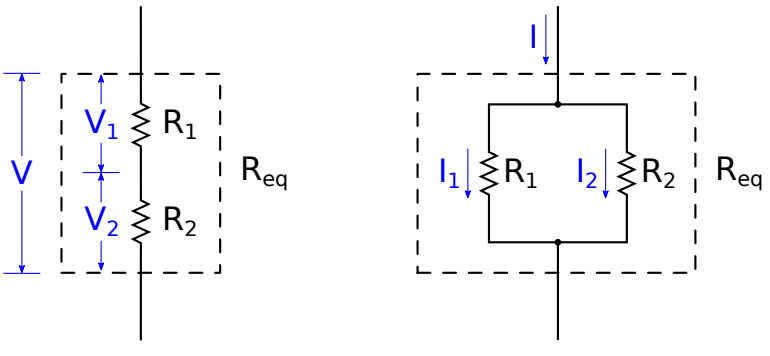

V_{out}/V_{in}

$$V = IR$$

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


V
V1
R1
V2
R2
Req
Series
(a)
I
I1
R1
I2
R2
Req
Parallel
(b)

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

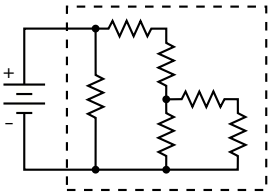
$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + ...$$

$$V_1 = \frac{R_1}{R_1 + R_2} V$$

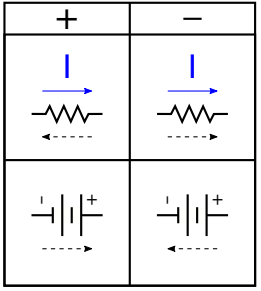
$$V_2 = \frac{R_2}{R_1 + R_2} V$$

$$I_1 = \frac{R_2}{R_1 + R_2} I$$

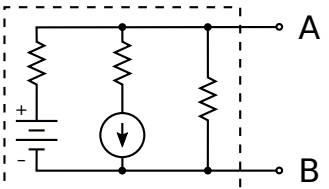
$$I_2 = \frac{R_1}{R_1 + R_2} I$$



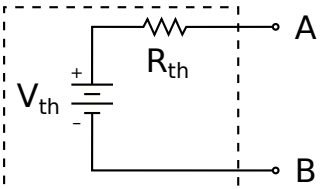
$$\sum_{\text{loop}} V_i = 0$$


+
−
I
I
-
+
-
+

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



(a)



(b)


R_{th}

$$X_L = j\omega L$$

$$\omega = 2\pi f$$

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

Z

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

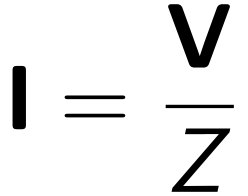
$$i(t) = Re\left(I\, e^{j(\omega t+\phi_i)}\right) = I\cos(\omega t + \phi_i)$$

