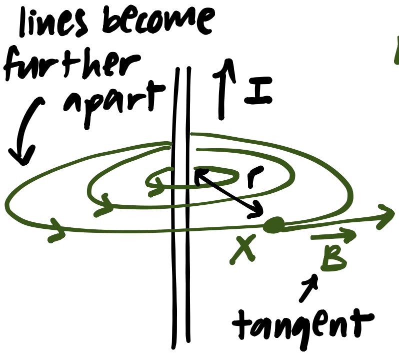
# MAGNETIC FIELD DUE TO CURRENT-CARRYING CONDUCTORS







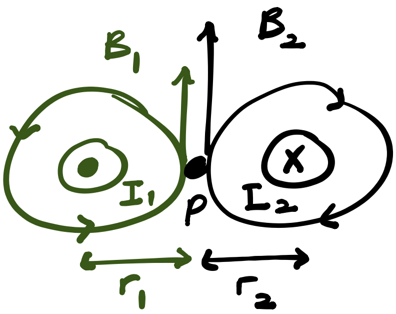
Right-Hand Rule

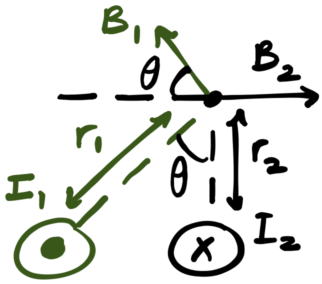
$B \propto I$ $\quad B \propto \frac{1}{r}$

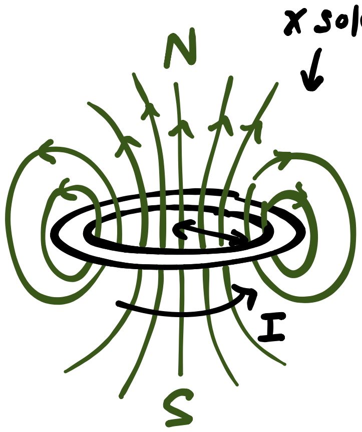
$$\boxed{B = \frac{\mu_0 I}{2\pi r}}$$

permeability of free space $= 4\pi \times 10^{-7}\ Hm^{-1}$

* Magnetic field due to a current
  * in a very long straight wire
  * in a circular arc of wire
* Forces between two parallel current-carrying wires
* Magnetic field due to a solenoid
* Ferromagnetism
* Electromagnet



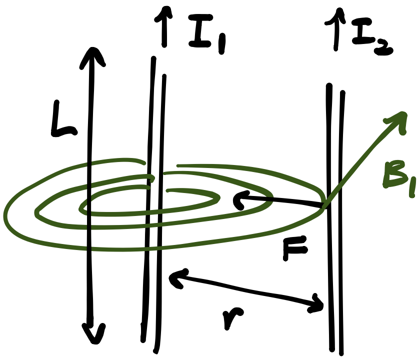




number of turns

$$\boxed{B = \frac{\mu_0 N I}{2r}}$$


Right-Hand Rule

$\Sigma B = B_1 + B_2$

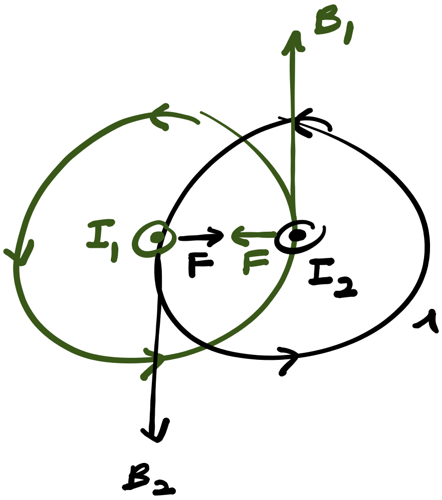


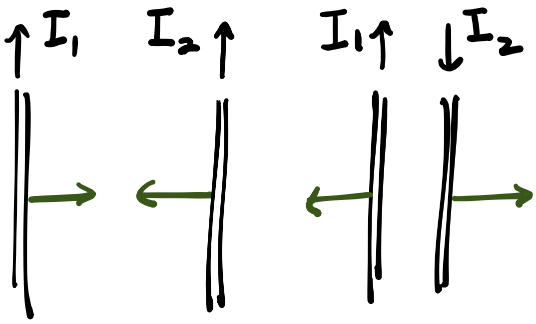

$B_1 = \frac{\mu_0 I_1}{2\pi r} \longrightarrow$ ①

magnetic field due to $I_1$

$F = I_2 L B_1 \longrightarrow$ ②

force on $I_2$ due to $B_1$




Attractive Force

Repulsive Force

① & ②

$$F = \frac{\mu_0 I_1 I_2}{2\pi r} L$$

Force per unit length

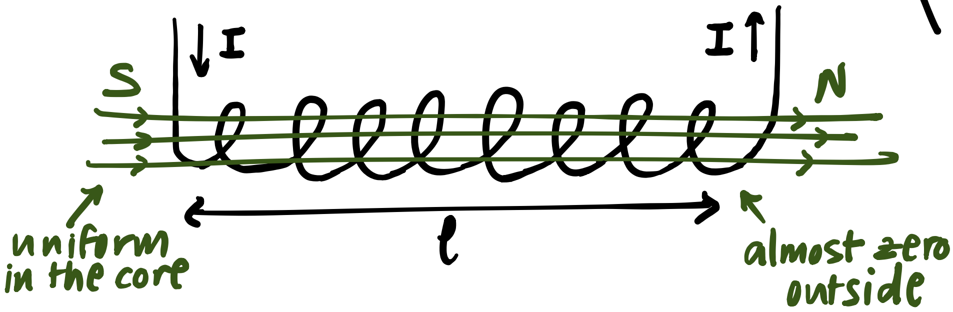
$$\boxed{\frac{F}{l} = \frac{\mu_0 I_1 I_2}{2\pi r}}$$

