9 August 2020

وَمَا أُوتِيتُمْ مِنَ الْعِلْمِ إِلَّا قَلِيلًا

19 ذو الحجة 1441

Analog IC Design

Lecture 02
Review on Circuits and Systems Basics

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Faculty of Engineering
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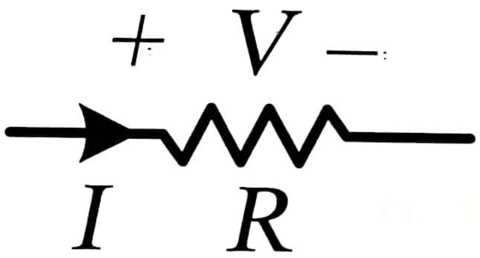
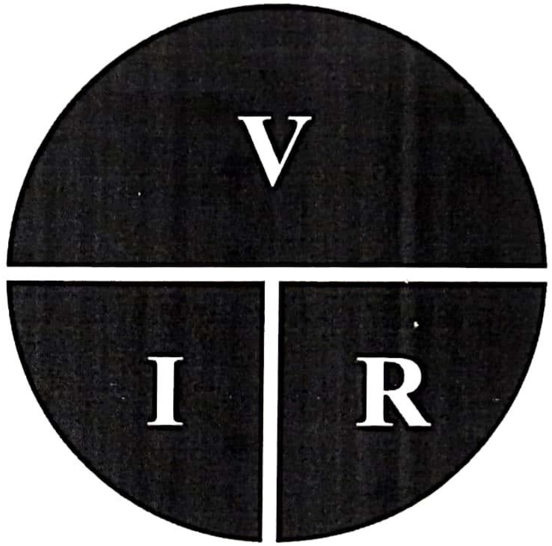
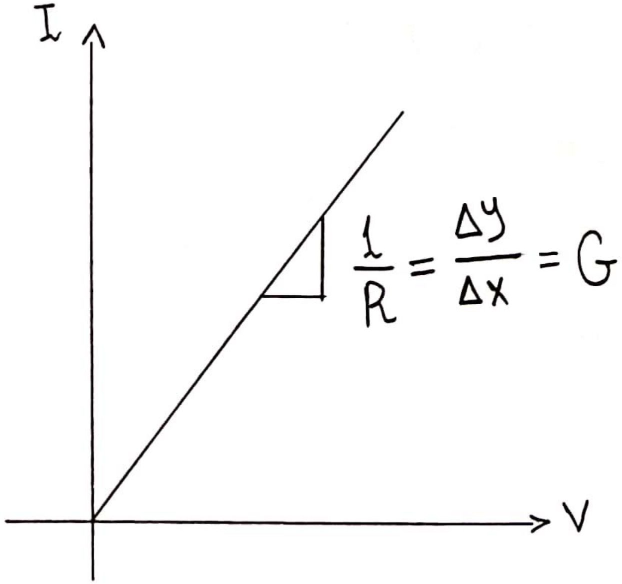
Ohm's Law







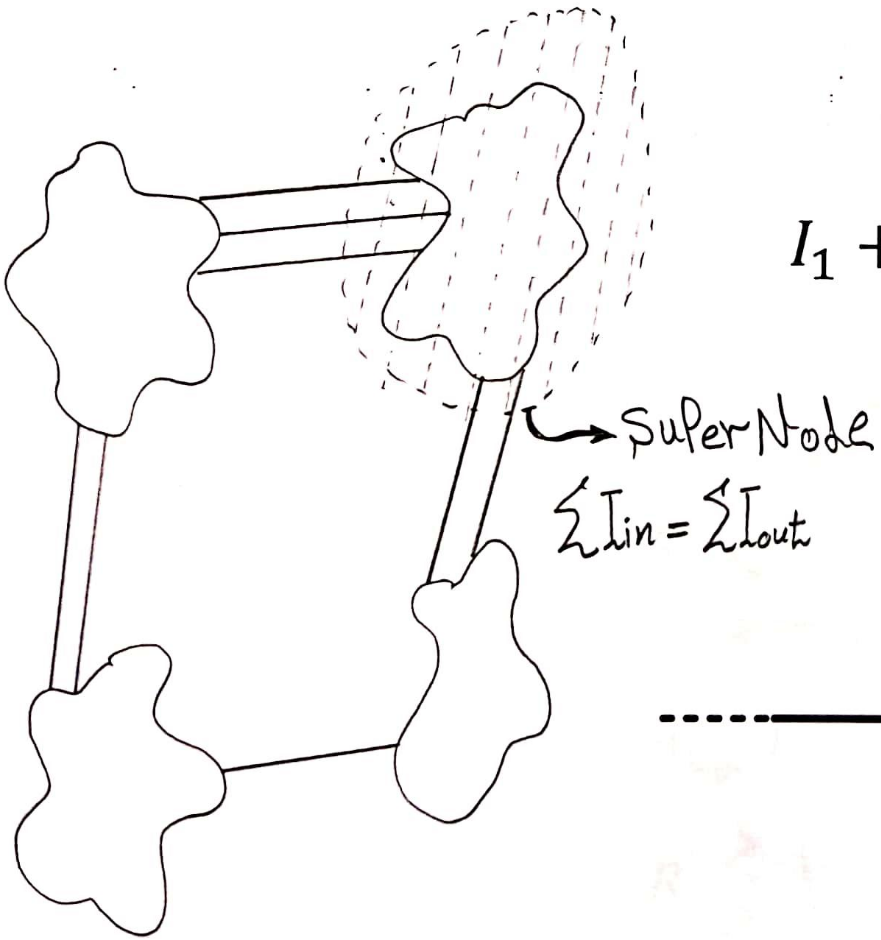
$$V = IR$$

$$I = \frac{V}{R}$$

$$R = \frac{V}{I}$$

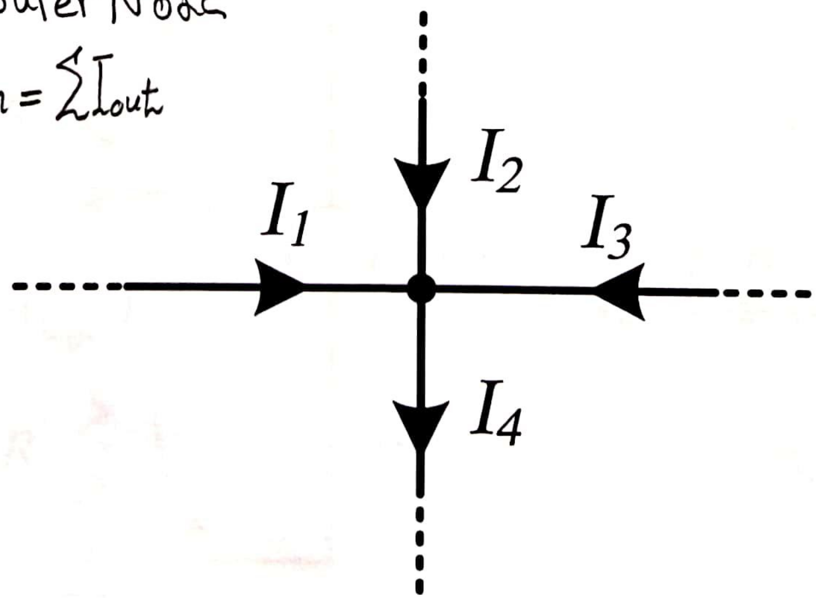
Kirchhoff's Current Law (KCL)

- The sum of all currents flowing into a node is zero.



