ELEC2104 – Semester 2

Introduction and Review

Unit of Study Coordinator : Prof. Xiaoke Yi
Lecturer: Dr. Suen Xin Chew

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COURSE LOGISTICS

i. Course Website

› **https://cusp.sydney.edu.au/students/view-unit-page/alpha/ELEC2104**

ii. Mixed-mode delivery

	Online (Zoom)	Recording	Face-to-face
Lectures	✓	✓	✗
Tutorials	✓	✗	✓
Labs	✓	✗	✓

COURSE LOGISTICS

iii. Staff

› **Unit of Study Coordinator – Prof Xiaoke Yi**

- xiaoke.yi@sydney.edu.au
- Office number: Level 3, J13 - Link Building next to Electrical Engineering Building OR Room3018, Sydney Nano Hub, The University of Sydney
- Research interests: Optoelectronics, Sensing, Signal processing, Silicon photonics, Integrated photonic circuits

https://www.sydney.edu.au/engineering/about/our-people/academic-staff/xiaoke-yi.html

COURSE LOGISTICS

iii. Staff

- **Lecturer - Dr. Suen Xin Chew**
  - suenxin.chew@sydney.edu.au
  - Office number: Level 3, J13 Link Building
  - Consultation hours:
    - Online : Mondays after lectures (1-2pm)
    - Zoom link : https://uni-sydney.zoom.us/j/9750012764
  - Background
    - Bachelors of Electrical Engineering at University of Sydney - 1st class Honours, University Medal
    - PhD at University of Sydney
    - Visiting Fellow at Harvard University

COURSE LOGISTICS

iii. Staff

- **Lab Coordinator - Dr. Rui Hong Chu**
  - rui.chu@sydney.edu.au
  - Office number: 522A (Labs are in Lab 440)

- **Tutors**

	Tutorials	Labs
1.	**Adam Bova** abov2820@uni.sydney.edu.au	**Bo Liu** bo.liu@sydney.edu.au
2.	**Jony Kaushik** jkau9173@uni.sydney.edu.au	**Huan Li** huli0307@uni.sydney.edu.au
3.	**Xiaoyi Tian** xiaoyi.tian@sydney.edu.au	**Yikai Yang** yikai.yang@sydney.edu.au

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iv. Class Materials

› Recommended Textbook

- **Microelectronic Circuit Design** by R. Jaeger and T. Blalock

› Lecture

- Lecture notes available on Canvas
- Lecture pre-recordings will be available
- One 2-hour lecture session (online zoom) on Mondays 11 – 1pm
- Zoom link – available on Canvas (under **"ZOOM"** tab)

› Tutorials/Labs

- Online sessions will run concurrently with face-to-face sessions
- Attendance will be taken for face-to-face sessions for safety measures (ie. contact tracing should this information be required) – not for assessment

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v. Assessment details

	Component	Group/Individual	Weight	Due
1.	Labs		10%	At the end of lab sessions
	- Face-to-face	Group report		
	- Online	Individual report		
2.	Term project	Group	5%	Week 12
3.	Online quizzes	Individual	5%	Midnight Sundays
4.	Assignments	Individual	10%	Week 6, Week 11
5.	Final exam	Individual	70%	End of Semester

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Term project – Starts in Week 9

- Duration : Week 9 to Week 12
- 4 weeks lab sessions dedicated for term project
- Group of 2-3 must consist of a mixture of remote and on-campus students
  - Equal opportunity for remote students to learn some hands-on experience
  - Communication is the key
  - Approach lab tutors if you have difficulties finding group members
- Will be assessed based on a group report and demo

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Summary for this Week:

- Tutorials – starts this week
- Online quizzes – starts this week, due Sunday midnight
- Labs – no lab this week, starts in Week 3

COURSE SYLLABUS

Week	Date	Lecture	Lab	Tutorial
Week 1	24/8/2020	Introduction and Circuit Review	No Lab	Tut 1
Week 2	31/8/2020	Basic Semiconductor Physics	No Lab	Tut 2
Week 3	7/9/2020	PN Junctions	Lab 0 – RC Filters	Tut 3
Week 4	14/9/2020	Diode Models and Circuits	Lab 1 - DIodes	Tut 4
Week 5	21/9/2020	Physics of Bipolar Transistors	Lab 2 – Diodes and Rectifiers	Tut 5
Week 6	28/9/2020	BJT Circuits and Analysis	Lab 3 - BJT	Tut 6
		COMMON WEEK		
Week 7	12/10/2020	MOSFET Circuits and Analysis	Lab 4 – Optical Link	Tut 7
Week 8	19/10/2020	Operational Amplifiers	Lab 5 - MOSFET	Tut 8
Week 9	26/10/2020	Digital CMOS Circuits	Project starts	Tut 9
Week 10	2/11/2020	Filter designs	Project cont.	Tut 10
Week 11	9/11/2020	Second order systems	Project cont.	Tut 11
Week 12	16/11/2020	Review	Project demo	Tut 12

COVID safety measures for face-to-face sessions

- All students who have cold or flu symptoms should isolate themselves from others.
- If you are unwell with any symptoms, please excuse yourself from this class and get tested for COVID-19 as soon as possible. We will support you to continue the work remotely.
- Wash hands before class.
- Use hand sanitisers regularly.
- Use the wipes provided in class to clean bench/equipment that you use at the start and end of lab/tut session.
- It is not mandatory, but you are encouraged to wear masks in lab/tut session.
- BYO PPE for use on campus

Tips for students joining online

- Remember that you are still in a space with other students.
- Mute your microphone when not speaking.
- Use earphones or headphones - the mic is better and you'll disturb others less.
- If you have a webcam and feel comfortable doing so, please switch it on so we can see you!
- Try not to talk over someone else.
- Use the chat function to send messages to the teacher or classmates during class.

› Integrated Circuits (Ics) are in every corner of our lives

Television

Advanced Medical Care

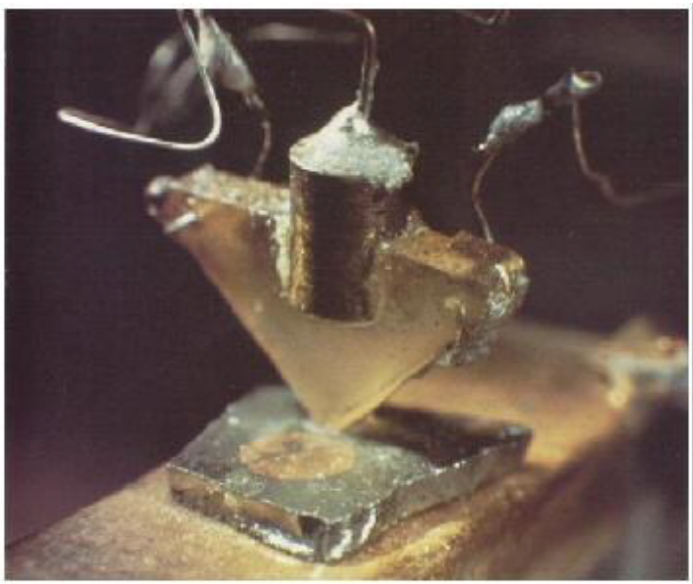
Personal Computer

Mobile Phones / Smart Phones

Automobile

› Overview: Invention of the Transistor

- Vacuum tubes ruled in the first half of 20th century – large, expensive, power-hungry
- 1947: first point contact transistor
- John Bardeen and Walter Brattain at Bell Labs



The heart and soul of microelectronics – A device with just three terminals!

