Z_1

Z_2

ω_o

V_{out}/V_{in}

ϕ

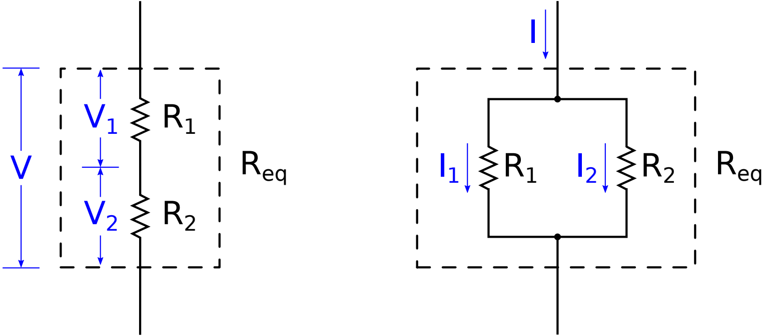
V

/

$$V = IR$$

R

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



Series

(a)

Parallel

(b)

R_{eq}

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

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

$R_1||R_2||R_3\ldots$

V_1

$=$

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

V_2

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

I_1

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

l_2

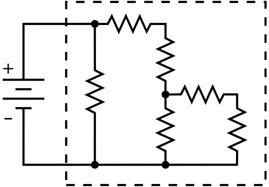
$$\frac{R_1}{R_1 + R_2} I$$

$/_1$

R_1

l_2

R_2



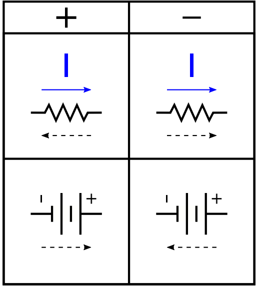
Δ

Y

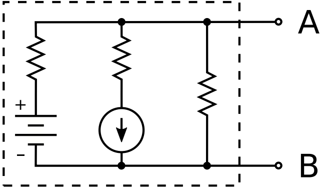
$$\Delta - Y$$

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

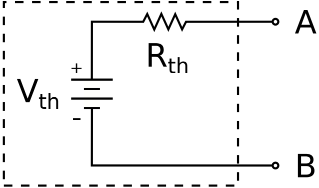
V_i


+
−
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

$$v(t)$$

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

$i(t)$

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

ϕ_i

ϕ_V

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

V

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

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

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

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

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

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

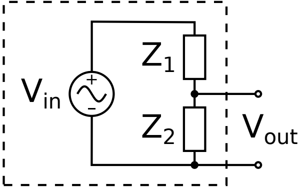
$$\langle P \rangle = \frac{IV}{2} \cos(\phi_v - \phi_i) = \frac{V^2}{2Z} \cos(\phi_v - \phi_i)$$

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

$$\phi_{v} - \phi_{i}$$

$$-\pi/2$$

V



V_{in}
+
−
Z_1
Z_2
V_{out}

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

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

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

V_{out}

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

V_{in}

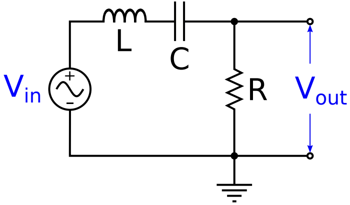
$$\tan\phi = \frac{Im\left(\frac{Z_2}{Z_1+Z_2}\right)}{Re\left(\frac{Z_2}{Z_1+Z_2}\right)}$$

