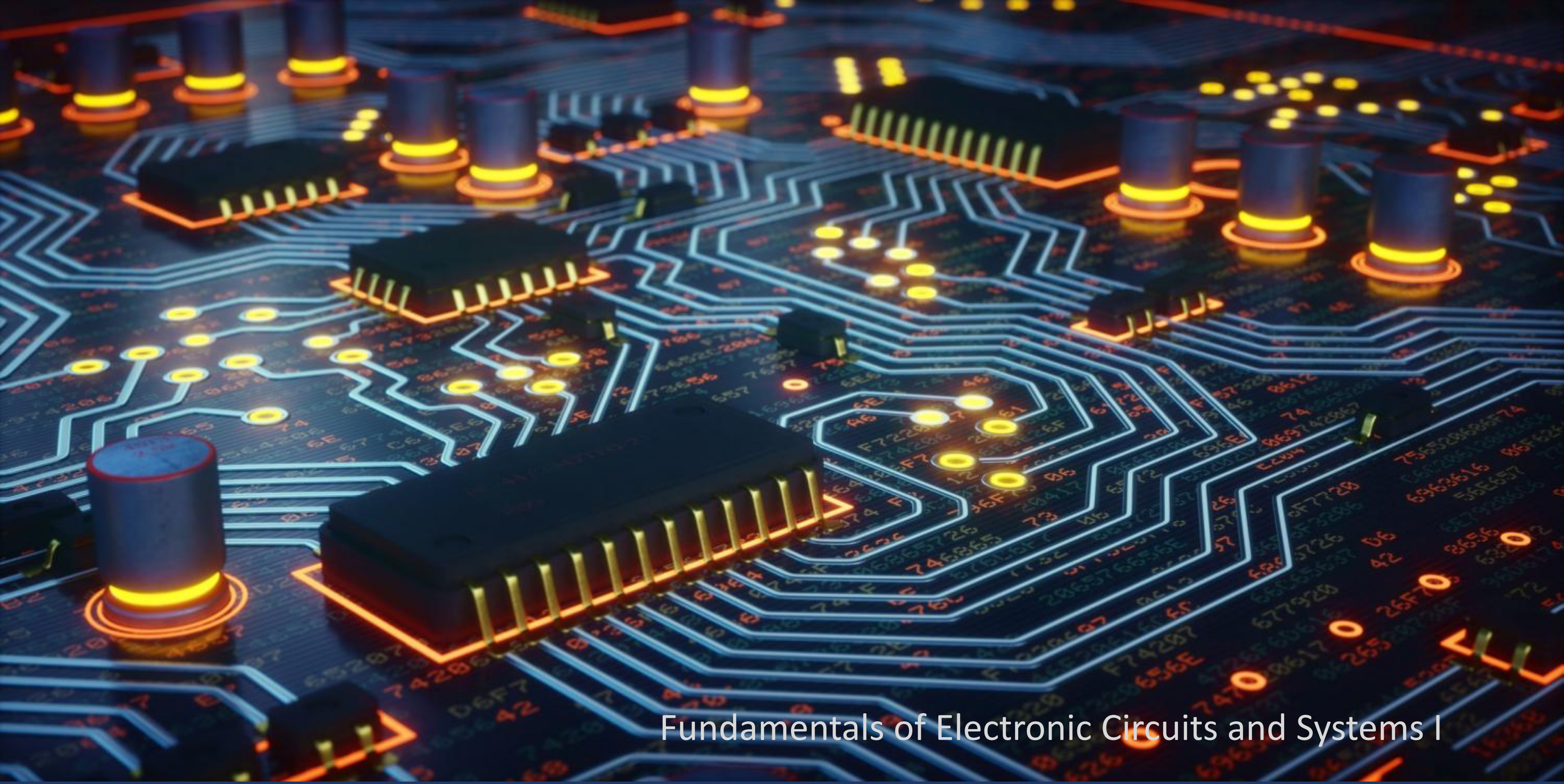


Fundamentals of Electronic Circuits and Systems I

Wrap Up

Milin Zhang

Dept of EE, Tsinghua University

Physics → Foundations of Electronic Circuits & Systems

L1：LMD

- The rate of change of magnetic flux linked with any portion of the circuit must be zero for all time.