Solenoid

$$\boxed{B = \mu_0 n I}$$

$n = \frac{N}{l}$ number of turns

independent of area and shape



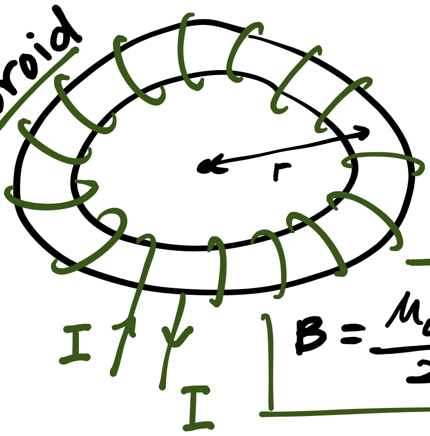

$$\boxed{B = \mu_0 \mu_r n I}$$

ferromagnetic material

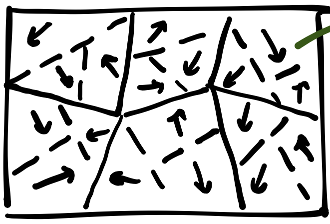
* nickel
* iron
* cobalt

# Ferromagnetism

## Toroid

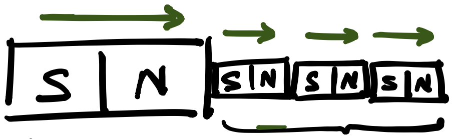



$$\boxed{B = \frac{\mu_0 N I}{2\pi r}}$$



domain (elementary magnet)

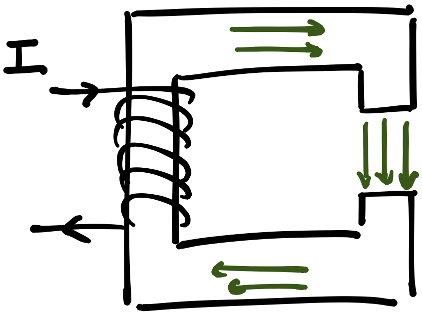
$B_0 + B$

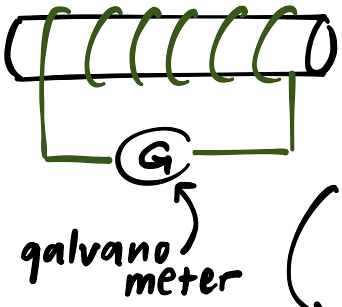



external magnetic field

ferromagnetic material

## Electro-magnet



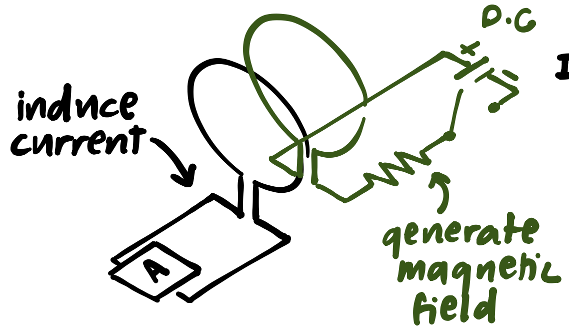


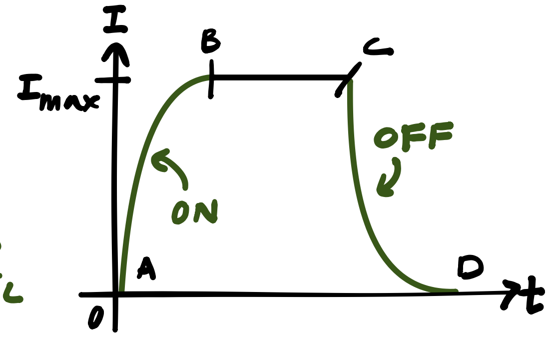

+ve ← | N | S | → −ve
increasing — magnetic field — decreasing

changing magnetic field → induce → e.m.f
relative motion between the coil & magnetic field

- Electromagnetic induction
- Faraday's Law of induction
- Lenz's Law
- Induced e.m.f. in a coil located in a magnetic field
- E.m.f. induced in a moving conductor
- Eddy currents

↑ induced current, if
- ↑ magnet strength
- ↑ speed
- ↑ area of coil
- ↑ number of turns




## Faraday's Law of Induction

$$\boxed{\mathcal{E} = -\frac{d\phi}{dt}}$$

against the change

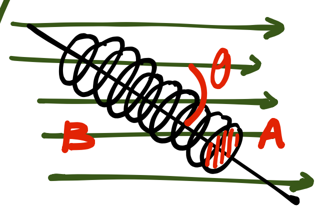
AB: $\frac{dI}{dt} > 0$ — current induced, $\frac{dB}{dt} > 0$