$e^{j\omega t}$

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

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

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

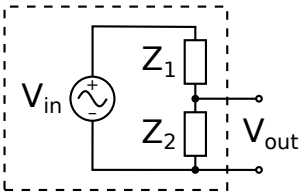


$$\mathbf{P} = \mathbf{I}^{*}\mathbf{V} = IV\, e^{j(\phi_v - \phi_i)}$$

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


$\cos^2(\omega t)$

$-\pi/2$


V_{in}
Z_1
Z_2
V_{out}

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

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

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


Vout

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

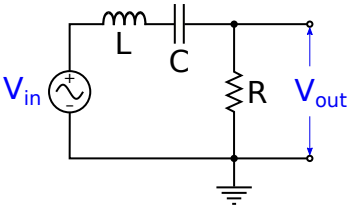

Vin

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

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

$\frac{1}{2}$

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


L
C
R
V_{in}
V_{out}

$$Z_2 = R$$

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

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

$a + jb$

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

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

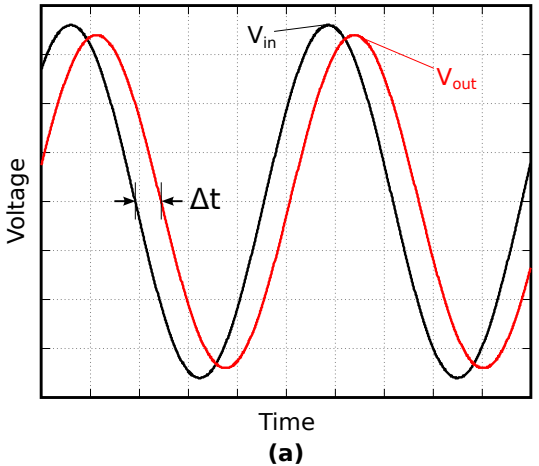
$v_{out}(t)$

$v_{in}(t)$

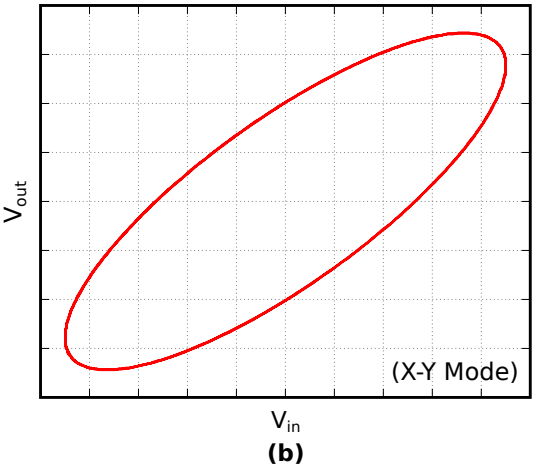
$$\Delta t = t_{V_{out}} - t_{V_{in}}$$

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

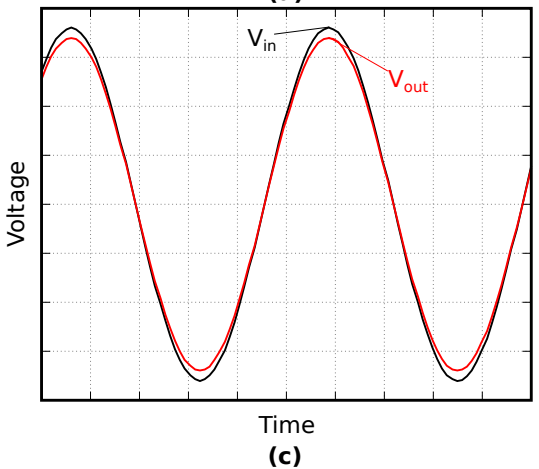

V_{out}


V_{in}
V_{out}
Δt
Voltage
Time

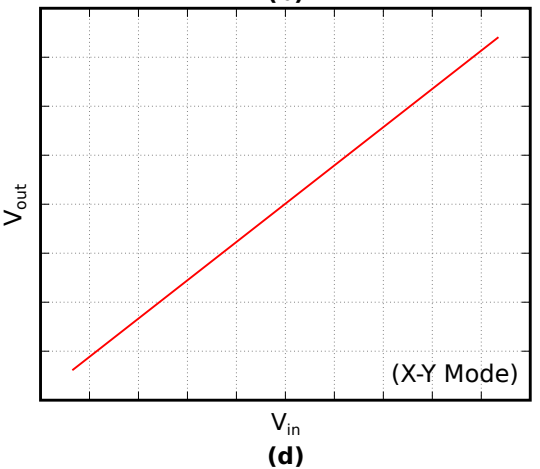
(a)


V_{out}
(X-Y Mode)
V_{in}

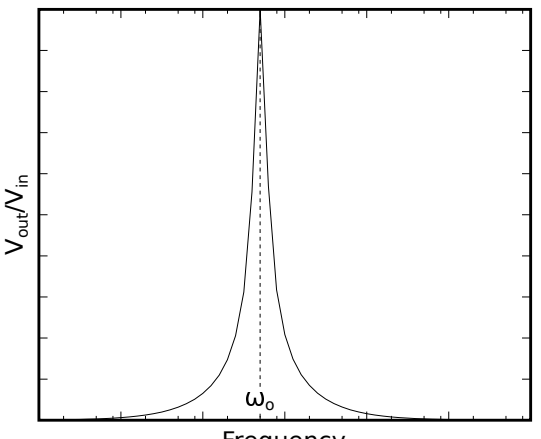
(b)


