John Tyler

Senior Lecturer

ELEN, TAMU

(409) 845-7508

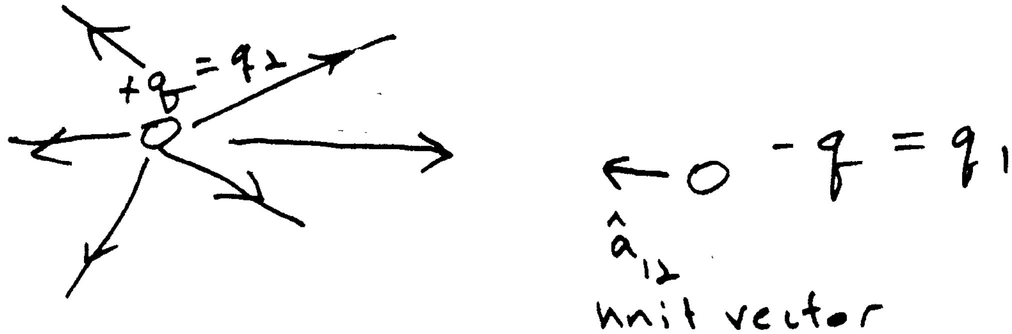
tyler@ee.tamu.edu

Electric Circuits

1. Fundamentals
2. Resistive Circuits with DC
3. Circuit Solution Techniques
4. Capacitors and Inductors
5. First Order Transients
6. AC Signals
7. AC Circuits
8. Op Amps

1. Fundamentals

Charge Q or $q(t)$



Coulomb's Force $\vec{F}$

$$\vec{F}_{12} = \hat{a}_{12} \frac{q_1 q_2}{r_{12}^2} k$$

$$= q_1 \left(\hat{a}_{12} \frac{q_2}{r_{12}^2} k \right)$$

$$= q_1 \vec{E}_2$$

$\vec{F}_{12}$ attractive if $q_1 q_2 < 0$

$\vec{F}_{12}$ repulsive if $q_1 q_2 > 0$

Electric Fields $\vec{E}$, $\vec{D}$

$\vec{D}$ - displacement

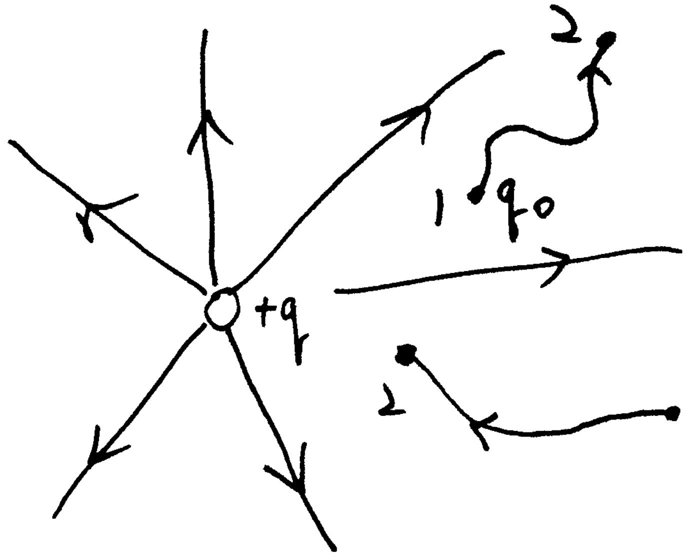
- electric flux dens.

$\vec{E}$ - electric field

$\vec{D} = \epsilon \vec{E}$

Voltage V, $v(t)$, $\mathcal{E}$ or e

└ potential difference



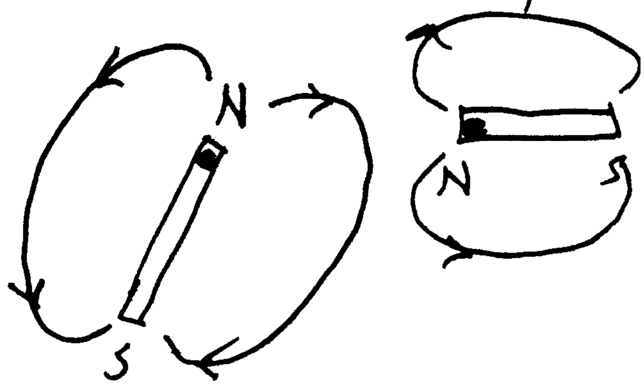
$\Delta V = [\text{Volts}]$

Magnetic Fields $\vec{H}$, $\vec{B}$

$\vec{B}$ = mag. flux density

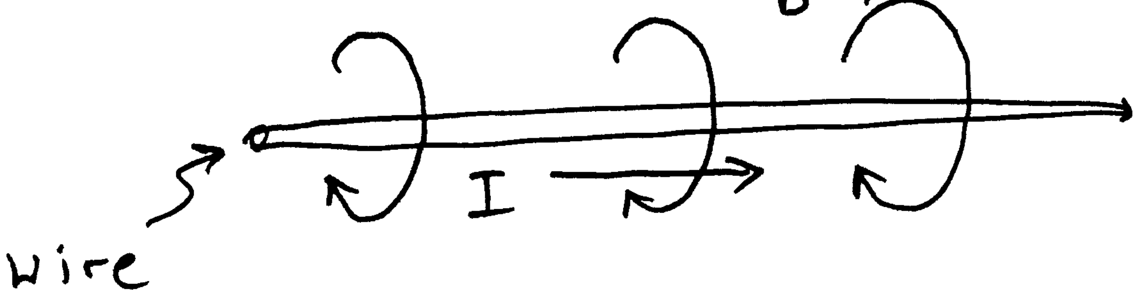
$\vec{H}$ = mag. field intensity

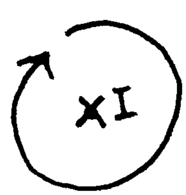
$\vec{B} = \mu \vec{H}$



Current I, $i(t)$

$\vec{B} = \mu \vec{H}$





I going into page

right hand rule

Induced Voltage v or e

Faraday's Law

$$v = -\frac{d}{dt}\Phi$$

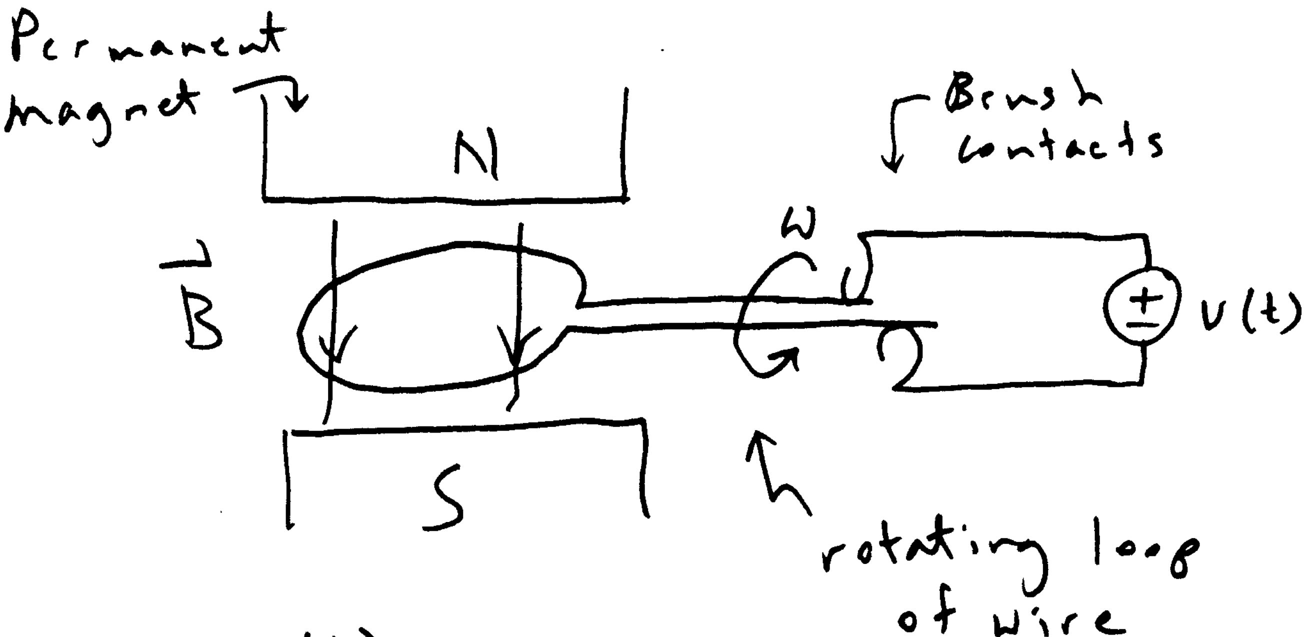
mag flux

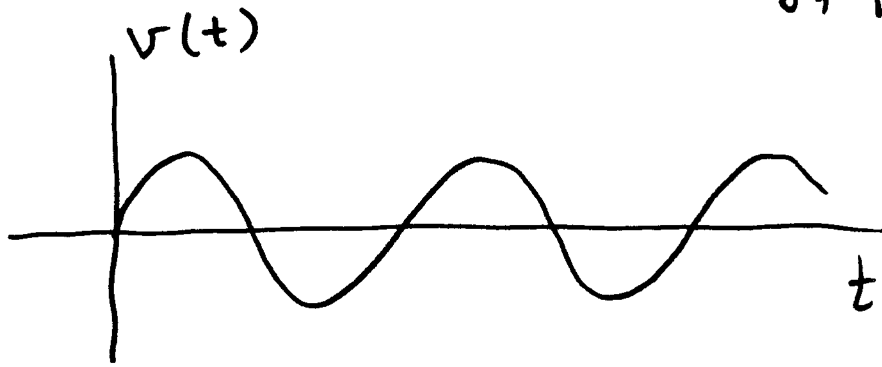
$$\Phi = \oint \vec{B} \cdot \vec{da}$$

$$= \int B A \cos(90°)\, da$$

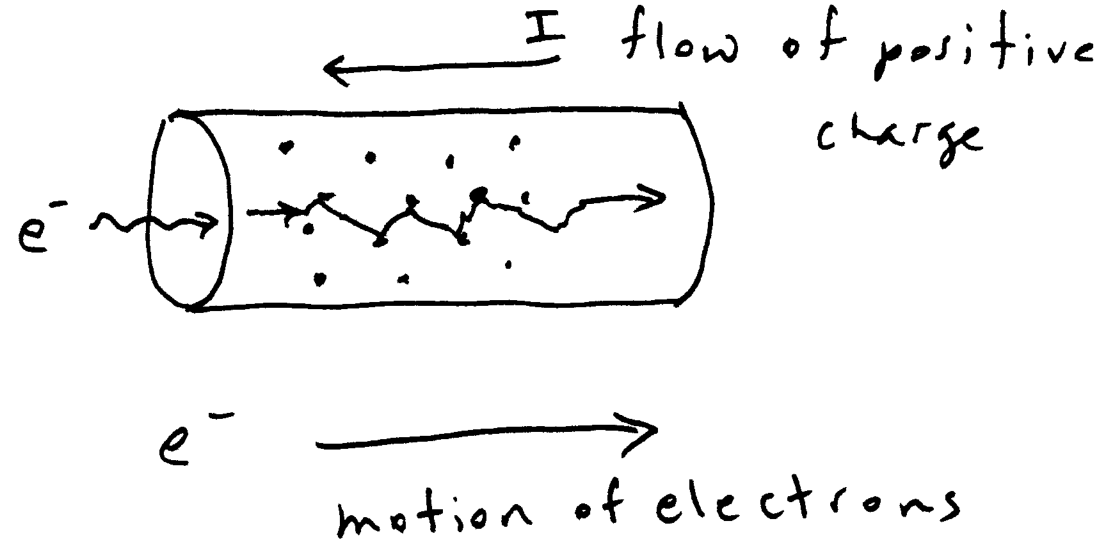
$$= \underline{B \cdot A} \quad \text{special case}$$

$$v(t) = -\frac{d}{dt} B \cdot A$$


Permanent magnet
N
S
$\vec{B}$
ω
Brush contacts
v(t)
rotating loop of wire

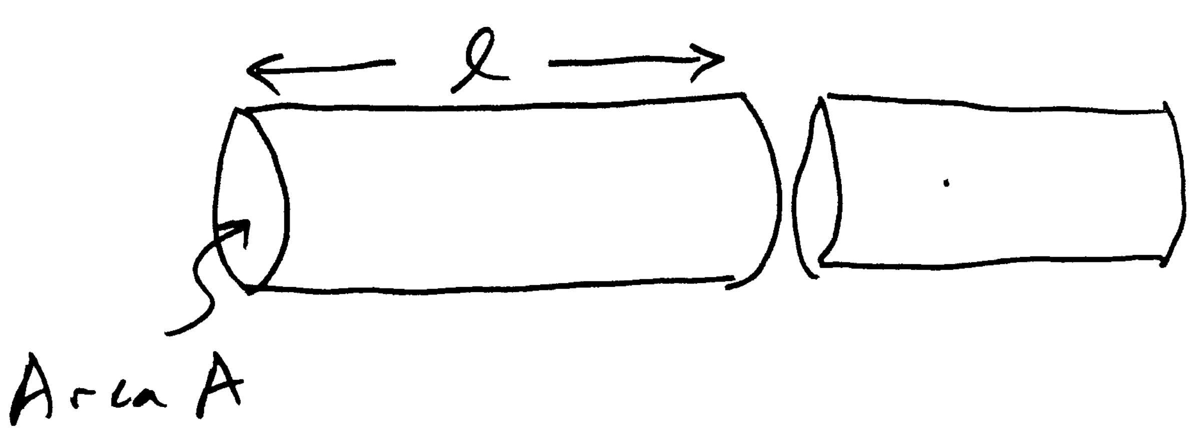

v(t)
t

Resistivity ρ

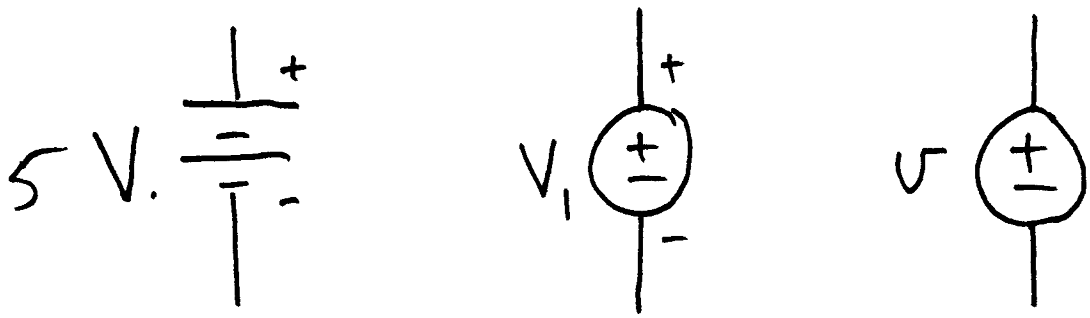


Resistance R

$$R = \rho \frac{\ell}{A} = [\text{Ohms}] = [\Omega]$$



Voltage Sources

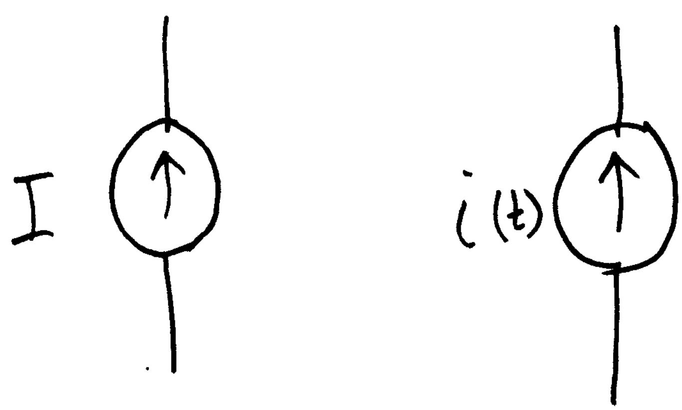


$V_1 = 2\,V.$

$v(t) = 2\cos(3t)$

[Volts]