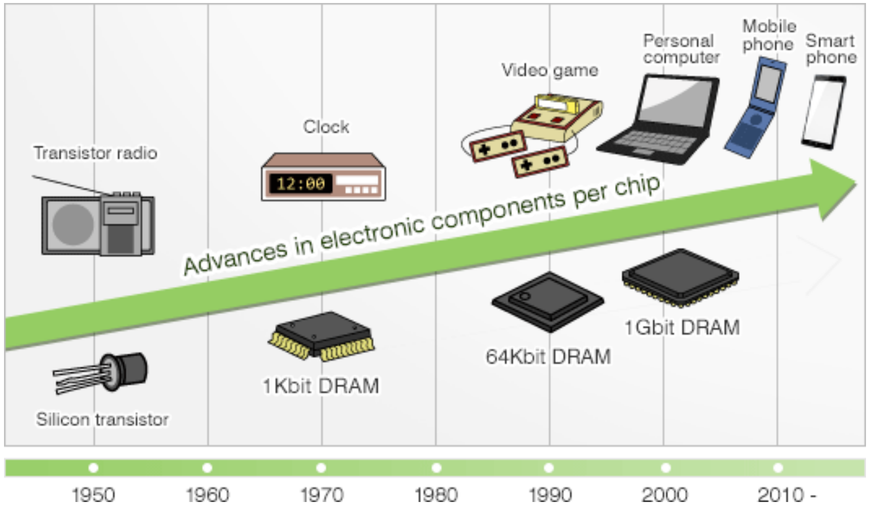
- Overview: Types of transistors
  - **Bipolar Transistors**
    - npn or pnp silicon structure
    - Small current into very thin base layer controls large currents between emitter and collector
    - Base currents limit integration density
  - **Metal Oxide Semiconductor Field Effect Transistors (MOSFET)**
    - nMOS and pMOS MOSFETS
    - -Voltage applied to insulated gate controls current between source and drain
    - -Low power allows very high integration

Growth of microelectronics

1958: First-integrated circuit
- Flip-flop using two transistors
- Built by Jack Kilby at Texas Instruments

2011: Integrated circuits have billions of transistors
- 10-Core Xeon Westmere-EX (2.6 billion transistors) 45 nm
- NVIDIA GF100 (3 billion transistors) 40 nm
- Altera Stratix V FPGA (3.8 billion transistors) 28 m

53% compound annual growth over 45 years
- No other technology has grown so fast for so long
- Driven by miniaturization of transistors
- Smaller is cheaper, faster, lower in power