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
V_{in}
V_{out}
+
−

$$Z_2 = R$$

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

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

$$a + jb$$

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

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

$$v_{out}(t)$$

$v_{in}(t)$

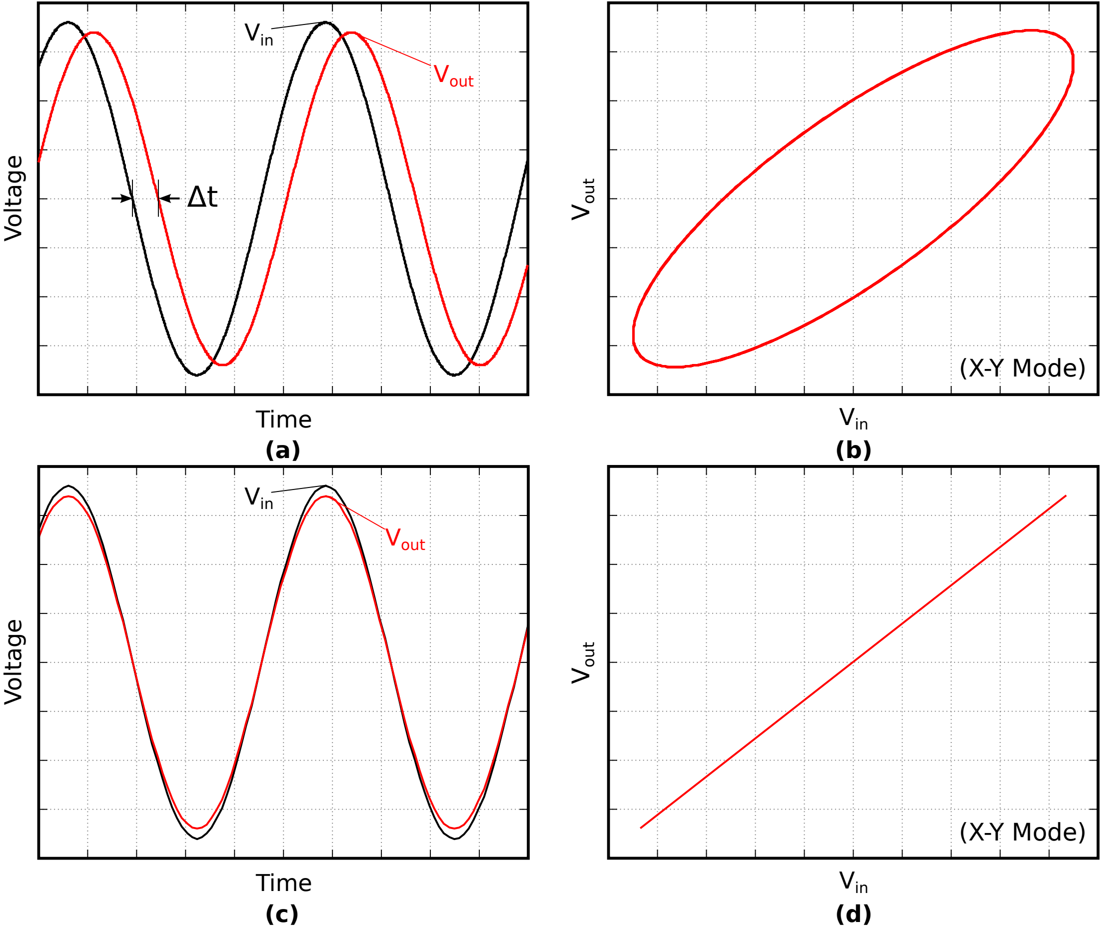
$$\Delta t = t_{V_{out}} - t_{V_{in}}$$

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