Current Sources



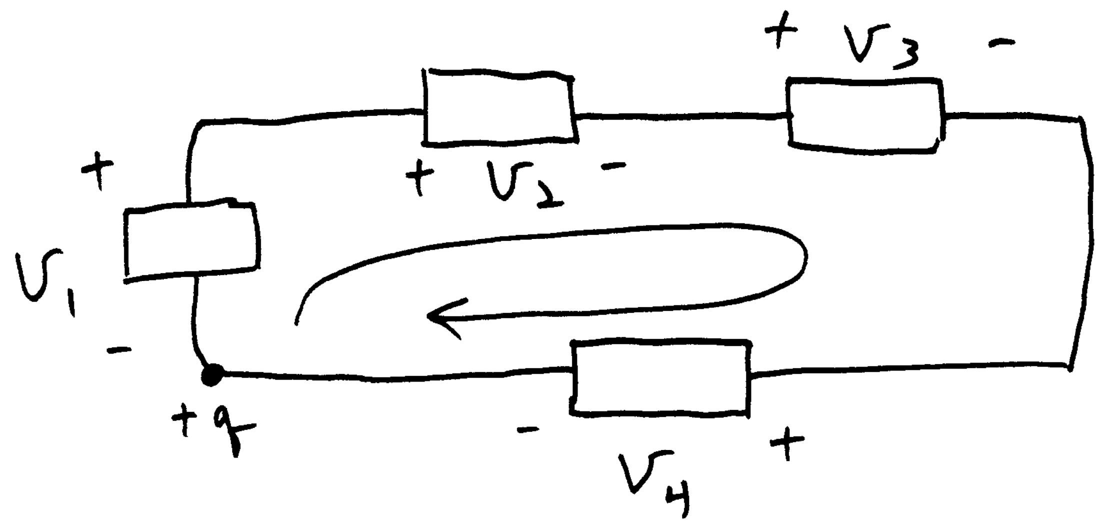
$I = 3A.$

$i(t) = 4\cos(800\pi t)$

[Amps]

Kirchhoff's Laws

KVL: $$\sum_{n=1}^{N} v_n = 0$$

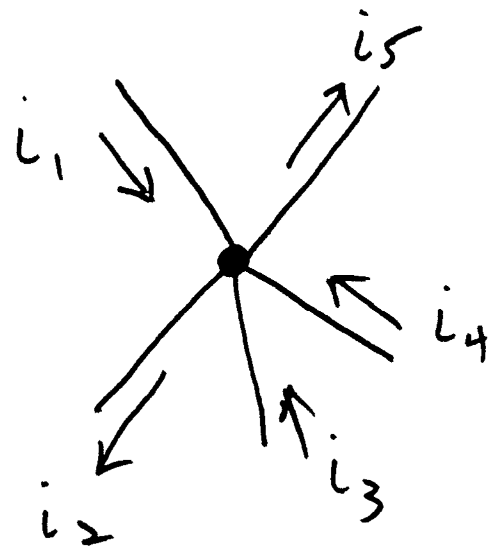


$$-v_1 + v_2 + v_3 + v_4 = 0$$

$$+v_1 - v_2 - v_3 - v_4 = 0$$

energy conservation for circuits

KCL - charge is conserved



$$\sum_{n=1}^{N} i_n = 0$$

$$+i_1 - i_2 + i_3 + i_4 - i_5 = 0$$

$$i_2 = i_1 + i_3 + i_4 - i_5$$

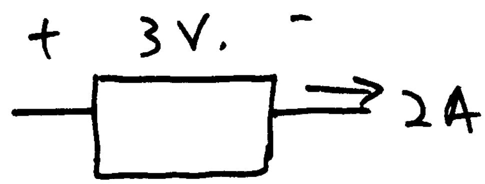
$$i_1 + i_3 + i_4 = i_2 + i_5$$

Electric Power, Energy

Power = [Watts]

Energy = [Joules]

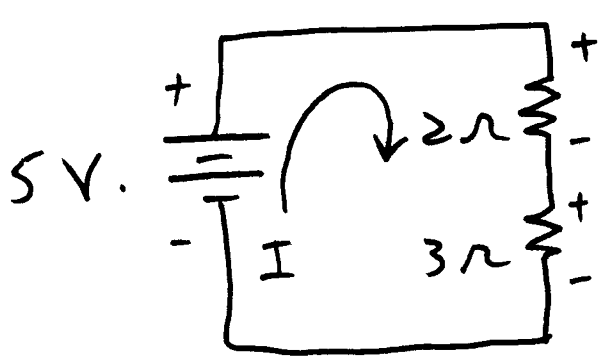
$P = VI$



$= 3 \cdot 2 = 6\,W.$

Power Balance

$$P_{generated} = P_{dissipated}$$



Ohm's Law

$V = RI$

5 Watts gen.

2. Resistive Circuits

Ohm's Law $\quad V = R I$

$$= \left(\rho \frac{\ell}{A}\right) I$$

Circuit Symbol

R_2 $\qquad$ $2\,k\Omega$

k - kilo $\quad$ M - mega

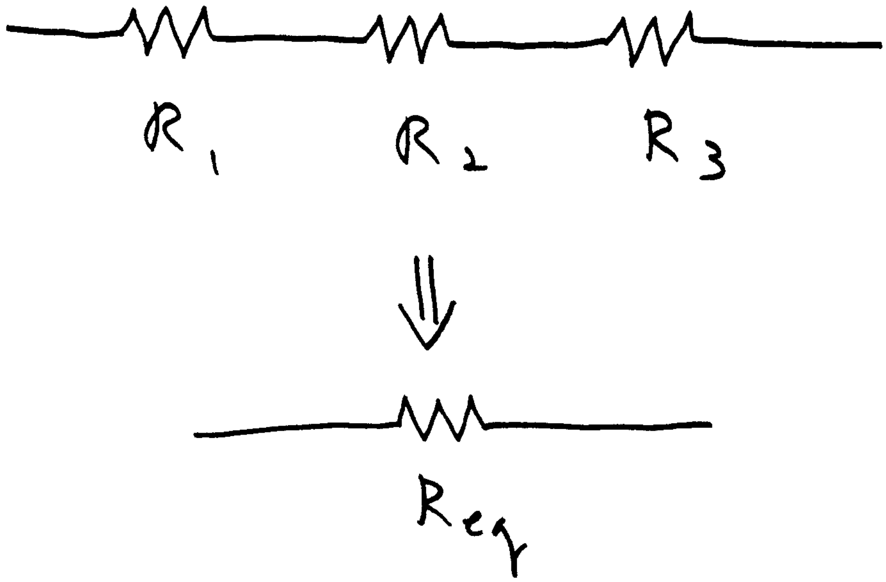
Power in resistors

$$P = VI$$

$$= V\left(\frac{V}{R}\right) = \frac{V^2}{R}$$

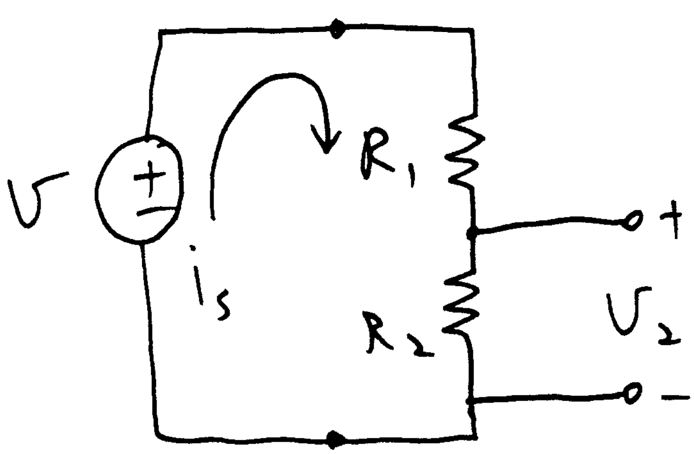
$$= (RI)I = RI^2$$

Resistors in Series



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

Voltage Divider



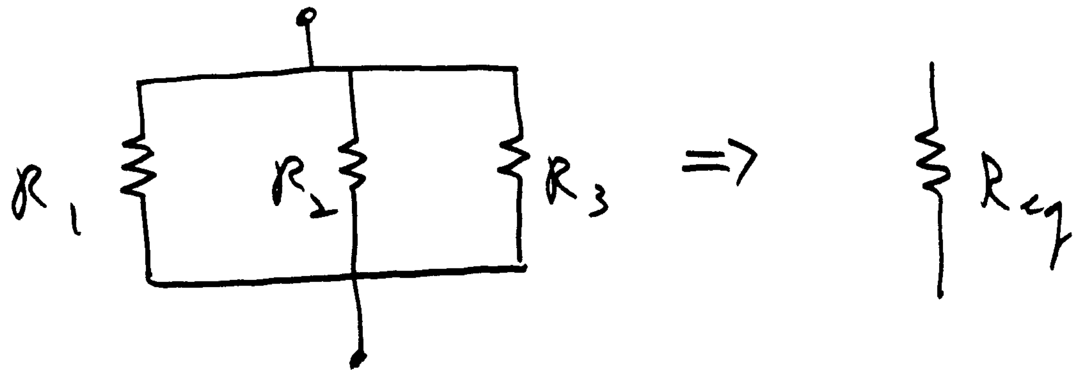
$$i_s = \frac{v}{R_{eq}}$$

$$= \frac{v}{R_1 + R_2}$$

$$v_2 = R_2 \, i_s$$

$$= v \left(\frac{R_2}{R_1 + R_2} \right)$$

Resistors in Parallel

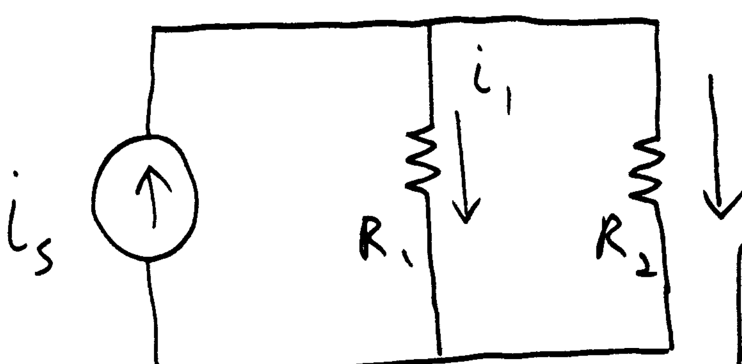


$$R_{eq} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

Two Resistors (special case)

$$R_{eq} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} = \underline{\underline{\frac{R_1 R_2}{R_1 + R_2}}} \qquad \frac{[\Omega]^2}{[\Omega]}$$

Current Divider



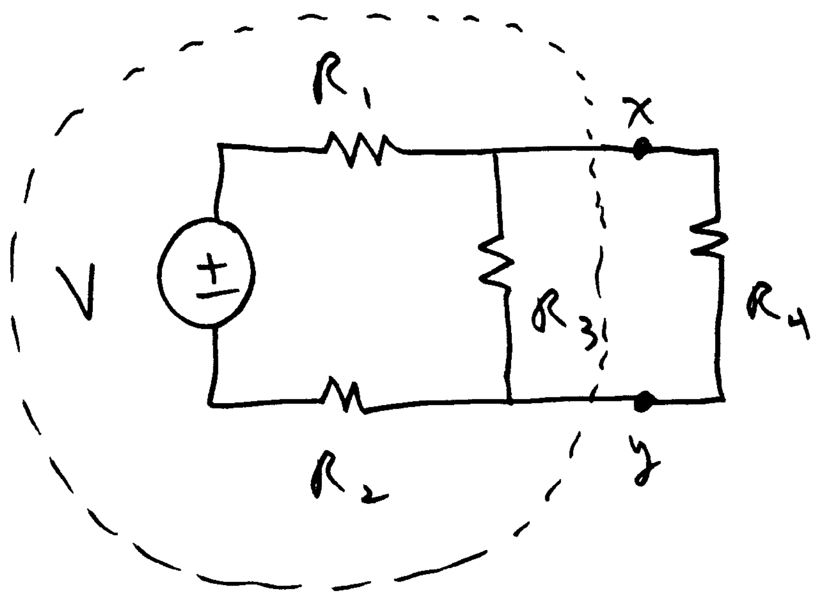
$$i_2 = i_s \left(\frac{R_1}{R_1 + R_2}\right)$$

$$\boxed{i_1 = i_s \left(\frac{R_2}{R_1 + R_2}\right)}$$

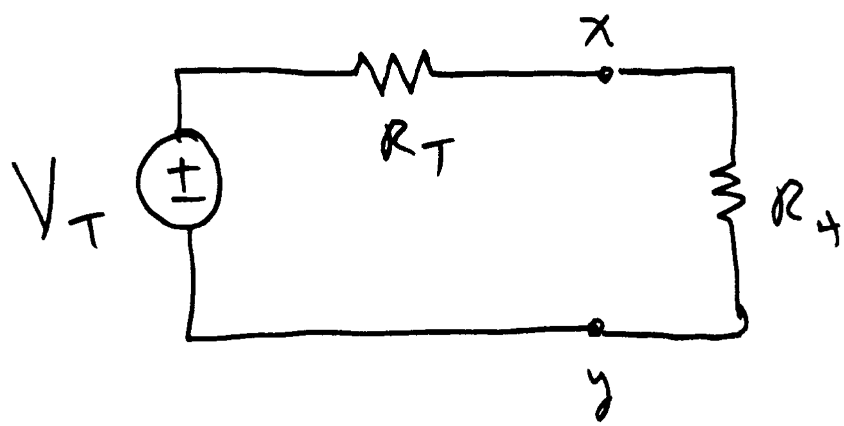
Thevenin Equivalent

V_{oc} , I_{sc} , V_T , R_T

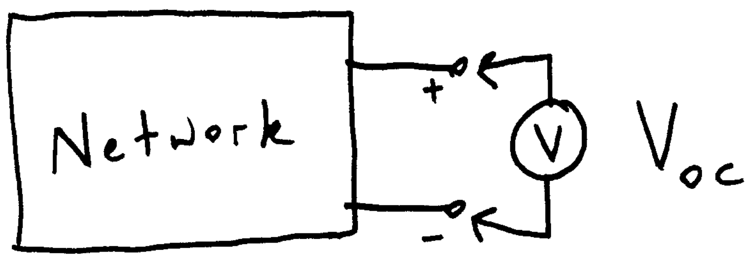
Network - interconnection of sources + others