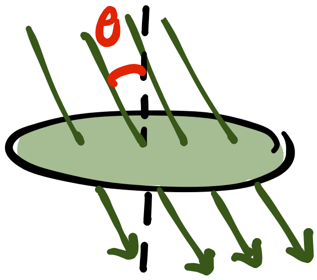
BC: $\frac{dI}{dt} = 0$ — no induced current

BD: $\frac{dI}{dt} < 0$ — current induced, $\frac{dB}{dt} < 0$

magnetic flux: $\phi = BA\cos\theta$

flux linkage: $\phi = NBA\cos\theta$




$\mathcal{E} \propto \frac{dB}{dt}$

$\mathcal{E} \propto \frac{dI}{dt}$

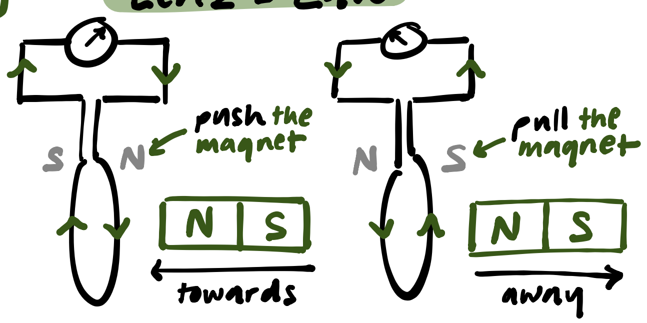
$\mathcal{E} \propto \frac{d\phi}{dt}$

$B \propto I$

$$\therefore \mathcal{E} = -\frac{Nd(BA\cos\theta)}{dt}$$

$\phi = BA \Rightarrow \phi \propto I$

## Lenz's Law




**Changing B**

$$-A\cos\theta\frac{dB}{dt}$$

**Changing A**

$$-B\cos\theta\frac{dA}{dt}$$

**Changing θ**

$$-BA\frac{d(\cos\theta)}{dt}$$

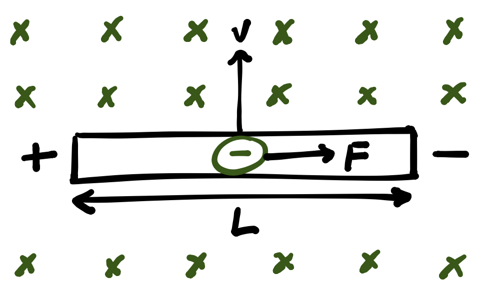
$$BA\sin\theta \cdot \frac{d\theta}{dt}$$

$$BA\omega\sin(\omega t)$$

ω — angular velocity

$y = \cos\theta$

$$\frac{dy}{dt} = \frac{dy}{d\theta} \times \frac{d\theta}{dt}$$



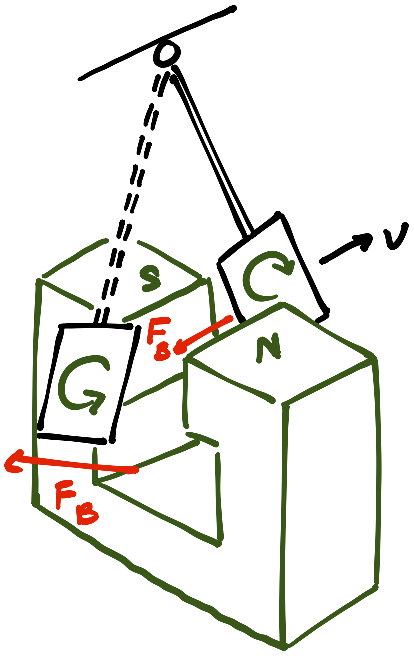

## E.M.F Induced in a Moving Conductor

$$\boxed{\mathcal{E} = BLv}$$

$$\mathcal{E} = \left|-\frac{d\phi}{dt}\right| = \frac{d(BA)}{dt} = BL\frac{dx}{dt}$$

$$\mathcal{E} = BLv$$

# EDDY CURRENTS

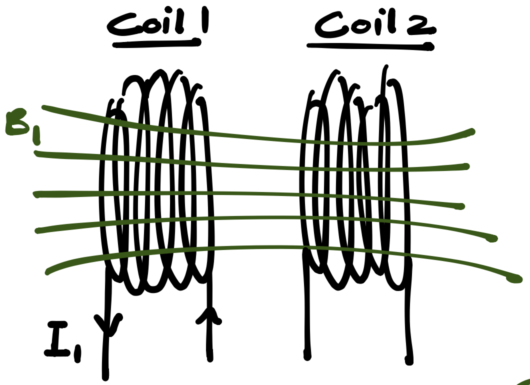



$\frac{dB}{dt} > 0$ when pendulum enters magnetic field

$\frac{dI}{dt} > 0 \Rightarrow$ eddy current

interaction between the eddy current and magnetic field $\Rightarrow F_B$

- Mutual inductance
- Self-inductance
- Storage and release process of an inductor
- Energy in a magnetic field
- RL circuits VS RC circuits




$$\frac{dI}{dt} \neq 0 \qquad \frac{d\phi}{dt} \neq 0$$

$$\frac{dB}{dt} \neq 0 \Rightarrow \mathcal{E} \neq 0$$

$$\mathcal{E}_2 \propto -\frac{\Delta I_1}{\Delta t}$$

(1) $$\boxed{\mathcal{E}_2 = -M\frac{\Delta I_1}{\Delta t}}$$

mutual inductance — $\mu_r$, $A$, $N$

(2) $$\mathcal{E}_2 = -N_2\frac{\Delta \phi}{\Delta t}$$

From 1 and 2:

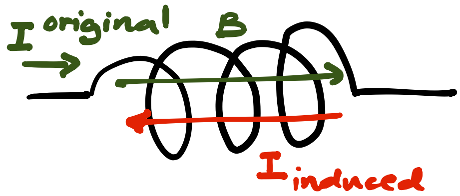
$$\boxed{M = N_2\frac{\Delta \phi}{\Delta I_1}}$$

$$M = N_2\frac{(\Delta B)A}{\Delta I_1}$$

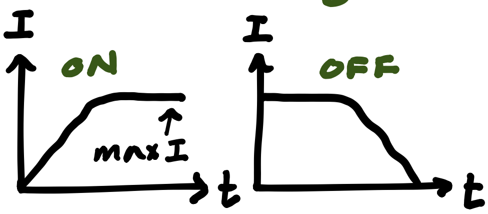
$$= N_2\frac{\mu_0 N_1 \Delta I_1}{l}\frac{A}{\Delta I_1}$$

$$\boxed{M = \frac{\mu_0 N_1 N_2 A}{l}}$$

## Self Inductance




$I_{induced} < I_{original}$




$\frac{dI}{dt}$ is reduced $\Rightarrow \mathcal{E}$ is reduced

self inductance — $\mu_r$, $A$, $N$

$$\boxed{\mathcal{E} = -L\frac{\Delta I}{\Delta t}}$$

$$-L\frac{\Delta I}{\Delta t} = -N\frac{\Delta \phi}{\Delta t}$$

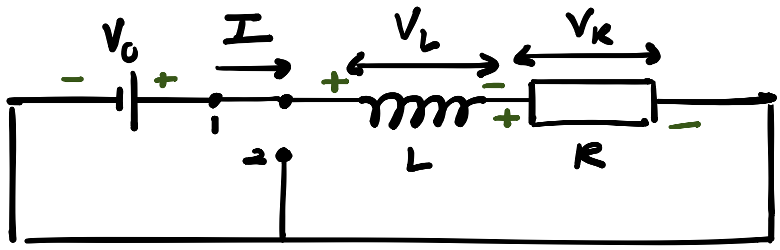
$$\boxed{L = N\frac{\Delta \phi}{\Delta I}}$$

$$\boxed{L = \frac{\mu_0 N^2 A}{l}}$$

INDUCTANCE

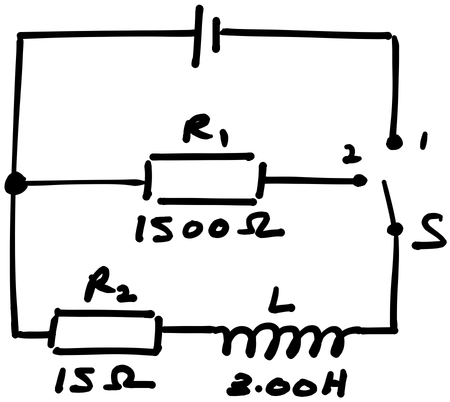
unit: H

## Storage Process



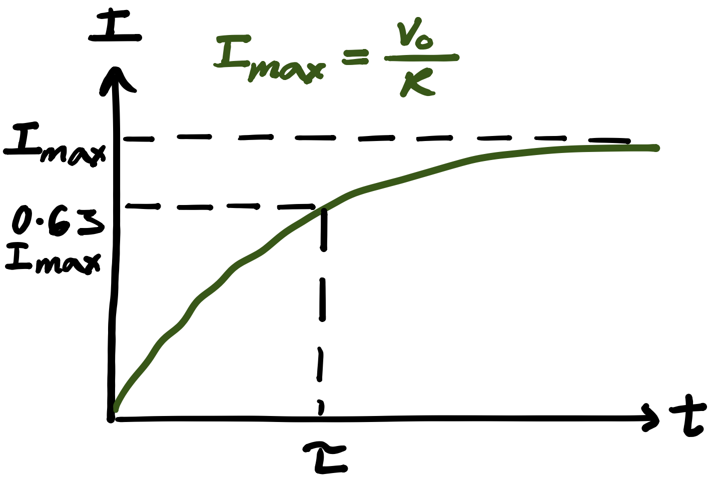

| | $I$ | $V_L$ | $V_R$ |
|---|---|---|---|
| switch 1 $t=0$ | $I=0$, $\frac{dI}{dt}=max$ | $V_L = L\frac{dI}{dt}$, $V_L = max$ | $I=0$, $V_R=0$ |
| $t=t_1$ | $I\uparrow$, $\frac{dI}{dt}\downarrow$ | $V_L\downarrow$ | $V_R\uparrow$ |
| $t=t_2$ | $I=max$, $\frac{dI}{dt}=0$ | $V_L=0$ | $V_R=max$ |