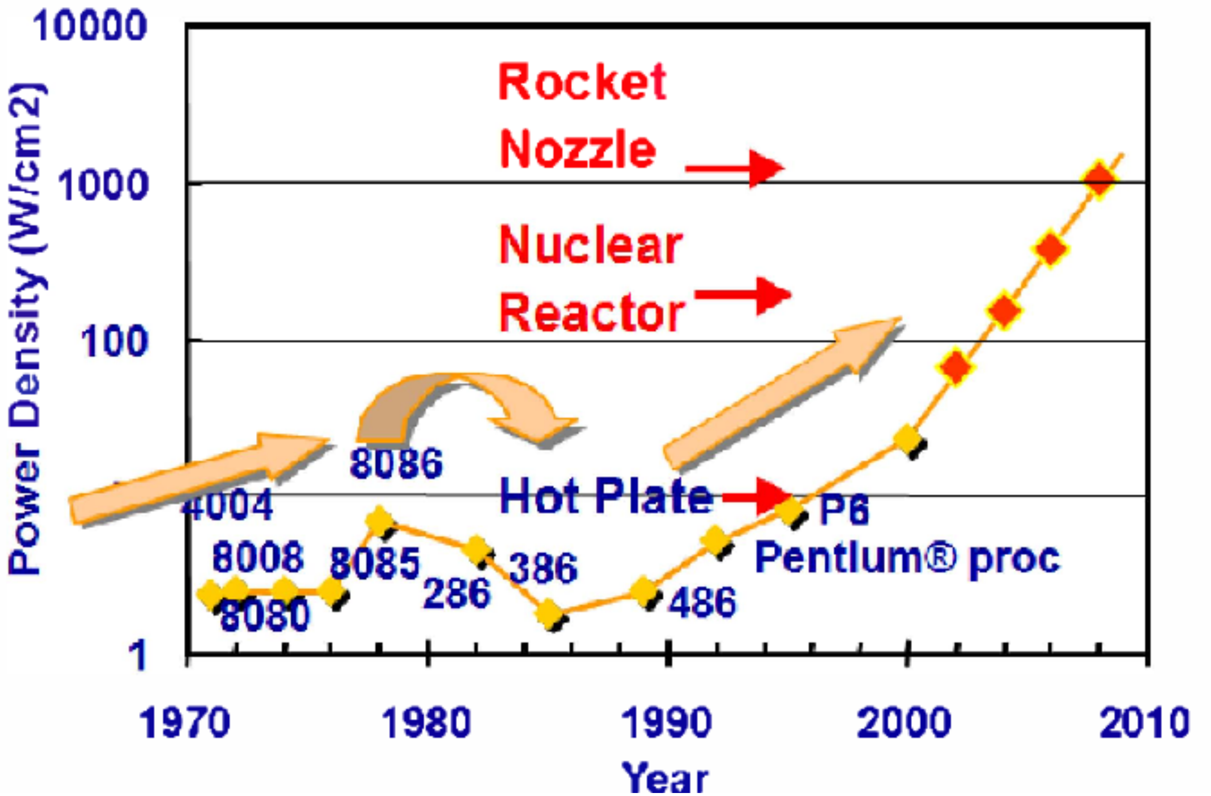
Moore’s Law

› History

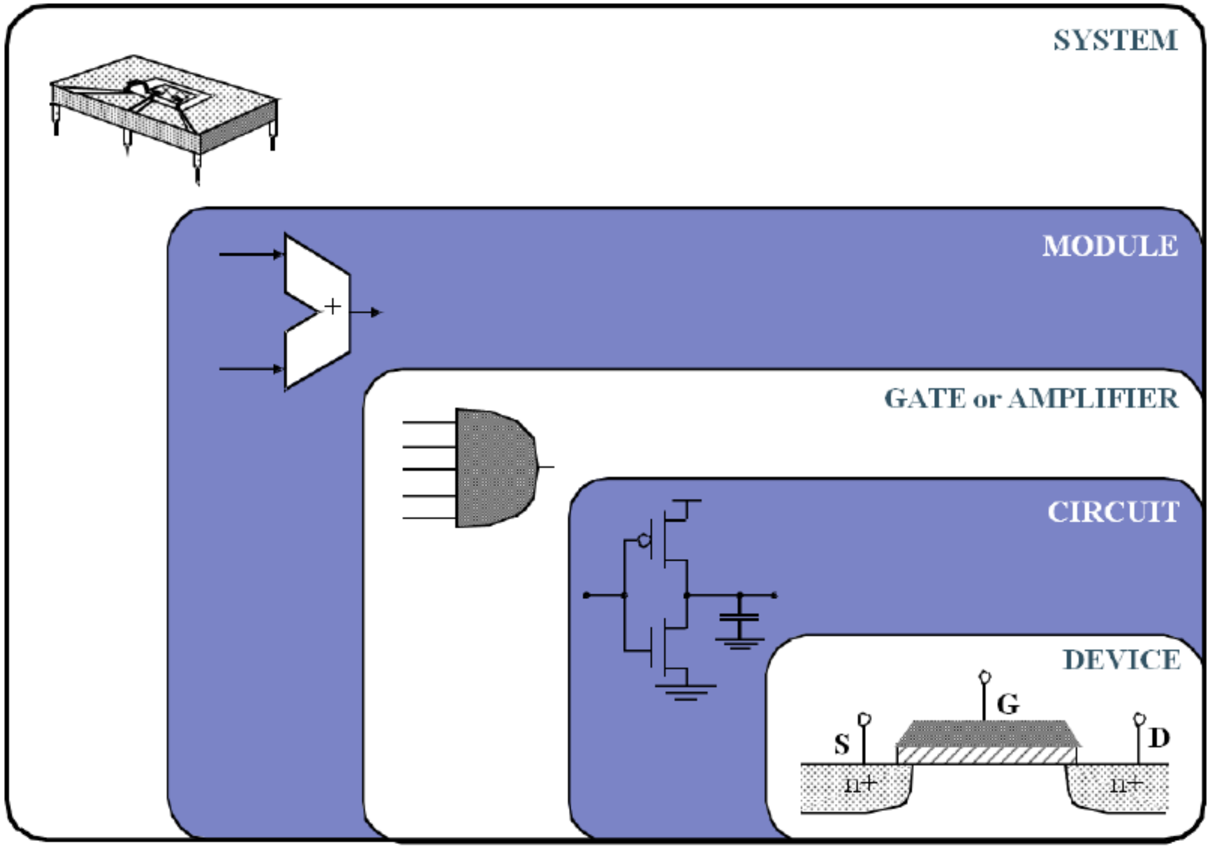
- In 1965, Gordon Moore, noted that the number of transistors on a chip doubled every 18 to 24 months
- He made the now famous prediction that semiconductor technology will double its effectiveness every 18 months.
- In 2005, “It can’t continue forever. The nature of exponentials is that you push them out and eventually disaster happens.”