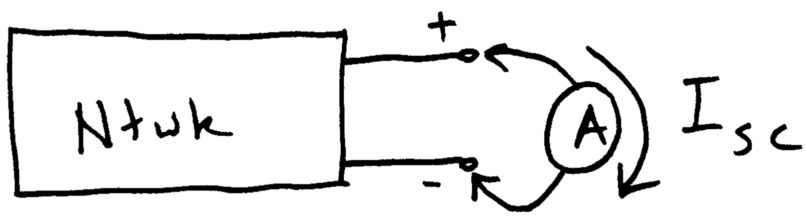


$\Downarrow$



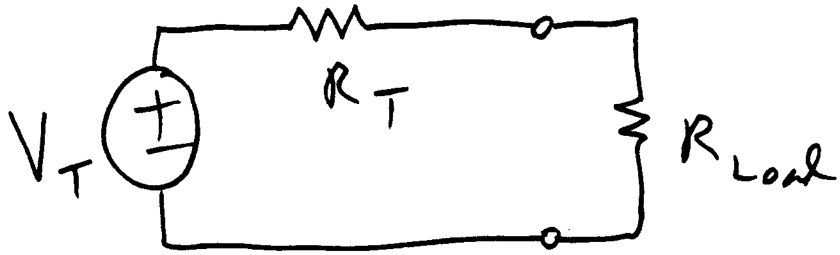
V_{oc} - open circuit voltage





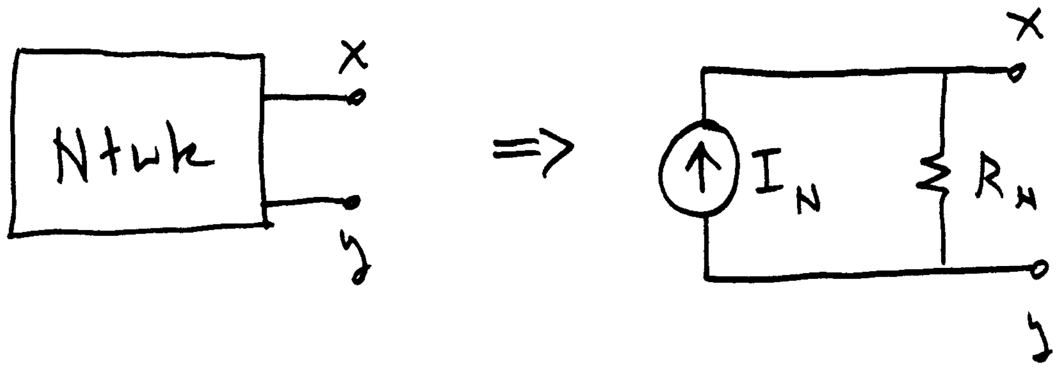
Thev. Equiv.

$$\left\{ \begin{aligned} V_T &= V_{oc} \\ R_T &= \frac{V_{oc}}{I_{sc}} \end{aligned} \right.$$



Norton Equivalent

V_{oc}, I_{sc}, I_N, R_N

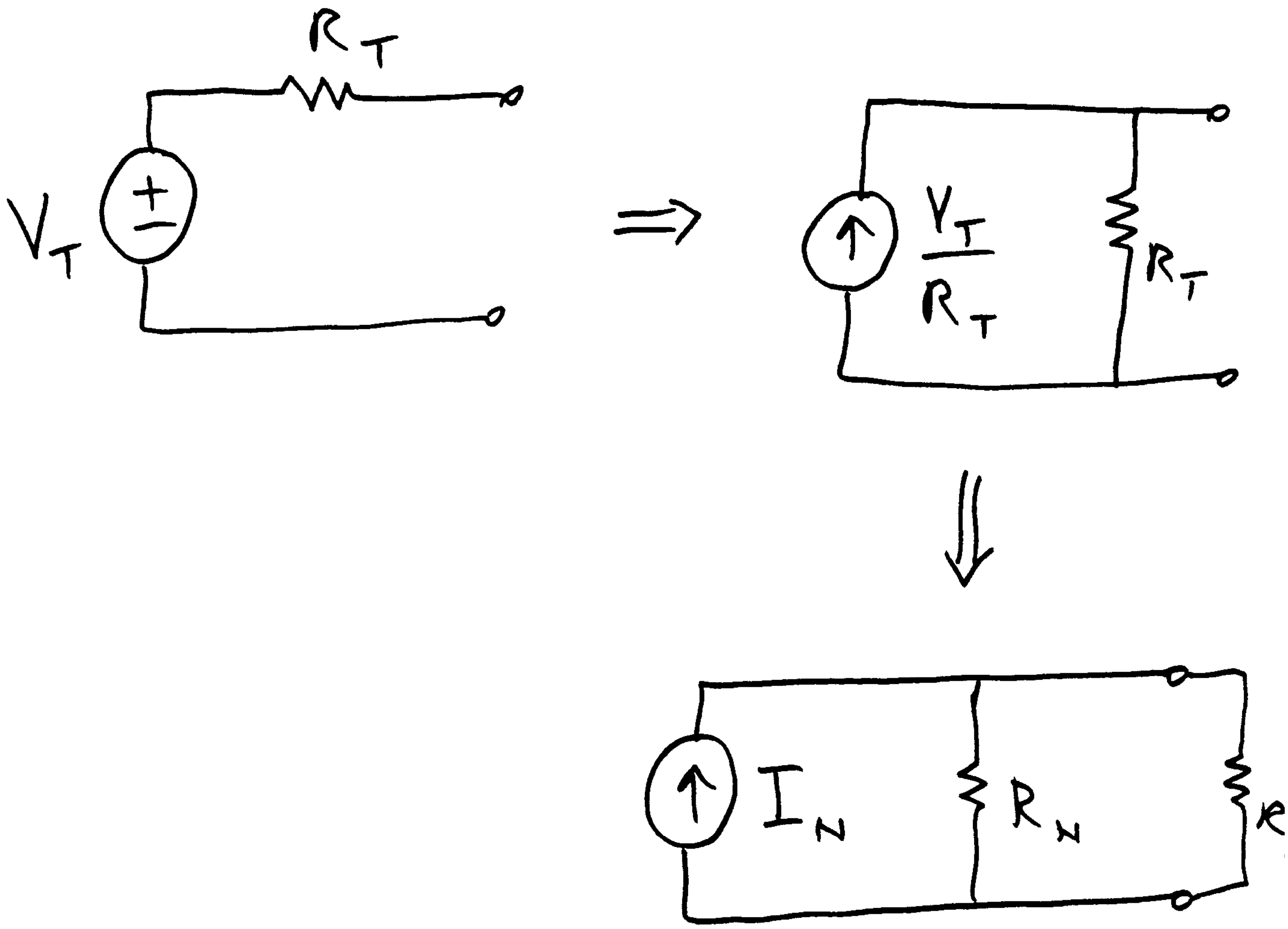


Norton Equiv.
$$\begin{cases} I_N = I_{sc} \\ R_N = \dfrac{V_{oc}}{I_{sc}} \qquad (= R_T) \end{cases}$$

$$V_{oc} = R_N I_{sc} = R_N I_N$$

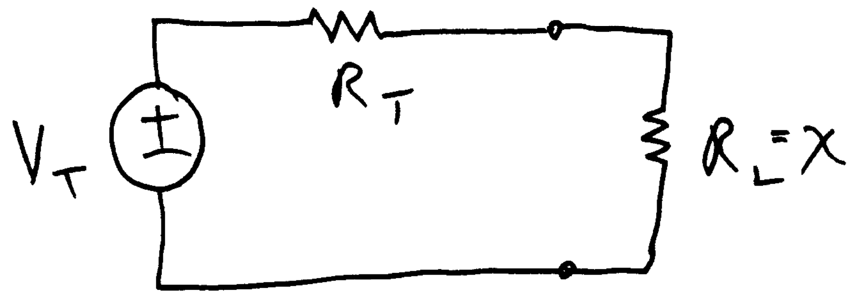
$$V_T = R_N I_N$$

Source Transformation



i.e. Thevenin $\Longleftrightarrow$ Norton

Maximum Power Transfer



$P_L = I^2 R_L$

What R_L gives maximum P_L?

$$I = \frac{V_T}{R_{eq}} = \frac{V_T}{R_T + x}$$

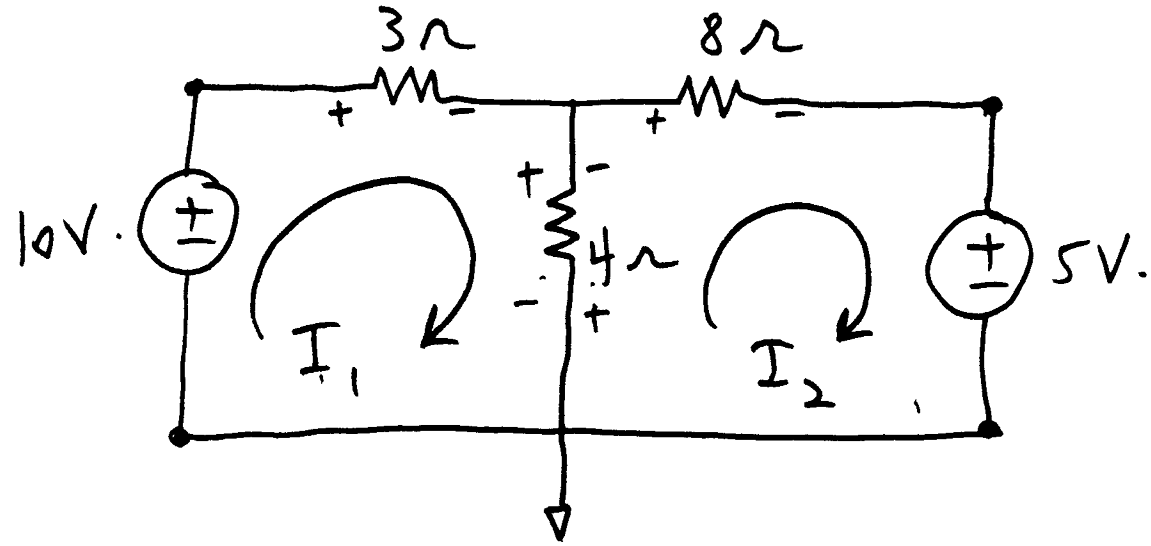
$$P_L = \left(\frac{V_T}{R_T + x}\right)^2 x$$

$$= V_T^2 \frac{x}{(R_T + x)^2}$$

$$\frac{dP_L}{dx} = 0 \longrightarrow \underline{x = R_T}$$

3. Circuit Solution Techniques

Loop Currents



KVLs

loop1: $-10 + 3I_1 + 4(I_1 - I_2) = 0$

loop 2: $+5 + 4(I_2 - I_1) + 8I_2 = 0$

$$7I_1 - 4I_2 = 10$$

$$-4I_1 + 12I_2 = -5$$

Solve for I_1, I_2

$$7I_1 - 4I_2 = 10$$

$$-4I_1 + 12I_2 = -5$$

Ans: $\underline{\underline{I_1 = 1.47}}\,[A]$, $I_2 = 0.0735$

$\underline{\underline{I_2 = 73.5}}\,[mA]$

Check:

$$-10\,V. + (3\Omega)(I_1) + (8\Omega)(I_2) + 5 = ?$$

KVL around outside loop

$$0 \approx -0.002$$

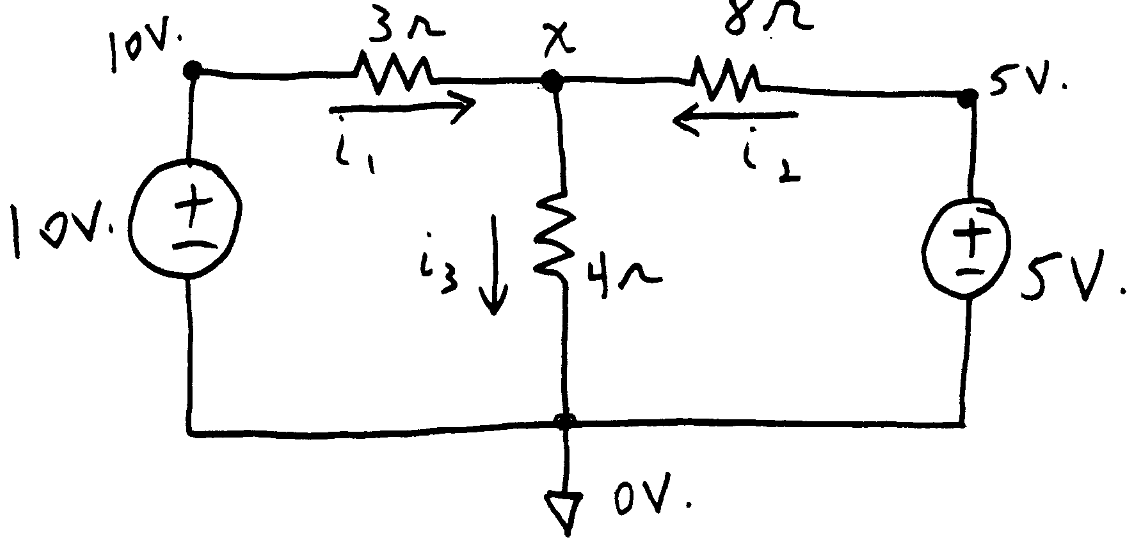
Also loop1 KVL check

$$-10\,V. + (3\Omega)\,I_1 + (4\Omega)(I_1 - I_2) \stackrel{?}{=} 0$$

$$-10 + 3(1.47) + 4(1.47 - 0.0735) \stackrel{?}{=} 0$$

$$-0.004 \approx 0$$

Node Voltages



Node voltage at x : V_x

KCL at x: $i_1 + i_2 = i_3$

$$\left(\frac{10 - V_x}{3}\right) + \left(\frac{5 - V_x}{8}\right) = \left(\frac{V_x - 0}{4}\right)$$

$$8(10 - V_x) + 3(5 - V_x) = 6 V_x$$

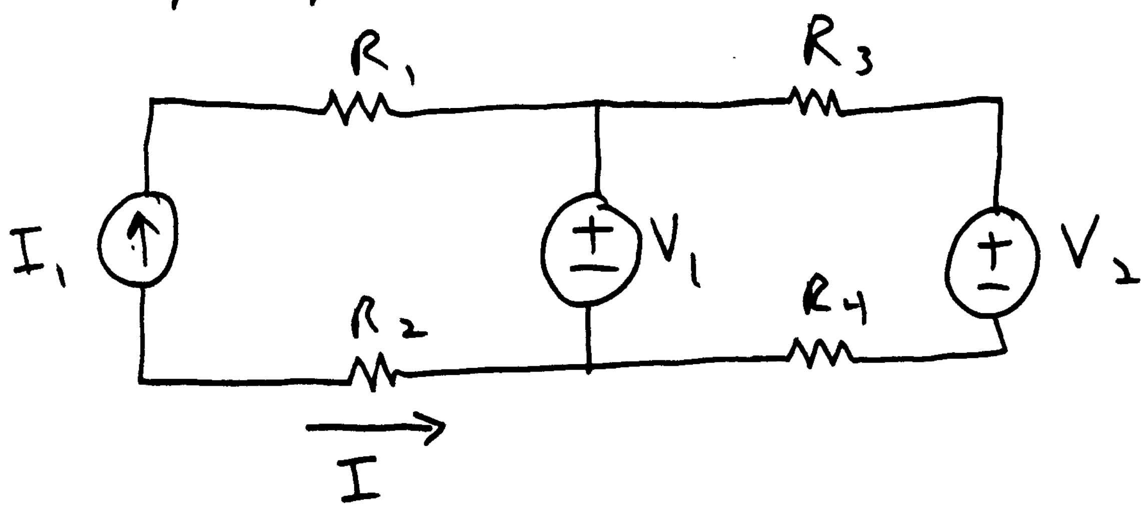
$$V_x = 5.59 \text{ V.}$$

Compare

From loop currents:

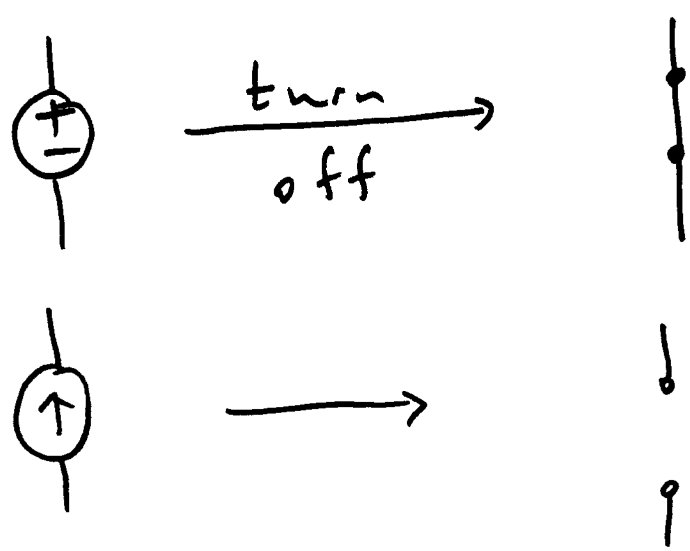
$$4(I_1 - I_2) = 4(1.47 - 0.0735) \cong 5.59$$

Superposition



$$I = I_{cs} + I_{vs1} + I_{vs2}$$

↳ "turn off" the other two sources

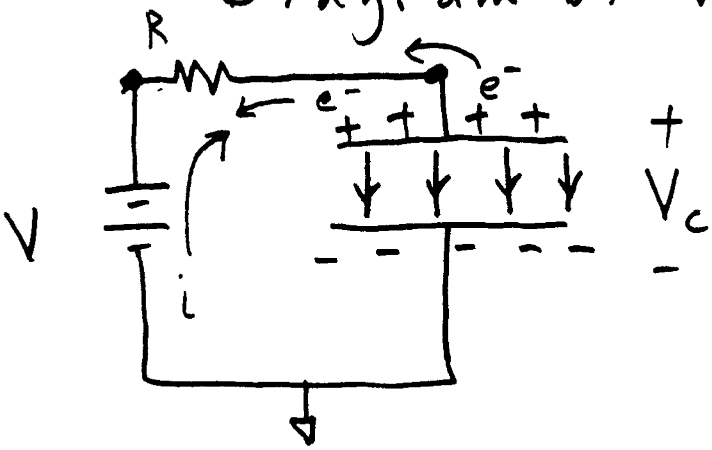


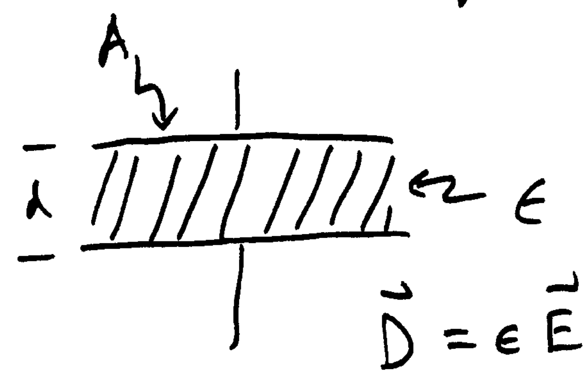
4. Capacitors + Inductors

Capacitor Symbol

$C = [\text{Farad}]$ mF μF nF

Diagram of Parallel Plate Cap.





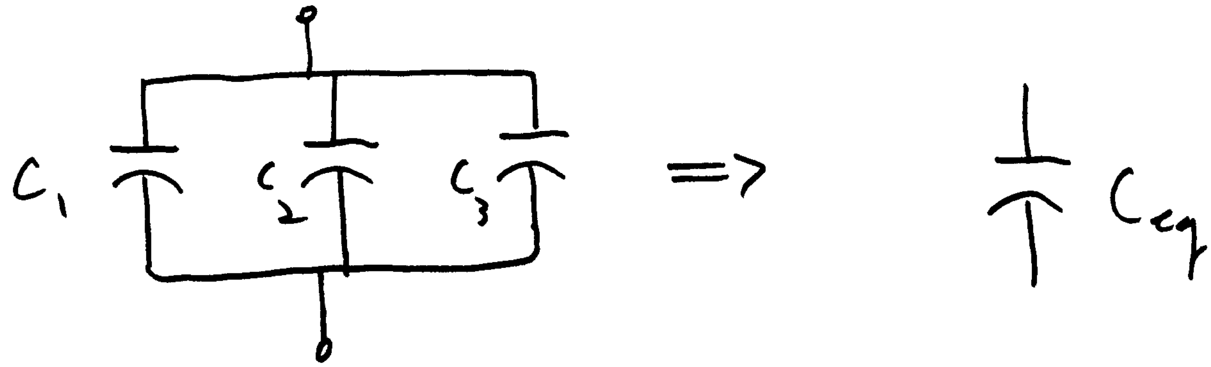
Basic Theory $\quad Q = CV$

$$C = \epsilon \frac{A}{d} \qquad q(t) = C\,v(t)$$

Math model: $\boxed{i(t) = C \frac{d}{dt} v(t)}$

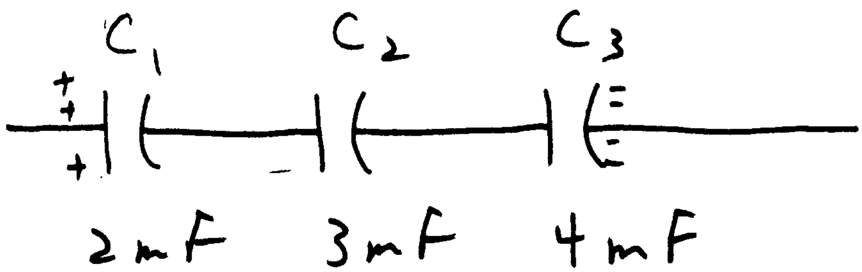
Recall: $\dfrac{dq(t)}{dt} \equiv i(t) = [A.] = \left[\dfrac{\text{Coul}}{s}\right]$

Capacitors in Parallel

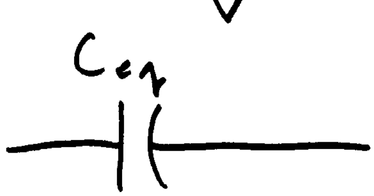


$$C_{eq} = C_1 + C_2 + C_3$$

Capacitors in Series



$\Downarrow$



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

Energy Storage in Capacitors

$$w = \int p\,dt \qquad p = \frac{dw}{dt}$$

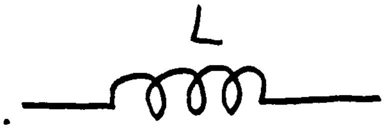
$$= \int v\,i\,dt$$

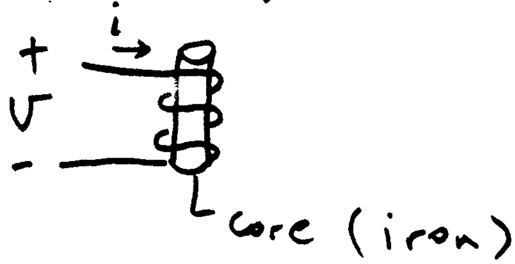
$$w_c = \int v\left(C\,\frac{dv}{\cancel{dt}}\right)\cancel{dt}$$

$$= C\int v\,dv$$

$$= C\,\frac{v^2}{2}$$

$$\boxed{w_c(t) = \frac{1}{2}C\left[v_c(t)\right]^2}$$

Inductor Symbol 

Basic theory 

Math model: $\boxed{v(t) = L \frac{d}{dt} i(t)}$

$L = [\text{Henry}]$

Inductors in series

$$L_{eq} = L_1 + L_2 + L_3$$

Inductors in parallel

$$L_{eq} = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}}$$

Energy Storage in Inductors

$$w = \int p \, dt$$

$$= \int v \, i \, dt$$

$$w_L = \int L \frac{di}{\cancel{dt}} \, i \, \cancel{dt}$$

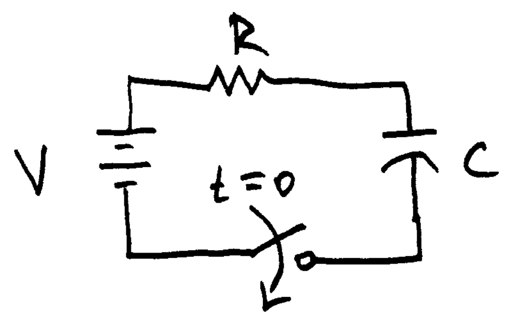
$$= L \int i \, di$$

$$\boxed{w_L(t) = \frac{1}{2} L \left[i(t) \right]^2} = [J]$$

5. First Order Transients

"transient" vs. "steady state"

↑ changing ↑ constant



Capacitor in steady state

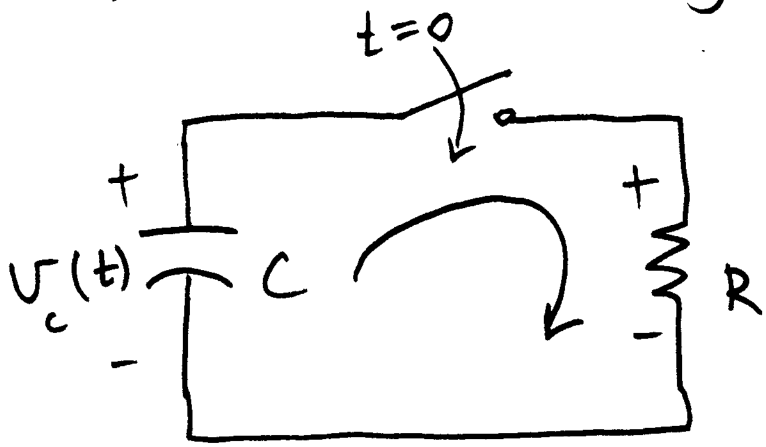
$$i = C\frac{dv}{dt} = C\frac{d}{dt}(\text{constant})$$

$$\left.\begin{array}{l} i = 0 \\ v \neq 0 \end{array}\right\} \text{ like an open circuit}$$

Inductor in steady state

$$v = L\frac{di}{dt} \xrightarrow{s.s.} \underbrace{v = 0 \,,\; i \neq 0}_{\text{like a short circuit}}$$

Capacitor Discharge

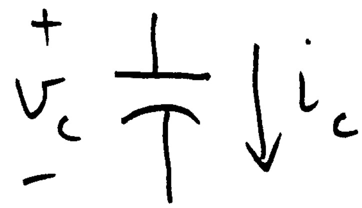


$v_c(t)$ = voltage across cap

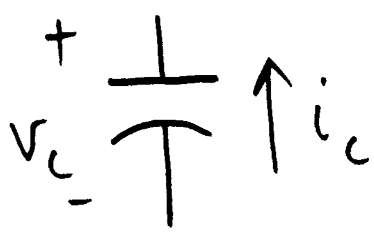
$v_c(0) = V$, initially charged

Passive Sign Convention

$i = +C \frac{dv}{dt}$ iff



If

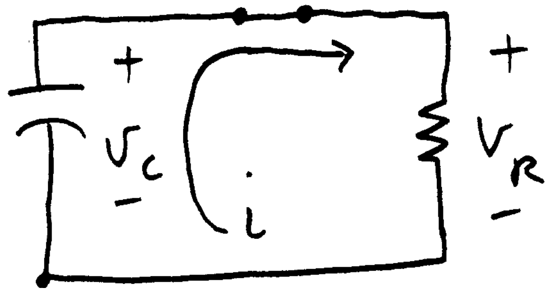


then $i = -C \frac{dv}{dt}$

"active"

↑ delivering energy

For $t > 0$



$$v_c(0) = V$$

KVL: $-v_c + v_R = 0$

$$i = -C\frac{dv}{dt} \rightarrow \underline{v = -\frac{1}{C}\int i\,dt}$$

passive sign convention

$$= \frac{-\int i\,dt}{C}$$

$$= \frac{-q}{C}$$

$$q = -Cv$$

$$-\left(-\frac{1}{C}\int i\,dt\right) + Ri = 0$$

$$\frac{1}{C}i + R\frac{di}{dt} = 0 \qquad \frac{di}{dt} + \frac{1}{RC}i = 0$$

$$\frac{di}{dt} + \frac{1}{RC} i = 0$$

solve by assuming an exponential sol'n

$$\boxed{i(t) = \frac{V}{R} e^{-t/RC}}$$

$$i = A e^{st}$$

calculation

$$\frac{di}{dt} = A s e^{st} = s i$$

$$s i + \frac{1}{RC} i = 0$$

$$s = -\frac{1}{RC}$$

$$i = A e^{-t/RC}$$

$$V(0) = R i(0) = V$$

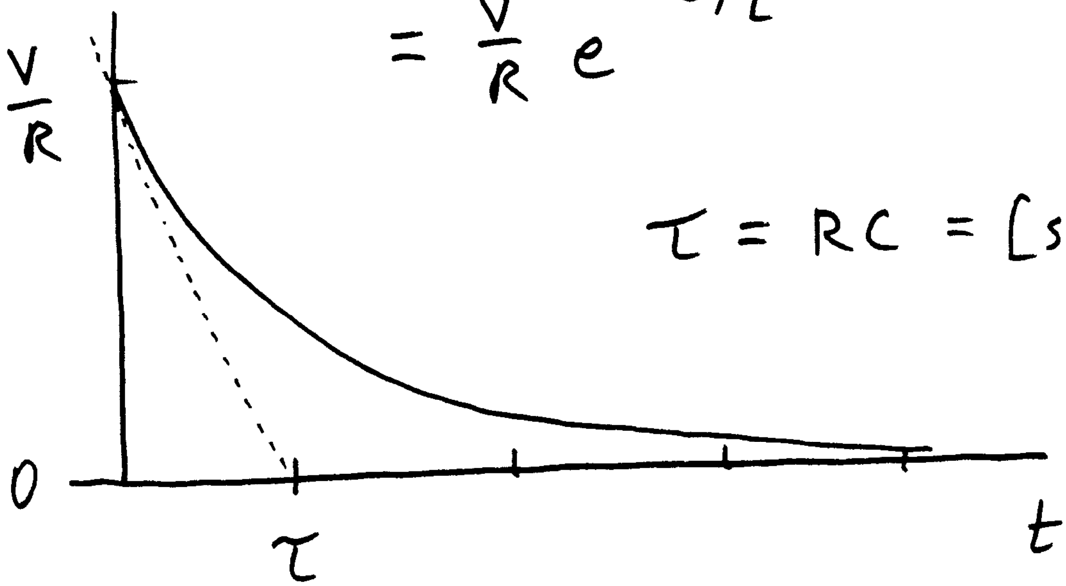
$$R(A e^{0}) = V$$

$$A = \frac{V}{R} \rightarrow \boxed{i(t) = \frac{V}{R} e^{-t/R}}$$

result

$$i = \frac{V}{R} e^{-t/RC}$$

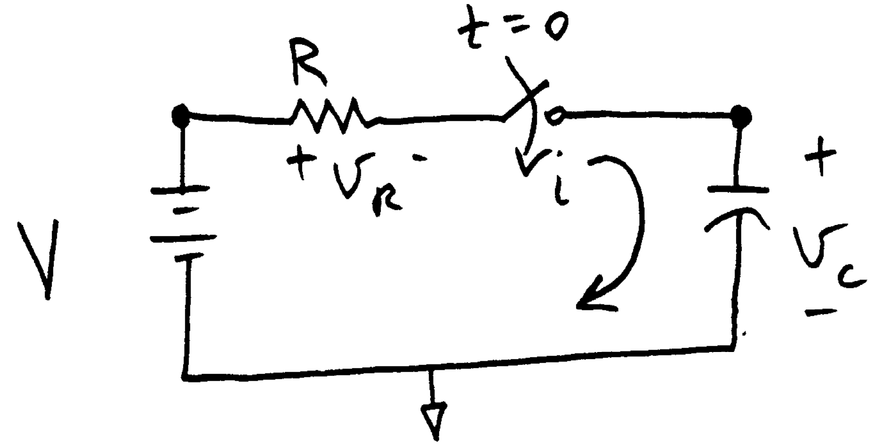
$$= \frac{V}{R} e^{-t/\tau}$$



$$\tau = RC = [s]$$

Transient period ends after 5τ.