$$\Sigma I = 0$$

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



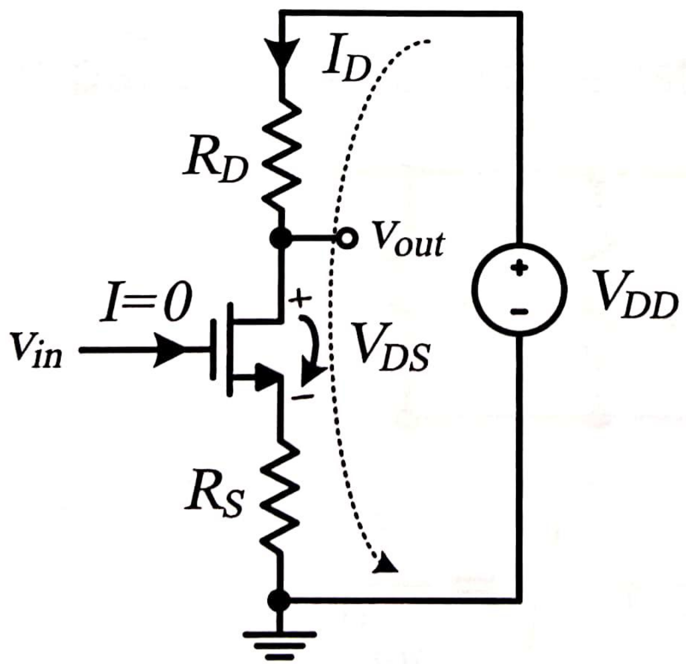
Kirchhoff's Voltage Law (KVL)

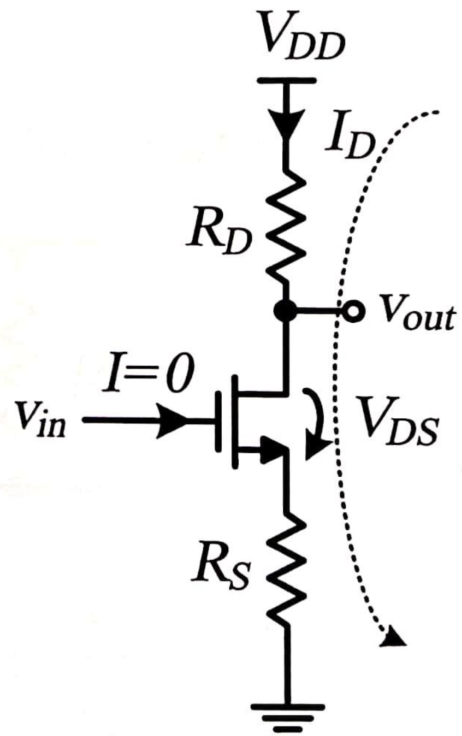
- The sum of all voltage drops around any closed loop is zero

$$\Sigma V = 0$$

$$-V_{DD} + I_D R_D + V_{DS} + I_D R_S = 0$$

$$V_{DD} = I_D (R_D + R_S) + V_{DS}$$



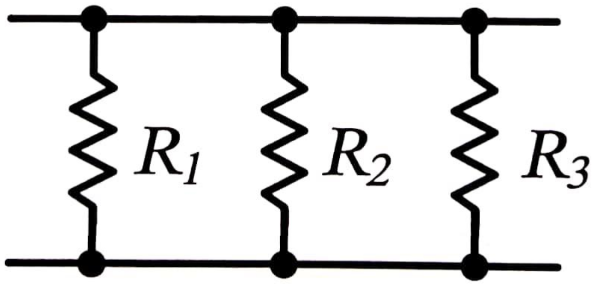


Resistor Combinations

- Resistors in series: Largest resistor dominates

$$R_{eq} = R_1 + R_2 + R_3$$

- Resistors in parallel: Smallest resistor dominates



$G_{eq} = G_1 + G_2 + \text{-----}$

equivalent Conductance

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Voltage and Current Dividers

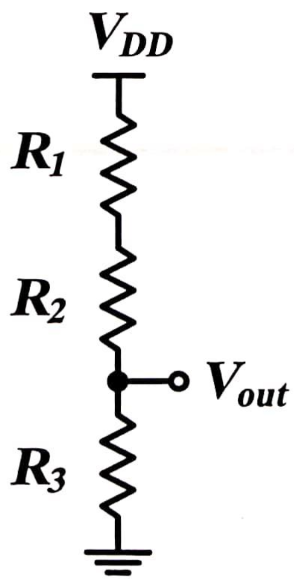
- Voltage divider → the largest resistor takes most of the voltage
- Current divider → the smallest resistor (largest conductance) takes most of the current
  - Remember that current flows in the least resistance path

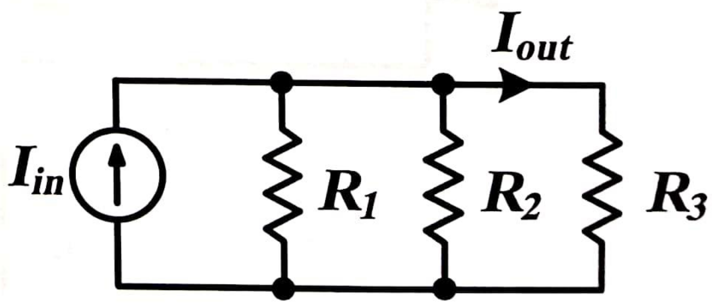
$$V_{out} = V_{DD} \cdot \frac{R_3}{R_1 + R_2 + R_3}$$

General Voltage divider

$$I_{out} = I_{in} \cdot \frac{G_3}{G_1 + G_2 + G_3}$$

General Current Divider



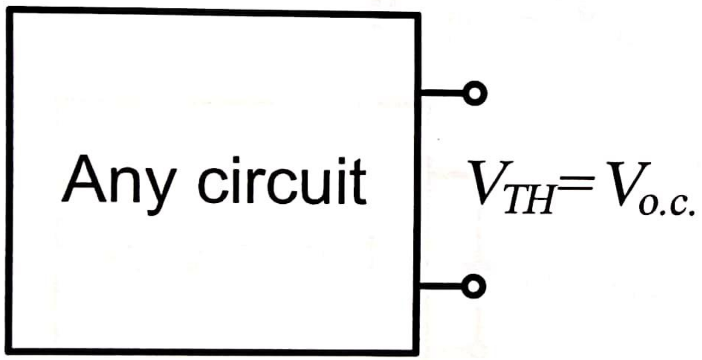


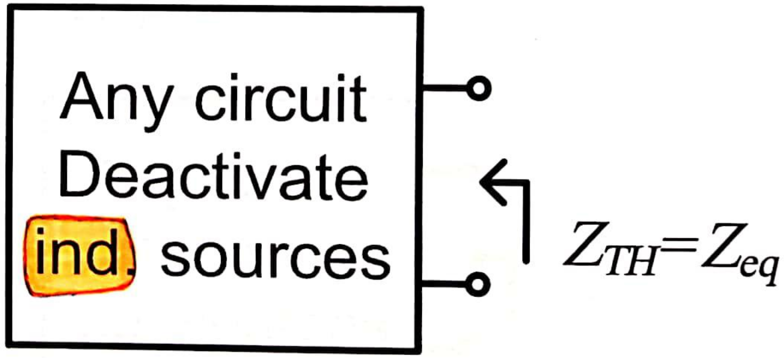
Thevenin Equivalent Circuit

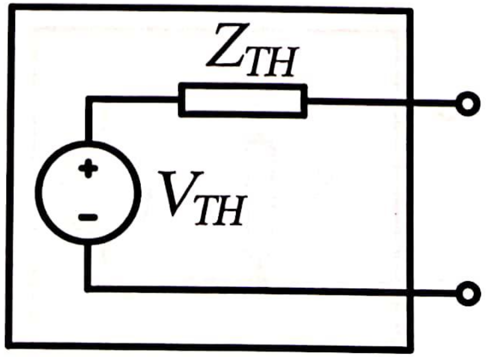
- Any one port circuit can be replaced by a voltage source and a series impedance