Trend of power dissipation with scaling

› Power Issues



Design abstraction levels



Integration of microelectronics

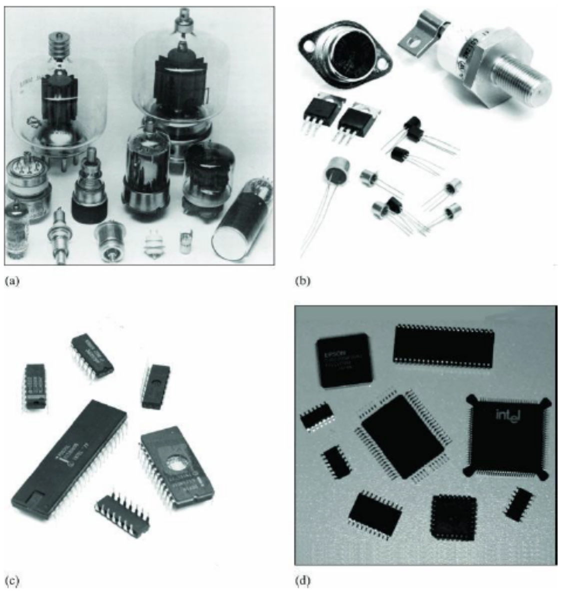
Increasing scales of integration

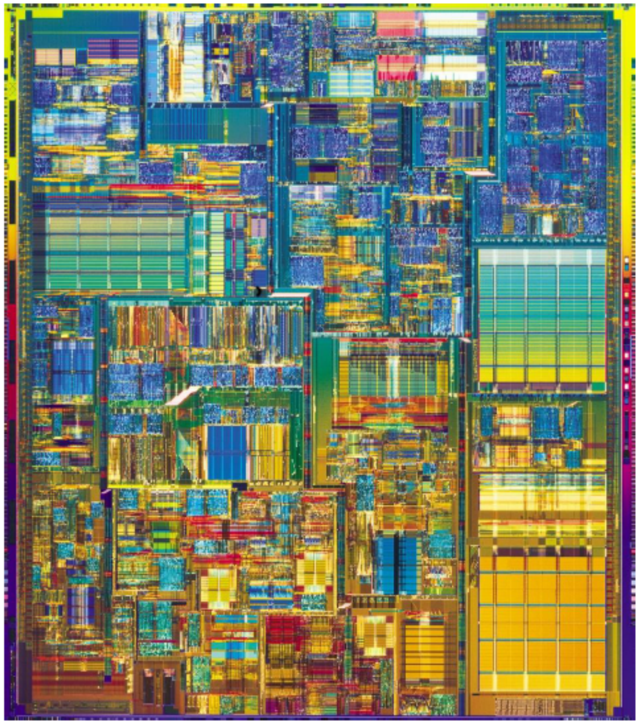
Vacuum Tubes

Discrete Transistors

SSI and MSI Integrated Circuits

VLSI Surface-Mount Circuits

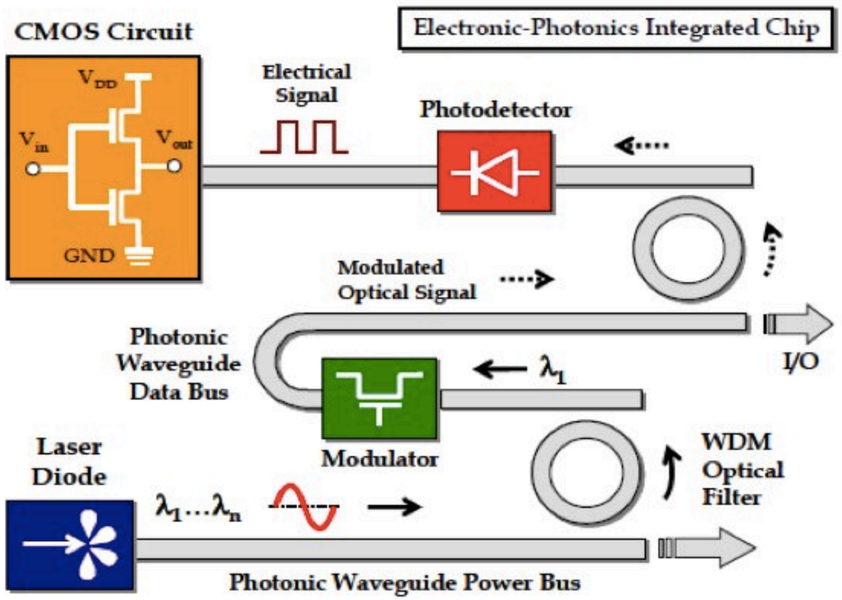


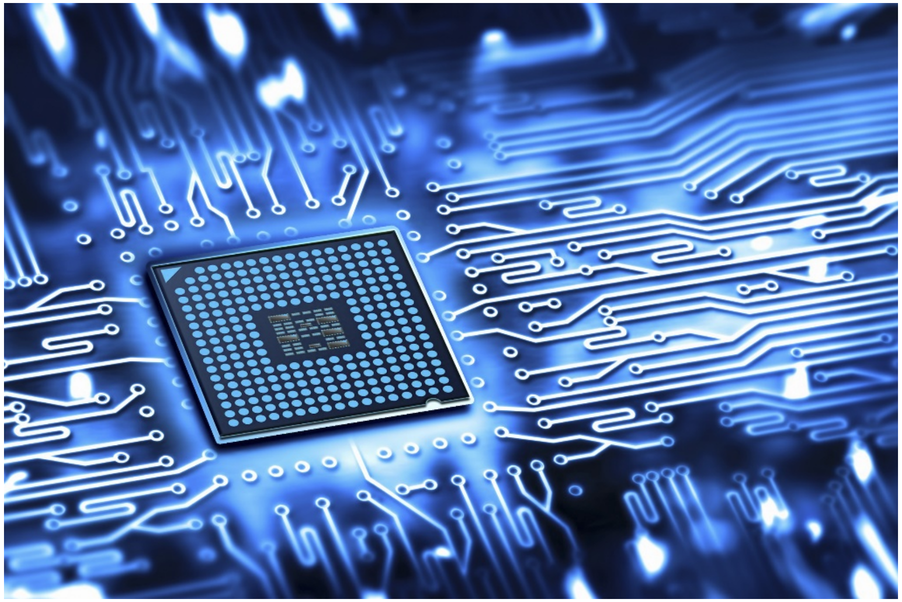


Pentium 4
180-90 nm process
42-125M transistors

Optical integrated ICs

- Photonic integrated circuits – integrated circuits with optical functions
  - Optical signal processing of electrical signals





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CMOS Fabrication

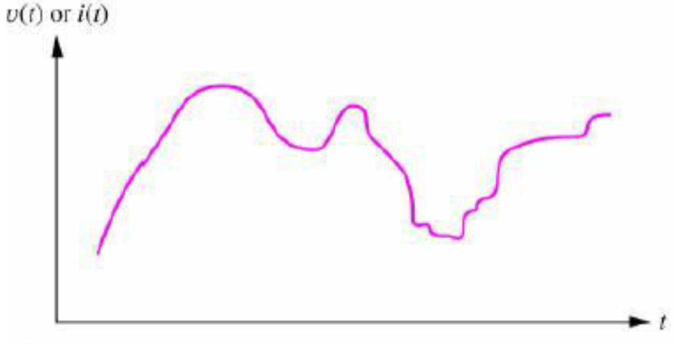
Research & Prototype Foundry (RPF)

- Our very own fabrication facility on campus (Building A31)
- Development of optical chips, electronic devices and new quantum technology

Domains of Electrical Signal Processing

Processing of Electrical Signals and Information

› Electrical engineers design and build systems to process information
  - Personal computers, control systems, signal processing, etc
› In electronic circuits, information is represented in terms of voltages or currents
  - Digital circuits: voltage or current is either ON or OFF
  - Information is represented as 1s and 0s
  - Analog circuits: voltage or current is present at continuous levels



Domains of Electrical Signal Processing

Domains: Signal Amplitude and Time

- Continuous Amplitude (CA) versus Discrete Amplitude (DA)
- Continuous Time (CT) versus Discrete Time (DT)
- Put the two together to obtain a Framework:
  - DTDA: Digital signal processors and computers
    - Digitization of amplitude makes circuit insensitive to analogue imperfections such as tolerance, matching, and noise. Requires sampling in the time domain leading to aliasing.
  - CTCA: Amplifiers, RF front-end of mobile phone
    - Does not require time sampling and does not suffer from aliasing, but is sensitive to tolerance, matching, and noise.
  - DTCA: Digital camera and switched-capacitor filters
    - Can suffer from both aliasing and sensitivity to tolerance, matching and noise
  - CTDA: Spike-based signal processing (human brain)
    - Eliminates aliasing and maintains advantages of amplitude quantization
    - Research area for electronic devices

Domains of Electrical Signal Processing

Domains: Current and Voltage Signals

- The information represented in voltage or current interacts with wires and circuit elements in an electrical circuit.
  - This is how information is processed.
- Think of voltage and current as variables
- Think of electrical circuits as mathematical equations
- Just like mathematical equations are used to manipulate the value of variables, electrical circuits are used to manipulate, or "process", voltage and current.
- Any electrical circuit can be described using mathematical equations.
  - To design a circuit, choose the equations you need to modify the current and voltage variables to suit your purpose!

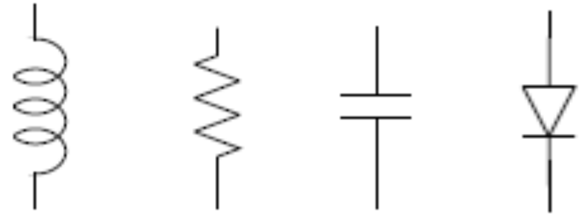
Circuit Elements

Passive Elements

› You should already understand how passive elements operate in a circuit

› Passive elements are unable to amplify or generate energy

- Resistors
  - Resistance (R) is measured in Ohms (Ω)
  - Conductance (G), reciprocal of R, is measured in siemens (S)
- Capacitors
  - Capacitance (C) is measured in Farads (F)
- Inductors
  - Inductance (L) is measured in Henries (H)
- Diodes

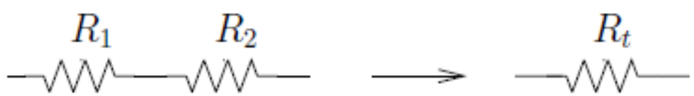


Review of Circuits

What does a resistor do to an electrical signal?

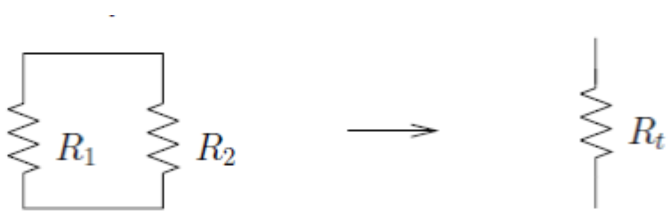
Ohm's Law

- V = IR
- Resistors in series



$$R_t = R_1 + R_2$$

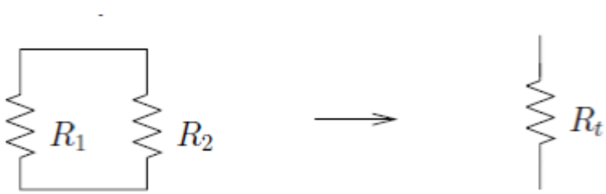
- Resistors in par



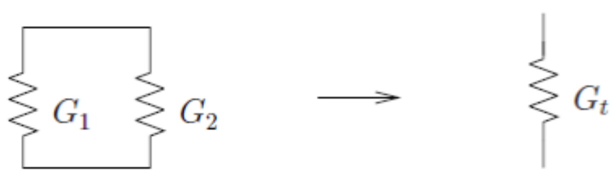
$$R_t = R_1 \parallel R_2 = \left(\frac{1}{R_1} + \frac{1}{R_2}\right)^{-1}$$

Conductance

- Inverse of resistance
  - G = 1/R
- Conductance may be used in place of resistance to simplify equations involving multiple parallel elements
- Resistors in parallel
- Conductan



$$R_t = R_1 \parallel R_2 = \left(\frac{1}{R_1} + \frac{1}{R_2}\right)^{-1}$$

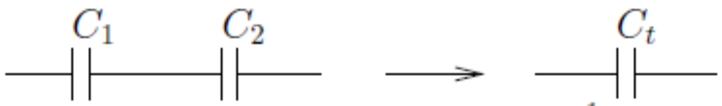


$$G_t = G_1 \parallel G_2 = G_1 + G_2$$

What does a capacitor do to an electrical signal?

