Z_1

Z_2

ω_o

V_{out}/V_{in}

ϕ

V

/

$$V = IR$$

R

$$P_{\text{diss}} = I^2 R = \frac{V^2}{R}$$

$$R_{\text{eq}}$$

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

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

$R_1 || R_2 || R_3 \ldots$

V_1

$=$

$$\frac{R_1}{R_1 + R_2} V$$

V_2

$$\frac{R_2}{R_1 + R_2} V$$

/1

$$\frac{R_2}{R_1 + R_2} I$$

l_2

$$\frac{R_1}{R_1 + R_2} I$$

$/_1$

R_1

I_2

R_2

Δ

Y

$$\Delta - Y$$

$$\sum_{\text{loop}} V_i = 0$$

V_i

$$\sum_{\text{junction}} I_i = 0$$

V_{th}

A

B

R_{th}

$\pi/2$

$$X_L = j\omega L$$

$$\omega = 2\pi f$$

L

j

$$\sqrt{-1}$$

i

$$X_C = -\frac{j}{\omega C}$$

C

Z

$$v(t)$$

$$Re\left(V\,e^{j(\omega t+\phi_v)}\right) = V\cos(\omega t+\phi_v)$$

$i(t)$

$$Re\left(I\,e^{j(\omega t+\phi_i)}\right) = I\cos(\omega t + \phi_i)$$

ϕ_i

ϕ_V

$$e^{j\omega t}$$

V

$$V\,e^{j\phi_v}$$

I

$$I\, e^{j\phi_i}$$

$$Re(\mathbf{V}\, e^{j\omega t})$$

$$Re(\mathbf{I}\, e^{j\omega t})$$

$$\mathbf{I} = \frac{\mathbf{V}}{Z}$$

$$\mathbf{P} = \mathbf{I}^*\mathbf{V} = IV\, e^{j(\phi_v - \phi_i)}$$

$$\langle P \rangle = \frac{IV}{2} \cos(\phi_v - \phi_i) = \frac{V^2}{2Z} \cos(\phi_v - \phi_i)$$

$$\cos^2(\omega t)$$

$$\phi_V - \phi_i$$

$$-\pi/2$$

V

I

$$\mathbf{V_{in}} - \mathbf{I}Z_1 - \mathbf{I}Z_2 = 0$$

$$\mathbf{V_{out}} = \mathbf{I}Z_2$$

$$\mathbf{V_{out}} = \frac{Z_2}{Z_1 + Z_2}\mathbf{V_{in}}$$

V_{out}

$$V_{out} = \sqrt{\mathbf{V}^*_{\mathbf{out}}\mathbf{V}_{\mathbf{out}}}$$

V_{in}

$$\tan\phi = \frac{Im\left(\frac{Z_2}{Z_1+Z_2}\right)}{Re\left(\frac{Z_2}{Z_1+Z_2}\right)}$$

A_V

$$A_V = \frac{V_{out}}{V_{in}} = \frac{|\mathbf{V_{out}}|}{|\mathbf{V_{in}}|} = \left| \frac{Z_2}{Z_1 + Z_2} \right| = \sqrt{\left(\frac{Z_2}{Z_1 + Z_2} \right)^* \left(\frac{Z_2}{Z_1 + Z_2} \right)}$$

$$\frac{1}{2}$$

$$A_v = \frac{1}{\sqrt{2}}$$

$$Z_2 = R$$

$$Z_1 = j\left(\omega L - \frac{1}{\omega C}\right)$$

$$\frac{V_{out}}{V_{in}} = \sqrt{\frac{R^2}{R^2 + (\omega L - 1/\omega C)^2}}$$

$$a + jb$$

$$\frac{Z_2}{Z_1 + Z_2} = \frac{R}{R + j\left(\omega L - \frac{1}{\omega C}\right)} = \frac{R^2 - jR\left(\omega L - \frac{1}{\omega C}\right)}{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$$