$$\oint E \cdot dl = -\frac{\partial \Phi_B}{\partial t} = 0$$

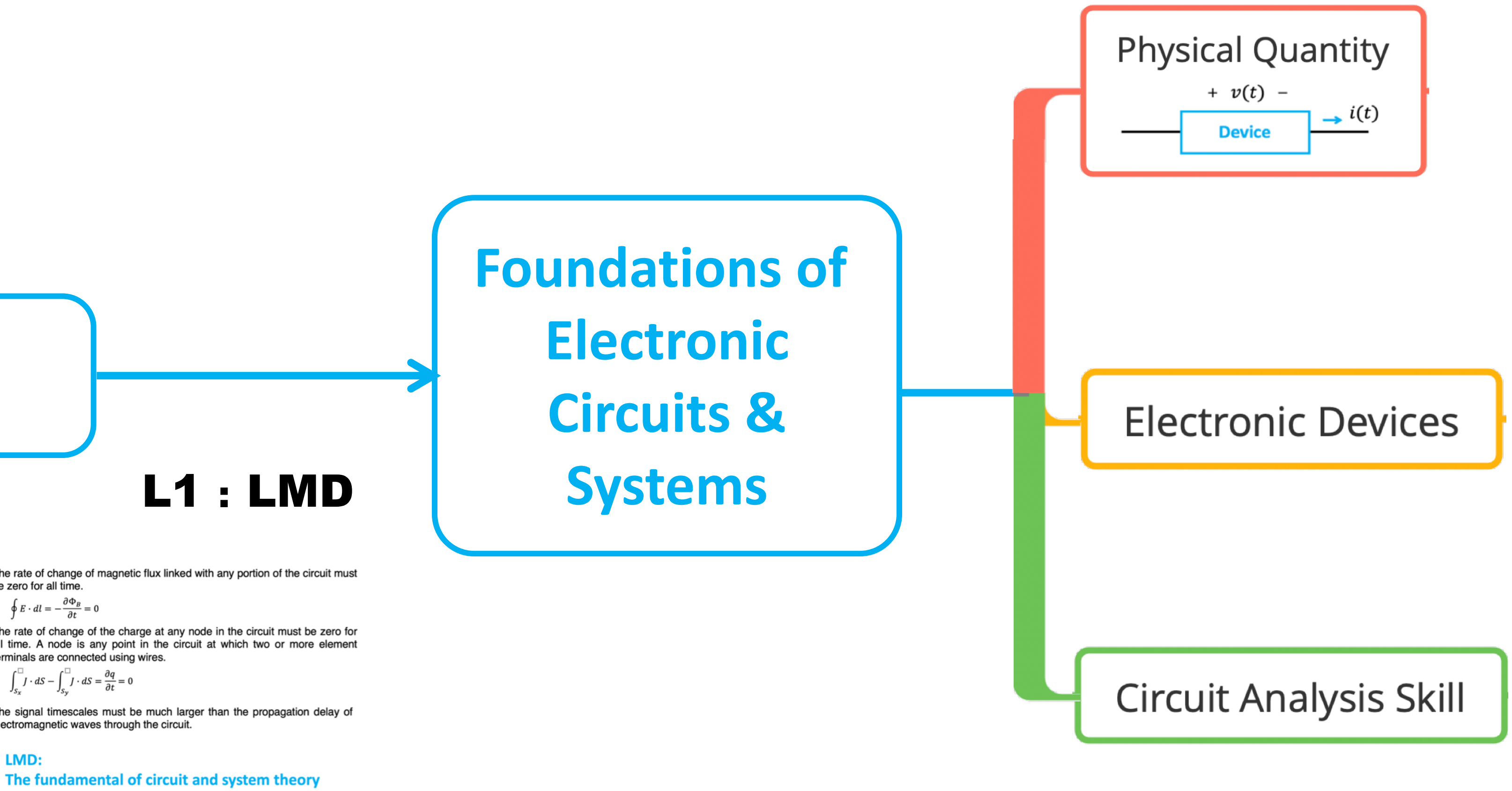
- The rate of change of the charge at any node in the circuit must be zero for all time. A node is any point in the circuit at which two or more element terminals are connected using wires.

$$\int_{S_x} J \cdot dS - \int_{S_y} J \cdot dS = \frac{\partial q}{\partial t} = 0$$

- The signal timescales must be much larger than the propagation delay of electromagnetic waves through the circuit.

LMD:

The fundamental of circuit and system theory


Foundations of Electronic Circuits & Systems
Physical Quantity
+ $v(t)$ −
$i(t)$
Device
Electronic Devices
Circuit Analysis Skill
L1：LMD
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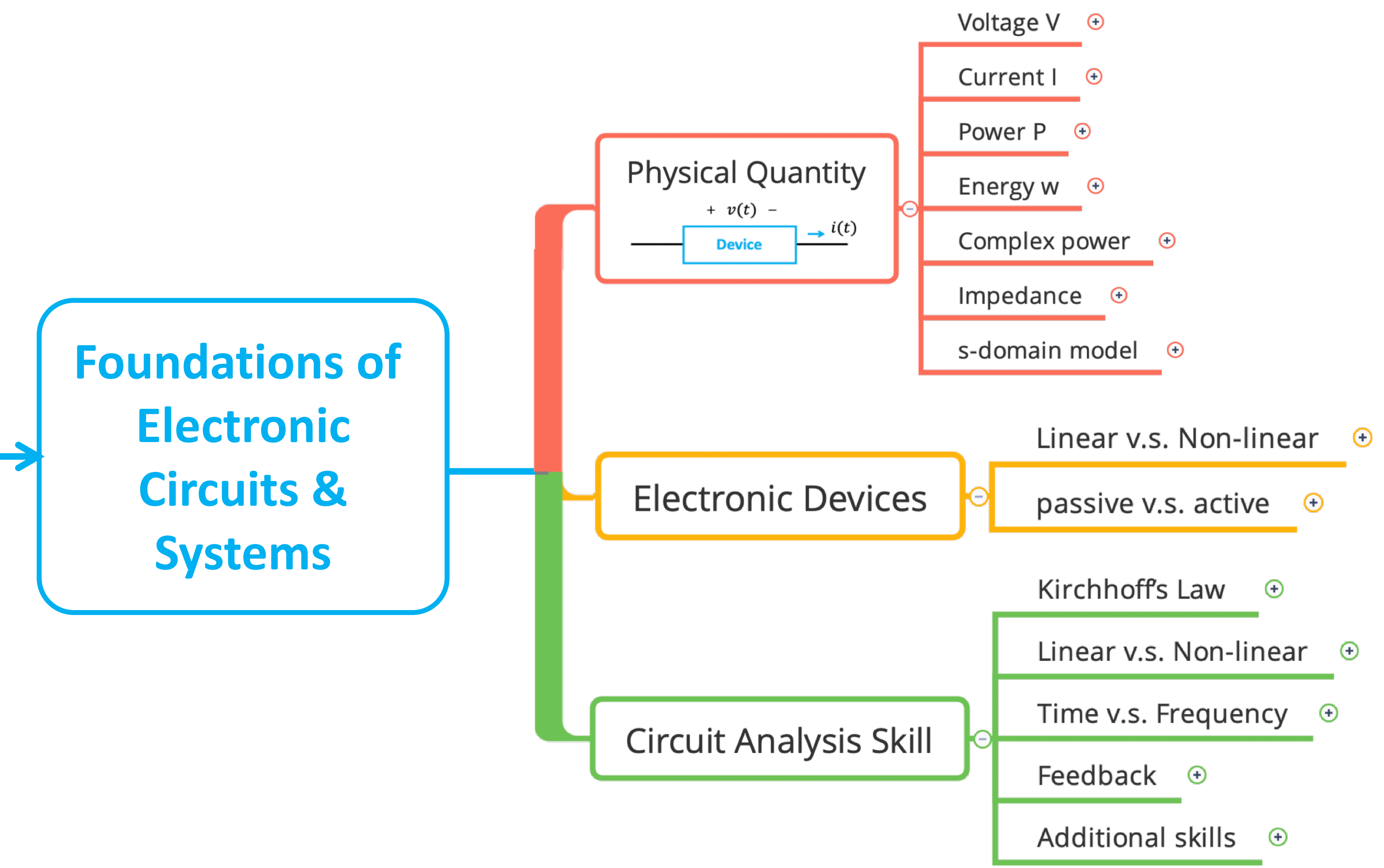
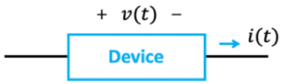