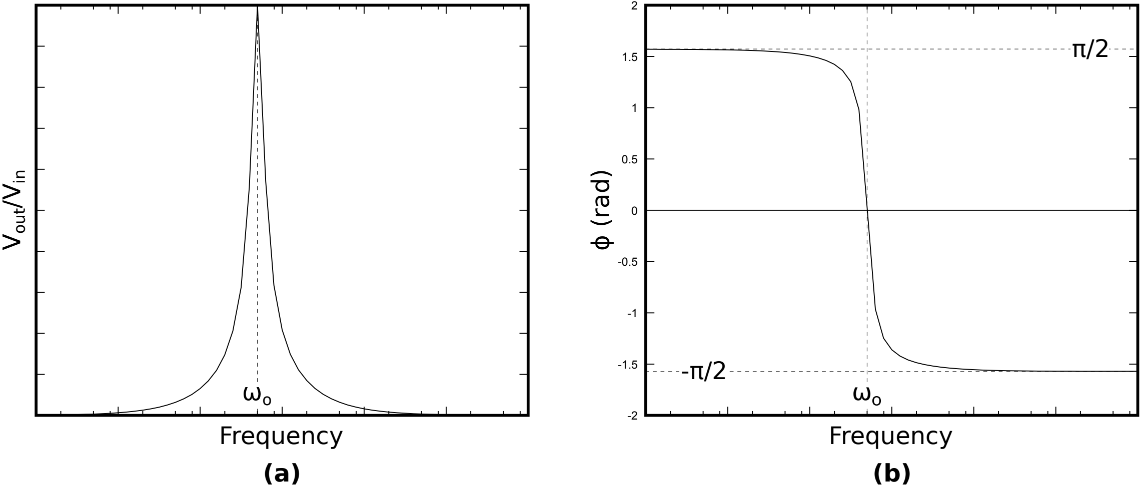
T

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
$\pi/2$
$-\pi/2$
ω_o
Frequency
(b)

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

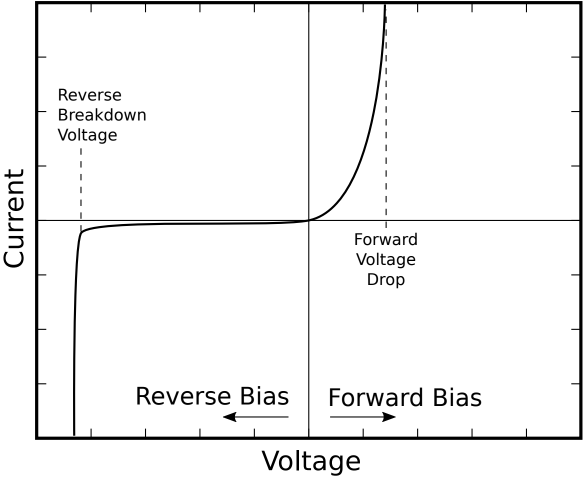
X_L

X_C

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

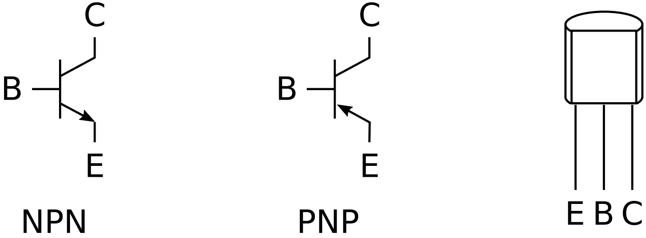
$$A_V = V_{out}/V_{in}$$

v_{out}


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

$V - I$

10^{-8}



(a) (b) (c)