$$\tan \phi = \frac{\frac{1}{\omega C} - \omega L}{R}$$

$v_{out}(t)$

$v_{in}(t)$

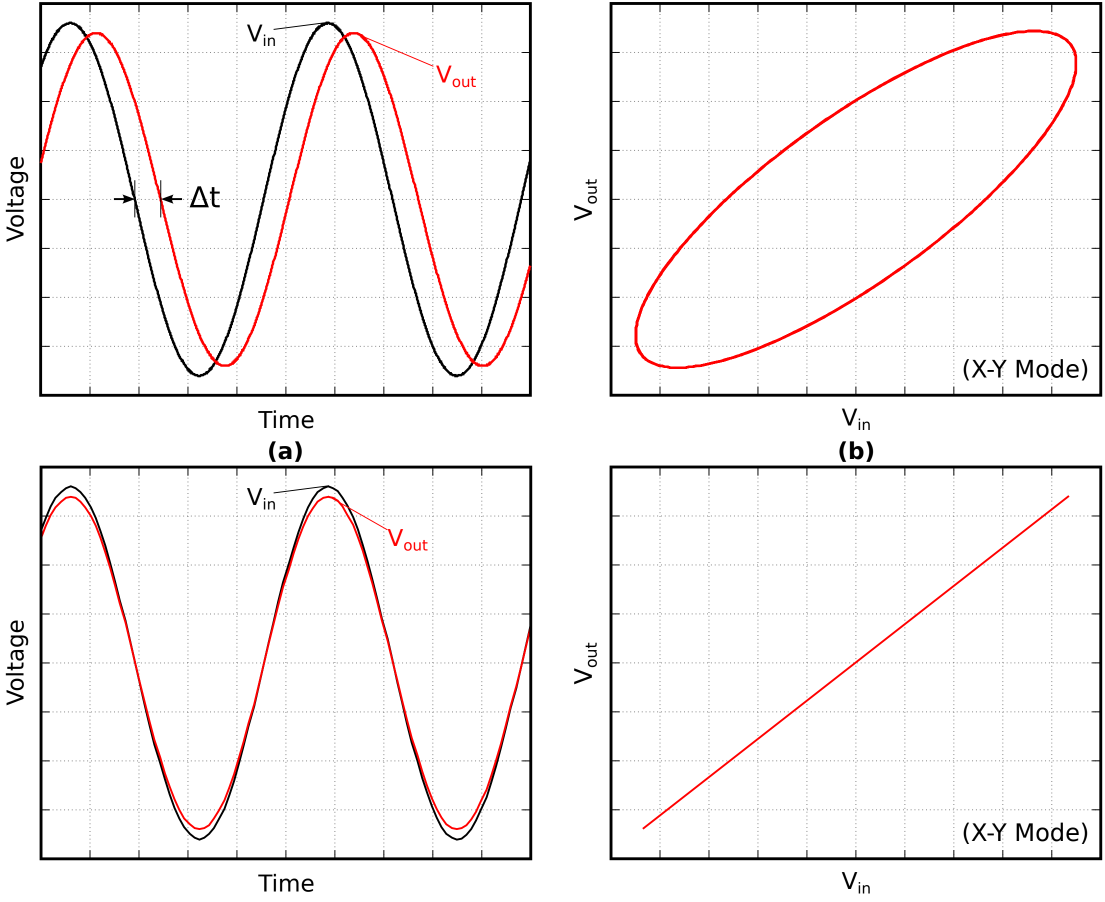
$$\Delta t = t_{V_{out}} - t_{V_{in}}$$

$$\Delta t = -\frac{\phi}{\omega} = -\frac{\phi}{2\pi f} = -\frac{\phi}{2\pi} T$$