V_{in}
V_{out}
Voltage
Time

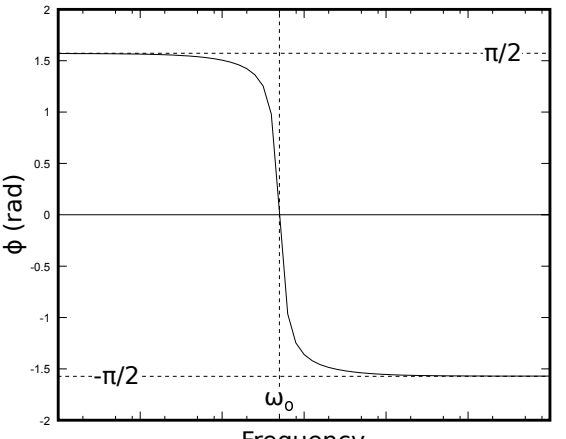
(c)


V_{out}
(X-Y Mode)
V_{in}

(d)


V_{out}/V_{in}
ω_o
Frequency

(a)

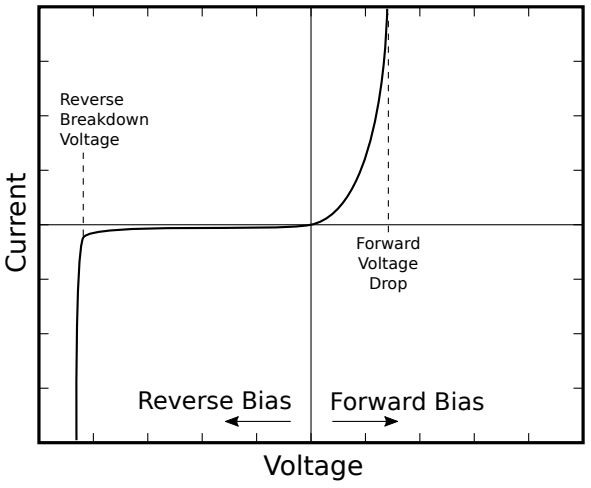

2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
ϕ (rad)
π/2
-π/2
ω_o
Frequency

(b)

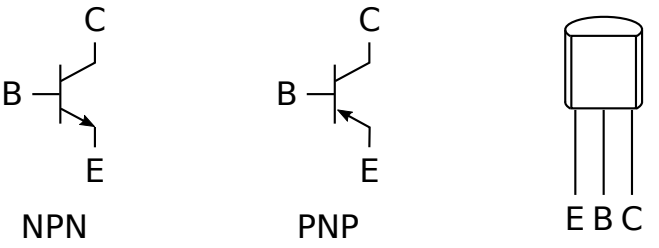
$$V_{out} = V_{in}$$

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

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


Reverse
Breakdown
Voltage
Forward
Voltage
Drop
Current
Reverse Bias
Forward Bias
Voltage

10^{-8}

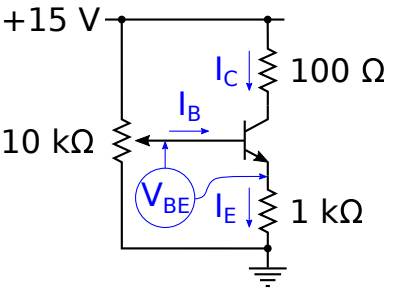

C
B
E
NPN
(a)
C
B
E
PNP
(b)
E B C
(C)


V_{BE}

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

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

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


+15 V
I_C
100 Ω
I_B
10 kΩ
V_{BE}
I_E
1 kΩ

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


(25 Ω)/I_C[mA]