$$V_{TH} = V_{o.c.}$$

$$Z_{TH} = Z_{eq} \text{ (turn OFF all independent sources)}$$



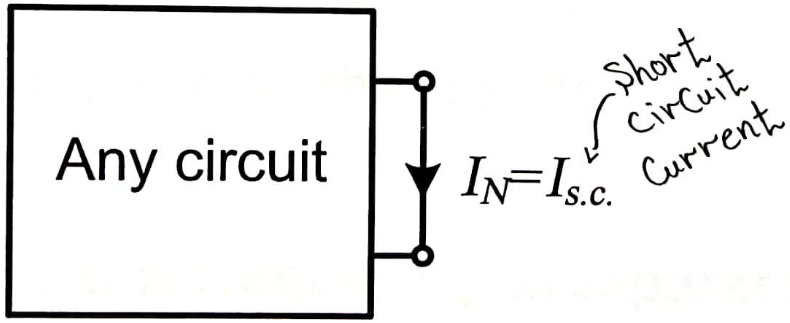


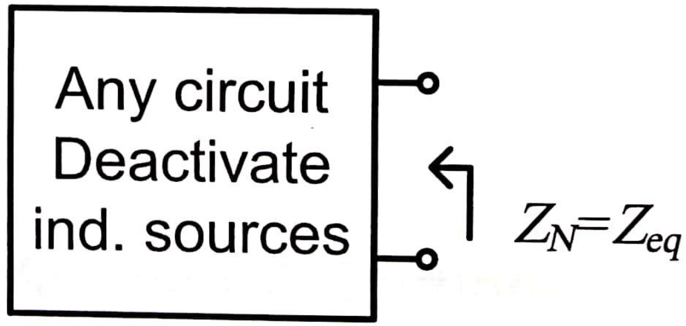


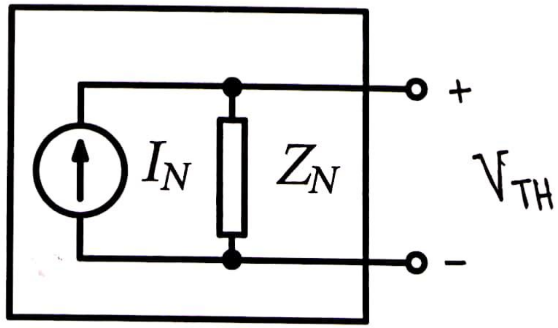
Norton Equivalent Circuit

- Any one port circuit can be replaced by a current source and a parallel impedance

$$I_N = I_{s.c.}$$
$$Z_N = Z_{eq} \text{ (turn OFF all independent sources)}$$
$$\boldsymbol{Z_N = Z_{TH}}$$
$$\boldsymbol{V_{TH} = V_{o.c.} = I_N \times Z_N}$$







Superposition Theorem

- ❑ Deactivate all independent sources except one
  - Independent voltage source → short circuit (s.c.)
  - Independent current source → open circuit (o.c.)
  - Do NOT deactivate dependent sources
- ❑ Solve the circuit
- ❑ Repeat the previous two steps for every source
- ❑ Algebraically add all the results

$V_o = V_o' + V_o'' + V_o'''$

We use this frequently to separate AC and DC solutions

*for this theorem to be Valid circuit should be linear.

Superposition Theorem

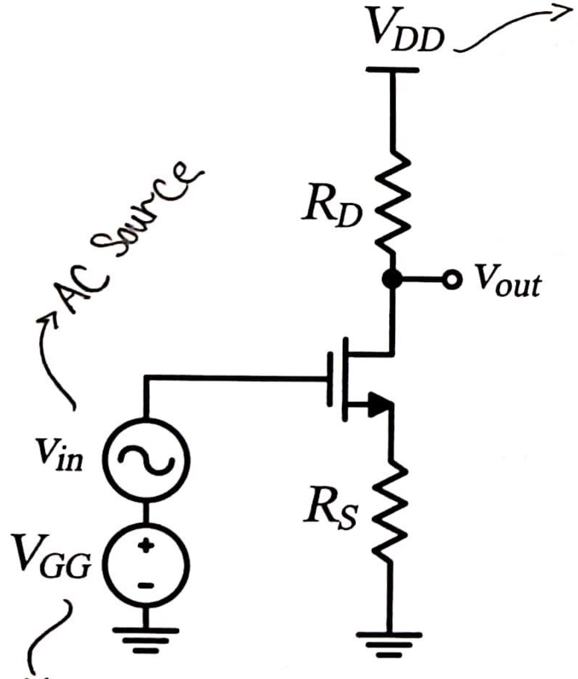
DC Analysis or DC equivalent circuit

AC Analysis or AC equivalent circuit

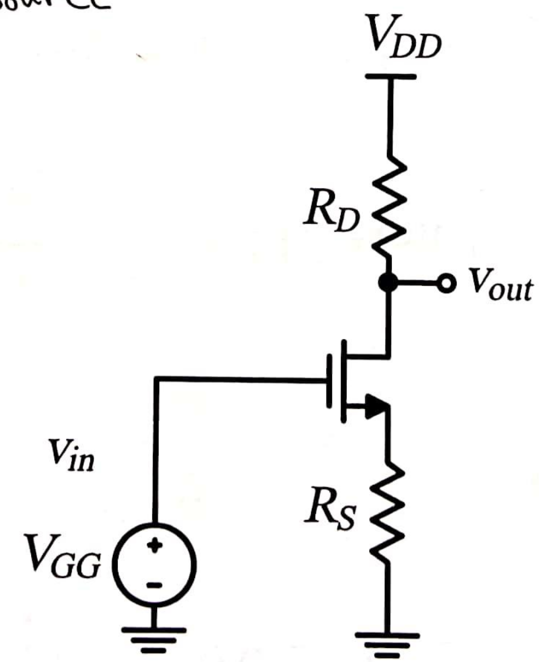
DC + AC = DC + AC

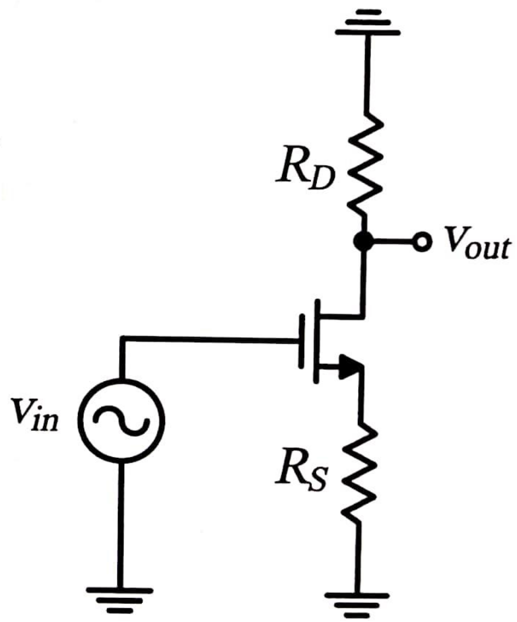
Dc Source

AC Source



Dc Source





Capacitance

$$Q = CV$$

$$i = \frac{dQ}{dt} = C\frac{dV}{dt}$$

cos(ωt) + jω sin(ωt)

$$V = V_o \cos\omega t = V_o \cdot Re\{e^{j\omega t}\} \Rightarrow V_o e^{j\omega t}$$

We omitth "Re" for simplicity

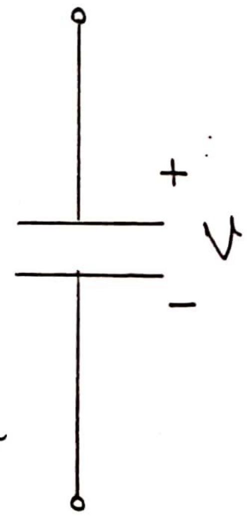
$$i = C\frac{dV}{dt} = j\omega C\left(V_o e^{j\omega t}\right) = j\omega C \cdot V$$

frequency Domain

S-Domain "Laplace"

Reactance

$$Z_C = \frac{V}{i} = \frac{1}{j\omega C} = \frac{1}{sC} \Rightarrow X_C = \frac{1}{\omega C}$$