Foundations of Electronic Circuits & Systems
Physical Quantity
+ v(t) −
Device
i(t)
Voltage V
Current I
Power P
Energy w
Complex power
Impedance
s-domain model
Electronic Devices
Linear v.s. Non-linear
passive v.s. active
Circuit Analysis Skill
Kirchhoff's Law
Linear v.s. Non-linear
Time v.s. Frequency
Feedback
Additional skills

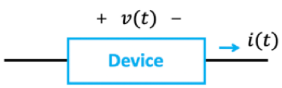
- **Physical Quantity**



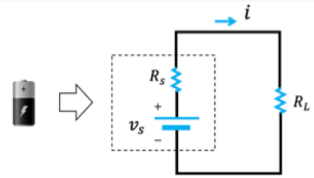
  - Voltage V
    - unit: volt
    - voltage in dB
      - $20log_{10}\frac{v}{1V}$ → dBV
      - $20log_{10}\frac{v}{1mV}$ → dBmV
    - Effective voltage
      - $v_{rms} = \sqrt{\frac{1}{T}\int_{t_0}^{t_0+T} v^2(t)dt}$
  - Current I
    - unit: amp
    - Effective current
      - $i_{rms} = \sqrt{\frac{1}{T}\int_{t_0}^{t_0+T} i^2(t)dt}$
  - Power P
  - Energy w
  - Complex power
  - Impedance
  - s-domain model

- **Electronic Devices**
  - Linear v.s. Non-linear
  - passive v.s. active

Physical Quantity



- Voltage V
- Current I
- Power P
  - unit: watt
  - Instantaneous power: $p(t) = v(t)i(t)$
  - Average power: $\bar{P} = \frac{1}{T}\int_{t_0}^{t_0+T} p(t)dt$
  - Maximum Power Transfer



Practical voltage source

- Voltage of R_L

$$v_{R_L} = v_s - iR_s$$

- Power at the load R_L

$$P_L = v_{R_L} i = (v_s - iR_s)i \;= -R_s\left(i^2 - \frac{v_s}{R_s}i\right) = -R_s\left(i - \frac{1}{2}\frac{v_s}{R_s}\right)^2 + \frac{1}{4}\frac{v_s^2}{R_s}$$

$$\le \frac{1}{4}\frac{v_{s,rms}^2}{R_s}$$ **The maximum power being absorbed by the load**

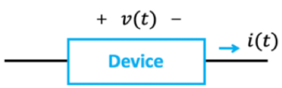
- When $R_s = R_L$ $\quad P_L = P_{L,max} = \frac{1}{4}\frac{v_{s,rms}^2}{R_s}$

- Energy w
  - unit: Joule: $w = \int_0^T p(t)dt$
- Complex power
- Impedance
- s-domain model

Electronic Devices

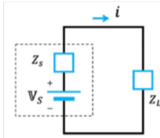
- Linear v.s. Non-linear
- passive v.s. active

Physical Quantity



Complex power

- Defination $\mathbb{S} = \frac{1}{2}\mathbb{V}\mathbb{I}^*$
- Average power
  - unit: watt
  - $\bar{P} = \Re\{\mathbb{S}\} = V_{rms}I_{rms}\cos(\varphi_V - \varphi_I)$
- Reactive power
  - unit: Volt-Ampere Reactive/VAR
  - $Q = \Im m\{\mathbb{S}\} = jV_{rms}I_{rms}\sin(\varphi_V - \varphi_I)$
- power factor
  - $pf = \frac{P}{V_{rms}I_{rms}} = \cos(\varphi_V - \varphi_I)$
- power angle
  - $\tan(\varphi_V - \varphi_I) = \frac{Q}{P}$
- Maximum Power Transfer



$$\begin{cases} I_L = \dfrac{V_s}{\sqrt{(R_s+R_L)^2+(X_s+X_L)^2}} \\ V_L = \dfrac{V_S\sqrt{R_L^2+X_L^2}}{\sqrt{(R_s+R_L)^2+(X_s+X_L)^2}} \end{cases}$$

- The average power at the load Z_L

$$P_L = V_{rms}I_{rms}\cos(\theta_{v_L} - \theta_{i_L}) \quad \text{where} \quad \theta_{v_L} - \theta_{i_L} = cos^{-1}\left(\frac{R_L}{\sqrt{R_L^2+X_L^2}}\right)$$

$$= \frac{V_{rms}^2 R_L}{(R_s+R_L)^2+(X_s+X_L)^2} \le \frac{V_{rms}^2 R_L}{(R_s+R_L)^2} \le \frac{1}{4}\frac{V_{rms}^2}{R_s}$$

- when $\begin{cases} R_s = R_L \\ X_s = -X_L \end{cases} \rightarrow Z_s = Z_L^* \quad P_{L,max} = \frac{1}{4}\frac{V_{rms}^2}{R_s}$

Impedance

Impedance is defined as the ratio of the phasor voltage to the phasor current

i-v relation	$i = \frac{v}{R}$	$i(t) = C\frac{dv(t)}{dt}$	$i(t) = i(t_0) + \frac{1}{L}\int_{t_0}^{t} v(x)dx$
v-i relation	$v = iR$	$v(t) = v(t_0) + \frac{1}{C}\int_{t_0}^{t} i(x)dx$	$v(t) = L\frac{di(t)}{dt}$
Impedance	R	$\frac{1}{j\omega C}$	$j\omega L$

s-domain model

s–domain model	R	$\frac{1}{sC}$	sL
s–domain i-v relation	$I(s) = \frac{V(s)}{R}$	$I(s) = sCV(s)$	$I(s) = \frac{V(s)}{sL}$

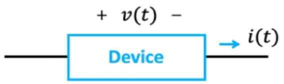
based on Laplace transform
(WILL LEARN IN SIGNAL & SYSTEM)