Capacitor Charging



$v_c(0) = 0\,[\text{V}]$

$v_c(\infty) = V$

KVL: $-V + v_R + v_c = 0$

$$-V + Ri + \frac{1}{C}\int i\,dt = 0$$

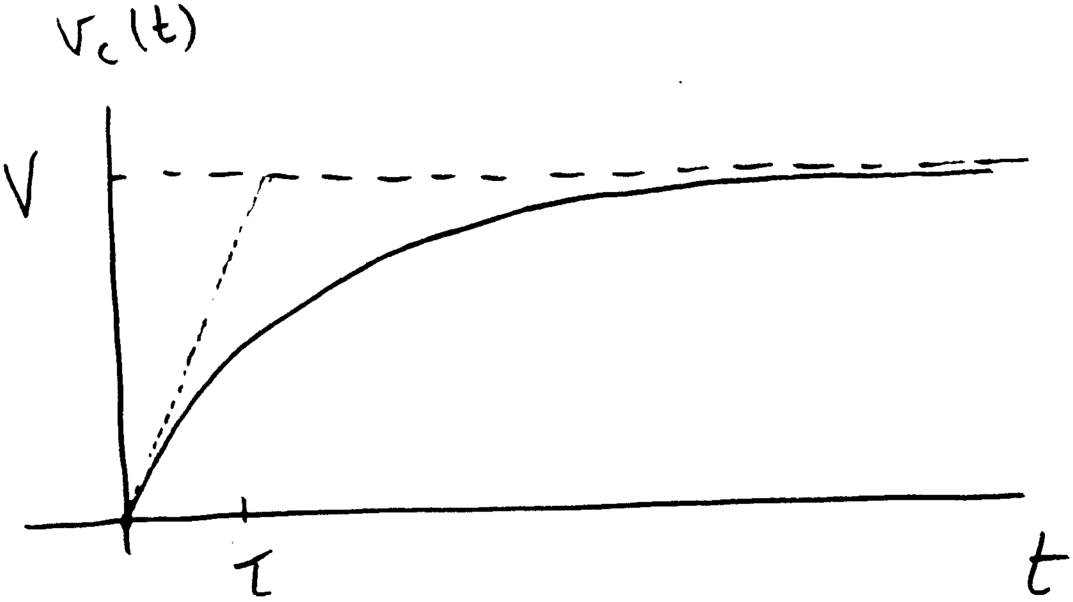
$$R\frac{di}{dt} + \frac{1}{C}i = 0$$

$$\vdots$$

$$i = I_o e^{-t/RC}$$

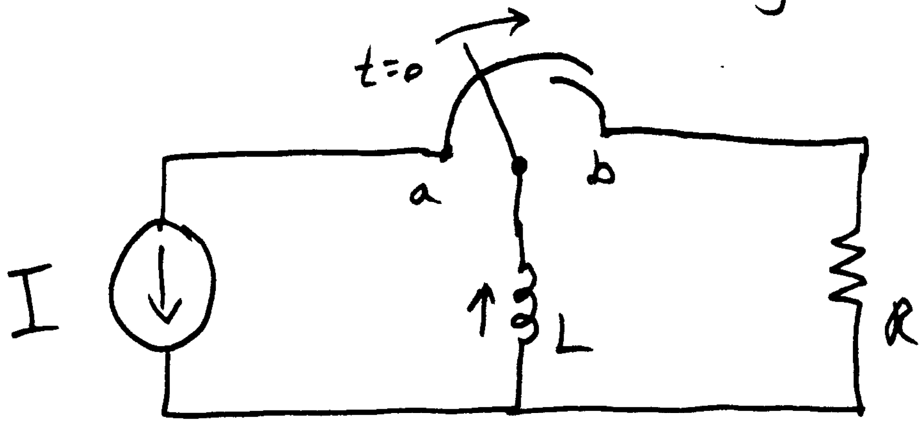
$$v_c(t) = V\left(1 - e^{-t/RC}\right)$$

$$v_c(0) = 0 \quad , \quad v_c(\infty) = V$$

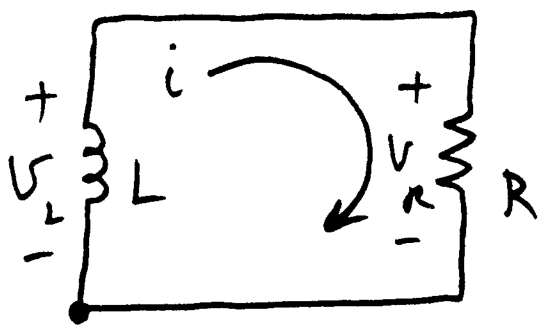


$\tau = RC$

Inductor "De-Energizing"



$i(0) = I$



For $t > 0$

$$v_L = -L\frac{di}{dt} \qquad v_R = Ri$$

$$-v_L + v_R = 0$$

$$-\left(-L\frac{di}{dt}\right) + Ri = 0$$

passive sign convention

$$\frac{di}{dt} + \frac{R}{L}i = 0$$

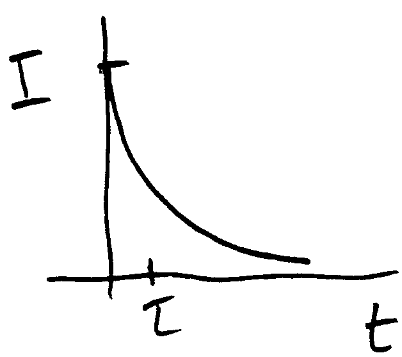
$$\frac{di}{dt} + \frac{R}{L} i = 0$$

$$i = Ae^{st}$$

$$si + \frac{R}{L} i = 0$$

$$s = -\frac{R}{L}$$

$$\boxed{i(t) = I e^{-\frac{R}{L} t}}$$



$$= I e^{-t/\tau}$$

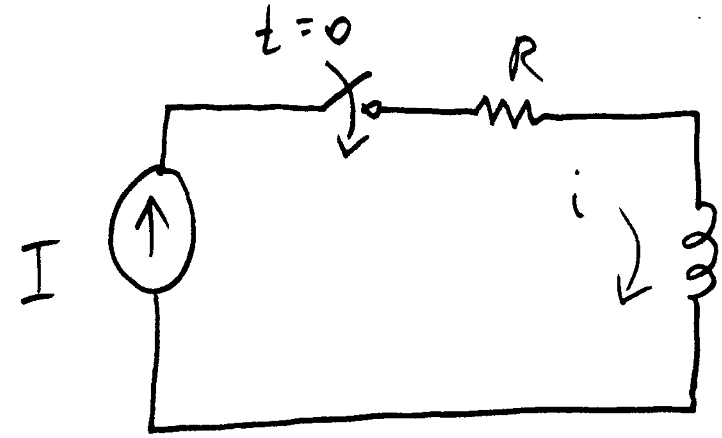
$$\tau = \frac{L}{R} = [s]$$

<u>Units</u>

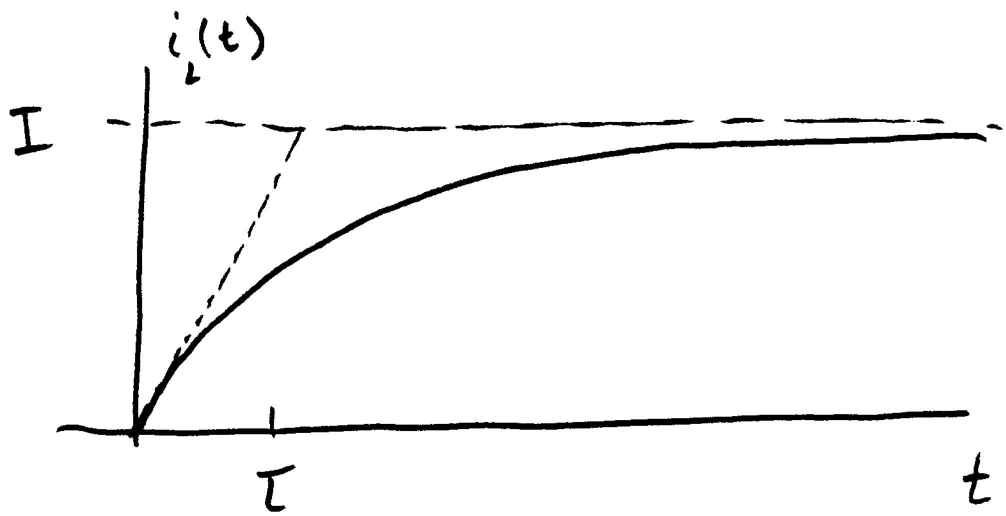
$$v = L \frac{di}{dt} \rightarrow L = \frac{v}{di/dt} = \left[\frac{V}{A/s}\right]$$

$$[F] = \left[\frac{As}{V}\right] \qquad [H] = \left[\frac{Vs}{A}\right] \checkmark$$

Inductor Energizing



$i(0) = 0$

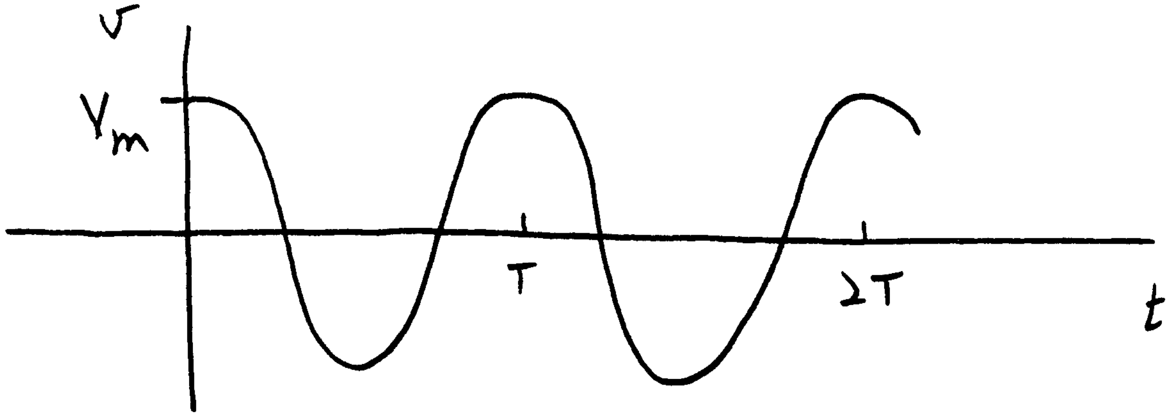


$$i(t) = I\left(1 - e^{-t/\tau}\right)$$

$$\tau = L/R$$

6. AC Signals

Waveform + terms



V_m - magn. or amplitude [V]

T - period [s]

f - frequency [Hz] $f = \frac{1}{T}$

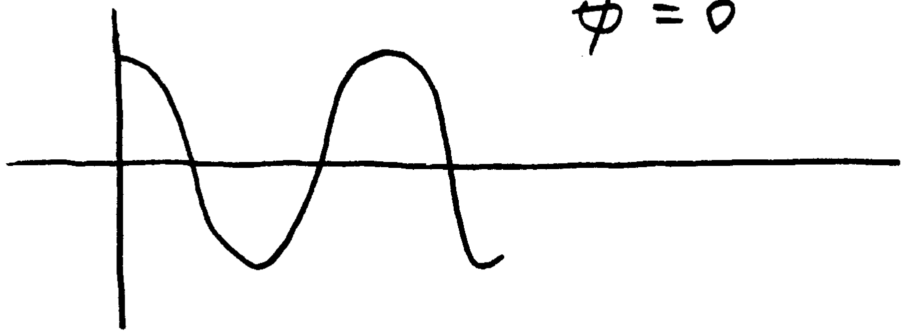
$\omega = 2\pi f = \frac{2\pi}{T} = [\text{rad}/\text{s}]$
↑ angular freq.

ϕ - phase angle

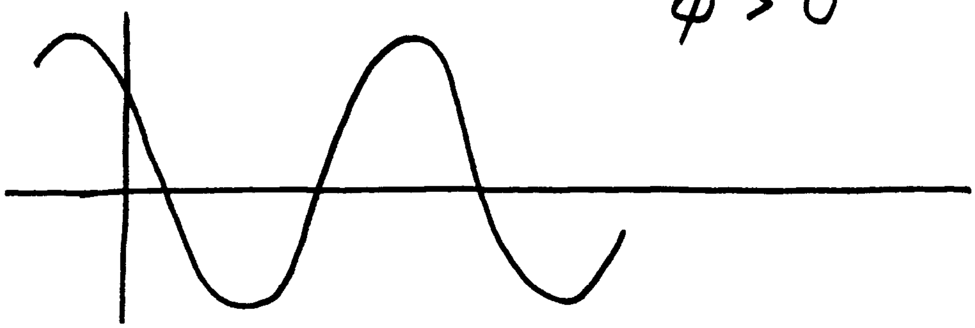
$$\boxed{v(t) = V_m \cos(\omega t + \phi)}$$

