Z_1

Z_2

ω_o

V_{out}/V_{in}

ϕ

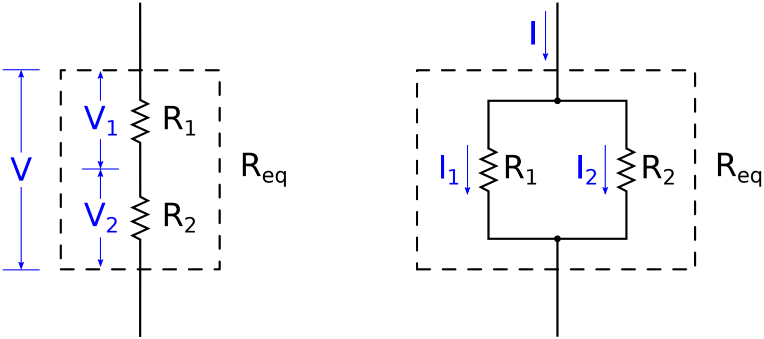
V

/

$$V = IR$$

R

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



Series

(a)

Parallel

(b)

R_{eq}

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

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

$R_1||R_2||R_3...$

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

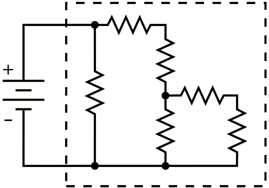
$$\frac{R_1}{R_1 + R_2} I$$

I_1

R_1

I_2

R_2



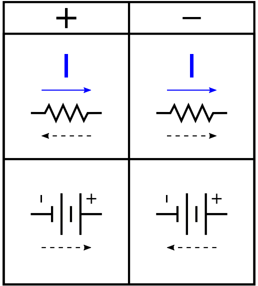
Δ

Y

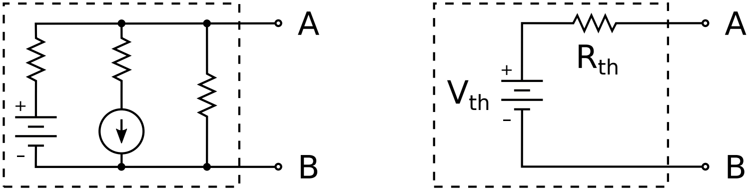
$$\Delta - Y$$

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

V_i


+
−
I
I

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



(a) (b)

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

$$v(t)$$

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

$i(t)$

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

ϕ_i

ϕ_V

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

V

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

I

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

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

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

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

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

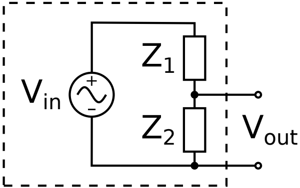
$$\langle P \rangle = \frac{IV}{2}\cos(\phi_v - \phi_i) = \frac{V^2}{2Z}\cos(\phi_v - \phi_i)$$

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

$$\phi_v - \phi_i$$

$-\pi/2$

V



V_{in}
+
−
Z_1
Z_2
V_{out}

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

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

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

$\mathbf{V_{out}}$

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

V_{in}

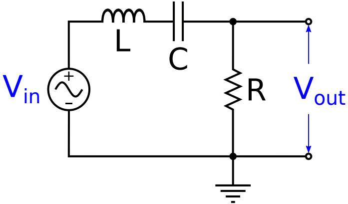
$$\tan\phi = \frac{Im\left(\frac{Z_2}{Z_1+Z_2}\right)}{Re\left(\frac{Z_2}{Z_1+Z_2}\right)}$$