V_{CE}


$V_{CE} \approx 0.25$


h_{FE}

$$I_C = h_{FE} I_B$$

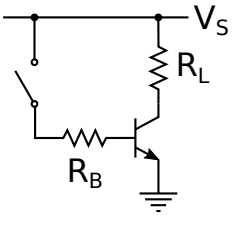
$$I_C = h_{FE} I_B$$

$h_{FE} \approx 100$


$V_{BE} < 0.7$

$I_C \approx 0$

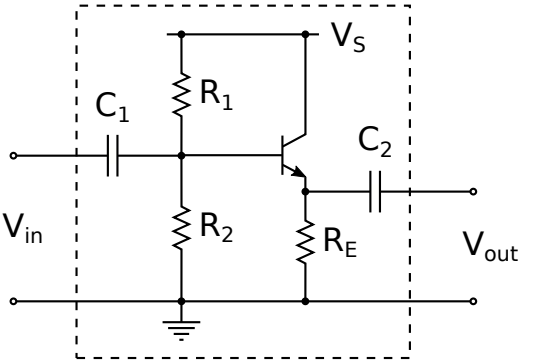
$$r_e = (25\ \Omega)/I_C[\text{mA}]$$


V_S
R_L
R_B


R_B

≈ 0.25

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

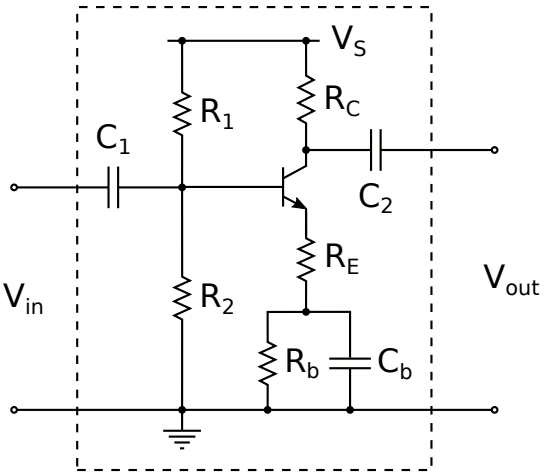

V_S
R_1
C_1
C_2
V_{in}
R_2
R_E
V_{out}

$A_v \approx 1$


R_1 / R_2

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

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


V_S
R_1
R_C
C_1
C_2
R_E
V_{in}
R_2
V_{out}
R_b
C_b

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

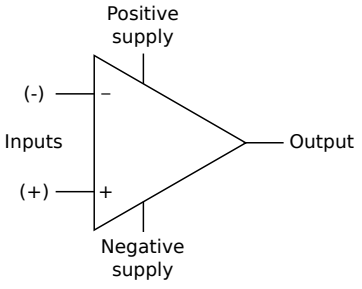
R_b

$R_E + r_e$

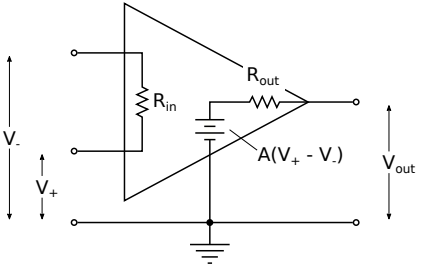
$$R_1 || R_2 \approx h_{FE}(R_E + R_b)/10$$


$R_1 || R_2$

$R_C || (R_E + R_b)$


Positive
supply
(-)
Inputs
(+)
Output
Negative
supply

(a)

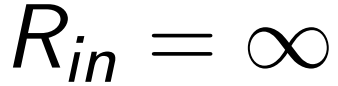

R_{out}
R_{in}
V_-
V_+
$A(V_+ - V_-)$
V_{out}

(b)

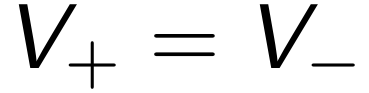

$V_+ - V_-$

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

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



$$R_{out} = 0$$



10^3

10^5

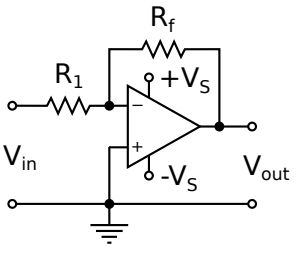
$$R_{in} = \infty,\ A = \infty,\ R_{out} = 0$$

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

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

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

$10^{12}\ \Omega$


R_f
R_1
$+V_S$
V_{in}
$-V_S$
V_{out}

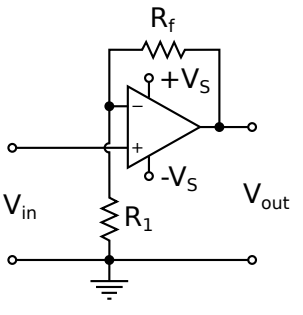
$$I = \frac{V_{in}}{R_1} = \frac{-V_{out}}{R_f}$$