Phase Shifts

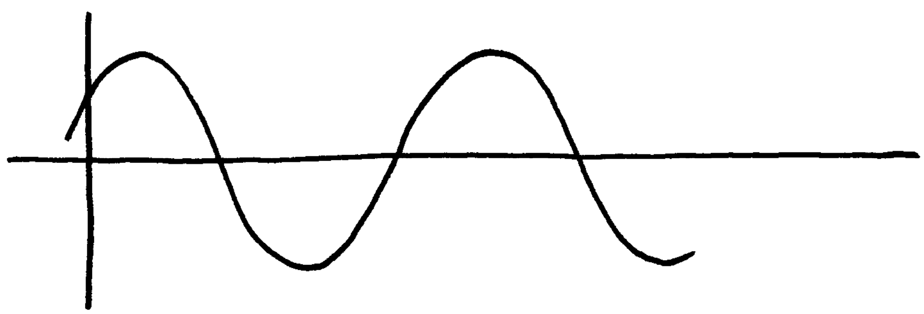
$\phi = 0°$



$\phi > 0$

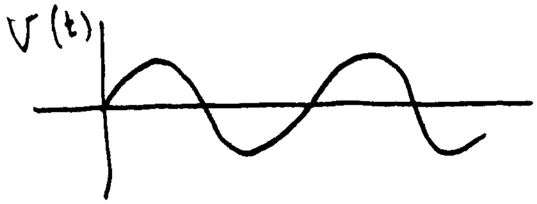


$\phi < 0$

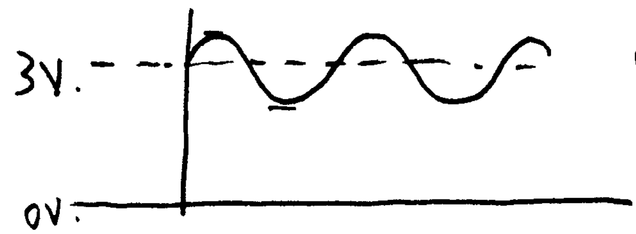


$$\boxed{i(t) = I_m \cos(\omega t + \phi)}$$

Average Value



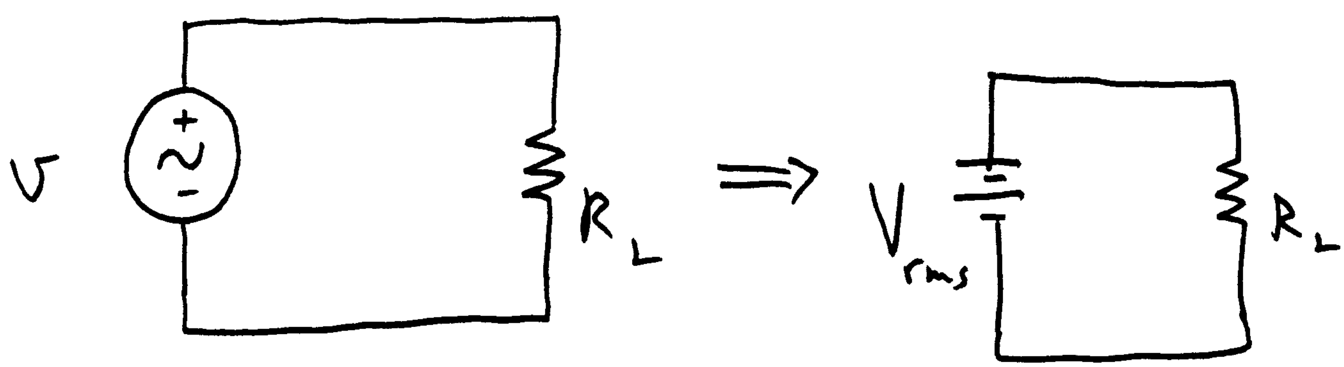
$$V_{av} = 0$$



$$v(t) = 3 + \frac{1}{2}\sin(\omega t)$$

$$\underline{V_{av} = 3}$$

Rms Value, or Effective Value



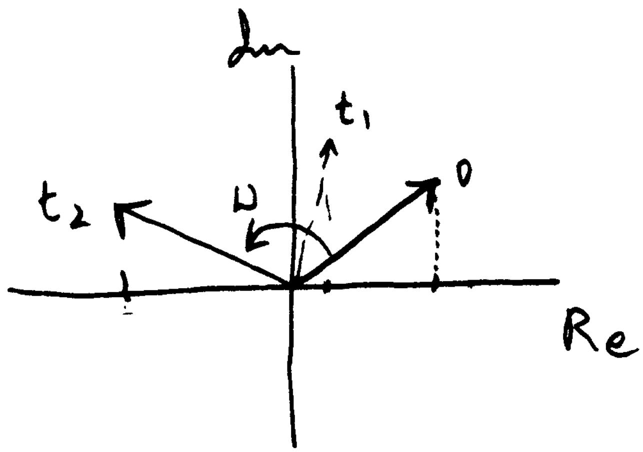
$$V_{rms} = V_{eff}$$

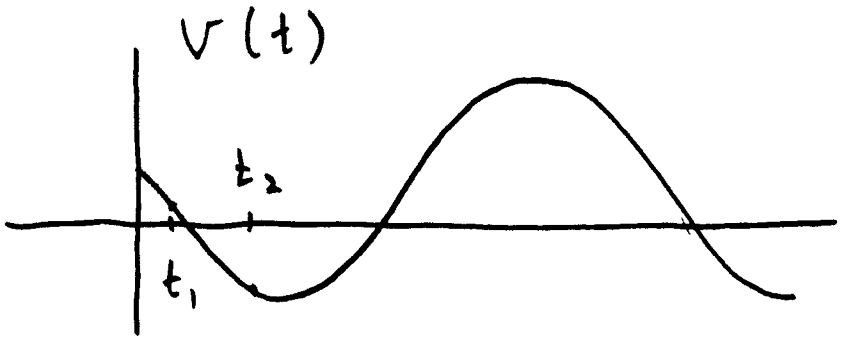
$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T v^2\,dt}$$

$$= \frac{1}{\sqrt{2}} V_m \quad \text{for} \quad V_{av} = 0$$

Phasors

- vector in complex plane
- fixed for analysis
- rotates at ω



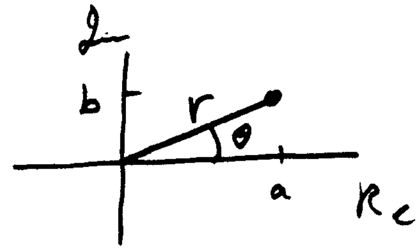


$$v(t) = V_m \cos(\omega t + \phi)$$

$$\mathbb{V} = V_m \angle \phi$$

Complex Algebra of Phasors

$$C = a + jb$$



$$= r \angle \theta$$

$$r = \sqrt{a^2 + b^2} \qquad \theta = \tan^{-1}\left(\frac{b}{a}\right)$$

C^* conjugate

$$j = \sqrt{-1}$$

$$j^2 = -1$$

$$C^* = a - jb$$

$$r = \sqrt{C^* C} = \sqrt{(a - jb)(a + jb)}$$

$$= \sqrt{a^2 + b^2}$$

$$C_1 \pm C_2 = (a_1 + a_2) + j(b_1 + b_2)$$

$$C_1 C_2 = (r_1 \angle \theta_1)(r_2 \angle \theta_2)$$

$$= (r_1 r_2) \angle \theta_1 + \theta_2$$

7. AC Circuits

$$\text{Impedance } Z = \frac{\mathbb{V}}{\mathbb{I}} = R + jX$$

(analogous to $R = \frac{V}{I}$)

$$\left.\begin{array}{l} R = \text{resistance} \\ X - \text{reactance} \end{array}\right\} [\Omega]$$

R: $Z_R = R$ pure real

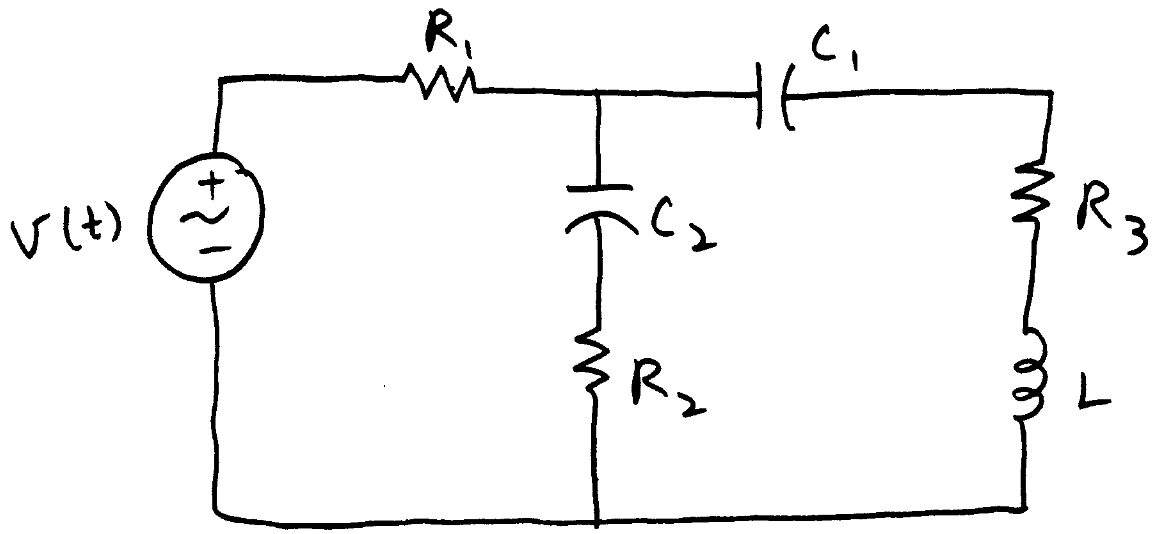
C: $Z_c = \frac{1}{j\omega C} = j X_c$ pure imag

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

$$\frac{1}{j} = -j \quad (-j^2 = 1)$$

L: $Z_L = j\omega L = jX_L \; ; \; X_L = \omega L$

Converting an AC circuit to its phasor equivalent



$$v(t) = 5 \cos(2000\pi t + 40°)$$

$V_m = 5$ V. $\omega = 2000\pi = 2\pi f$

$f = 1000$ Hz

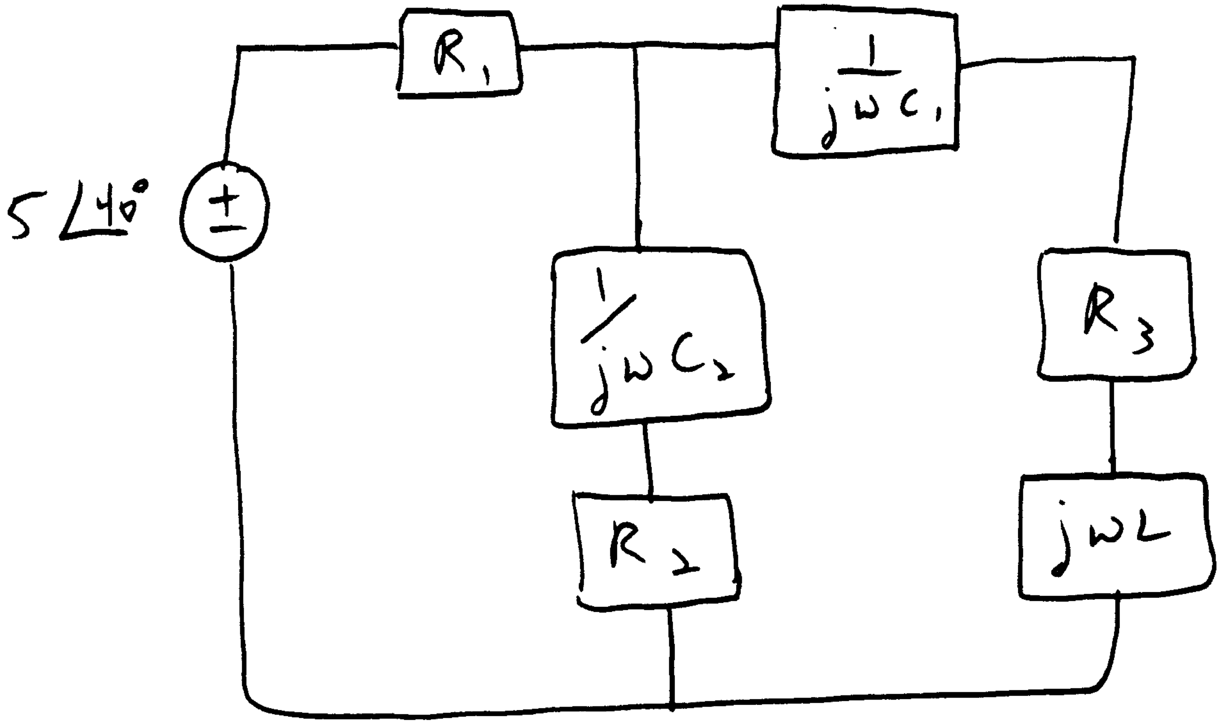
$\phi = 40°$

$$\mathbb{V} = 5 \angle 40°$$

$$Z_{C_1} = \frac{1}{j\omega C_1} \qquad Z_{C_2} = \frac{1}{j\omega C_2}$$

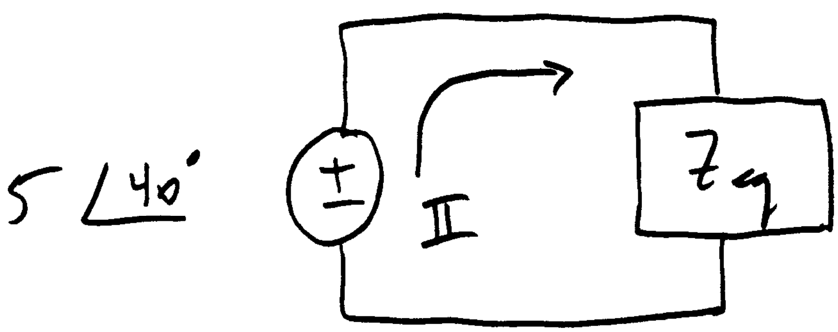
$$Z_L = j\omega L$$

Phasor equivalent circuit



$$Z_{sn} = \sum_{n=1}^{N} Z_n$$

$$Z_{pn} = \frac{1}{\sum_{n=1}^{N} \frac{1}{Z_n}}$$



$$\mathbb{V} = Z\,\mathbb{I}$$

$$\mathbb{I} = \frac{5\angle 40^\circ}{Z_{eq}}$$

Circuit Solution Techniques

Same as for DC, with phasors for V and I, impedance for resistance.

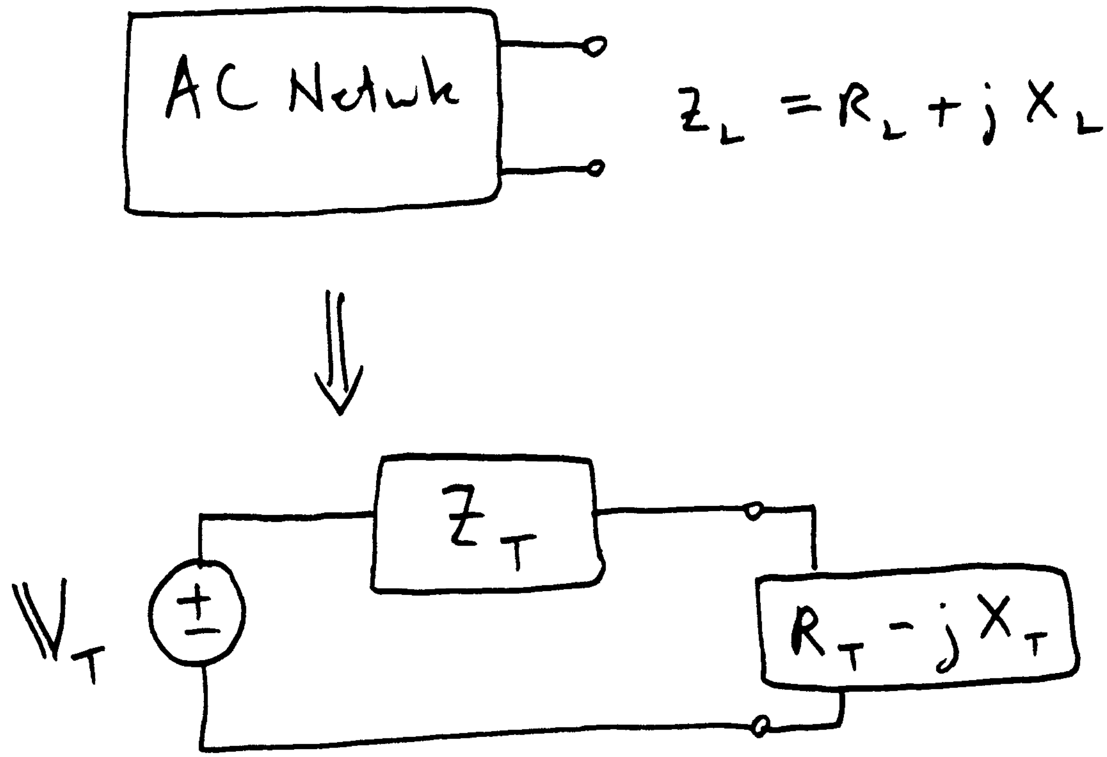
Loop current

Node voltages

Thevenin / Norton

Superposition

Maximum Power Transfer for AC circuit.