I_C

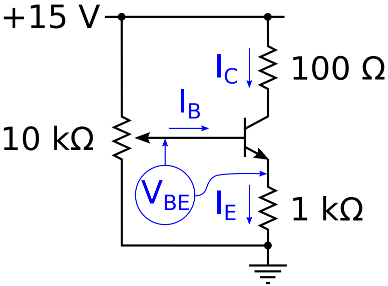
V_{BE}

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

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

≈ 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

$$V_C > V_E$$

$$V_{BE} \approx 0.7$$

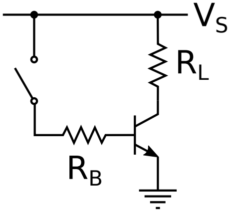
$$I_C = h_{FE} I_B$$

$$h_{FE} \approx 100$$

$$V_{BE} < 0.7$$

$$I_C \approx 0$$

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



V_S
R_L
R_B

R_L

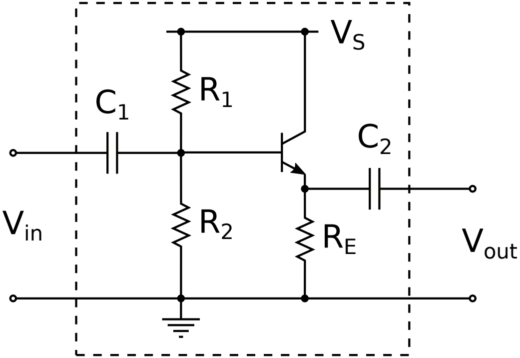
R_B

$\approx V_S$

$$\approx 0.25$$

V_S

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



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

$$A_v \approx 1$$

V_E

R_E

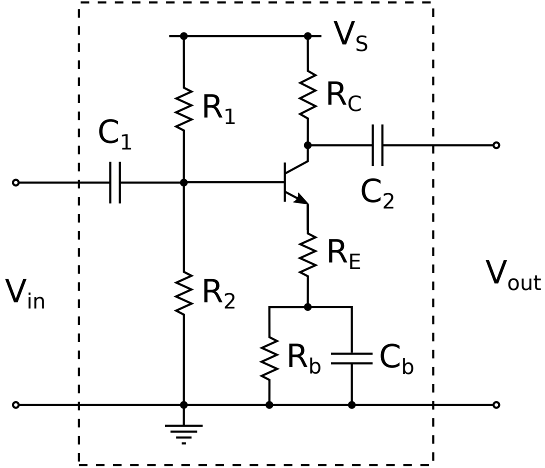
R_1/R_2

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

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

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

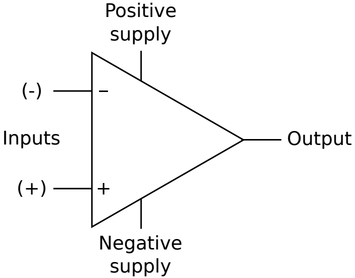
$$\approx \frac{R_b}{10}$$

$R_E + r_e$

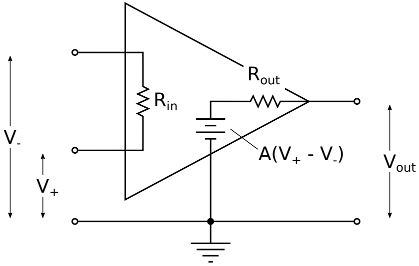
$$R_1||R_2 \approx h_{FE}(R_E + R_b)/10$$

$R_1 || R_2$

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


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

(a)


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

(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

$$V_+ \approx V_-$$

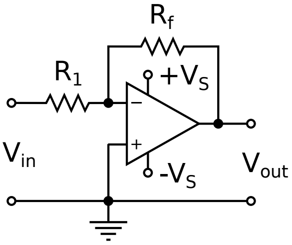
$$R_{in} = \infty, \ A = \infty, \ R_{out} = 0$$

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

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

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

$10^{12}\ \Omega$


R_f
R_1
+V_S
-V_S
V_in
V_out

R_f

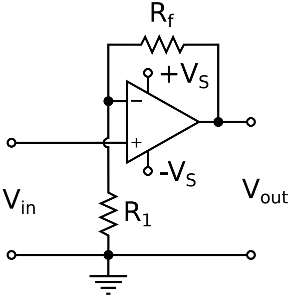
$$I = \frac{V_{in}}{R_1} = \frac{-V_{out}}{R_f}$$