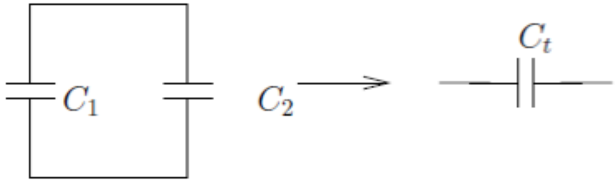
Current and voltage are a function of time

- $i(t) = C\dfrac{dv(t)}{dt}$
- Capacitors in series



$$C_t = \left(\frac{1}{C_1} + \frac{1}{C_2}\right)^{-1}$$

- Capacitors



$$C_t = C_1 \parallel C_2 = C_1 + C_2$$

What does an inductor do to an electrical signal?

Current and voltage are a function of time

- $v(t) = L\dfrac{di(t)}{dt}$
- Inductors in series
  - Add like resistors in series: $L_t = L_1 + \ L_2$
- Inductors in parallel
  - Add like resistors in parallel: $L_t = (L_1 + \ L_2)^{-1}$

What does an inductor do to an electrical signal?

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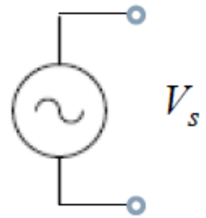
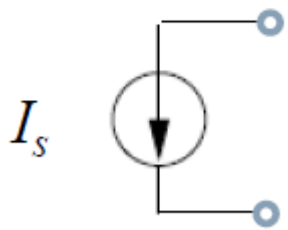
  - Add like resistors in parallel: $L_t = (L_1 + L_2)^{-1}$

Sources

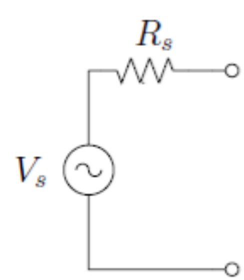
- An ideal voltage source maintains a constant voltage across its terminals no matter how much current is drawn from it

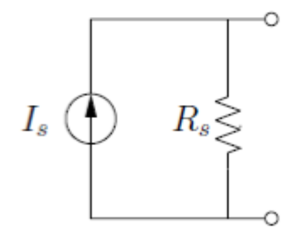


- An ideal current source maintains a constant current output regardless of the voltage across its terminals



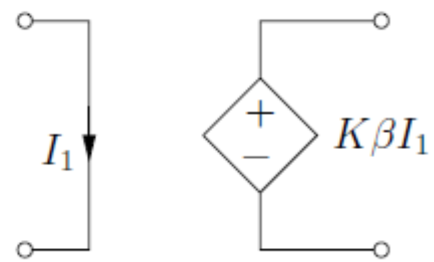
- Real voltage and current sources have some output impedance. This limits the amount of power they can provide.



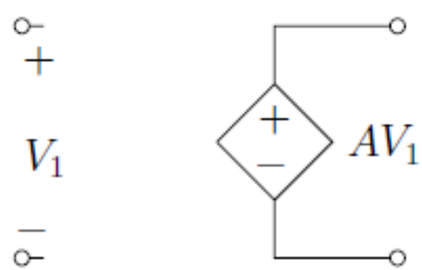


Dependent Sources – four types

› Dependent voltage sources are voltage sources whose output voltage depends on the value of other parameters in the circuit
  - Current-controlled voltage source. *K* is a transresistance and β is a current gain.

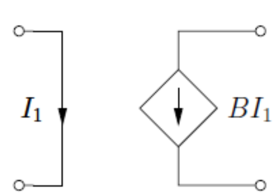


  - Voltage-controlled voltage sourc

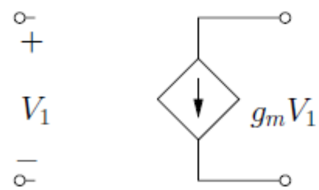


Dependent Sources – four types

- Dependent current sources are current sources whose output current depends on the value of other parameters in the circuit
  - Current-controlled current source. B is current gain.



  - Voltage-controlled current source. g_m is tr



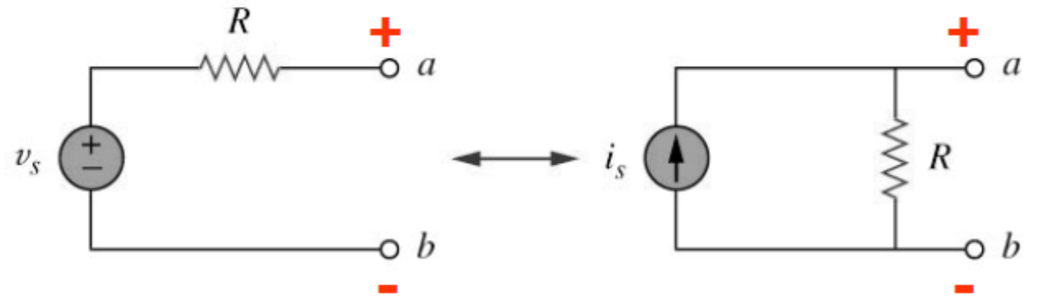
- These four types are linear depende
  - Current and voltage are associated with s onality
  - Important when we study transistor models

Source Transformations

- Using the principles of linearity, we can apply source transformations.
- Source transformations are frequently used when considering the current, voltage or power of a single element in a circuit.
- A source transformation is the process of replacing a voltage source in series with a resistor by a current source in parallel with a resistor (or vice versa).

In order for the two circuits to be equivalent with respect to terminals 'a' and 'b', we must have:

$$v_s = i_s R$$

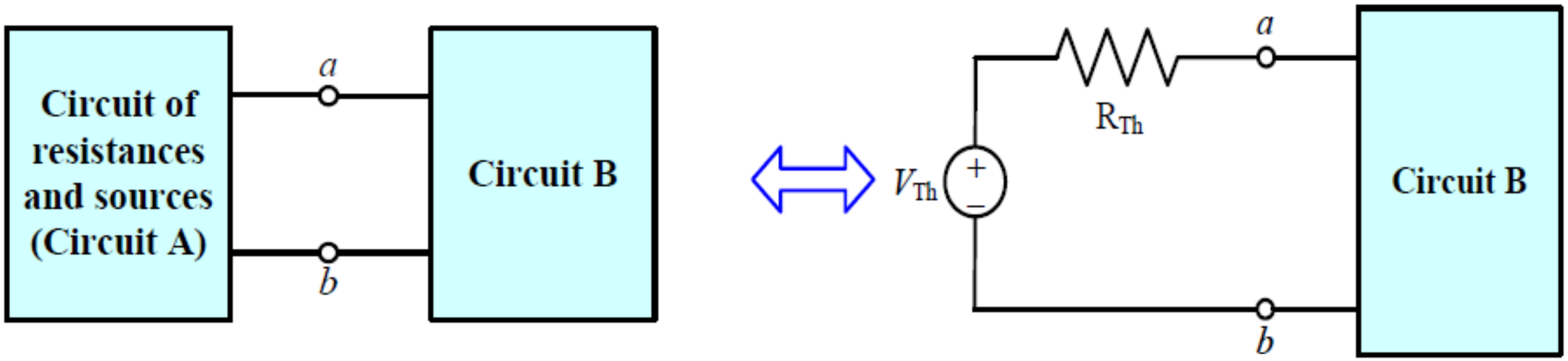


The arrow of the current source is directed toward the positive terminal of the voltage source.