$$Z_T = R_T + jX_T$$

$$\underline{Z_L = R_T - jX_T}$$

$$Z_{eq} = 2R_T$$ (imaginary part is cancelled)

$$Z_L = Z_T^*$$

Complex Power

$$p(t) = v(t)\,i(t) \xrightarrow{\text{phasors}} S = \mathbb{V}_{eff}\,\mathbb{I}_{eff}^{*}$$

$$= P + jQ$$

P power

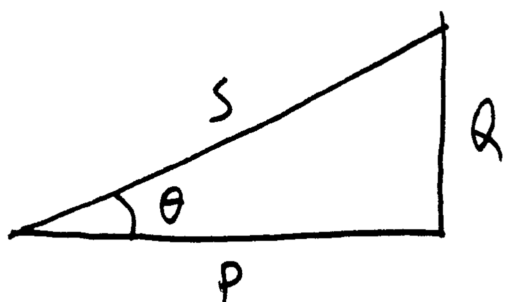
reactive power Q

Power Triangle, pf, rf

$S = [V \cdot A]$

$P = [\text{Watts}]$

$Q = [\text{VAR}]$



$\cos\theta \equiv pf$

$\sin\theta \equiv rf$

pf - power factor

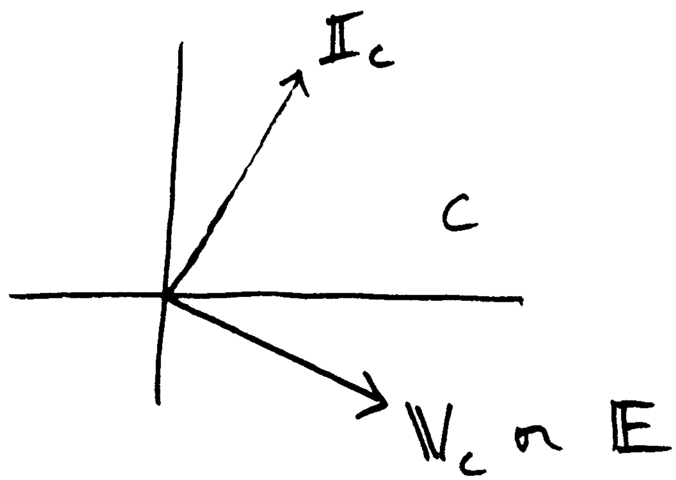
Leading and Lagging pf

Capacitor: $\mathbb{I}$ leads $\mathbb{V}$ by 90°

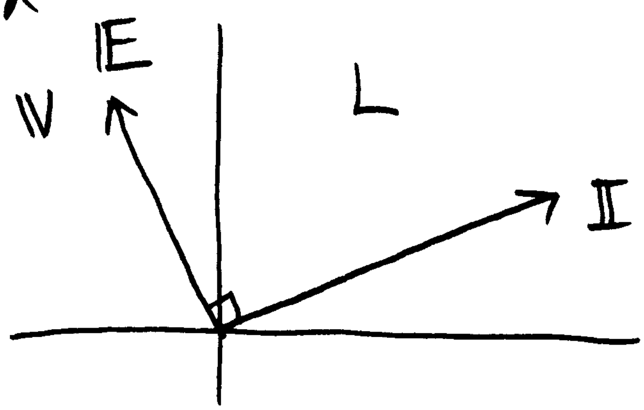
Inductor: $\mathbb{I}$ lags $\mathbb{V}$ by 90°

Phasor diagrams, <u>ELI the ICEman</u>

Cap

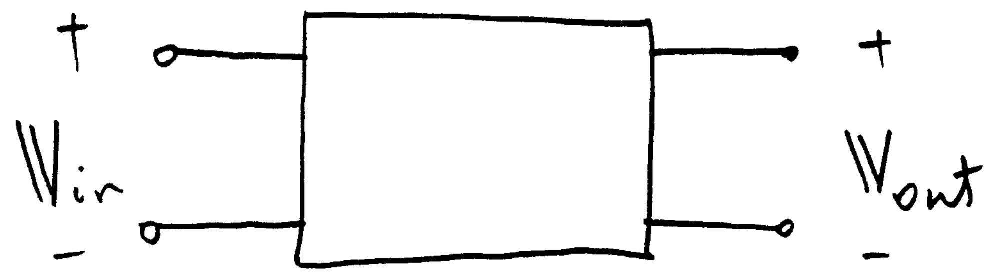


Ind



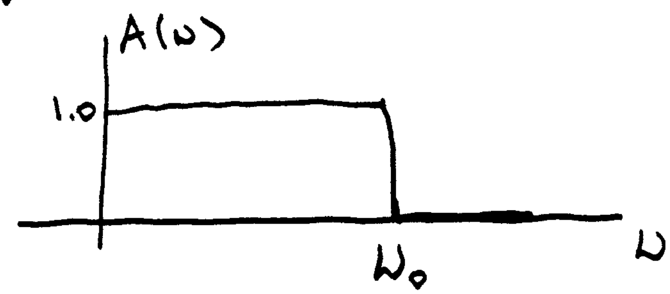
Frequency Response

$\mathbb{V}_{out}$ vs. $\mathbb{V}_{in}$ for various freq.



$$\frac{\mathbb{V}_{out}}{\mathbb{V}_{in}} \equiv A(\omega) \angle \phi(\omega)$$

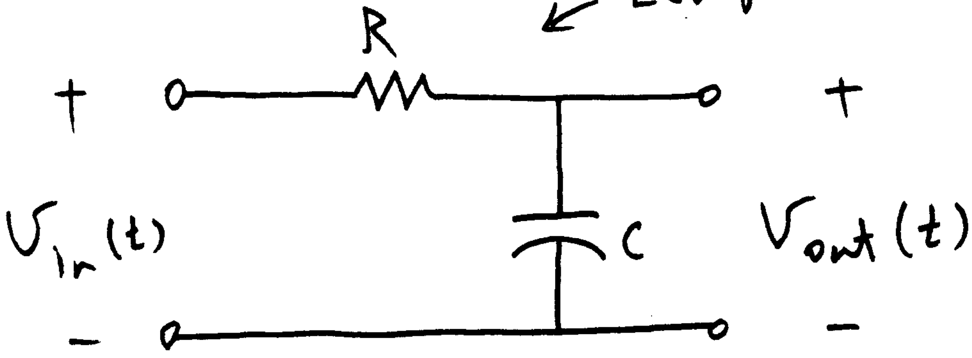
Lowpass (Ideal)

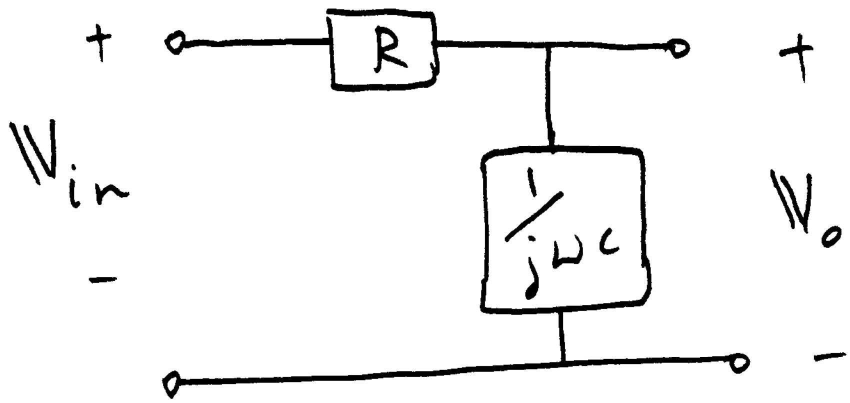


High pass (Ideal)

RC Filters

Low pass

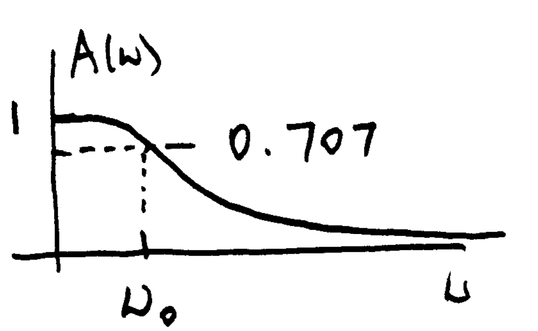


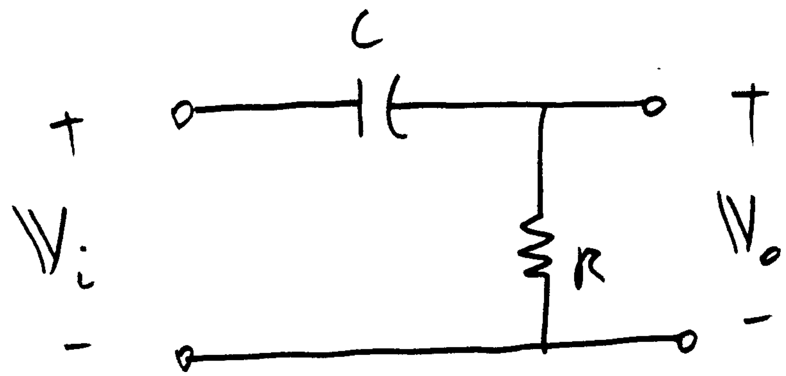


$$\mathbb{V}_o = \mathbb{V}_{in}\left(\frac{1/j\omega C}{1/j\omega C + R}\right)$$

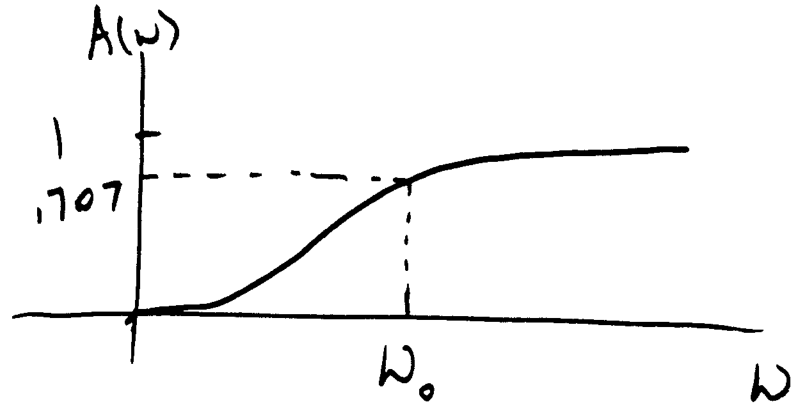
$$\frac{\mathbb{V}_o}{\mathbb{V}_{in}} = \frac{1}{1 + j\omega RC} \qquad \frac{1}{RC} \equiv \omega_o$$

$$= \frac{1}{1 + j\frac{\omega}{\omega_o}}$$



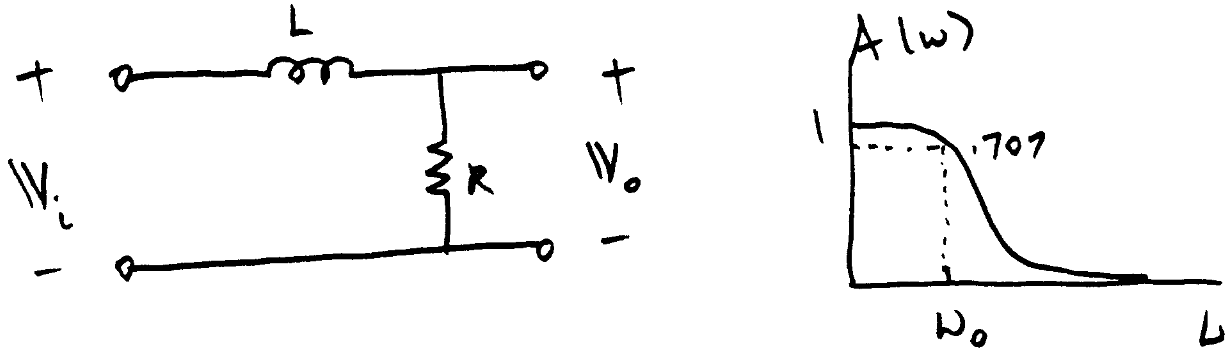


High pass

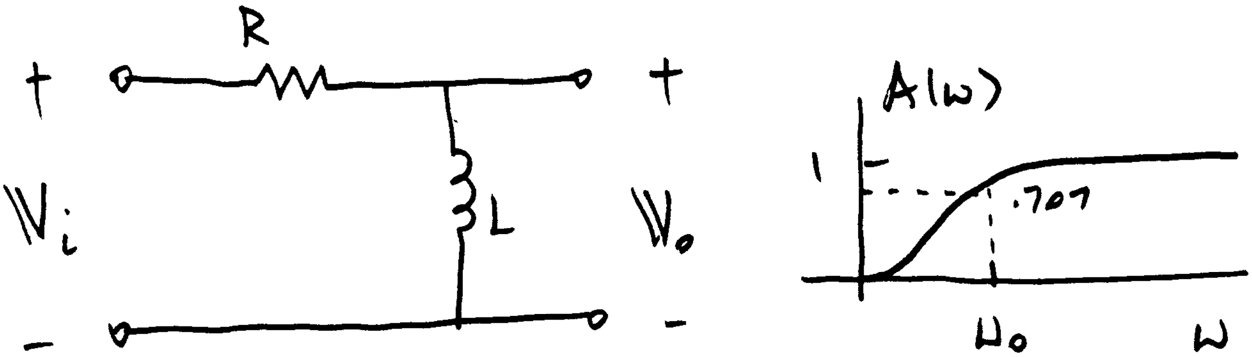


RL Filters

Low pass



High pass



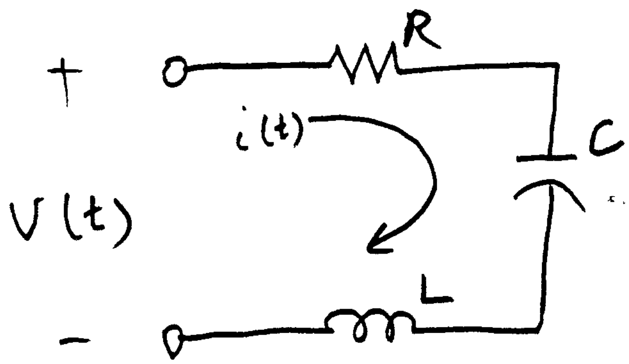
$$Z_L = j\omega L$$

$$Z_L(\omega = 0) = 0$$

$$Z_L(\omega \to \infty) \to \infty$$

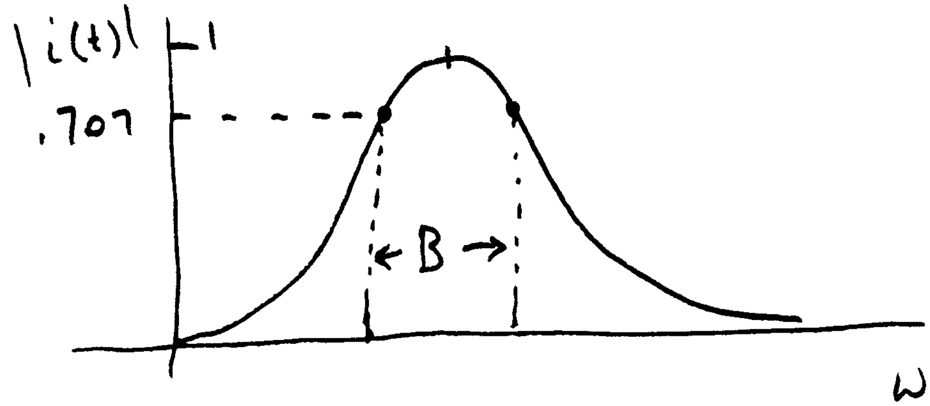
Recall $\tau = \frac{L}{R} \to \frac{R}{L} \equiv \omega_0$

RLC Filters and Resonance



$$Z_c = \frac{1}{j\omega L}$$

$$Z_L = j\omega L$$



$$Z_{eq} = R + j\omega L - j\frac{1}{\omega C}$$

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

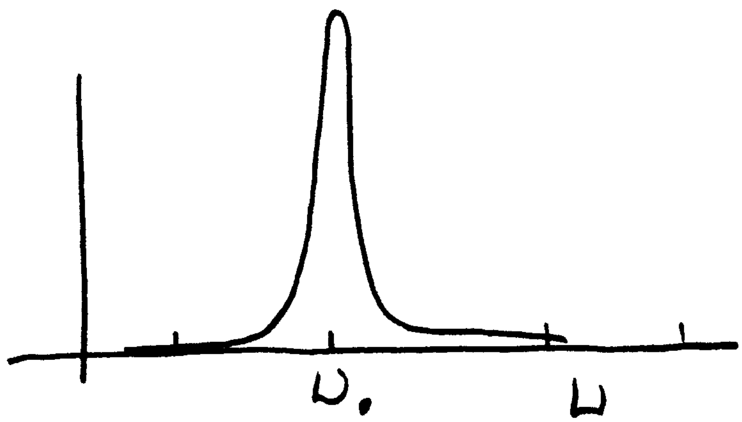
When $\omega_0 L = \frac{1}{\omega_0 C}$, $i(t)$ max.