A_V

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

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

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


L
C
R
Vin
Vout

$$Z_2 = R$$

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

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

$$a + jb$$

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

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

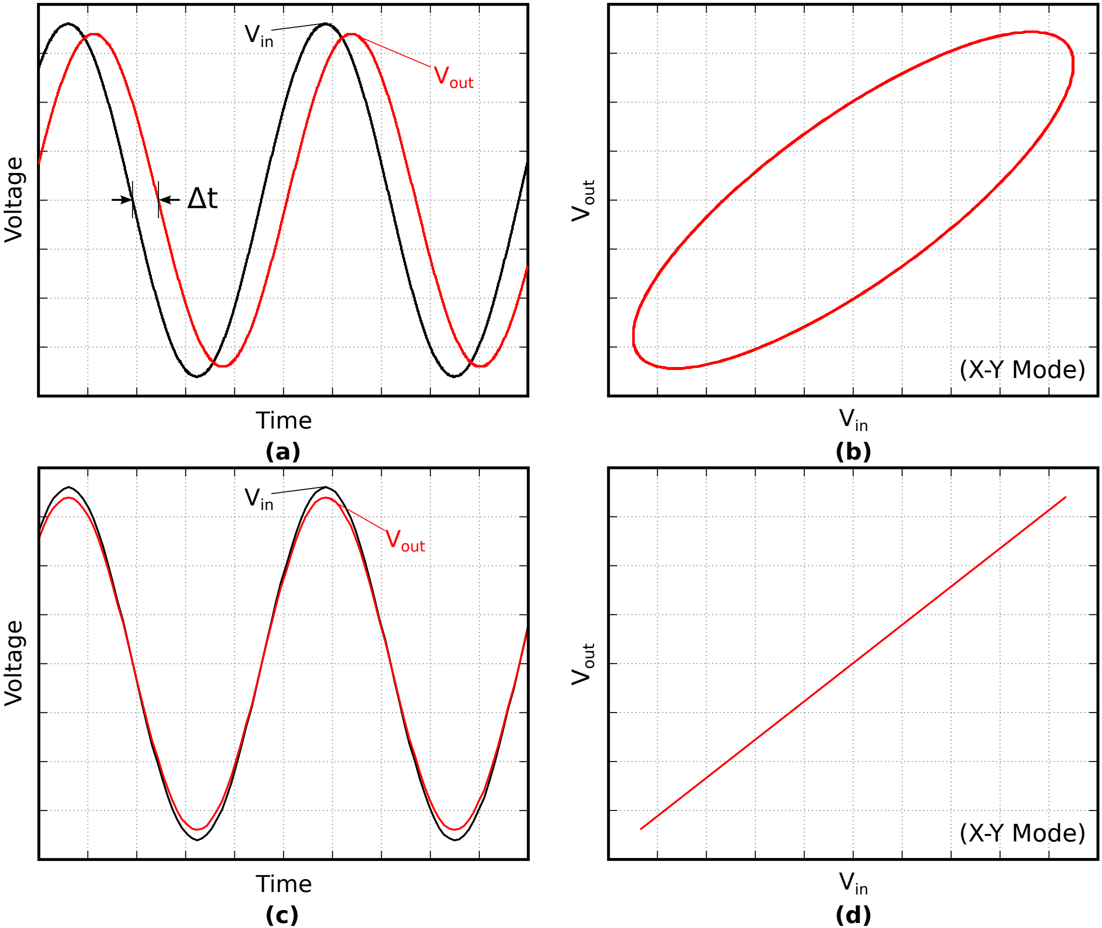
$v_{out}(t)$

$$v_{in}(t)$$

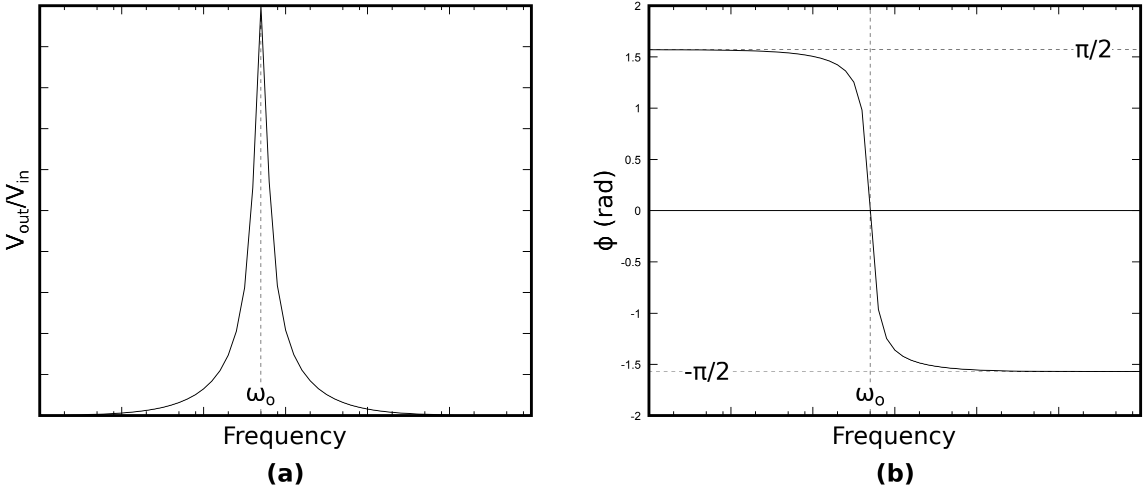
$$\Delta t = t_{V_{out}} - t_{V_{in}}$$

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

T



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

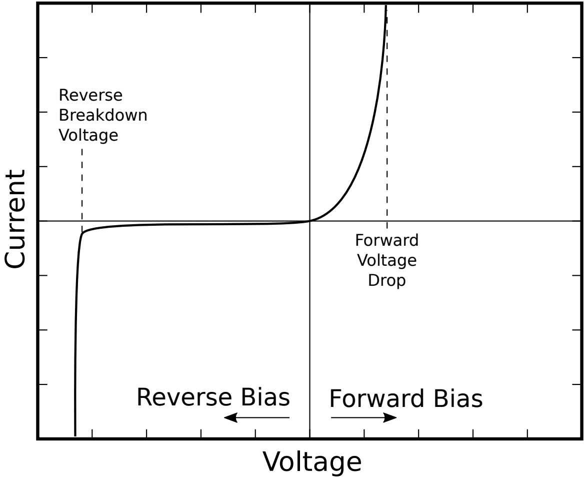
$$\omega_o = \frac{1}{\sqrt{LC}}$$

V_{out}

V_{in}

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

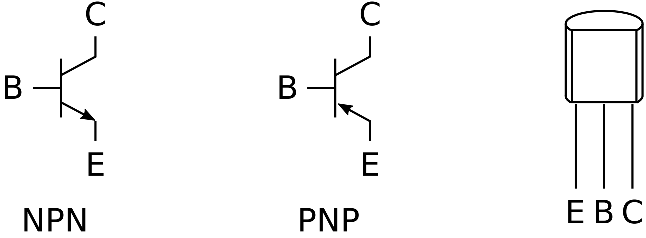
V_{out}



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

$V - I$

10^{-8}



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