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

$$R_{oa} || R_f$$

R_{oa}

R_f / R_1

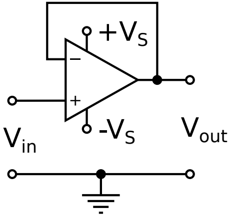


R_f
+V_S
-V_S
V_in
R_1
V_out

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

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

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

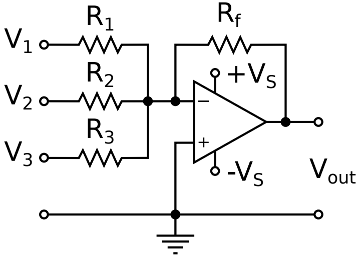


$+V_S$
$-V_S$
V_{in}
V_{out}

$$R_1 = \infty$$

$$R_f = 0$$

$$A_v = 1$$



R_1
R_f
V_1
R_2
$+V_S$
V_2
R_3
V_3
$-V_S$
V_{out}

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

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

I3

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

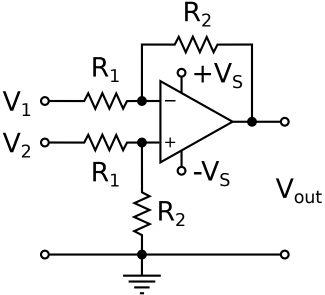
I_f

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

$$I_1 + I_2 + I_3 = I_f$$

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

R_1/R_f


R2
R1
+VS
V1
V2
R1
-VS
Vout
R2

$$I_1 + I_2 = I_3 + I_4$$

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

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

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

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

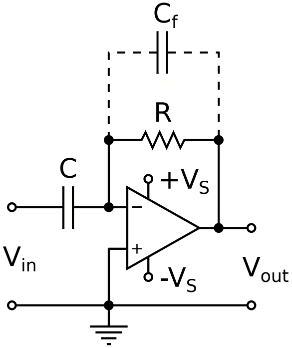
$$V_+ = \frac{R_2}{R_1 + R_2} V_2$$

$$V_- = V_+$$

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

V_1

V_2



Cf
R
C