Thevenin and Norton Equivalent Circuits

Thévenin Equivalent Circuit

Any two-terminal circuit containing resistances and sources can be replaced by an equivalent circuit consisting of just an independent voltage source in series with a resistance (without affecting the behaviour of the rest of the circuit).



Assumptions:

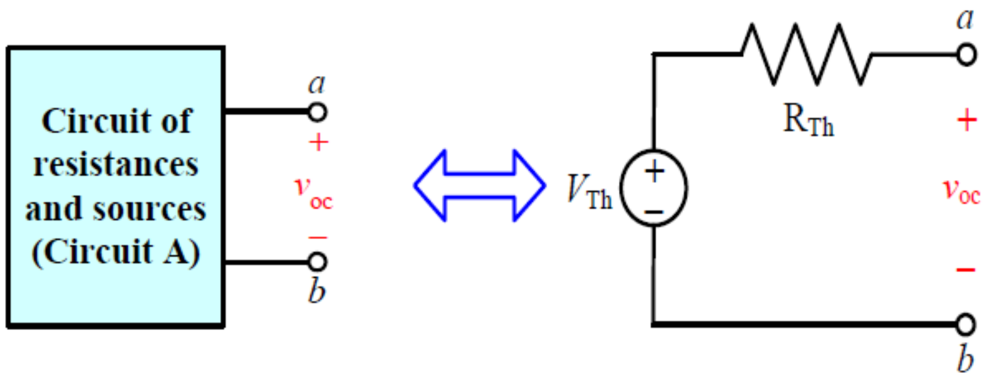
— This is the only connection between circuits A and B

— If there is a dependent source, then both the dependent source and its controlling variable must be either in circuit A or both parts must be in circuit B (i.e. each dependent source is either totally contained in circuit A or in circuit B)

Thevenin and Norton Equivalent

How do we compute the Thévenin equivalent circuit parameters?

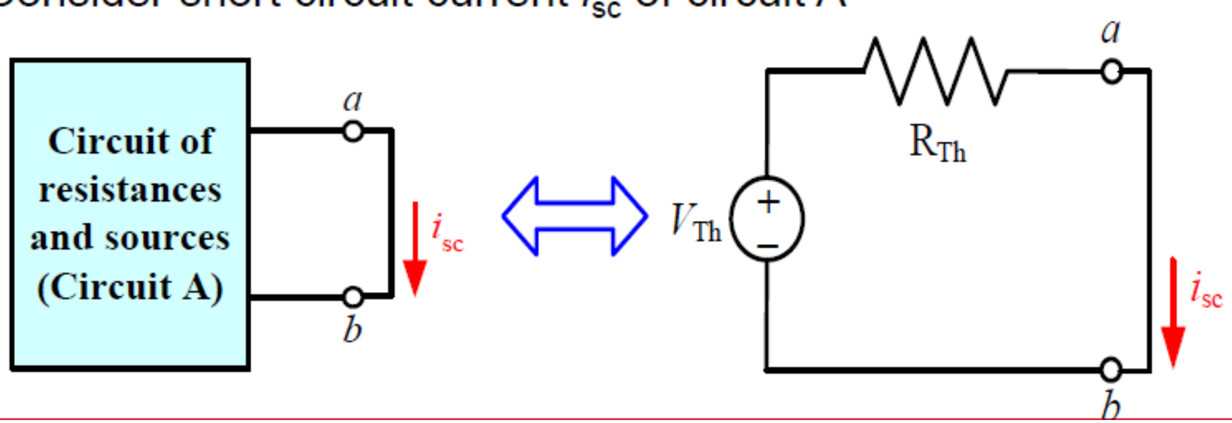
Consider open circuit voltage v_{oc} of circuit A



So we must have

$$\boxed{V_{Th} = v_{oc}}$$

Consider short circuit current i_{sc} of circuit A



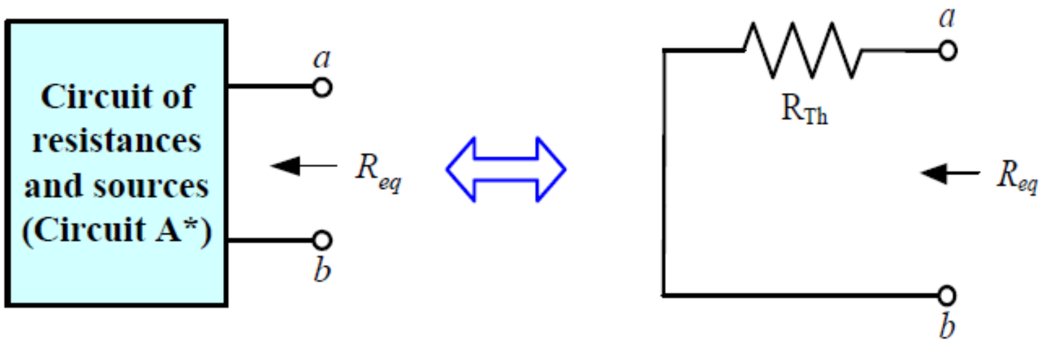
So we must have

$$V_{Th} = R_{Th}\, i_{sc}$$

$$\Rightarrow R_{Th} = \frac{V_{Th}}{i_{sc}} \quad \boxed{\Rightarrow R_{Th} = \frac{v_{oc}}{i_{sc}}}$$

Thevenin and Norton Equivalent

If circuit A does not contain dependent source, then R_{Th} can also be obtained by first zeroing the independent sources (resulting in circuit A*) and then computing its equivalent resistance as seen at the terminals.



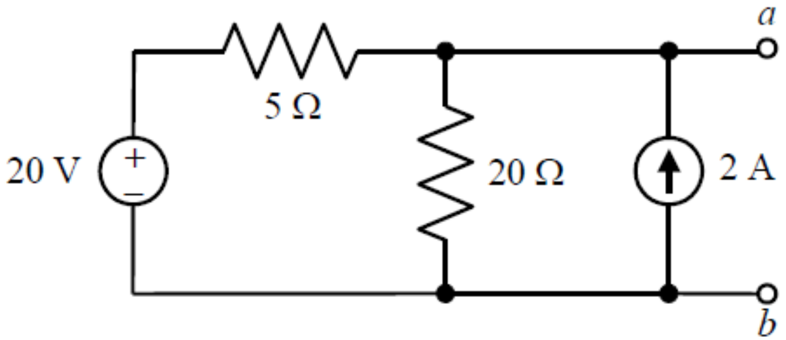
So we must have

$$\boxed{R_{Th} = R_{eq}}$$

Zeroing a voltage source corresponds to replacing it with a short circuit
Zeroing a current source corresponds to replacing it with an open circuit
Note that dependent current and voltage source are not zeroed in obtaining circuit A*. This is not an issue here as the above method does not apply to circuits with dependent sources, but later we will see a modification of this that does.