$V_0 = 18V$



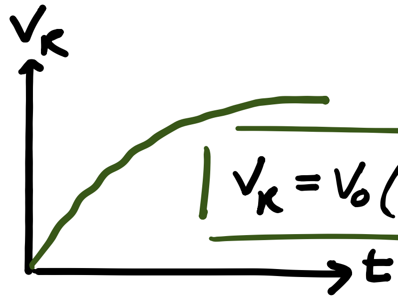

(1) $I = \frac{V_0}{R_2} = 1.2A$

(2) $V_1 = IR_1 = 1750V$

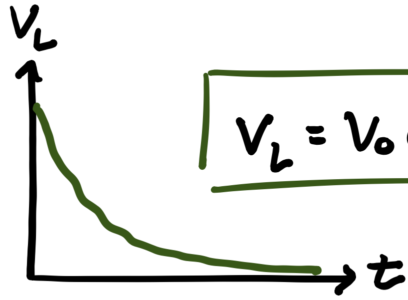



$I_{max} = \frac{V_0}{R}$

$$\boxed{I = \left(\frac{V_0}{R}\right)\left(1 - e^{-\frac{t}{\tau}}\right)}$$



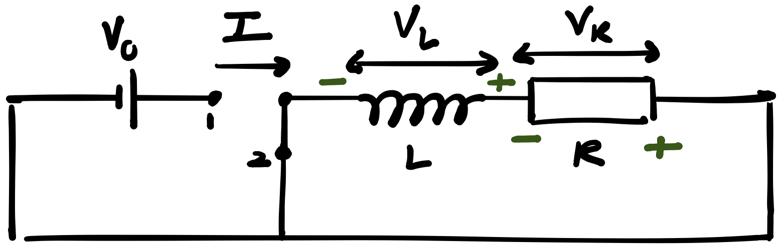

$$\boxed{V_R = V_0\left(1 - e^{-\frac{t}{\tau}}\right)}$$




$$\boxed{V_L = V_0 e^{-\frac{t}{\tau}}}$$

$\tau = \frac{L}{R} =$ t when I is 63% of $I_{max}$

## Release Process




| | I | $V_L$ | $V_R$ |
|---|---|---|---|
| switch 2 → $t=0$ | $I = max$, $\frac{dI}{dt} = max$ | $V_L = L\frac{dI}{dt}$, $V_L = max$ | $I = max$, $V_R = max$ |
| $t = t_1$ | $I\downarrow$, $\frac{dI}{dt}\downarrow$ | $V_L\downarrow$ | $V_R\downarrow$ |
| $t = t_2$ | $I = 0$, $\frac{dI}{dt} = 0$ | $V_L = 0$ | $V_R = 0$ |

$$\boxed{\begin{aligned} I &= I_{max} e^{-\frac{t}{\tau}} \\ V_R &= V_0 e^{-\frac{t}{\tau}} \\ V_L &= V_0 e^{-\frac{t}{\tau}} \end{aligned}}$$

$\tau =$ t when I is 37% of $I_{max}$

## ENERGY IN MAGNETIC FIELD

$V_0 = V_L + V_R \rightarrow V_0 = L\frac{dI}{dt} + IR$

$V_0 - L\frac{dI}{dt} - IR = 0$

$P = VI \rightarrow IV_0 - LI\frac{dI}{dt} - I^2R = 0$

$P = \frac{U}{t} \rightarrow \frac{dU}{dt} = LI\frac{dI}{dt}$

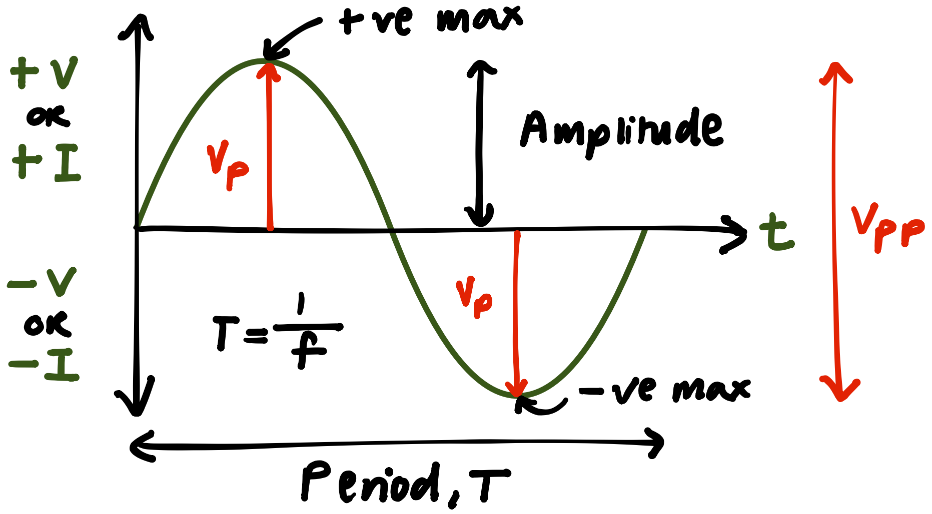
$U = Pt \rightarrow U = \int_0^I LI\,dI$