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


$$R_{oa} || R_f$$


R_{oa}

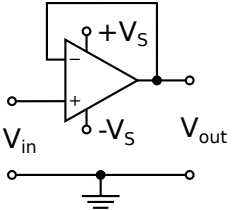

R_f / R_1


R_f
$+V_S$
$-V_S$
V_{in}
R_1
V_{out}

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

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

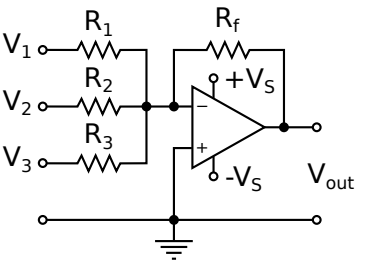
$$R_{oa} || (R_1 + R_f)$$


+V_S
-V_S
V_in
V_out

$$R_1 = \infty$$

$$R_f = 0$$

$A_v = 1$

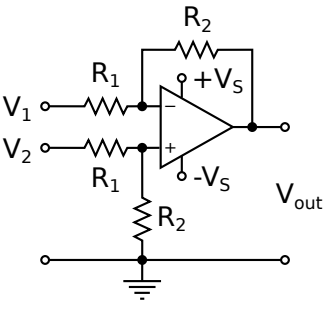

R1
Rf
V1
R2
+VS
V2
R3
V3
-VS
Vout

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

$$I_1 + I_2 + I_3 = I_f$$

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


R_1 / R_f

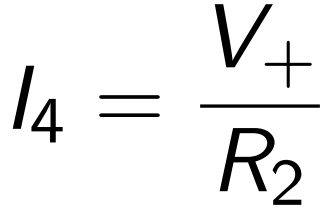

R2
R1
+VS
V1
V2
R1
-VS
Vout
R2

$$I_1 + I_2 = I_3 + I_4$$

$$I_1 = \frac{V_1 - V_-}{R_1}$$

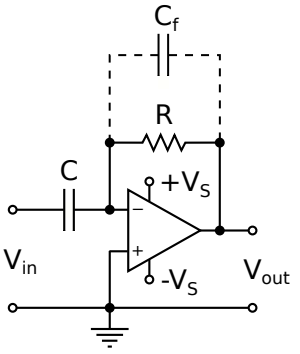
$$I_2 = \frac{V_2 - V_+}{R_1}$$

$$I_3 = \frac{V_- - V_{out}}{R_2}$$



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

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


C_f
R
C
$+V_S$
V_{in}
$-V_S$
V_{out}

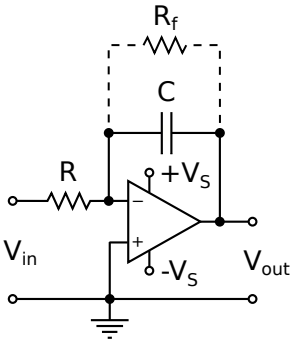
$$V_{out} = -IR$$

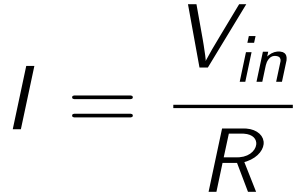
$$V_{in} = \frac{Q}{C}$$

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