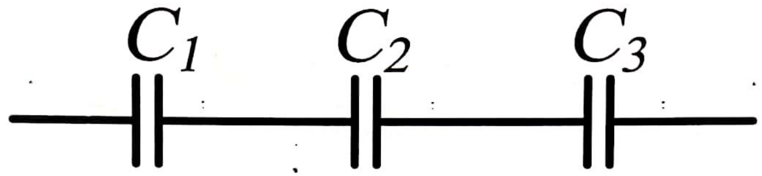


High frequency $\qquad \omega \uparrow\uparrow \Rightarrow X_C \to 0 \Rightarrow s.c.$

Small frequency $\qquad \omega \downarrow\downarrow \Rightarrow X_C \to \infty \Rightarrow o.c.$

Capacitance Combinations

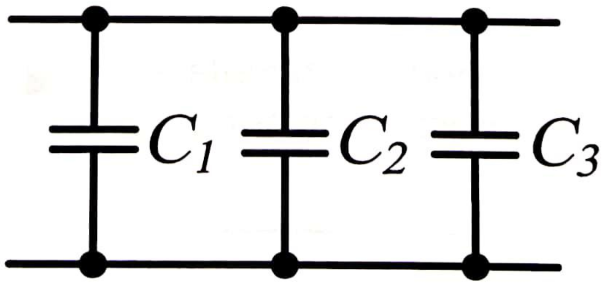
- Capacitors in series: Smallest capacitor dominates



$X_c = \frac{1}{\omega C}$

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

- Capacitors in parallel: Largest capacitor dominates



$$C_{eq} = C_1 + C_2 + C_3$$

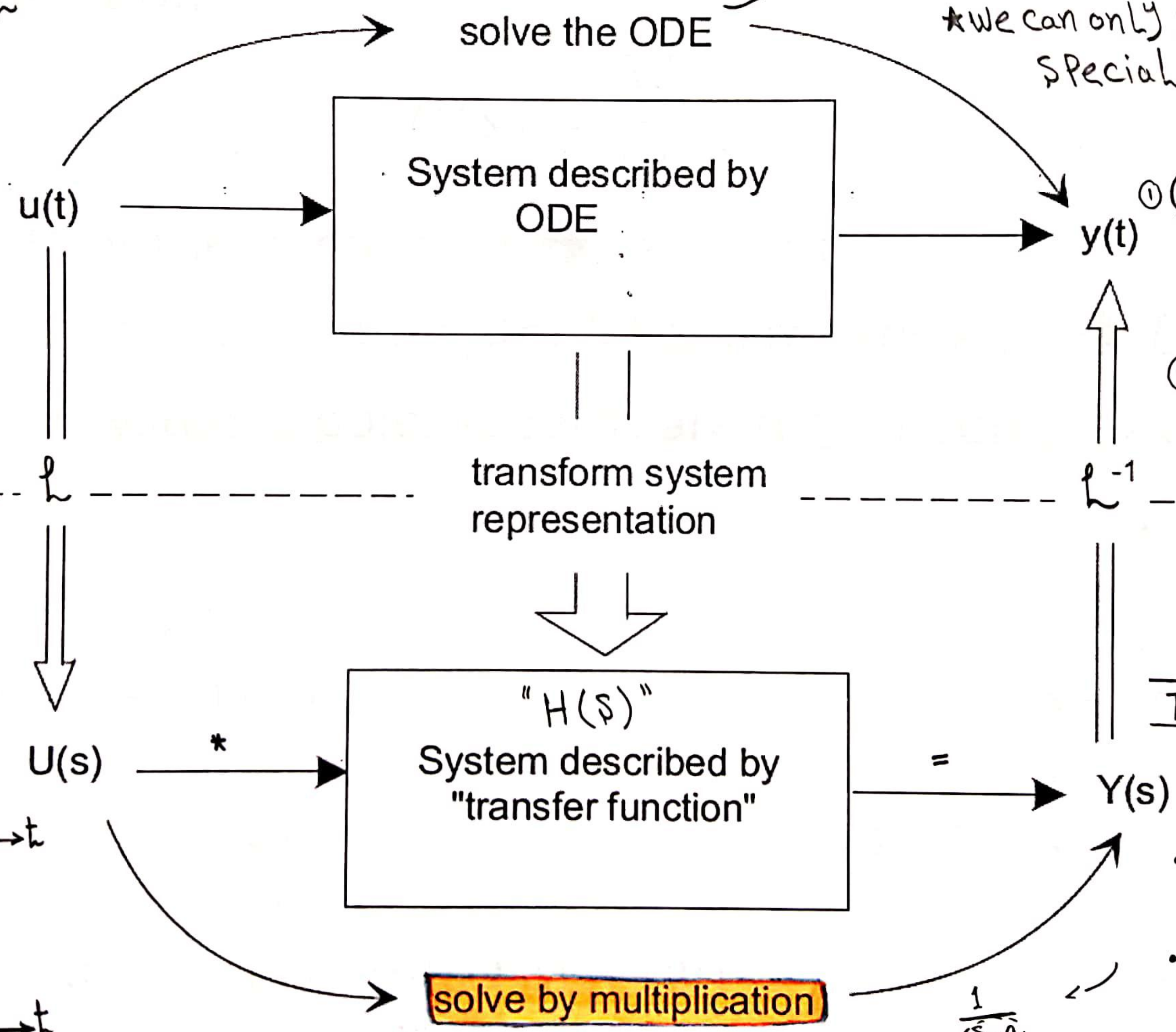
Laplace Transform (LT)

★ Systems Review

★ Most systems are described by ODE

- $Q = CV$

$i = \frac{dQ}{dt} = C\frac{dV}{dt}$



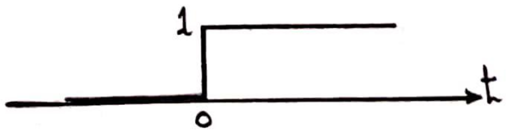
→ Difficult in most cases

★ we can only solve ODE's special cases

- So, we transform
  ① "ODE" into "transfer function"
  - ODE $\Rightarrow H(S)$
  ② $u(t) \Rightarrow U(S)$
  ③ $Y(S) = U(S) \cdot H(S)$
  ④ $Y(S) \xrightarrow{\mathcal{L}^{-1}} y(t)$ #

- $\delta(t)$ 'impulse signal'

- $u(t)$ " step signal"



Time domain	Laplace Transform
• e^{at}	• $\frac{1}{S-a}$
• $\int_0^t f(t) \cdot dt$	• $\frac{1}{S} F(S)$
• $\frac{df(t)}{dt}$	• $SF(S)$
• $\delta(t)$	• 1
• $u(t)$	• $1/S$

$\frac{1}{S-a}$

$\hookrightarrow S-a=0 \rightarrow S=a$

$\therefore$ there is a pole @ a

★ Actually step function '$u(t)$' is the integration of the impulse function '$\delta(t)$' so, by dividing $\mathcal{L}\{u(t)\}$ by 'S' $\therefore \mathcal{L}\{\delta(t)\} = \frac{1}{S}$

[D. Rowell, MIT 2.004, 2008]