$$\boxed{U = \frac{1}{2}LI^2}$$

## RC Circuits vs RL Circuits

| RC Circuits | | RL Circuits |
|---|---|---|
| $\tau = RC$ | | $\tau = \frac{L}{R}$ |
| $I = I_{max}e^{-\frac{t}{\tau}}$ | I | $I = I_{max}\left(1 - e^{-\frac{t}{\tau}}\right)$ <br> $I = I_{max}e^{-\frac{t}{\tau}}$ |
| $V_R = V_0e^{-\frac{t}{\tau}}$ | $V_R$ | $V_R = V_0\left(1 - e^{-\frac{t}{\tau}}\right)$ <br> $V_R = V_0e^{-\frac{t}{\tau}}$ |
| $V_C = V_0\left(1 - e^{-\frac{t}{\tau}}\right)$ <br> $V_C = V_0e^{-\frac{t}{\tau}}$ | $V_C/V_L$ | $V_L = V_0e^{-\frac{t}{\tau}}$ |
| $Q = Q_0\left(1 - e^{-\frac{t}{\tau}}\right)$ <br> $Q = Q_0e^{-\frac{t}{\tau}}$ | Q | |

$\tau = RC =$ t when I increases to 63% or decreases to 37%




- The sine wave
- The sine wave formula
- Transformers
- Rectification
- Half-wave rectification
- Full-wave rectification
- Smoothing circuits

- Peak Value, $V_p$
- Peak-to-Peak Value, $V_{pp}$

Instantaneous Value

$t_1 = V_1$

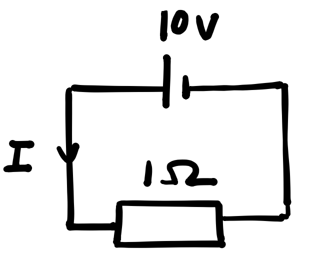
## Root Mean Square

r.m.s

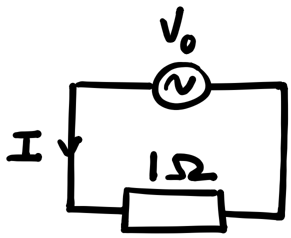
= effective value

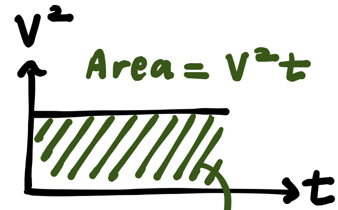
$$\boxed{\begin{gathered} P_{AC} = P_{DC} \\ (I_{rms})(V_{rms}) = IV \end{gathered}}$$

D.C. Circuit



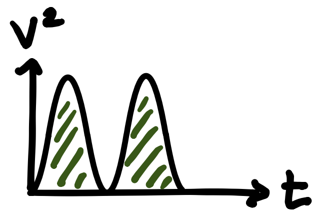

A.C. Circuit




$E = \frac{V^2}{\underline{R}} t$

constant




$V_0 = \sqrt{2}(V_{rms})$

$V_0 = \sqrt{2}(10)$

$V_0 = 14.14\,V$

only for sine function,

$$\boxed{V_{rms} = \frac{V_p}{\sqrt{2}}, \quad I_{rms} = \frac{I_p}{\sqrt{2}}}$$

$$(V_{rms})^2 = \frac{\int_0^T V^2 dt}{T}$$

area under graph

average

$$= \frac{1}{T}\int_0^T \underline{V_0^2 \sin^2(\omega t)}\,dt$$

$V = V_0 \sin\theta$

$$V_{rms} = \frac{V_0}{\sqrt{2}}$$

## Average Value

$$\boxed{\begin{gathered} V_{avg} = \frac{2}{\pi} V_p \\ I_{avg} = \frac{2}{\pi} I_p \end{gathered}}$$