Linear v.s. Non-linear

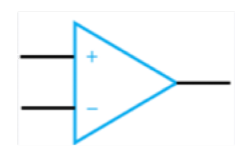
Electronic Devices

passive v.s. active

- **Physical Quantity**

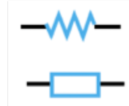
  

  - Voltage V
  - Current I
  - Power P
  - Energy w
  - Complex power
  - Impedance
  - s-domain model
- **Electronic Devices**
  - Linear v.s. Non-linear
    - A device is LINEAR if it satisfies 2 properties:
      - Additivity: response to SUM OF INPUTS is the SUM OF THE RESPONSES to each input applied separately
      - Homogeneity: if input (excitation) is multiplied by a constant, then output (response) is multiplied by the SAME constant
  - passive v.s. active
    - Passive devices
      - Resistor
      - Capacitor
      - Inductor
      - Comparison
      - Mutual inductance
    - Active devices
      - power source
      - Op-Amp = Operational Amplifier

- Kirchhoff's Law
- Linear v.s. Non-linear

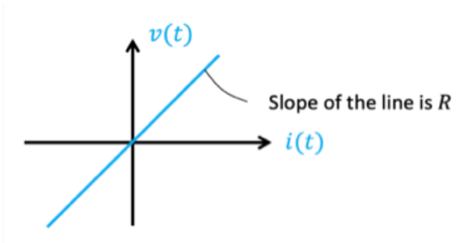
Resistance represents the ability to resist flow of electric current



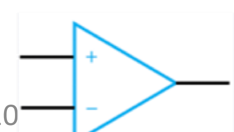
Ohm's law:
the voltage across a resistance is directly proportional to the current flowing through it.

$v(t) = Ri(t)$

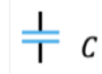
I-V relationship of ideal resistor



- Resistor
- Capacitor
- Inductor
- Comparison
- Mutual inductance
- power source
- Op-Amp = Operational Amplifier



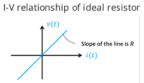
A CAPACITOR is a circuit element that consists of two conducting surface separated by a non-conducting, or dielectric, material.



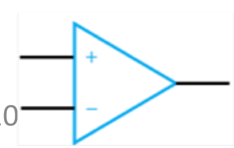
- unit: farad (F)
- I-V relationship $i(t) = C\frac{dv(t)}{dt}$
- Voltage on capacitor CANNOT change abruptly
- An capacitor is an open circuit at DC

Resistance represents the ability to resist flow of electric current

- Ohm's law: the voltage across a resistance is directly proportional to the current flowing through it. $v(t) = Ri(t)$
- I-V relationship of ideal resistor



- Resistor
- Capacitor
- Inductor
- Comparison
- Mutual inductance
- power source
- Op-Amp = Operational Amplifier



- Resistor
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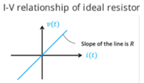
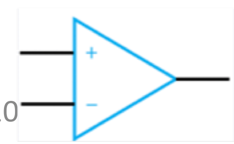
  - I-V relationship of ideal resistor



- Capacitor
  - A CAPACITOR is a circuit element that consists of two conducting surface separated by a non-conducting, or dielectric, material.
  - unit: farad (F)
  - I-V relationship $i(t) = C\frac{dv(t)}{dt}$
  - Voltage on capacitor CANNOT change abruptly
  - An capacitor is an open circuit at DC
- Inductor
  - An INDUCTOR is a circuit element that consists of a conducting wire usually in the form of a coil
  - I-V relationship $v(t) = L\frac{di(t)}{dt}$
  - unit: henry (H)
  - Current through inductor CANNOT change instantaneously
  - An inductor is a short circuit at DC
- Comparison
- Mutual inductance
- power source
- Op-Amp = Operational Amplifier



Resistance represents the ability to resist flow of electric current

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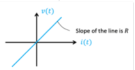
I-V relationship of ideal resistor



A CAPACITOR is a circuit element that consists of two conducting surface separated by a non-conducting, or dielectric, material. C

unit: farad (F)

I-V relationship $i(t) = C\frac{dv(t)}{dt}$

Voltage on capacitor CANNOT change abruptly

An capacitor is an open circuit at DC

An INDUCTOR is a circuit element that consists of a conducting wire usually in the form of a coil

I-V relationship $v(t) = L\frac{di(t)}{dt}$

unit: henry (H)

Current through inductor CANNOT change instantaneously

An inductor is a short circuit at DC

i-v relation	$i = \frac{v}{R}$	$i(t) = C\frac{dv(t)}{dt}$	$i(t) = i(t_0) + \frac{1}{L}\int_{t_0}^{t} v(x)dx$
v-i relation	$v = iR$	$v(t) = v(t_0) + \frac{1}{C}\int_{t_0}^{t} i(x)dx$	$v(t) = L\frac{di(t)}{dt}$
p (power transferred in)	$p = vi$	$p = vi$	$p = vi$
w (stored engergy)	0	$w = \frac{1}{2}Cv^2(t)$	$w = \frac{1}{2}Li^2(t)$
Series combination	$R_{eq} = R_1 + R_2$	$C_{eq} = \frac{C_1C_2}{C_1 + C_2}$	$L_{eq} = L_1 + L_2$
Parallel combination	$R_{eq} = \frac{R_1R_2}{R_1 + R_2}$	$C_{eq} = C_1 + C_2$	$L_{eq} = \frac{L_1L_2}{L_1 + L_2}$
DC behavior	NO	open circuit	short circuit
Instantaneous change of v	√	×	√
Instantaneous change of i	√	√	×

Resistor

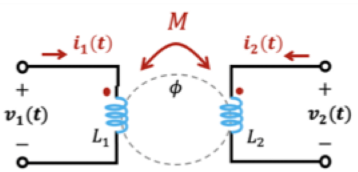
Capacitor

Inductor

Comparison

Mutual inductance

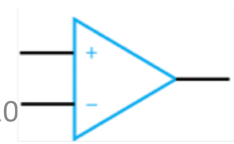
I-V relationship

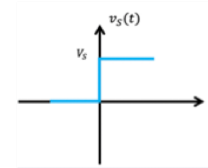


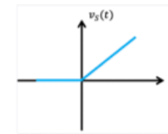
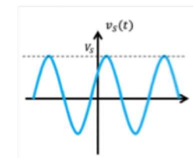
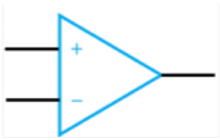
$$\begin{cases} v_1 = L_1\frac{di_1}{dt} + M\frac{di_2}{dt} \\ v_2 = M\frac{di_1}{dt} + L_2\frac{di_2}{dt} \end{cases}$$

power source

Op-Amp = Operational Amplifier



- Resistor
- Capacitor
- Inductor
- Comparison
- Mutual inductance
- power source
  - Voltage v.s. Current
  - Ideal v.s. Practical
  - DC v.s. AC
    - DC source: the output doesn't change with time
      - 