I_C

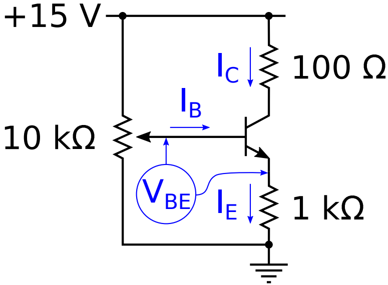
V_{BE}

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

I_o

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

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


+15 V
100 Ω
I C
I B
10 kΩ
V BE
I E
1 kΩ

$$\approx 0.7$$

Ω

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

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

V_{CE}

$$V_{CE} \approx 0.25$$

I_B

h_{FE}

$$I_C = h_{FE} I_B$$

I_E

$$V_C > V_E$$

$$V_{BE} \approx 0.7$$

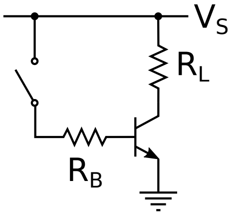
$$I_C = h_{FE} I_B$$

$$h_{FE} \approx 100$$

$$V_{BE} < 0.7$$

$$I_C \approx 0$$

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



V_S
R_L
R_B

R_L

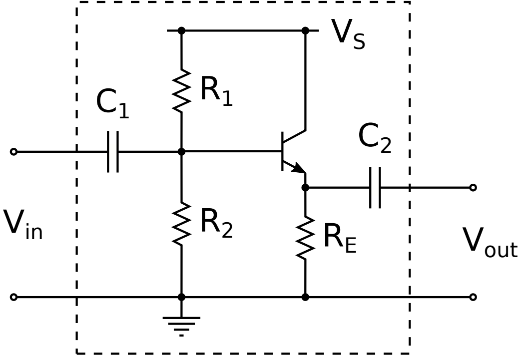
R_B

$$\approx V_S$$

≈ 0.25

V_S

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



V_S
R_1
C_1
C_2
R_2
R_E
V_in
V_out

$$A_v \approx 1$$

V_E

R_E

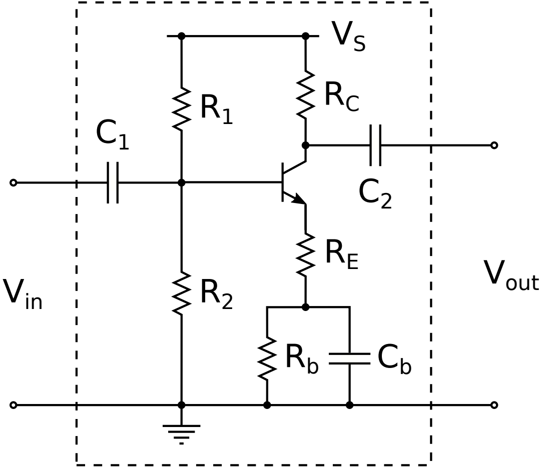
R_1/R_2

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

