s \times \frac{1M}{1M+100k} = v_s \times \frac{1M}{1.1M} = 0.9090 v_s$$

sub in

next we find $v_{i2}$

$$v_{i2} = 10 v_{i1} \frac{100k}{101k} = 9.9 v_{i1} = 9 v_s$$

because → gain is 10 for this stage

now for $v_{i3}$

$$v_{i3} = 100 v_{i2} \frac{10k}{11k} = 90.9 v_{i2} = 818 v_s$$

gain for stage 2 is 100

finally $v_L$

$$v_L = 1 v_{i3} \frac{100}{110} = 0.909 v_{i3} = 744 v_s$$

So $V_L = 744 v_s$

$$\therefore \boxed{\frac{V_L}{V_s} = 744}$$

← the overall gain!

What is this in dB?

$20 \log|744| = \underline{57.4 \text{ dB}}$

# Lecture 1

1. Unit Overview
2. Review of fundamental concepts
3. Amplifiers
4. **Prep for Lab 1**

# Preparation for Lab 1

## INTRODUCTION TO LTSPICE SIMULATION AND THE AD2

- You will be using LTspice to model some simple circuits
- You will build and measure these circuits on your breadboard using the Analog Discover 2 (AD2).

**Preparation before the timetables lab session:**

- Collect lunch-box lab kits
- Read lab module-1 worksheet (available on iLearn)
- Carry out the pre-lab tasks
- Install ‘Ltspice’ and ‘Waveforms’ on your personal computer