      DC voltage ouput @t>0
    - AC source: the output changes with time
      - 
      Example 1: ramp voltage source
      - 
      Example 2: Sinusoidal voltage source
  - Independent v.s Dependent
- Op-Amp = Operational Amplifier 

- Resistor
- Capacitor
- Inductor
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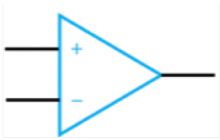
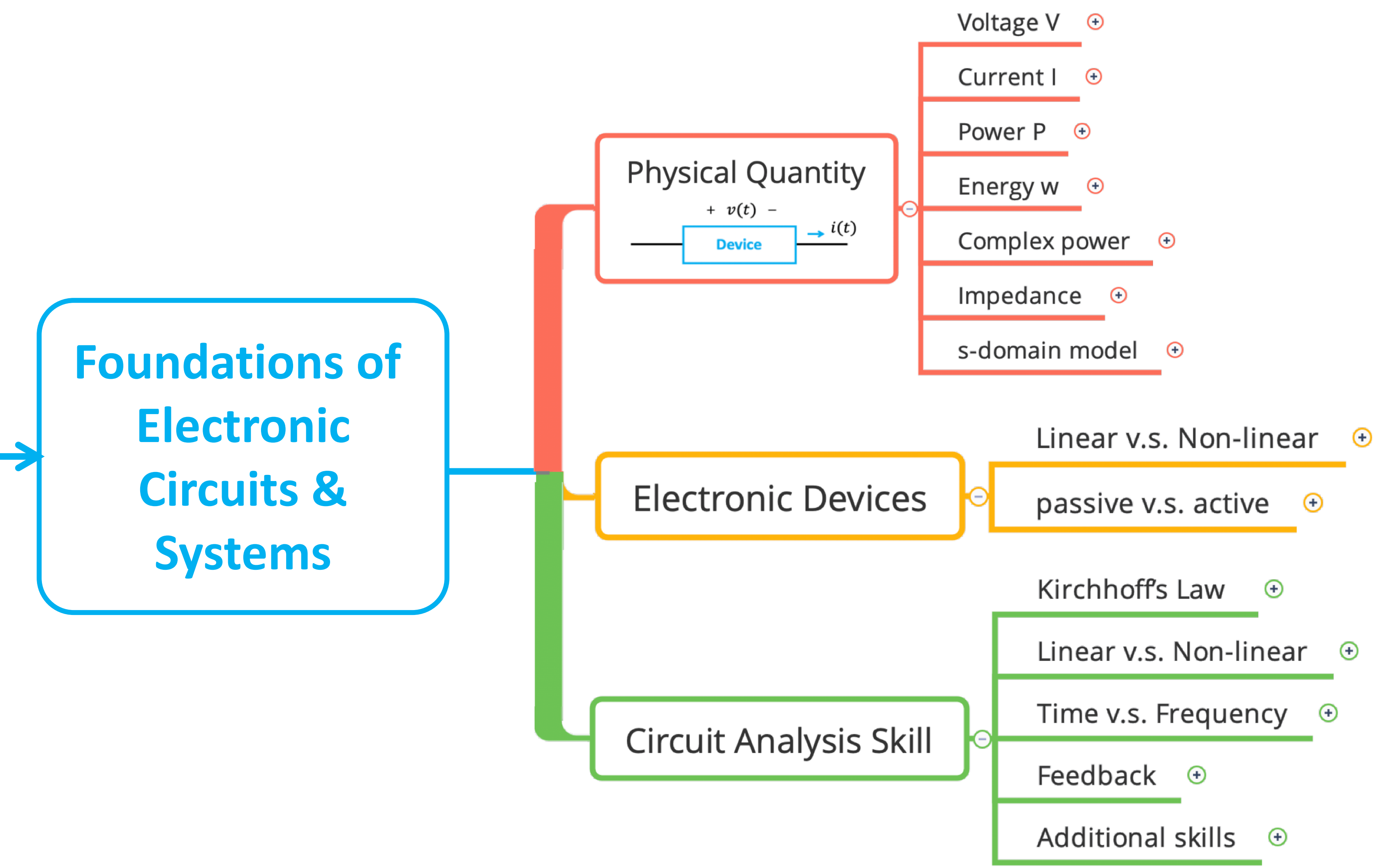
- power source
- Op-Amp = Operational Amplifier 
  - Basic characteristics
    - Voltage transfer characteristic
    - Ideal v.s. Practical
    - Model for linear region
    - Ideal op-amp in linear region
    - Offset issue
  - Applications
    - with op-amp in saturation region
    - The inverting configuration
    - The noninverting configuration
    - Differential amplifiers



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Circuit Analysis Skill
Kirchhoff's Law
Linear v.s. Non-linear
Time v.s. Frequency
Feedback
Additional skills

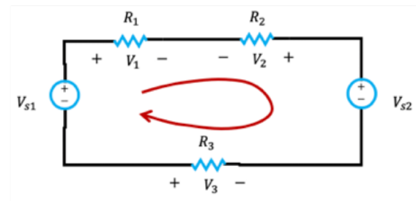
- Electronic Devices
  - passive v.s. active
- Circuit Analysis Skill
  - Kirchhoff's Law
    - KVL: Sum of voltages around a closed path is zero $\sum_{n-1}^{N} v_n = 0$
    - KCL: Sum of currents entering a node is zero $\sum_{n-1}^{N} i_n = 0$
  - Linear v.s. Non-linear
  - Time v.s. Frequency
  - Feedback
  - Additional skills