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


RC


R_f
C
R
$+V_S$
V_{in}
$-V_S$
V_{out}

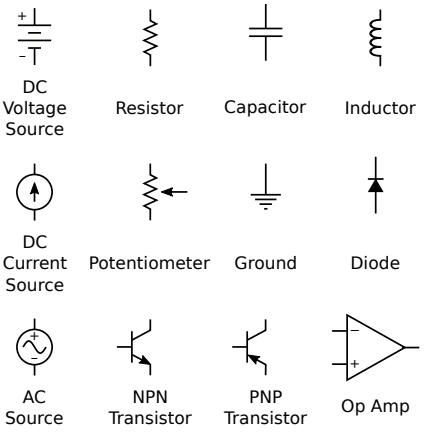


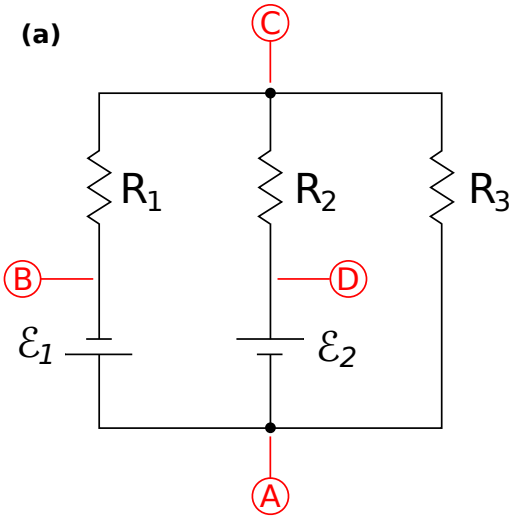
$$V_{out} = -\frac{Q}{C}$$

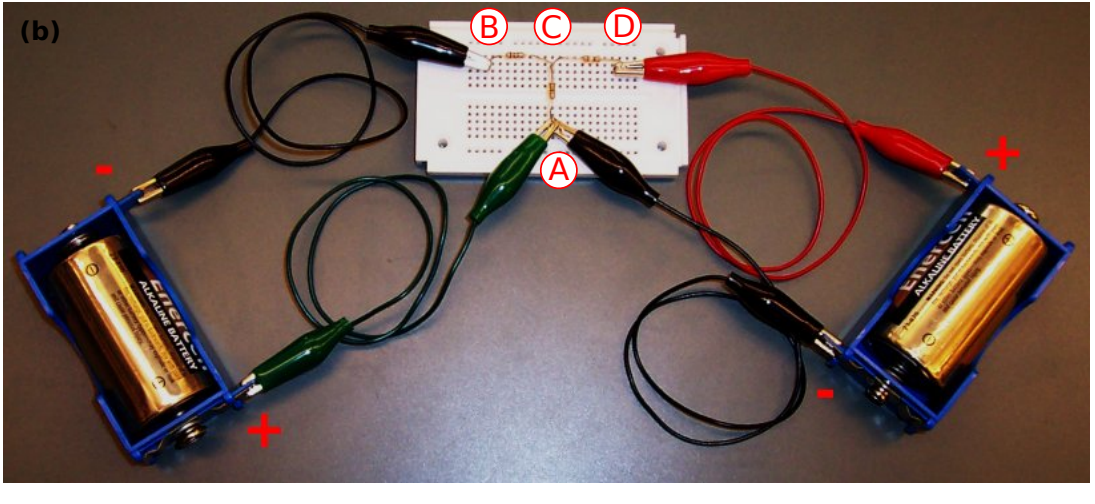
$$I \equiv dQ/dt$$

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

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


DC Voltage Source
Resistor
Capacitor
Inductor
DC Current Source
Potentiometer
Ground
Diode
AC Source
NPN Transistor
PNP Transistor
Op Amp


(a)
C
R1
R2
R3
B
D
ℰ1
ℰ2
A


(b)
B
C
D
A
-
+
+
-

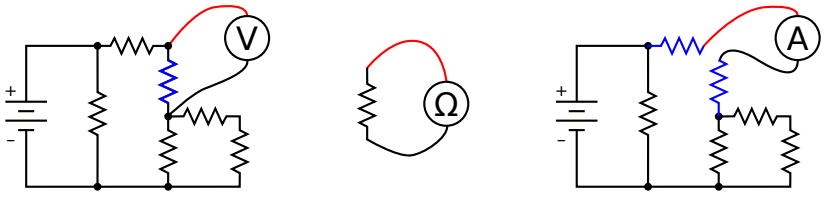
Distribution Strips
Terminal Strips
Channel
Terminal Strips
Distribution Strips
F G H I J
A B C D E
1
5
10
15
20

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

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

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

$\pm 320\ \Omega$



(a) **(b)** **(c)**


$Thing_1$


Thing2

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


Thing2

10^{8}


Thing1

10^{-12}

2

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

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

$1/\sqrt{2}$