Poles and Zeros

* missing two slides before this one.
03:00 → 09:25

- Transfer function

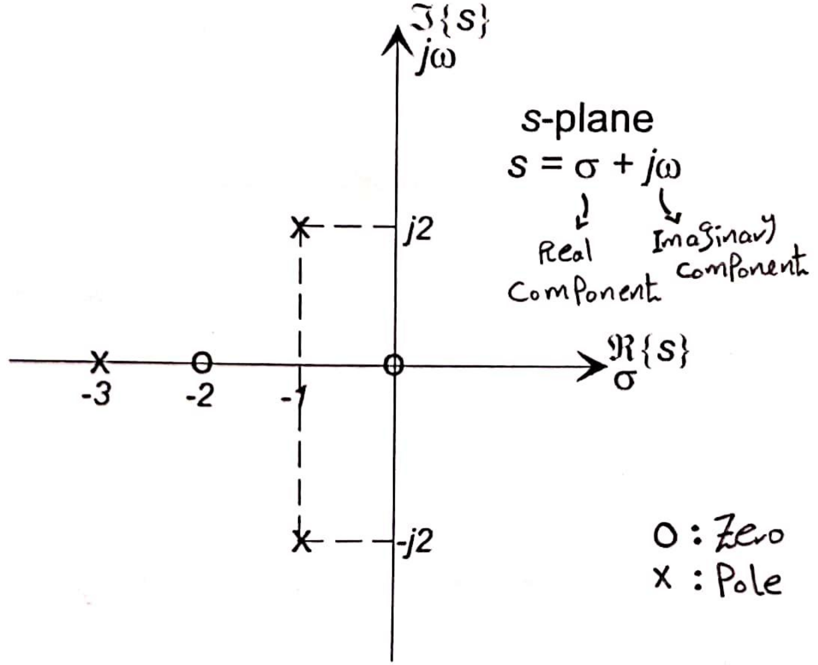
$$H(s) = \frac{N(s)}{D(s)}$$

$H(s) \to \infty$

$H(s) \to$ zero

- Zeros: roots of the numerator ➔ $N(s) = 0$
- Poles: roots of the denominator (characteristic eq.) ➔ $D(s) = 0$
- For physical systems, poles & zeros are real or complex conjugate
- Example:

$$\begin{aligned} G(s) &= \frac{5s^2 + 10s}{s^3 + 5s^2 + 11s + 5} \\ &= \frac{5s(s+2)}{(s+3)(s^2+2s+5)} \\ &= \frac{5s(s+2)}{(s+3)(s+(1+j2))(s+(1-j2))} \end{aligned}$$



[D. Rowell, MIT 2.004, 2008]

Pole-Zero Plot

Left half Plane

*missing slide before this one.
09:25 → 11:50

- Poles in LHP: Decaying exponential ➔ Stable system
  - BIBO: Bounded input bounded output

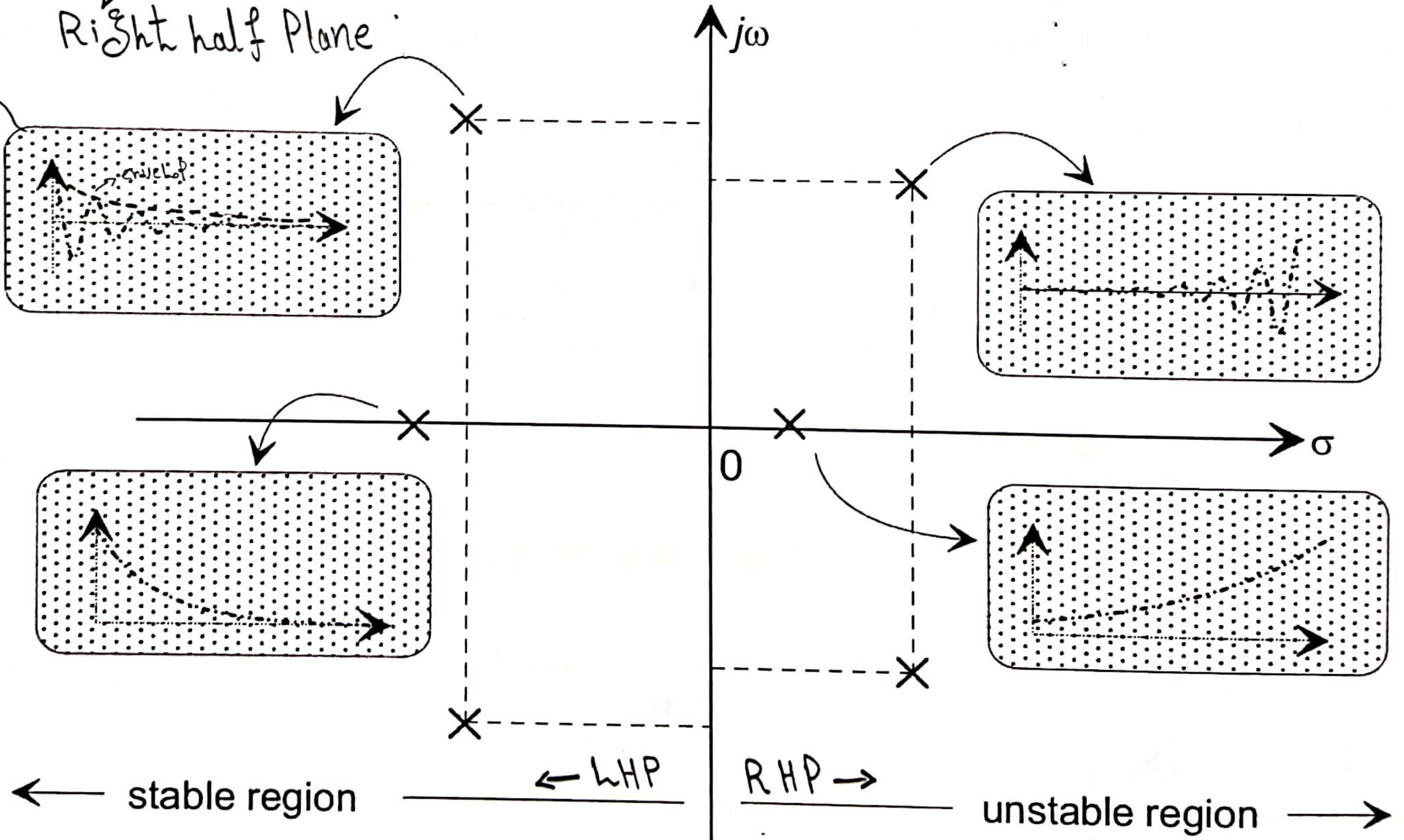
$\delta(t) \rightarrow \boxed{H(s)} \rightarrow \mathcal{L}^{-1}\{H(s)\}$

- Poles in RHP: Growing exponential ➔ Unstable system

Right half Plane

Complex Poles Produce oscillation

$e^{-\overset{+ve}{\sigma} t}$



$\sigma + j\omega$

$e^{(\sigma t + j\omega t)}$

$e^{\sigma}(e^{j\omega t})$

∵ +ve envelop

∴ Decaying oscillation

*Poles are what define the stability of the system
→ not the zeroes (Zeros can be either LHP or RHP with no effect on the stability)

Frequency Response

- Transfer function

① $s = \sigma + j\omega$, $\sigma \rightarrow 0$

② In circuits we deliver (transfer) our electricity using sinusoidal signal so, power engineers considered sinusoidal signal as the steady state so, it's easier with sinusoidals to use frequency response.

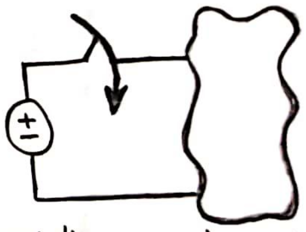
$$H(s) = \frac{N(s)}{D(s)}$$

③ "frequency response": if the input is sinusoidal @ specific frequency, then you'll see a magnitude response & phase response.

- "Fourier Transform" is a special case of "Laplace Transform": $s \Rightarrow j\omega$
  - $\sigma = 0$ ➔ Steady state response for sinusoidal input

④ ★ Laplace is used in transient.