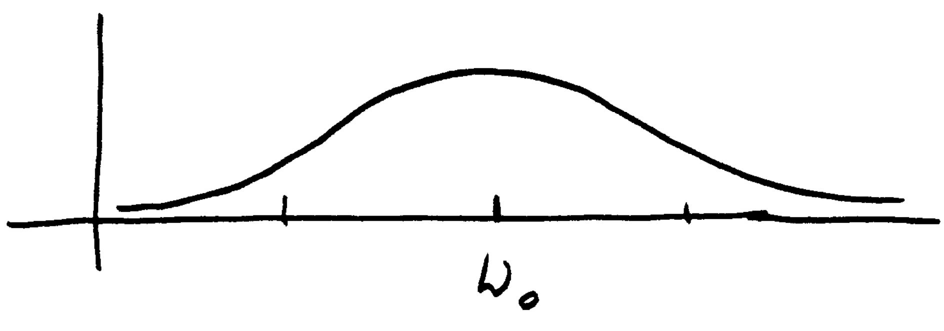
$$\omega_0 = \frac{1}{\sqrt{LC}} = \left[\mathrm{rad}/s\right]$$

Bandwidth B

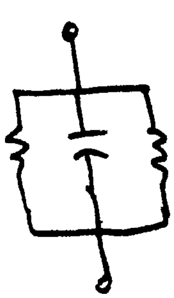
Resonant freq. ω_0

Quality factor $\quad Q = \dfrac{\omega_0}{B}$





Series res. $\quad Q = \dfrac{\omega_0 L}{R}$



Parallel $\quad Q = \omega_0 RC$

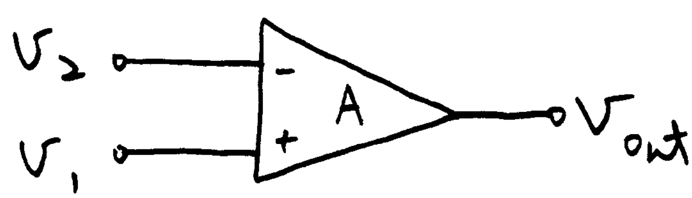
8. Op Amps

Operational Amplifier

amplifies signals

performs mathematical operations on signals

Circuit Symbol



$$v_{out} = A(v_1 - v_2)$$

Ideal Op Amp *

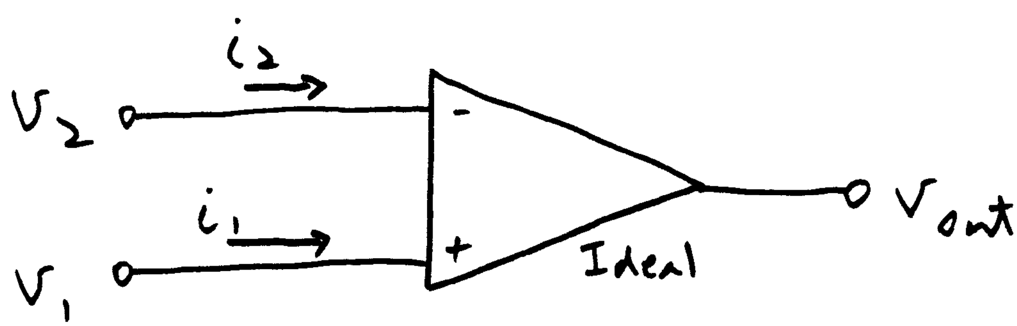
Let $A \to \infty$

$$(v_1 - v_2) = \frac{v_{out}}{A} \xrightarrow[A\to\infty]{} 0$$

So $\boxed{v_1 = v_2}$ *

Also (related limit)

$\boxed{i_1 = 0, \; i_2 = 0}$ *

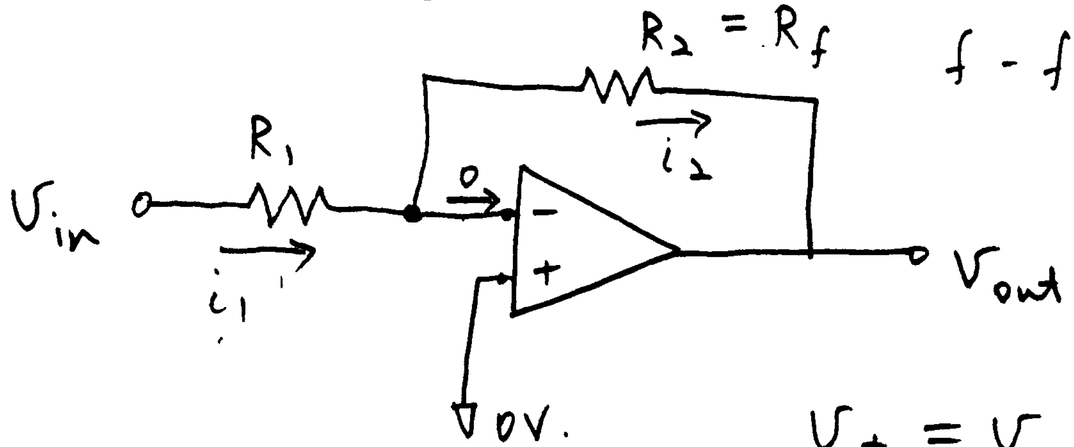


Relationships among inputs and output due to external resistors.

Op Amp Circuits

- Inverting Amp
- Non-inverting Amp
- Summing Amp
- Difference Amp
- Integrator
- Differentiator

Inverting Amp



f - feedback

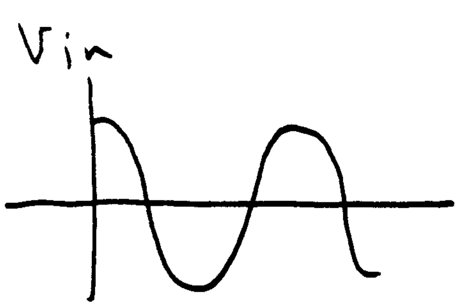
$$V_+ = V_-$$

KCL $\quad i_1 = 0 + i_2$

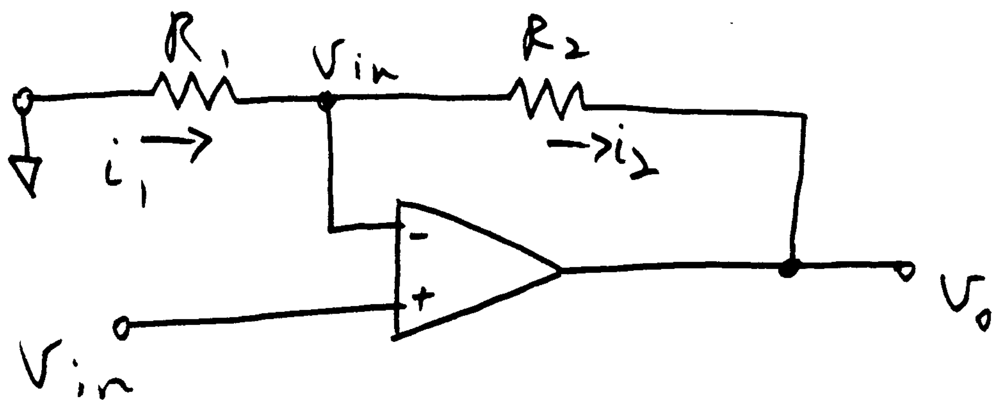
$$\frac{V_{in} - 0}{R_1} = \frac{0 - V_{out}}{R_2}$$

$$\boxed{V_{out} = -\frac{R_2}{R_1} V_{in}}$$

↑
inv.



Non-Inverting Amp

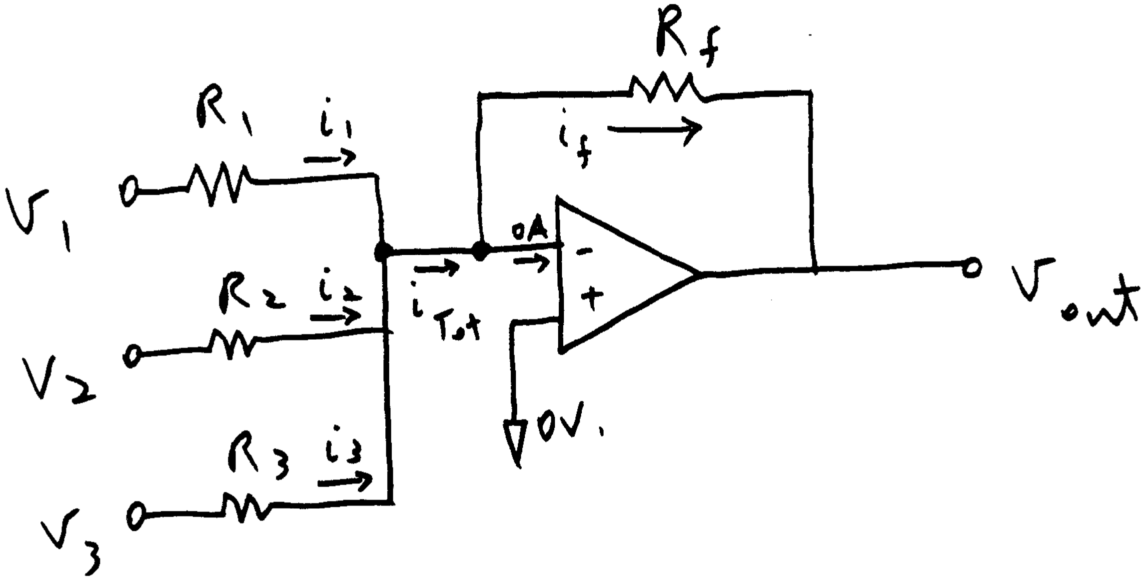


$$i_1 = i_2$$

$$\frac{0 - V_{in}}{R_1} = \frac{V_{in} - V_o}{R_2}$$

$$V_o = \left(1 + \frac{R_2}{R_1}\right) V_{in}$$

Summing Amp



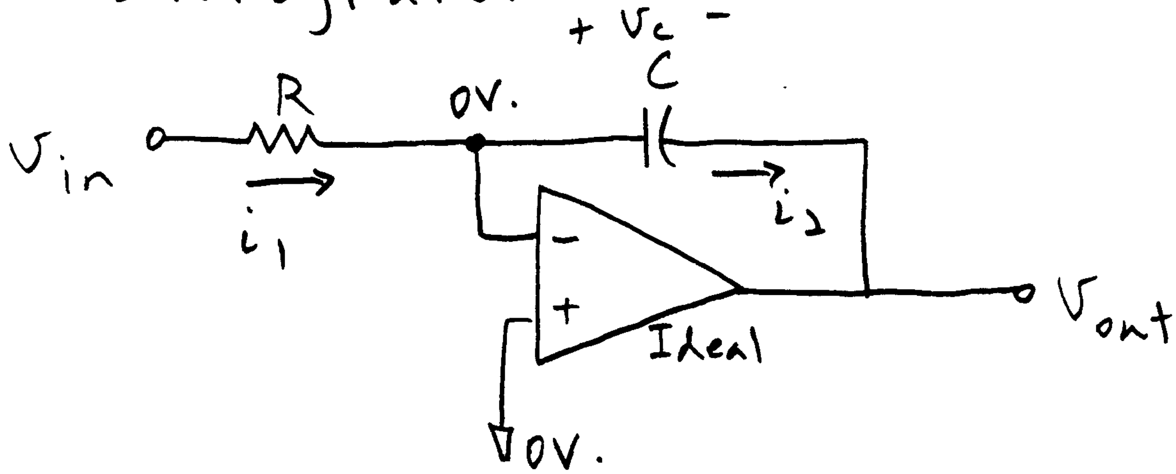
$$i_{Tot} = i_f$$

$$\frac{V_1 - 0}{R_1} + \frac{V_2 - 0}{R_2} + \frac{V_3 - 0}{R_3} = \frac{0 - V_{out}}{R_f}$$

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

- output is a weighted sum of the inputs.
- easily extended to more inputs

Integrator



$$i_1 = i_2$$

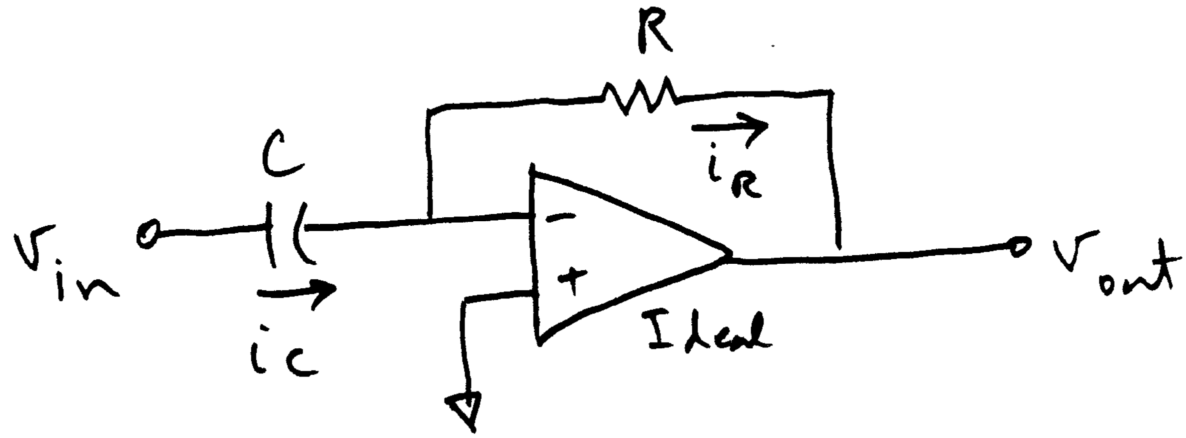
$$\frac{V_{in} - 0}{R} = C \frac{d}{dt} V_c$$

$$= C \frac{d}{dt}(0 - V_{out})$$

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

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

Differentiator



$$i_C = i_R$$

$$C \frac{d}{dt}(v_{in} - 0) = \frac{0 - v_{out}}{R}$$

$$v_{out} = -RC\frac{dv_{in}}{dt}$$

References

[1] NCEES FE Discipline Specific Reference Handbook

[2] EIT Review Manual, by Michael R. Lindeburg, PE

[3] Principles and Applications of Electrical Engineering, by Giorgio Rizzoni