Example

Compute the Thévenin equivalent circuit for the circuit shown below with dependent source.



Example

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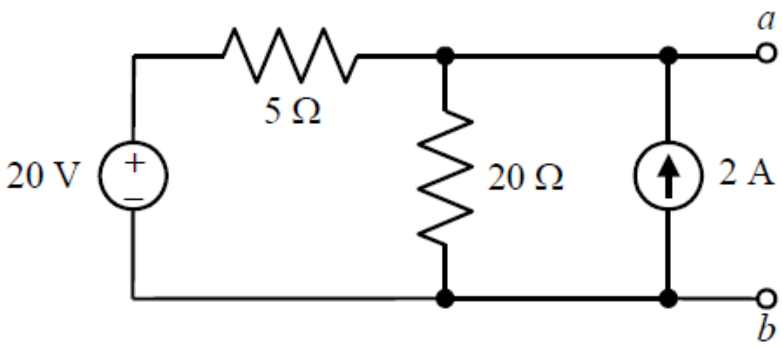
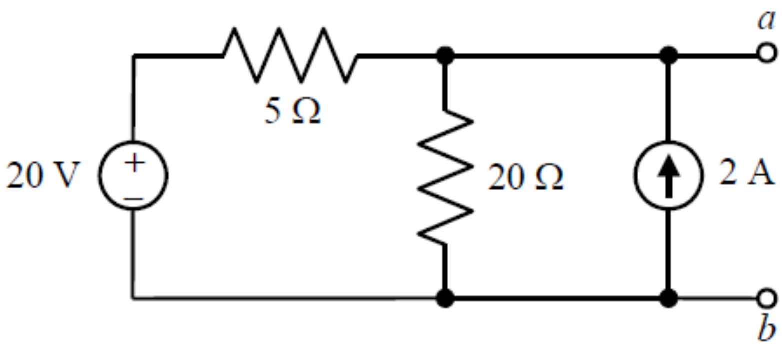


Example

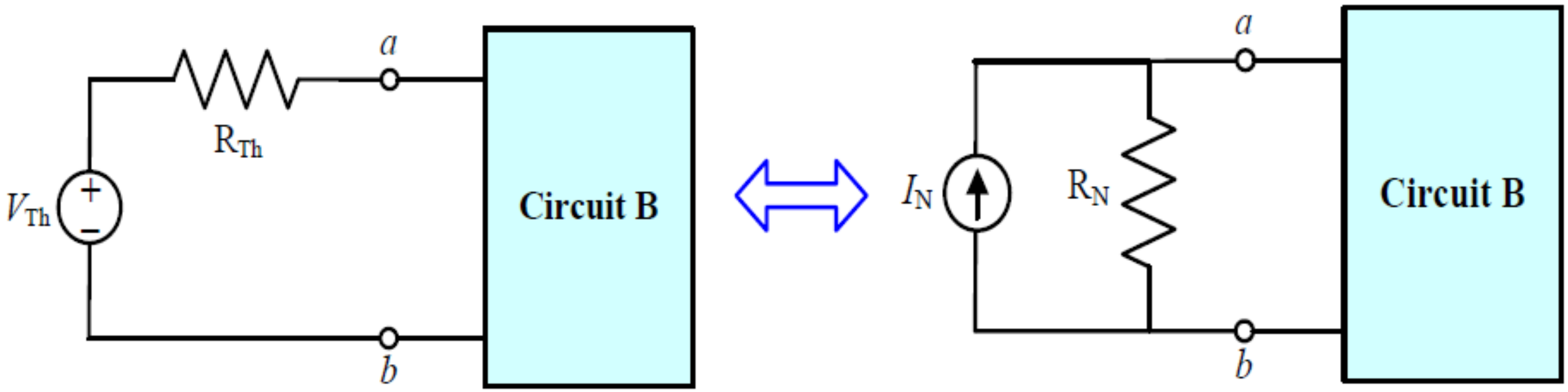
Compute the Thévenin equivalent circuit for the circuit shown below with dependent source.



Thevenin and Norton Equivalent Circuits

Norton Equivalent Circuit

Related to Thévenin equivalent circuit by a source transformation

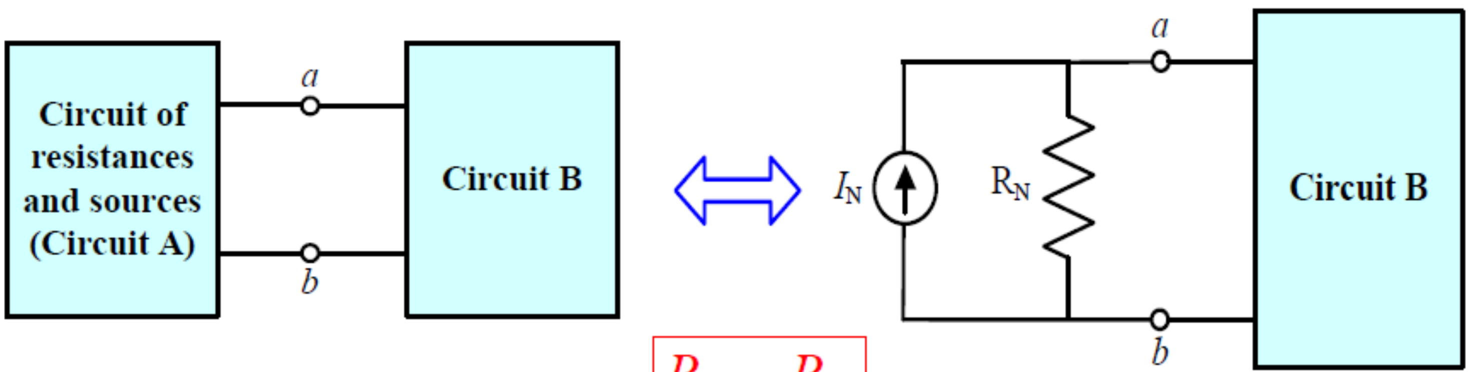


$$\boxed{R_N = R_{Th}}$$

$$\boxed{I_N = V_{Th} / R_{Th} = i_{sc}} \Leftrightarrow \boxed{V_{Th} = R_{Th} I_N}$$