KVL: Sum of voltages around a closed path is zero

$$\sum_{n-1}^{N} v_n = 0$$

KCL: Sum of currents entering a node is zero

$$\sum_{n-1}^{N} i_n = 0$$

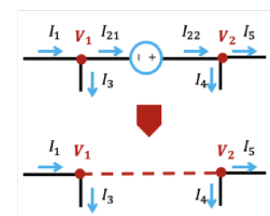


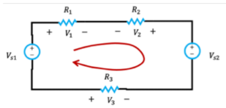
$$V_{s1} - V_1 + V_2 - V_{s2} + V_3 = 0$$

node voltage

- Step 1a: identify all extraordinary nodes
- Step 1b: Assign ground node
- Step 1c: assign node voltages to the rest
- Step 2a: perform KCL at each node
- Step 2b: apply ohm's law for each current
- Step 3: solve the system of equations

a SUPERNODE is formed when a voltage source connects two extraordinary nodes





$V_{s1} - V_1 + V_2 - V_{s2} + V_3 = 0$

node voltage

Step 1a: identify all extraordinary nodes
Step 1b: Assign ground node
Step 1c: assign node voltages to the rest
Step 2a: perform KCL at each node
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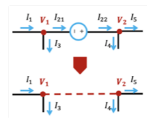
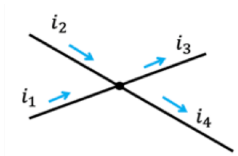
Step 3: solve the system of equations

a SUPERNODE is formed when a voltage source connects two extraordinary nodes



KVL: Sum of voltages around a closed path is zero $\sum_{n-1}^{N} v_n = 0$

KCL: Sum of currents entering a node is zero $\sum_{n-1}^{N} i_n = 0$

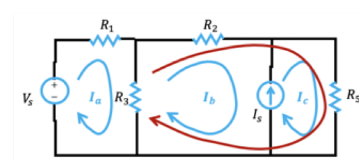


$i_1 + i_2 - i_3 - i_4 = 0$

mesh current

Step 1a: identify all mesh
Step 1b: assign each mesh an unknown current, usually in clockwise direction
Step 2a: apply KVL to each mesh
Step 2b: group terms by mesh-current
Step 3: solve the system of equations

a SUPERMESH is formed when a current source is connected in a path

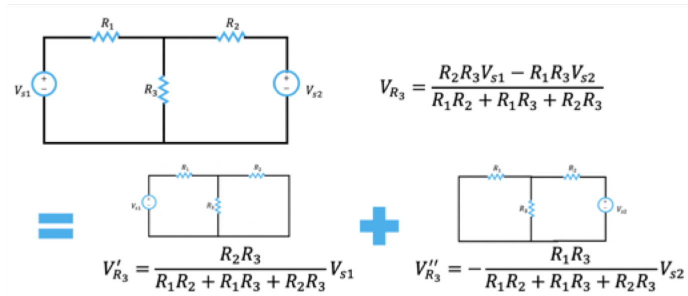


Electronic Devices

passive v.s. active

A CIRCUIT is LINEAR
if it possesses the properties
of additive and homogeneity

Superposition
trades off the examination
of several simpler circuits in
place of one complex circuit
LINEAR CIRCUIT ONLY



Consider one INDEPENDENT source
at a time, by "turning off" all other
INDEPENDENT sources

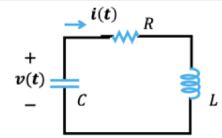
DEPENDENT sources are
left intact because they are
controlled by circuit variables

Circuit Analysis Skill

- Kirchhoff's Law
- Linear v.s. Non-linear
- Time v.s. Frequency
- Feedback
- Additional skills

step by step process
Step 1: write the circuit equations according to KCL/KVL
Step 2a: find the complementary solution
Step 2b: find the particular integral solution
Step 3: find initial V/I to solve the unknown

- 1st order examples
  - source free
  - with forcing func
- 2nd order examples
  - source free



Particular integral solution

$v_p(t) = 0$

Complementary solution

$v_c(t) = K_1 e^{s_1 t} + K_2 e^{s_2 t}$

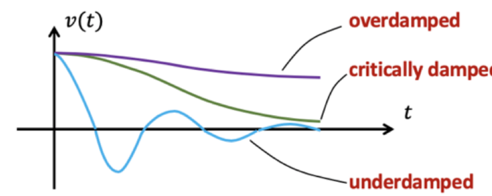
Where $\begin{cases} S_1 = -\zeta\omega_0 + \omega_0\sqrt{\zeta^2 - 1} \\ S_2 = -\zeta\omega_0 - \omega_0\sqrt{\zeta^2 - 1} \end{cases}$

and $\omega_0 = \frac{1}{\sqrt{LC}}$, $\zeta = \frac{R}{2\omega_0 L}$

Full solution $v(t) = v_p(t) + v_c(t)$

A DISCUSSION ON ζ

- If $\zeta < 1$ → **underdamped**
- If $\zeta = 1$ → **critically damped**
- If $\zeta > 1$ → **overdamped**



RLC circuit status
1. underdamped
2. critically damped
3. overdamped

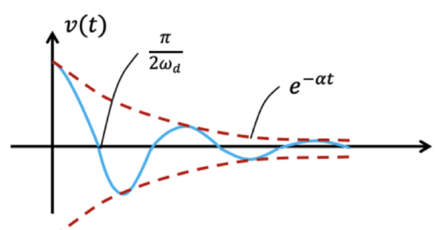
Understand the waveform

$$v_c(t) = e^{-\zeta\omega_0 t}[A_1 \cos(\omega_d t) + A_2 \sin(\omega_d t)]$$

Define **DAMPING FACTOR** $\alpha = \frac{R}{2L}$

Define **RESONATE FREQUENCY** $\omega_0 = \frac{1}{\sqrt{LC}}$

Define **DAMPING RATIO** $\zeta = \frac{\alpha}{\omega_0} = \frac{R}{2\omega_0 L}$



Transient v.s. Steady

Frequency Response

step by step process
Step 1: write the circuit equations according to KCL/KVL
Step 2a: find the complementary solution
Step 2b: find the particular integral solution
Step 3: find initial V/I to solve the unknown

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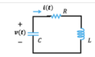
  - source free
  - with forcing func
- 2nd order examples
  - source free



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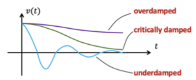