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

C_1

C_2



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

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

R_C

r_e

R_b

C_b

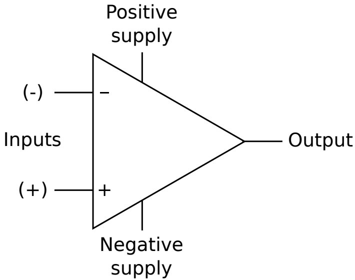
$$\approx \frac{R_b}{10}$$

$$R_E + r_e$$

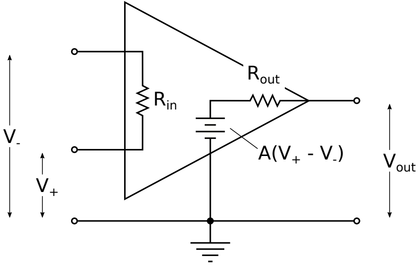
$$R_1 || R_2 \approx h_{FE}(R_E + R_b)/10$$

$$R_1 || R_2$$

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


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

(a)


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

(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

$$V_+ \approx V_-$$

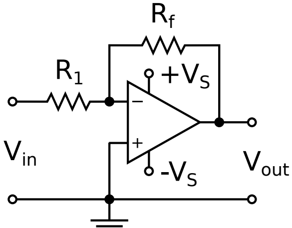
$$R_{in} = \infty, \; A = \infty, \; R_{out} = 0$$

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

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

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

$10^{12}\ \Omega$


R_f
R_1
+V_S
−
+
-V_S
V_in
V_out

R_f

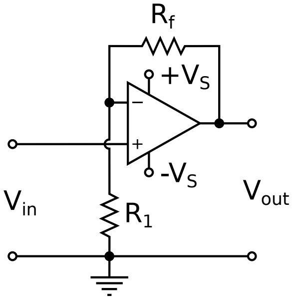
$$I = \frac{V_{in}}{R_1} = \frac{-V_{out}}{R_f}$$