+VS
−
+
-VS
Vin
Vout

$$C_f < C$$

C_f

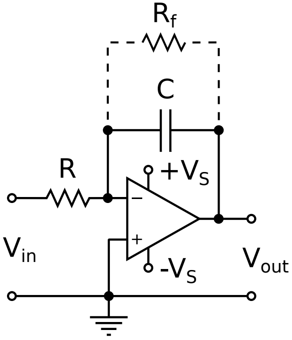
$$V_{out} = -IR$$

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

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

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

RC



R
f
C
R
+V
S
−
+
V
in
-V
S
V
out

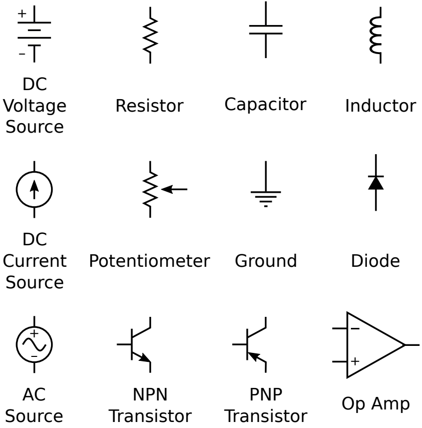
$$I = \frac{V_{in}}{R}$$

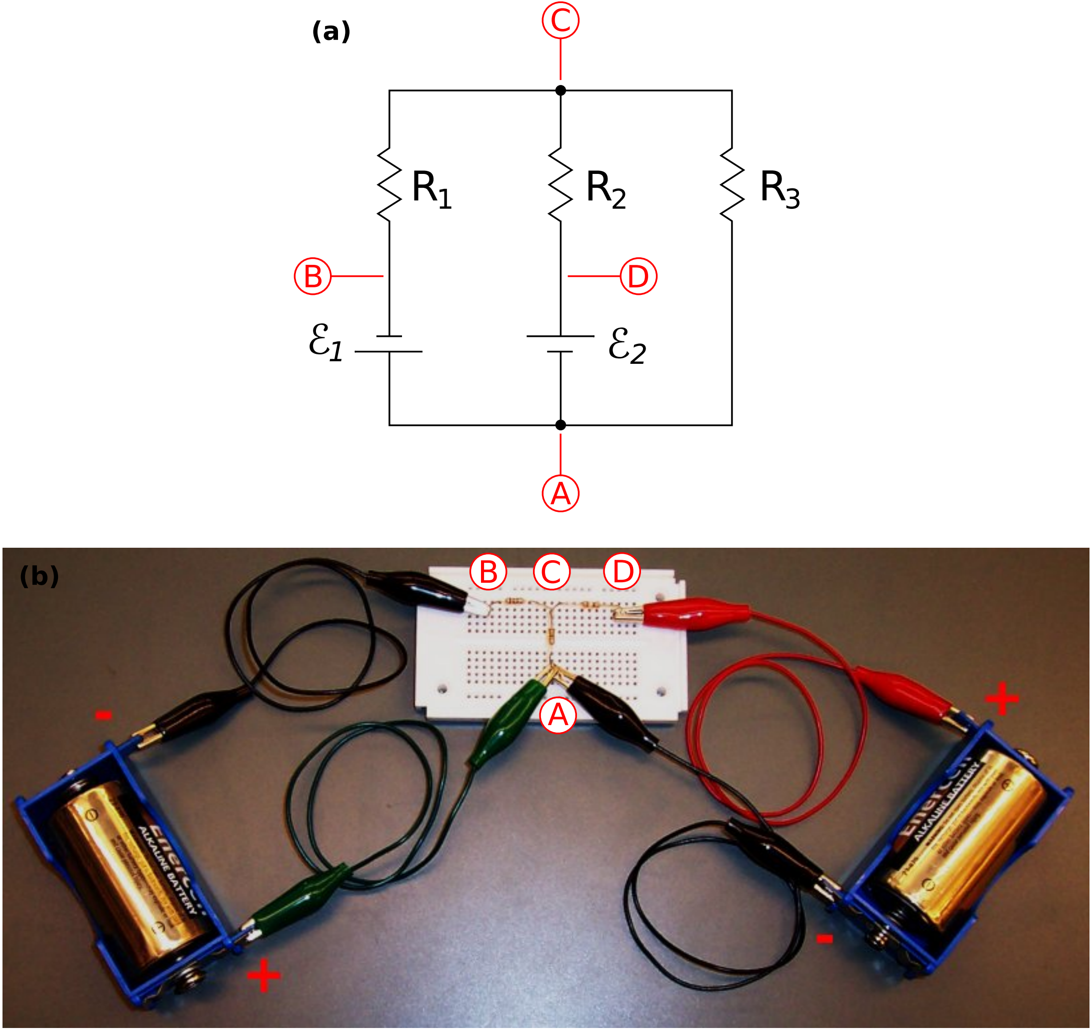
$$V_{out} = -\frac{Q}{C}$$

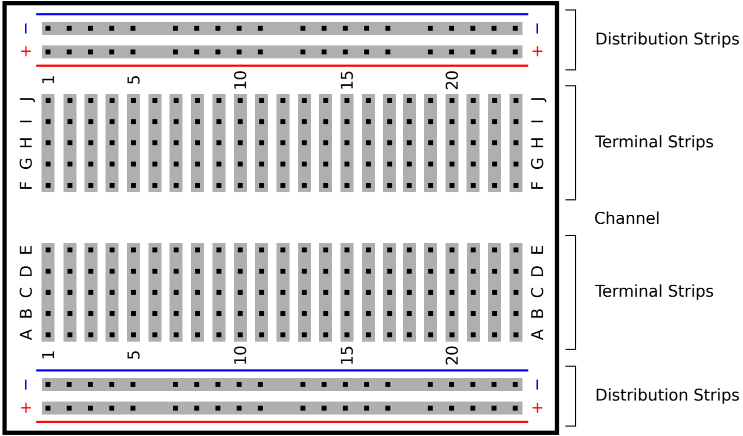
$$I \equiv dQ/dt$$

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

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


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


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



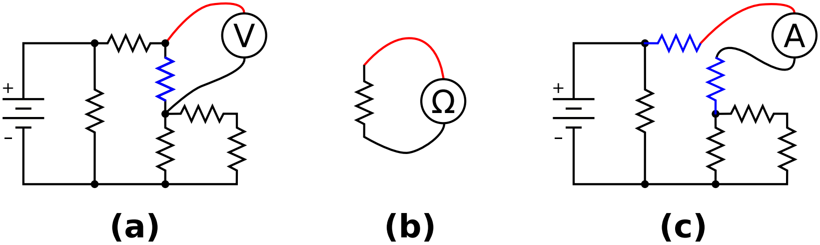
Distribution Strips
Terminal Strips
Channel
Terminal Strips
Distribution Strips
J I H G F
E D C B A
1 5 10 15 20

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

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

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

$\pm 320\ \Omega$


V
Ω
A
+
−
(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

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

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

$$1/\sqrt{2}$$

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