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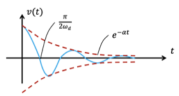


TRANSFER FUNCTION of a circuit or system describes the output response to an input excitation as a function of the angular frequency

$$\mathbb{G}(\omega) = \frac{\mathbb{V}_{out}(\omega)}{\mathbb{V}_{in}(\omega)}$$

- Filters
- Quality factor
  - Q is the ratio of energy stored to energy lost at the resonant frequency

$$Q = 2\pi \frac{W_S}{W_D}$$

- Bode plot
  - Bode plot generates a "straight-line" approximation of the transfer function
  - Basic rules

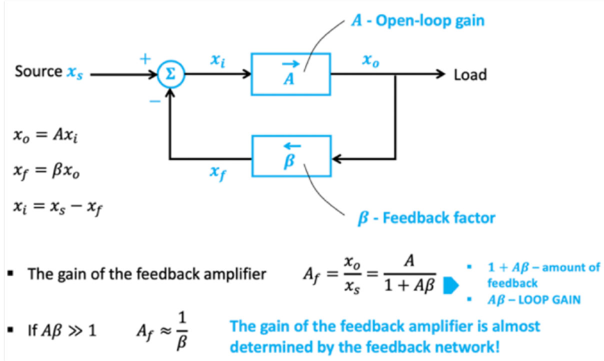
Transient v.s. Steady

Frequency Response

Electronic Devices

passive v.s. active

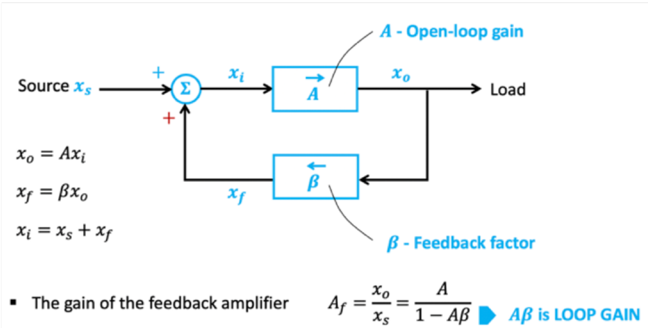
General negative feedback structure



Negative feedback

benefits from negative feedback

General positive feedback structure

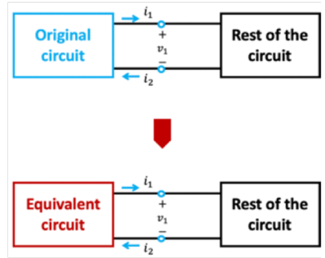


Positive feedback

Circuit Analysis Skill

- Kirchhoff's Law
- Linear v.s. Non-linear
- Time v.s. Frequency
- Feedback
- Additional skills

the general concept

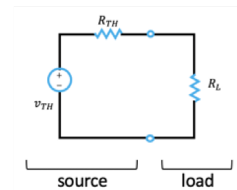


w/o source

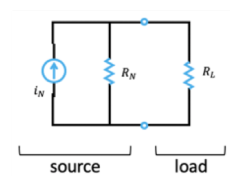
- resistors in series: sum of resistance $R_{eq} = \sum_{i=1}^{N} R_i$
- resistors in parallel: sum of conductance $\frac{1}{R_{eq}} = \sum_{i=1}^{N} \frac{1}{R_i}$
- capacitors in series $\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$
- capacitors in parallel $C_{eq} = C_1 + C_2 + C_3$

w/ source

- Thévenin's theorem
  LINEAR two-terminal circuit can be replaced by an equivalent circuit composed of a voltage source and a series resistor



- Norton's theorem
  LINEAR two-terminal circuit can be replaced by an equivalent circuit composed of a current source and a parallel resistor



- step by step process to find Thévenin's/Norton's equivalent

ar

Equivalent circuits

Source transformation

One-Port Network

Two-Port Network

ar

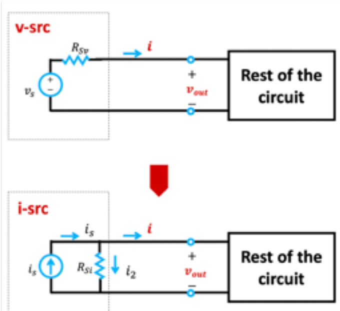
Equivalent circuits

Source transformation

One-Port Network

Two-Port Network

Goal: to turn a voltage source into current source, and vice-versa



- For the v-src, according to KVL

$$-v_s + iR_{Sv} + v_{out} = 0$$

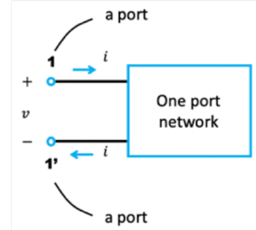
- For the i-src, according to KCL

$$\begin{cases} i_s = i + i_2 \\ i_2 = \dfrac{v_{out}}{R_{Si}} \end{cases}$$

- If $R_{Sv} = R_{Si} = R_S$

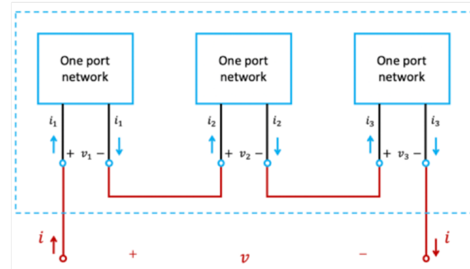
$$\mathbf{v_s = i_s R_S}$$

ONE PORT NETWORK
is a two terminal electrical network in which, current enters through one terminal and leaves through another terminal.