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

$R_{oa}||R_f$

R_{oa}

R_f / R_1

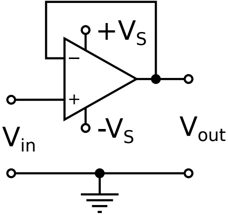


R_f
$+V_S$
$-V_S$
V_{in}
V_{out}
R_1
−
+

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

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

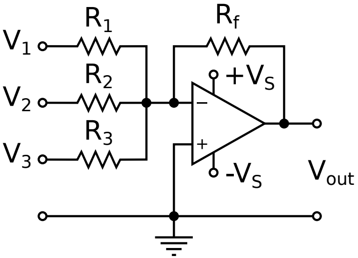
$$R_{oa}||(R_1 + R_f)$$


+VS
-VS
Vin
Vout
−
+

$$R_1 = \infty$$

$$R_f = 0$$

$$A_v = 1$$


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

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

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

I_3

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

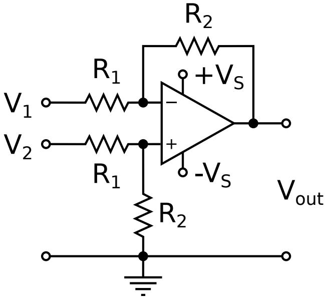
I_f

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

$$I_1 + I_2 + I_3 = I_f$$

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

R_1/R_f



R2
R1
+VS
V1
V2
R1
-VS
Vout
R2

$$I_1 + I_2 = I_3 + I_4$$

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

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

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

l_4

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

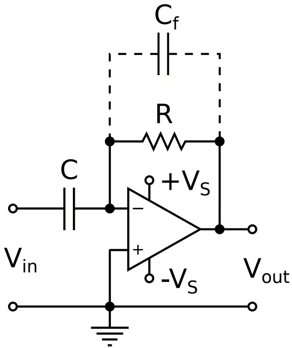
$$V_+ = \frac{R_2}{R_1 + R_2} V_2$$

$$V_{-} = V_{+}$$

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

V_1

V_2



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

$$C_f < C$$

C_f