- Transfer function ➔ Frequency response: $s \Rightarrow j\omega$

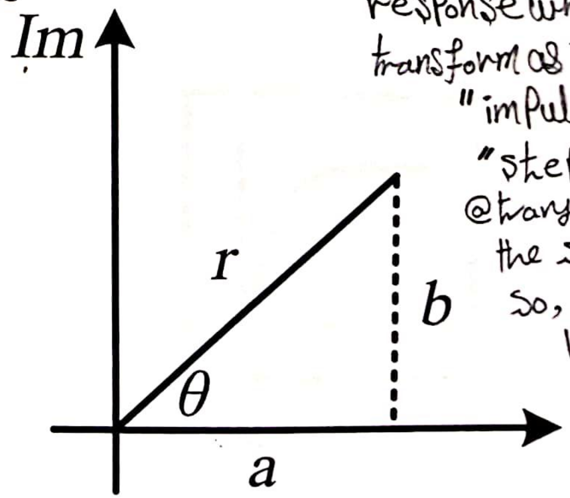


★ this is a transient response which fits Laplace transform as it deals with "impulse signal" "step signal" @ transience you see the step response so, you deal with Laplace.

$$\frac{1}{a+jb} = \frac{1}{r} e^{-j\theta}$$

$$\underbrace{H(j\omega)}_{\text{freq. response}} = \frac{V_{out}(j\omega)}{V_{in}(j\omega)} = \underbrace{|H(j\omega)|}_{\text{magnitude}} \underbrace{e^{j\phi}}_{\text{phase}}$$

- $a + jb = re^{j\theta}$
- $r = \text{Magnitude}(a + jb) = \sqrt{a^2 + b^2}$
- $\theta = \text{Phase}(a + jb) = \tan^{-1}\frac{b}{a}$



es should be

Frequency Response

- Y-axis: magnitude of frequency response, x-axis: frequency

LPF

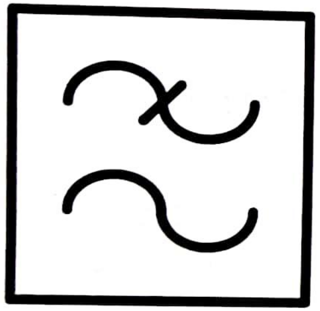
Low Pass Response

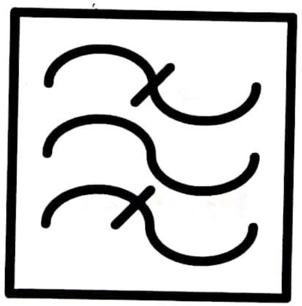
BPF

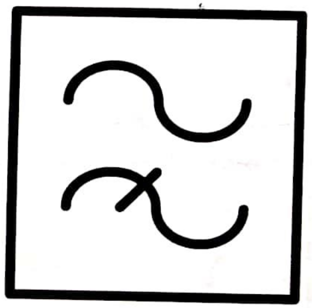
Band-Pass filter

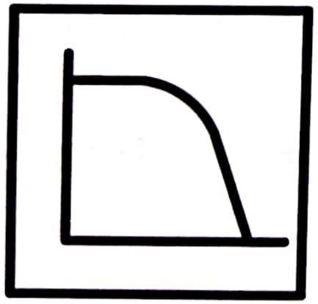
HPF

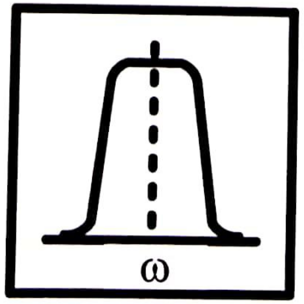
High Pass response

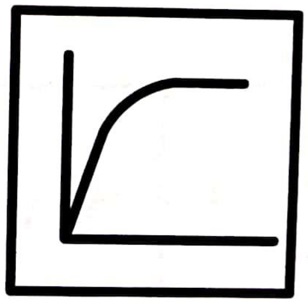












★ Actually there is no system that have a high Pass response extended to infinity, @ some Point it must goes down to zero as: every system have a capacitancy and the capacitance @ infinity is a short circuit.

1st Order LPF

③★ no. of Zeroes should be equal to no. of Poles.
So, where is the Zero?

Voltage Divider

$$H(s) = \frac{v_{out}(s)}{v_{in}(s)} = \frac{1/sC}{R + 1/sC} = \frac{1}{1 + sRC} = \frac{1}{(1 + s\tau)}$$

1 → ≠0 So, no Zeroes?

$(1+s\tau)$ → =0 → 1 Pole @ $S = -\frac{1}{\tau}$

Transfer function or Frequency response

$$H(j\omega) = \frac{v_{out}(j\omega)}{v_{in}(j\omega)} = \frac{1/j\omega C}{R + 1/j\omega C} = \frac{1}{1 + j\omega RC} = \frac{1}{1 + \frac{j\omega}{\omega_c}}$$

$\frac{1}{\tau} = \omega_c$

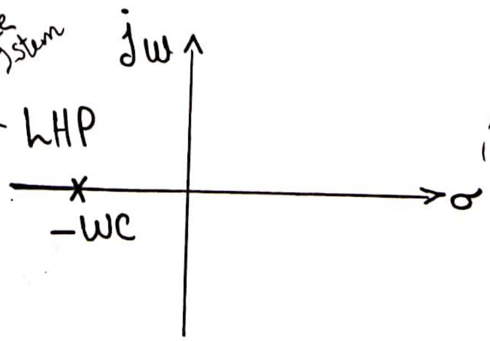
- $\tau = RC$: time constant

② ★ $W_c = \frac{1}{RC} \rightarrow \frac{1}{time}$ = angular freq.

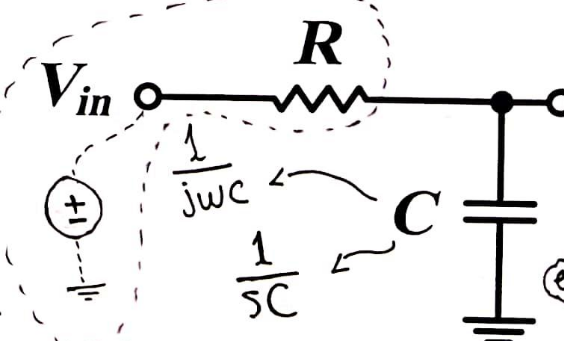
- $\omega_c = \frac{1}{\tau} = \frac{1}{RC}$: cutoff/corner frequency
- Poles: $s_p = -\frac{1}{\tau} = -\omega_c$ → Pole frequency
- Zeros: ? ⑤ → $C = \frac{1}{jwC}$ → $w \rightarrow \infty$, ⑥ $\therefore S_Z = \infty$ doesn't affect the freq. response or the transfer func. as we won't see it.

where is the Zero? ④ • the zero is the thing which makes the transfer function = 0 ∴ Vout = 0 ↓ this happens when cap = S.C.

- $|H(j\omega)| = \frac{1}{\sqrt{1+\left(\frac{\omega}{\omega_c}\right)^2}}$ → magnitude; 1 → real; $\frac{\omega}{\omega_c}$ → Imaginary
- $P(H(j\omega)) = -\tan^{-1}\frac{\omega}{\omega_c}$ → Phase; as complex no. is in the denominator

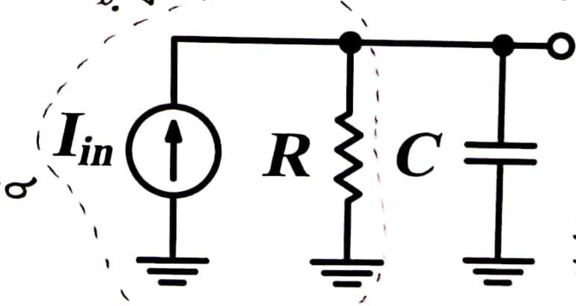


Pole-Zero Plot



① $X_c = \frac{1}{wC}$ (extremes)
⇓ Low ∴ $X_c = \infty$ ∴ O.C
⇑ high ∴ $X_c = 0$ ∴ S.C → Blocks high freq. signals ∴ ★ Low Pass Filter