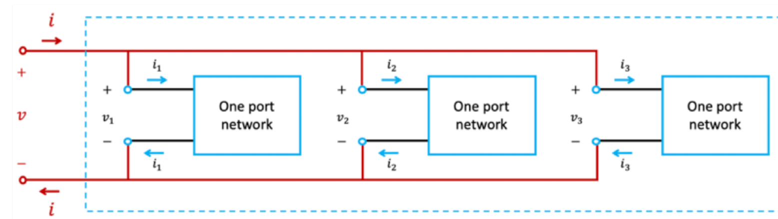
Connections

in series



- According to KVL $v = v_1 + v_2 + v_3$
- According to KCL $i = i_1 = i_2 = i_3$

in parallel



- According to KVL $v = v_1 = v_2 = v_3$
- According to KCL $i = i_1 + i_2 + i_3$

another way to find Thévenin / Norton's equivalent

Step 1a: remove the load
Step 1b: apply a test voltage to the port
Step 2: find the relationship between v-test & i-test

ar

Equivalent circuits

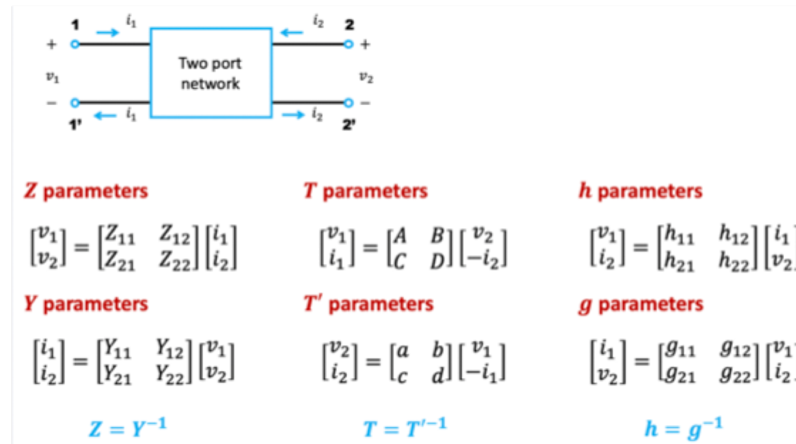
Source transformation

One-Port Network

Two-Port Network

TWO PORT NETWORK
is a pair of two terminal electrical network
in which, current enters through one terminal
and leaves through another terminal.

Know how to calculate the network parameters



PARAMETERS
If two of the four variables are independent
and another two variables as dependent,
the coefficients of the independent variables
are called as PARAMETERS

Connections
- in series
- in parallel
- cascading

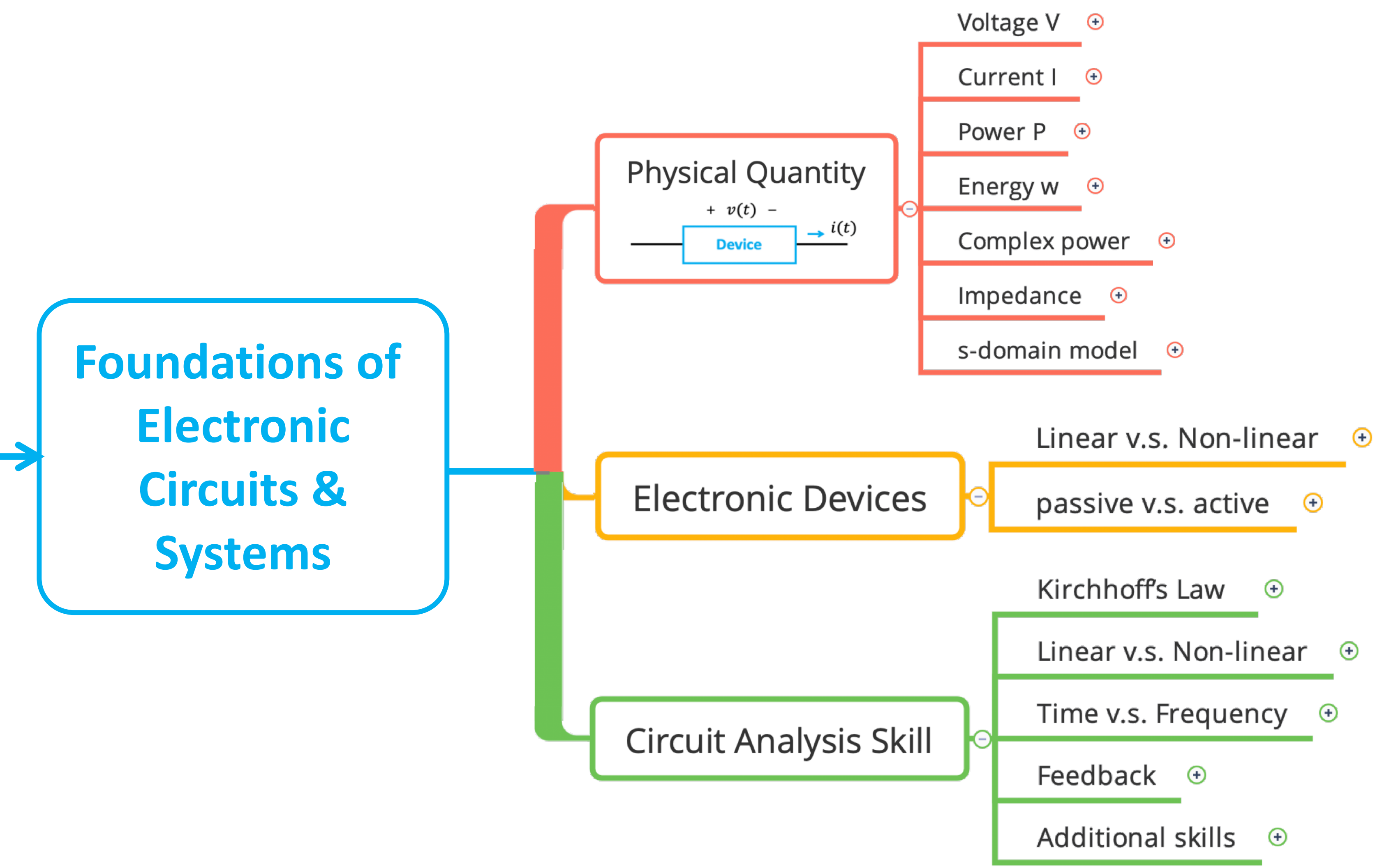
ar

Equivalent circuits

Source transformation

One-Port Network

Two-Port Network


Foundations of Electronic Circuits & Systems
Physical Quantity
+ v(t) −
Device
i(t)
Voltage V
Current I
Power P
Energy w
Complex power
Impedance
s-domain model
Electronic Devices
Linear v.s. Non-linear
passive v.s. active
Circuit Analysis Skill
Kirchhoff's Law
Linear v.s. Non-linear
Time v.s. Frequency
Feedback
Additional skills


Good luck