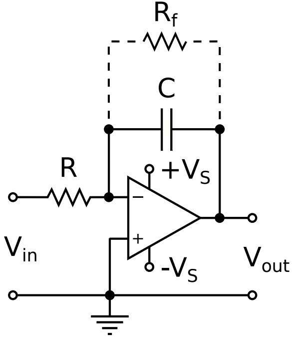
$$V_{out} = -IR$$

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

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

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

RC


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

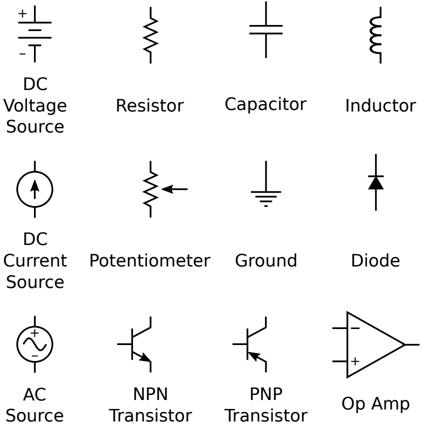
$$I = \frac{V_{in}}{R}$$

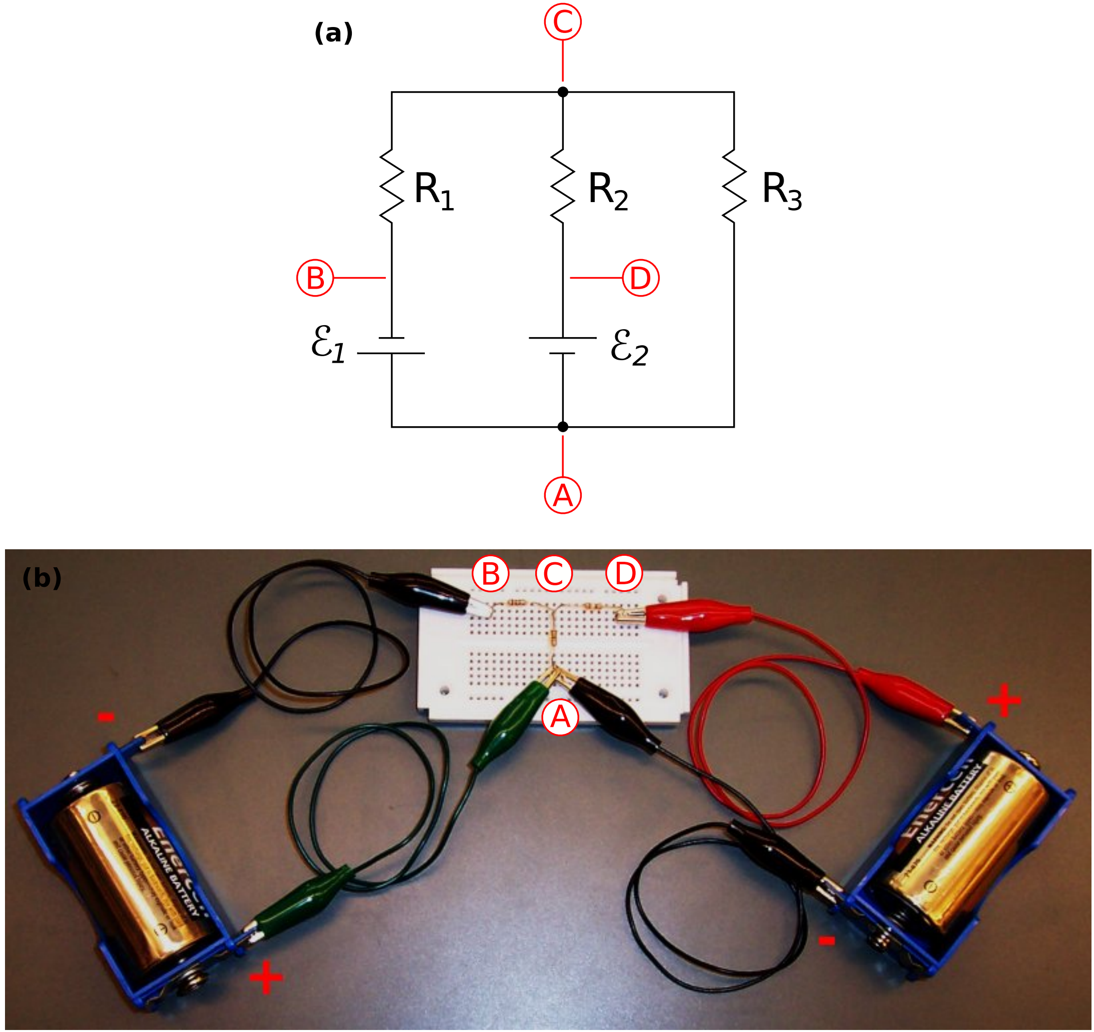
$$V_{out} = -\frac{Q}{C}$$

$$I \equiv dQ/dt$$

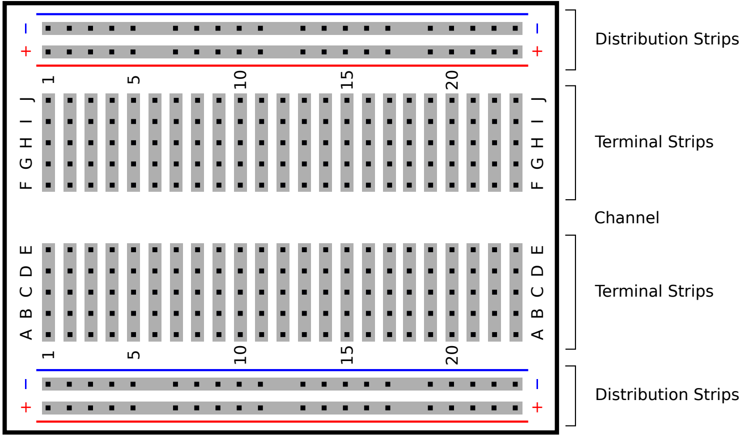
$$Q = \int dQ = \frac{1}{R} \int V_{in}\, dt$$

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


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



(a)
C
R_1
R_2
R_3
B
D
$\mathcal{E}_1$
$\mathcal{E}_2$
A
(b)
B
C
D
A
-
+
+
-

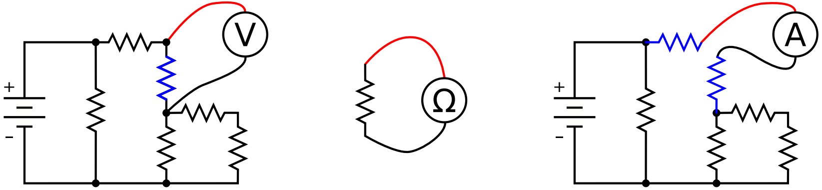

Distribution Strips
Terminal Strips
Channel
Terminal Strips
Distribution Strips
- +
1 5 10 15 20
J I H G F
E D C B A
1 5 10 15 20
- +

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

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

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

$\pm 320\ \Omega$



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

$Thing_1$

$Thing_2$

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

Thing_2

10^8

Thing_1

10^{-12}

2

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

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

$$1/\sqrt{2}$$