only for sine wave

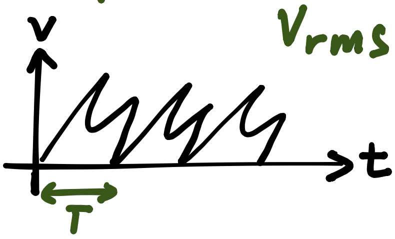
min operational value

- area under half cycle

## Special Waveforms


$$V_{avg} = \frac{\text{area in 1 cycle}}{\text{period}}$$

consider +ve & −ve




$$V_{rms} = \sqrt{\frac{\text{area}}{\text{period}}}$$

$x \cdot y^2$

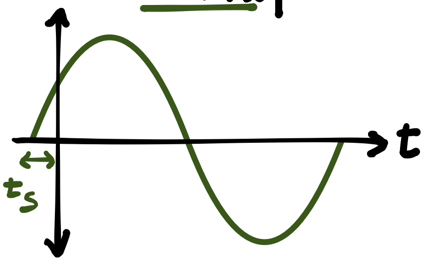
## Instantaneous Voltage

$V = V_p \sin\theta$

$$\boxed{V = V_p \sin(\underline{\omega} t)}$$

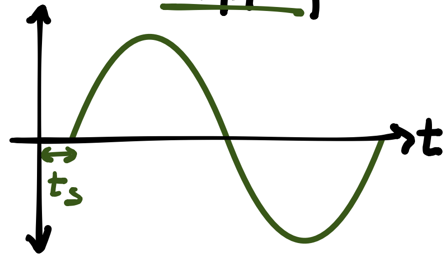
$\omega = 2\pi f$

### Leading




$V = V_p \sin(\omega t + \phi)$

### Lagging

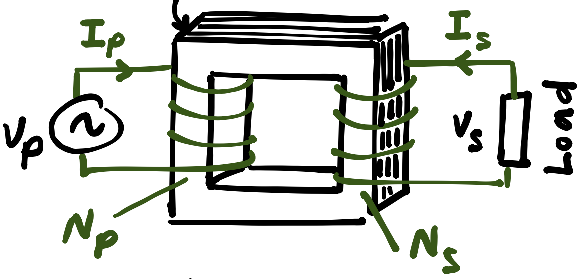



$V = V_p \sin(\omega t - \phi)$

$\phi = (2\pi f) t_s$ radians

phase shift

## TRANSFORMER




- same frequency
- phase difference of $\pi$ or $180°$

$N_s > N_p$ : step up

$N_p > N_s$ : step down

$$\frac{V_s}{V_p} = \frac{N_s A \frac{dB}{dt}}{N_p A \frac{dB}{dt}}$$

100% efficiency

$$\boxed{\frac{V_s}{V_p} = \frac{N_s}{N_p}}$$

$\frac{\text{secondary}}{\text{primary}}$

Turns-Ratio Equation

$P_p = P_s$

$V_p I_p = V_s I_s$

$$\boxed{\frac{V_s}{V_p} = \frac{I_p}{I_s}}$$

$$\boxed{\frac{V_s}{V_p} = \frac{N_s}{N_p} = \frac{I_p}{I_s}}$$

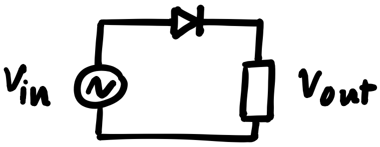
Efficiency ≠ 100%

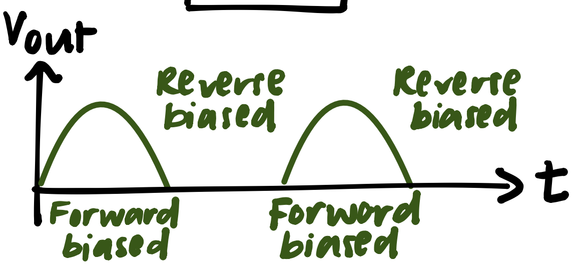
- resistance in coils
- eddy currents
- hysteresis
- flux leakage