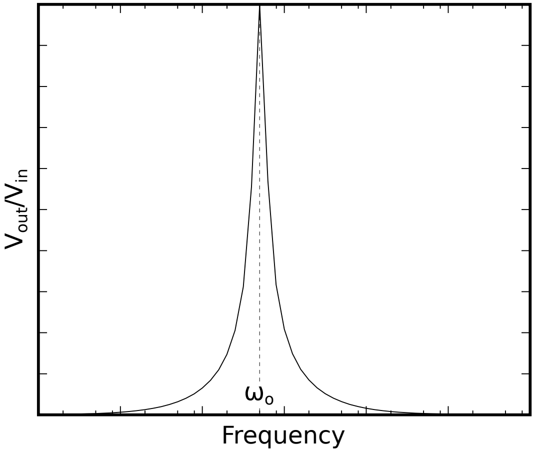
T

V_{out}

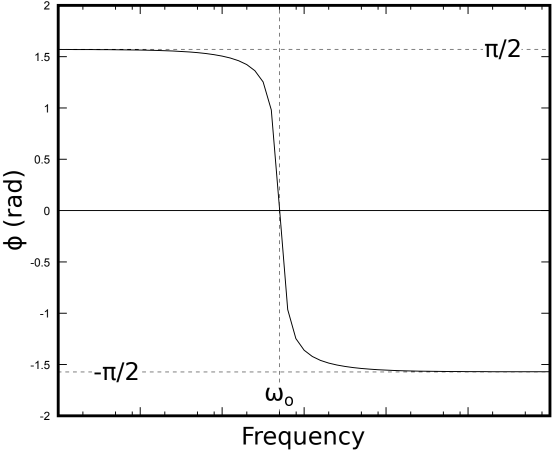
V_{in}



Voltage
V_{in}
V_{out}
Δt
Time
(a)
V_{out}
V_{in}
(X-Y Mode)
(b)
Voltage
V_{in}
V_{out}
Time
(c)
V_{out}
V_{in}
(X-Y Mode)
(d)


V_out/V_in
ω_o
Frequency

(a)


φ (rad)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
π/2
-π/2
ω_o
Frequency

(b)