Thevenin and Norton Equivalent Circuits

Norton Equivalent Circuit

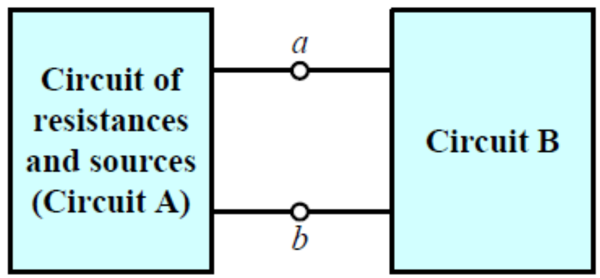


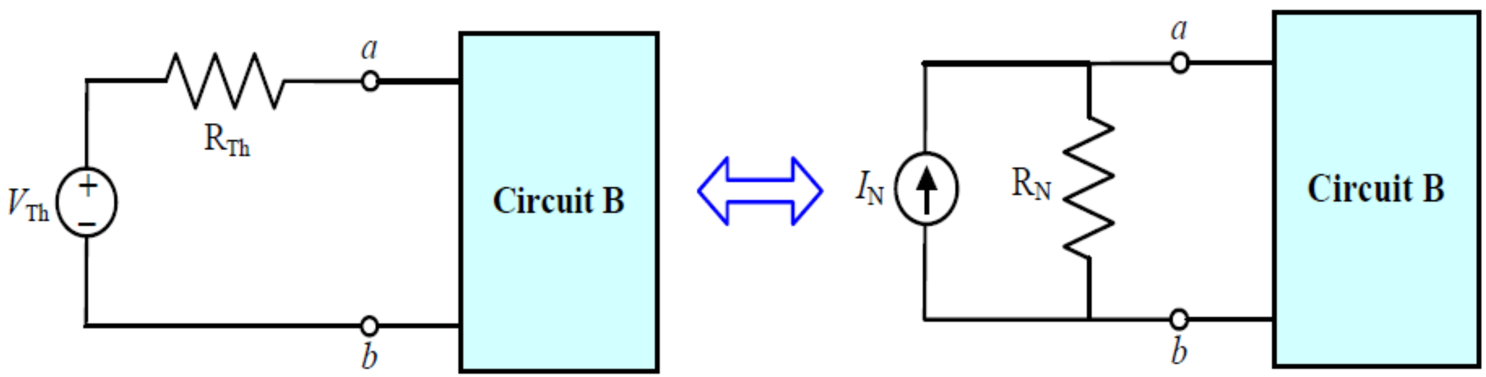
$$\boxed{R_N = R_{Th}}$$

Any two-terminal circuit containing resistances and sources can be replaced by an equivalent circuit consisting of just an independent current source in parallel with a resistance (without affecting the behaviour of the rest of the circuit). Assumptions are same as those for Thévenin equivalent circuit.

Thevenin and Norton Equivalent Circuits

Summary:





$$V_{Th} = V_{oc} \qquad R_{Th} = R_N \qquad I_N = I_{sc}$$

Review of Circuits

Notation

- Conductance is the reciprocal of resistance (G=1/R).
  - Ohm's Law: V = IR
  - R = V/I
  - G = I/V
  - Thus, conductance is the ratio of current to voltage
- Transconductance is the ratio of change in current to change in voltage

$$g_m = \frac{\Delta I_{\text{out}}}{\Delta V_{\text{in}}}$$

- Much of the circuit analysis w… us on changes in current and voltage rather than static values.
- This is called small-signal analysis
- Small-signals are represented using lower-case letters:

$$g_m = \frac{i_{\text{out}}}{v_{\text{in}}}$$

Non-linear circuits

- So far, you have probably only worked with linear circuit elements
- This means the values of the components do not change with the level of voltage or current
- In reality, few devices are linear
- For example, the resistor that forms an incandescent light bulb filament increases in resistance as the current through it increases

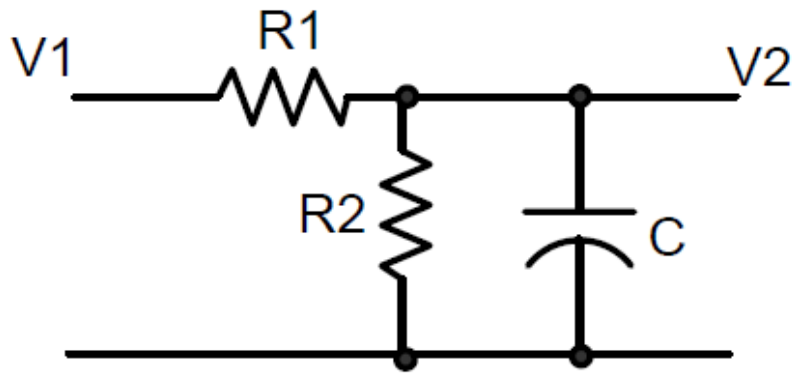
A light bulb filament is a non-linear resistor.
Increasing the voltage applied to a light bulb past a certain point will not make the light any brighter.
This also prevents the light bulb from burning out too quickly.

Non-linear circuits

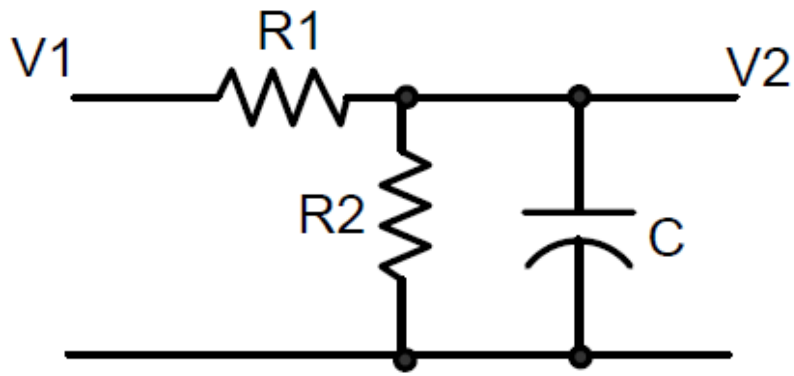
- Linear circuit networks are easy to model using mathematical equations
- However: transistors, diodes, non-ideal resistors, capacitors, current and voltage sources, etc – are all non-linear
- Non-linear circuits are more difficult to analyse precisely
- Multisim and other circuit simulators can provide accurate results
- Numerical methods can be used to approximate circuit behaviour
- Alternately, we can apply *small-signals* to the circuit elements
- If our current and voltage signals only change within a small range of values, even non-linear circuit elements such as transistors can behave linearly.
- In this course, we will study both linear and non-linear circuit behaviour.
- We will learn when mathematical approximations are appropriate

Review: Little Test

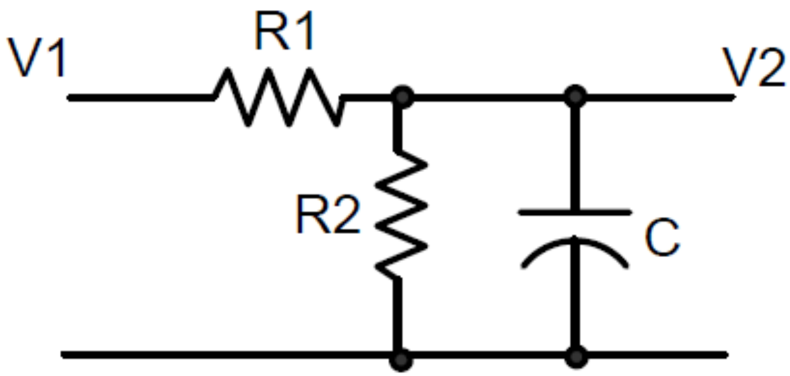
For now a little test: what is ratio of V2/V1 ?



Review: Little Test



Review: Little Test



Review: Little Test