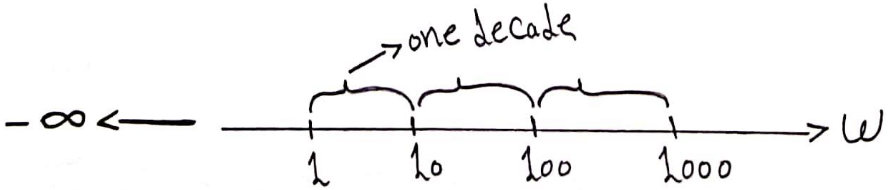
trans. Source

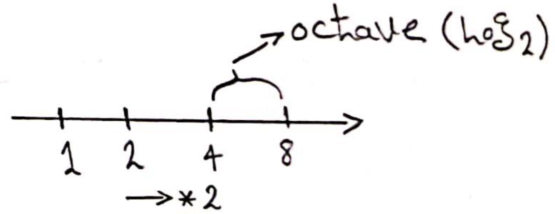


Bode Plot Rules

★ to Plot frequency response

	Pole	Zero
Magnitude	-20 dB/decade → *10 Actual Mag @ pole: -3 dB	+20 dB/decade Actual Mag @ zero: +3 dB
Phase	-90º → to be stable system Actual Phase @ pole: -45º	LHP zero: +90º Actual Phase @ zero: +45º RHP zero: -90º Actual Phase @ zero: -45º



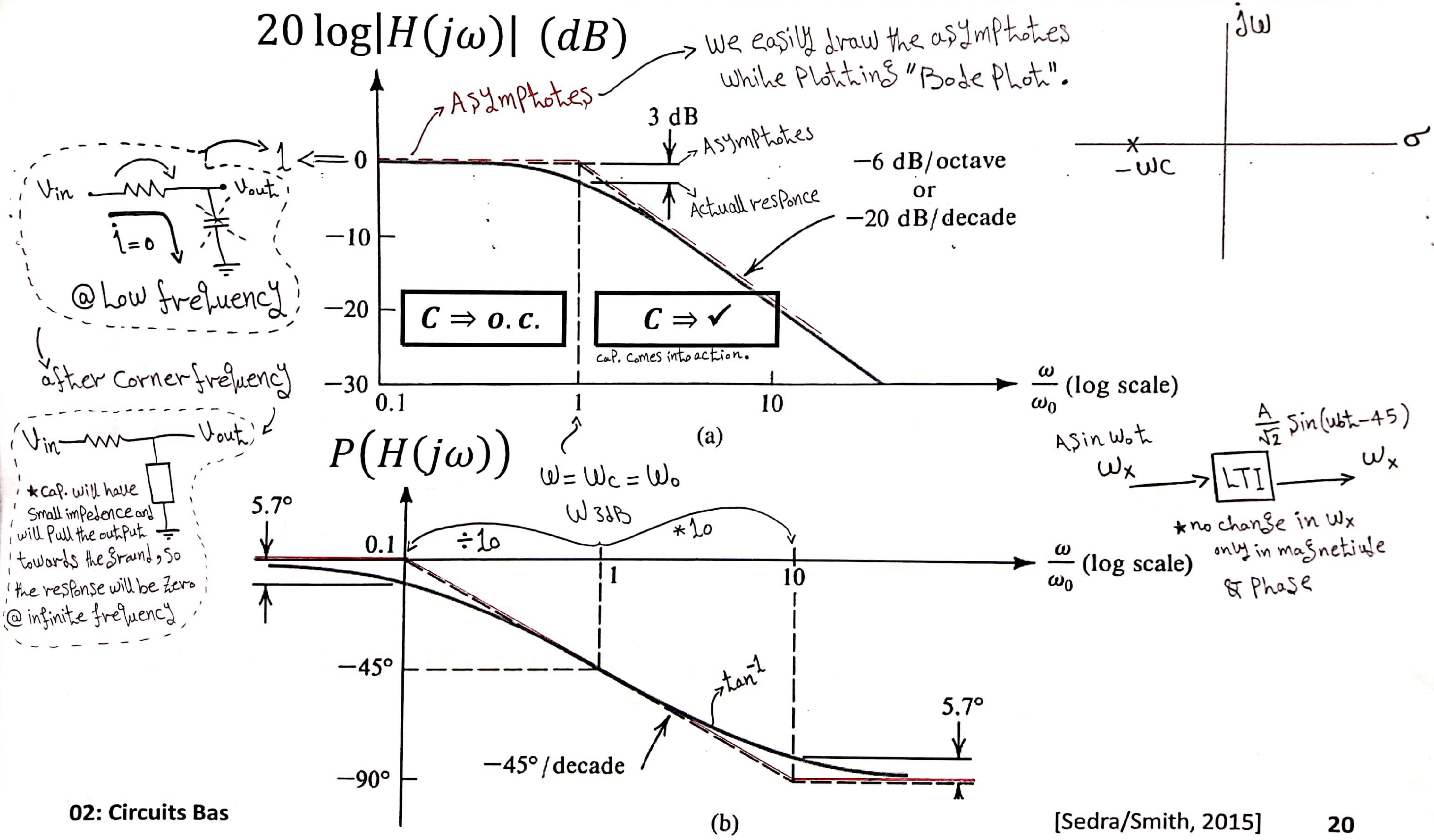


→ RHP: Right-half plane ($Re\{s\} > 0$)

→ LHP: Left-half plane ($Re\{s\} < 0$)

1st Order LPF Bode Plot

missing 1 next slide
36:36 —> 38:49



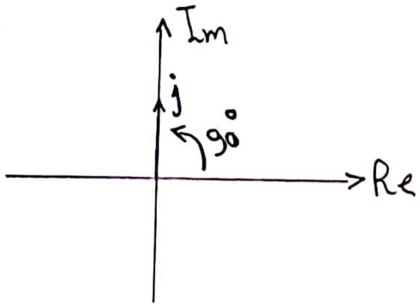
[Sedra/Smith, 2015]

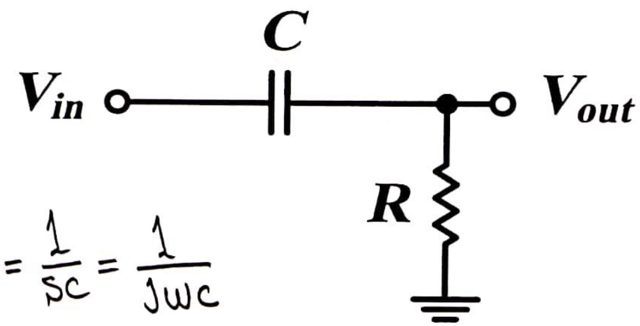
1st Order HPF

$$H(s) = \frac{v_{out}(s)}{v_{in}(s)} = \frac{R}{R + 1/sC} = \frac{sRC}{1 + sRC} = \frac{s\tau}{1 + s\tau}$$

$$H(j\omega) = \frac{v_{out}(j\omega)}{v_{in}(j\omega)} = \frac{R}{R + 1/j\omega C} = \frac{j\omega RC}{1 + j\omega RC} = \frac{\frac{j\omega}{\omega_c}}{1 + \frac{j\omega}{\omega_c}}$$

- ❑ Poles: $s_p = -\frac{1}{\tau} = -\omega_c$
- ❑ Zeros: $s_z = 0$
- ❑ $|H(j\omega)| = \frac{\frac{\omega}{\omega_c}}{\sqrt{1+\left(\frac{\omega}{\omega_c}\right)^2}}$
- ❑ $P\big(H(j\omega)\big) = 90^o - \tan^{-1}\frac{\omega}{\omega_c}$





★ $C = \frac{1}{sC} = \frac{1}{jwC}$

w

w↓↓
∴ open circuit
∴ Vout → 0

w↑↑
∴ Short circuit
∴ Vout ≃ Vin

★ if Cap. between output & GND
↳ shunt output to GND
∴ LPF

★ if Cap. between i/p & o/p in signal path
∴ HPF

Bode Plot Rules

	Pole	Zero
Magnitude	-20 dB/decade Actual Mag @ pole: -3 dB	+20 dB/decade Actual Mag @ zero: +3 dB
Phase	-90º Actual Phase @ pole: -45º	LHP zero: +90º Actual Phase @ zero: +45º RHP zero: -90º Actual Phase @ zero: -45º