$$V_{out} = V_{in}$$

X_L

$$X_C$$

$$\omega_o = \frac{1}{\sqrt{LC}}$$

$$A_V = V_{out}/V_{in}$$

v_{out}

$$V - I$$

10^{-8}

I_C

V_{BE}

$$I_C = I_o \left(e^{\frac{V_{BE}}{kT/e}} - 1 \right)$$

I_o

$$e = 1.6 \times 10^{-19}$$

$$k = 1.38 \times 10^{-23}$$

≈ 0.7

Ω

$$r_e = \frac{dV_{BE}}{dI_C} = \frac{kT/e}{I_C}$$

$(25\ \Omega)/I_C[\mathrm{mA}]$

V_{CE}

$$V_{CE} \approx 0.25$$

I_B

h_{FE}

$$I_C = h_{FE} I_B$$

I_E

$$V_C > V_E$$

$$V_{BE} \approx 0.7$$

$$I_C = h_{FE} I_B$$

$$h_{FE} \approx 100$$

$$V_{BE} < 0.7$$

$$I_C \approx 0$$

$$r_e = (25\ \Omega)/I_C[\mathrm{mA}]$$

R_L

R_B

$$\approx V_S$$

≈ 0.25

V_S

$\approx 10\ I_C/h_{fe}$

$$A_v \approx 1$$

V_E

R_E

R_1/R_2

$$V_B \approx V_E + 0.6\ \text{V}$$

$$R_1 || R_2 \approx h_{FE} R_E / 10$$

C_1

C_2

$$A_v = -\frac{R_C}{R_E}$$

R_C

r_e

R_b

C_b

$$\approx \frac{R_b}{10}$$

$$R_E + r_e$$

$$R_1||R_2 \approx h_{FE}(R_E + R_b)/10$$

$$R_1 || R_2$$

$$R_C || (R_E + R_b)$$

$$V_+ - V_-$$

$$-V_S \leq V_{out} \leq V_S$$

$$-V_S < V_{out} < V_S$$

$$-V_S$$

$$A = \infty$$

$$R_{in} = \infty$$

$$R_{out} = 0$$

$$V_+ = V_-$$

10^3

10^5

$$V_{+} \approx V_{-}$$

$$R_{in} = \infty, \ A = \infty, \ R_{out} = 0$$

$$V_+ = V_-, \ -V_S < V_{out} < V_S$$

$$V_+ > V_- \implies V_{out} = V_S$$

$$V_+ < V_- \implies V_{out} = -V_S$$

$10^{12}\ \Omega$

R_f

$$I = \frac{V_{in}}{R_1} = \frac{-V_{out}}{R_f}$$

$$A_v = -\frac{R_f}{R_1}$$

$R_{oa} || R_f$

R_{oa}

R_f / R_1

$$V_{in} = \frac{R_1}{R_1 + R_f} V_{out}$$

$$A_v = 1 + \frac{R_f}{R_1}$$

$R_{oa}||(R_1 + R_f)$

$$R_1 = \infty$$

$$R_f = 0$$

$$A_v = 1$$

$$\frac{V_1}{R_1}$$

$$\frac{V_2}{R_2}$$

I3

$$\frac{V_3}{R_3}$$

I_f

$$\frac{V_{out}}{R_f}$$

$$I_1 + I_2 + I_3 = I_f$$

$$V_{out} = -\left(\frac{R_1}{R_f}V_1 + \frac{R_2}{R_f}V_2 + \frac{R_3}{R_f}V_3\right)$$

R_1/R_f

$$I_1 + I_2 = I_3 + I_4$$

$$\frac{V_1 - V_-}{R_1}$$

$$\frac{V_2 - V_+}{R_1}$$

$$\frac{V_- - V_{out}}{R_2}$$

l4

$$\frac{V_+}{R_2}$$

$$V_+ = \frac{R_2}{R_1 + R_2} V_2$$

$$V_- = V_+$$

$$V_{out} = -\frac{R_2}{R_1}\left(V_1 - V_2\right)$$

V_1

V_2

$C_f < C$

C_f

$$V_{out} = -IR$$

$$V_{in} = \frac{Q}{C}$$

$$I \equiv \frac{dQ}{dt}$$

$$V_{out} = -RC\frac{dV_{in}}{dt}$$

RC

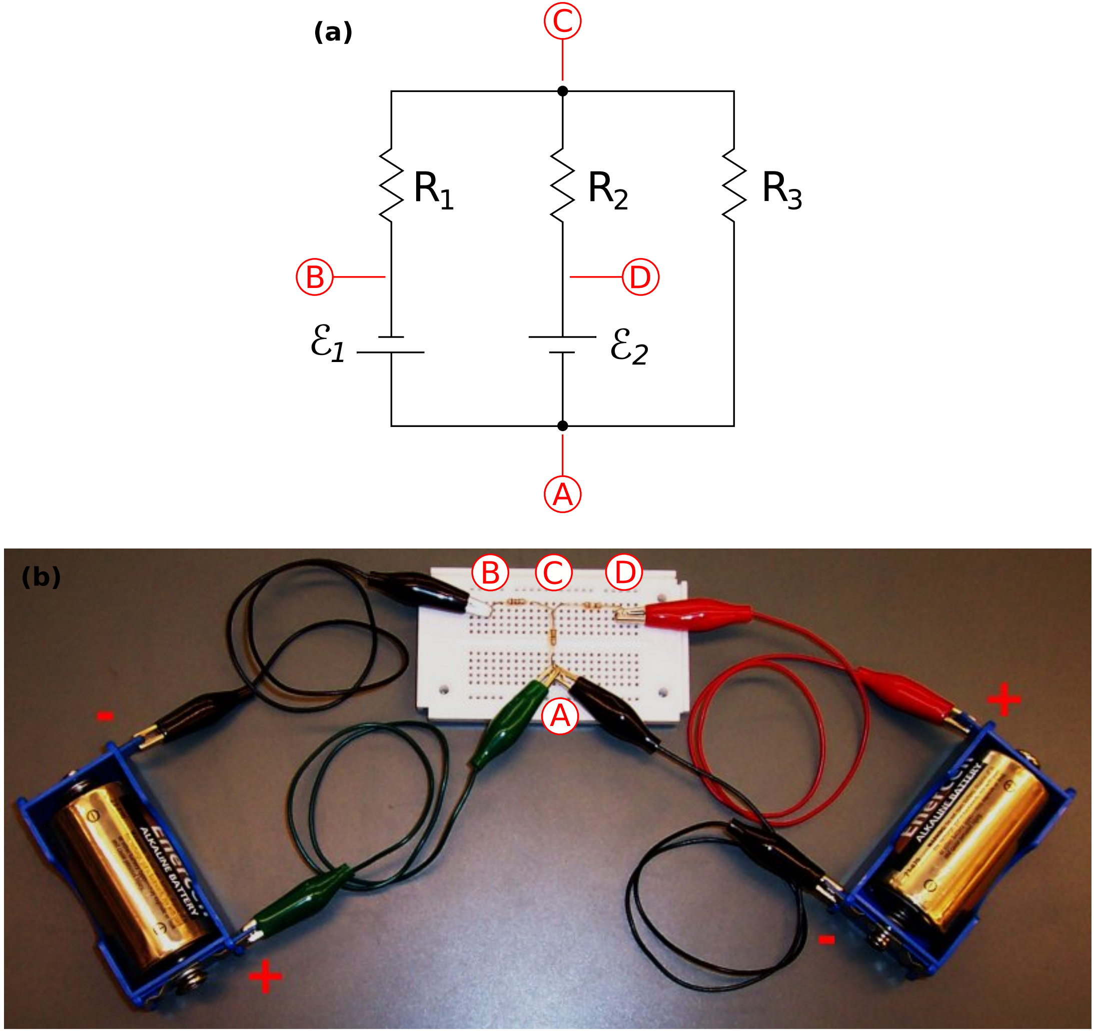
$$I = \frac{V_{in}}{R}$$

$$V_{out} = -\frac{Q}{C}$$

$$I \equiv dQ/dt$$

$$Q = \int dQ = \frac{1}{R} \int V_{in} \, dt + \text{constant}$$

$$V_{out} = -\frac{1}{RC} \int V_{in} \, dt + C$$


(a)
C
R1
R2
R3
B
D
ℰ1
ℰ2
A
(b)
B
C
D
A
-
+
+
-

color	black	brown	red	orange	yellow	green	blue	violet	gray	white
digit	0	1	2	3	4	5	6	7	8	9
multiplier	1	10	100	1k	10k	100k	1M	10M	100M	1000M

$$
\begin{aligned}
R = [\text{band1}][\text{band2}] \times 10^{[\text{band3}]} \quad & \pm \quad 5\%\ (\text{gold}) \\
& \pm \quad 10\%\ (\text{silver})
\end{aligned}
$$

$$R = 64 \times 10^2\ \Omega = 64 \times 100\ \Omega = 6400\ \Omega$$

$\pm 320\ \Omega$

$Thing_1$

$Thing_2$

$$dB = 10 \log \left(\frac{\mathsf{Thing}_2}{\mathsf{Thing}_1} \right)$$

Thing_2

10^8

Thing_1

10^{-12}

2

$$10\log\left(\frac{P_{out}}{P_{in}}\right) = 10\log\left(\frac{1}{2}\right) = 10(-0.3010) = -3.01$$

$$A_v = |V_{out}|/|V_{in}|$$

$$1/\sqrt{2}$$

$$|A_v| / |A_{v_{max}}|$$