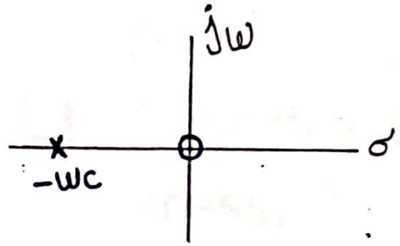
→ RHP: Right-half plane ($Re\{s\} > 0$)

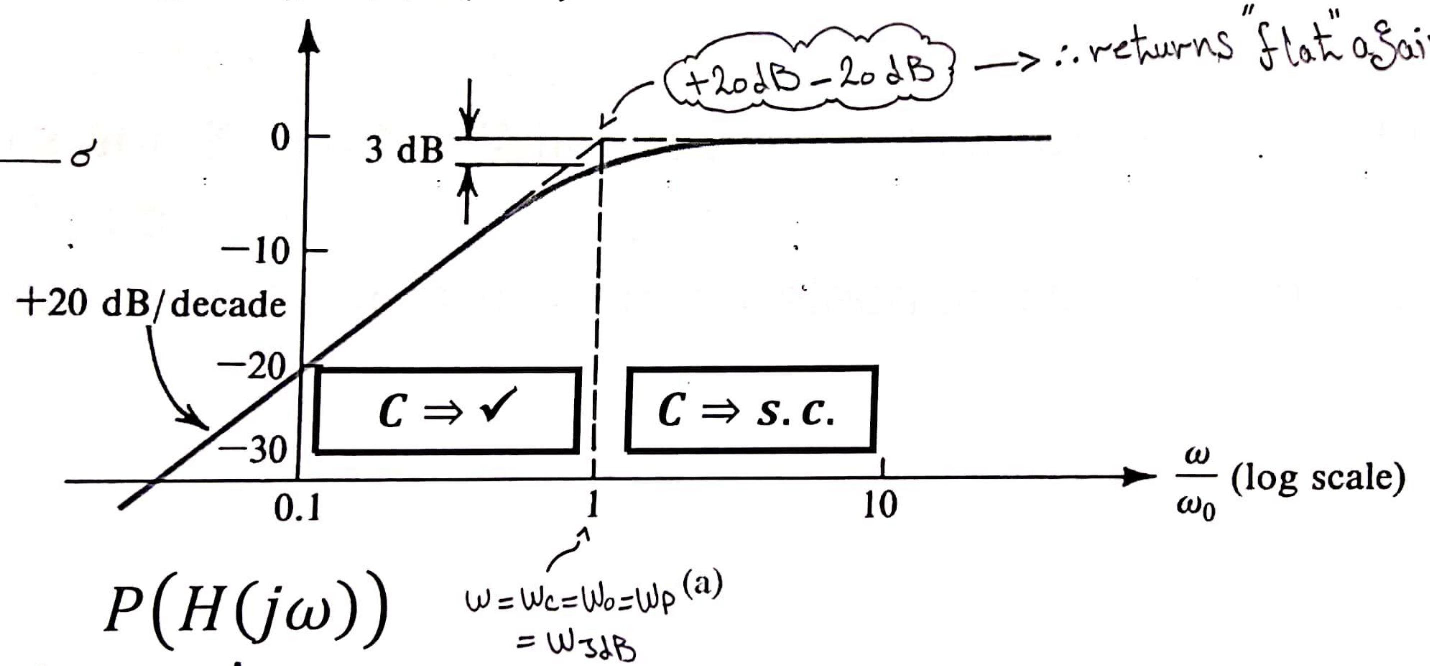
→ LHP: Left-half plane ($Re\{s\} < 0$)

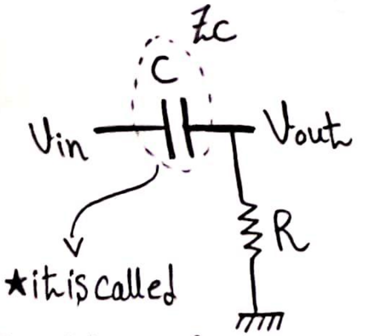
1st Order HPF Bode Plot

→missing 4 slides "next"

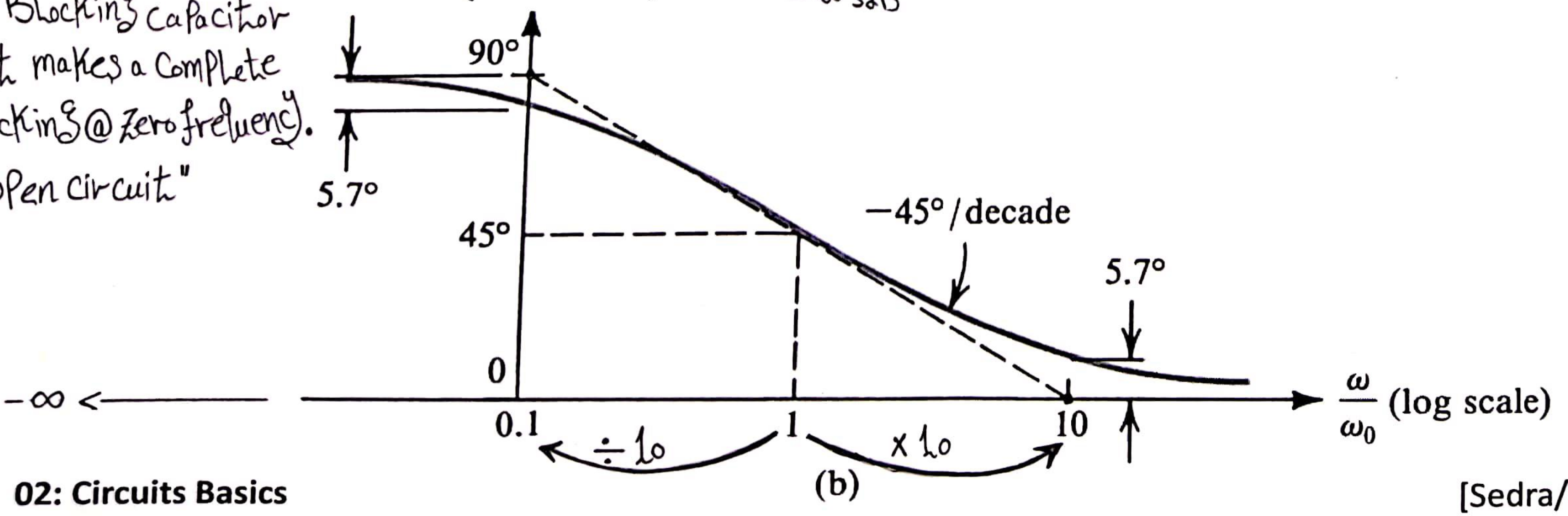
45:05 → end







★it is called DC Blocking capacitor as it makes a complete blocking @ zero frequency. "open circuit"



References

- T. Floyd and D. Buchla, "Electronics Fundamentals, Circuits, Devices, and Applications," 8th ed., Pearson, 2014
- A. Sedra and K. Smith, "Microelectronic circuits," Oxford University Press, 7th ed., 2015
- B. Razavi, "Fundamentals of microelectronics," 2nd ed., Wiley, 2014

Thank you!

Dr. Hesham Omran's Lectures

Fady Sabry Negm's Notes

وَمَا أُوتِيتُمْ مِنَ الْعِلْمِ إِلَّا قَلِيلًا

Allah almighty said in the Qur'an :
"and you ⌜O humanity⌝ have been given but little knowledge."

لو أن الناس كلما استصعبوا أمرًا تركوه ما قام للناس دنيا ولا دين

The Muslim Caliph Umar ibn Abdulaziz, May Allah have mercy on him, Said:
"If every time people found something difficult, they abandoned it, then neither worldly affairs nor religion would have ever been established for people."

- All Credits for these lectures go to **Dr. Hesham Omran**, Associate Professor at Ain Shams University and CTO at Master Micro, May Allah bless Dr. Hesham for these Lectures.

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- These Notes were made by: **Fady Sabry Negm** and any success or guidance is from Allah, and any mistake or lapse is from me and Satan.