* Efficiency affects the current only

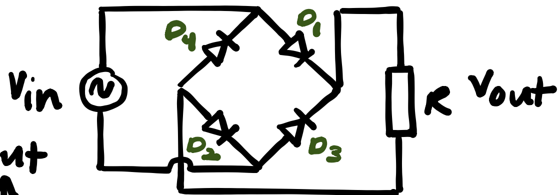
## RECTIFICATION

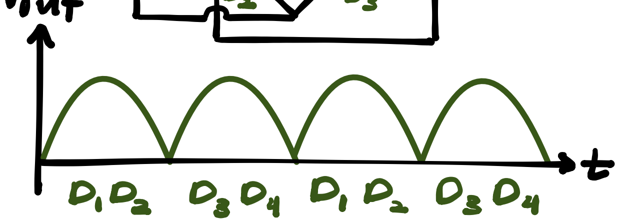
### Half-wave



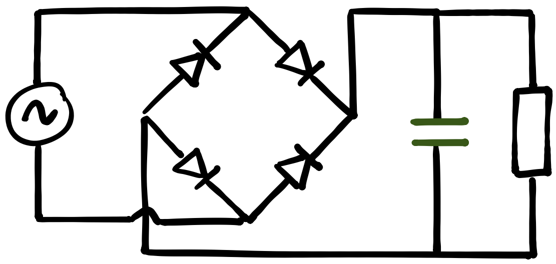



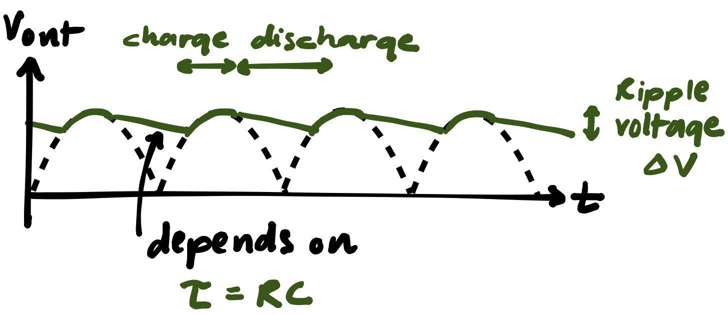

### Full-wave

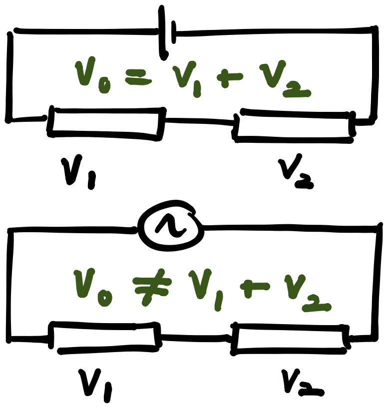



## Smoothing Circuits





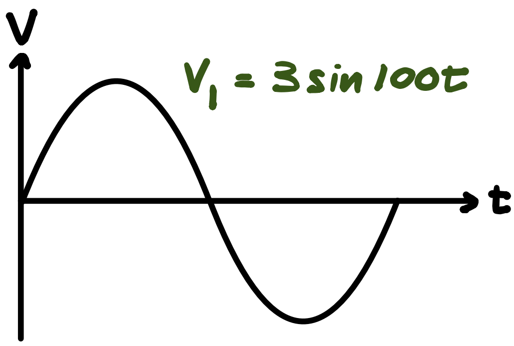


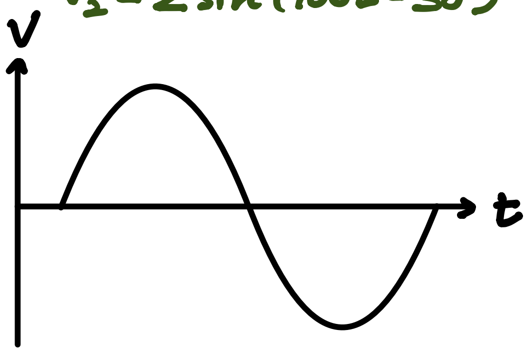

## PHASOR

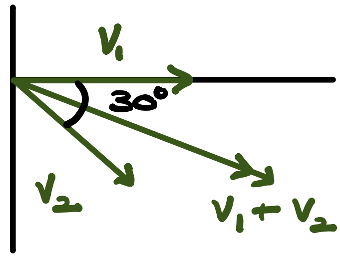
$$\boxed{V = V_p \sin\theta}$$

- counter clockwise
- 1 complete rev
- vertical component = instantaneous V

* Phasors
* Resistor, capacitor, and inductor in a.c. circuits
* Impedance
* RC circuits
* LR circuits

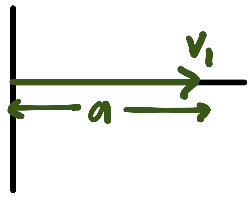


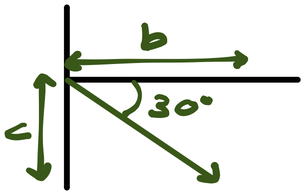




$V = 4.82\sin(100t - 11.97°)$

$V_1 = 3\angle 0°$ $\qquad$ $V_2 = 2\angle -30°$



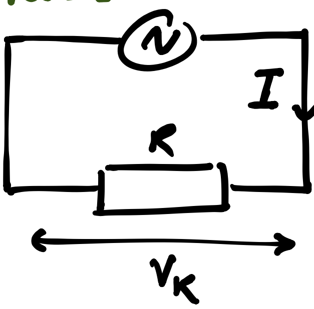

$V = V_1 + V_2$
$= a + (b - jc)$
$V = (a + b) - jc$

$V_1 = a$
$V_1 = a\angle 0°$
* $j = 0$

$V_2 = b + j(-c)$
$= b - jc$
$V_2 = \sqrt{b^2 + c^2}\angle -30°$

$V = 3\angle 0° + 2\angle -30°$
$V = 4.837\angle -11.93°$
$V = 4.837\sin(100t - 11.93°)$

## Resistor



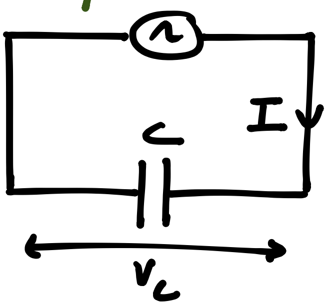

$V_R \angle 0°$
$R\angle 0°$
$I\angle 0°$
R

$V_R = V_0\sin(\omega t)$

$I = \frac{V_R}{R}$

$$\boxed{I = I_0\sin(\omega t)}$$

## Capacitor




$V_C \angle 0°$
$X_C \angle -90°$
$I_0 \angle 90°$
$-jX_C$

$V_C = V_0\sin(\omega t)$

$Q = CV$

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

$$\boxed{I = \omega \cdot C V_0 \cos(\omega t)}$$

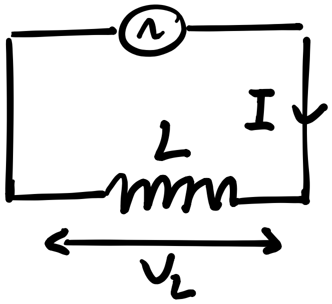
$V = IR$

$V_0\cos(\omega t) = I\left(\frac{1}{\omega C}\right)$

$X_C$, capacitive reactance

$$\boxed{X_C = \frac{1}{2\pi f C}}$$

## Inductor




$V_L \angle 0^\circ$

$X_L \angle 90^\circ$ ↶ $+jX_L$

$I \angle -90^\circ$

$V_L = V_0 \sin(\omega t)$

$V_L = L\frac{dI}{dt}$

$$\boxed{I = -\left(\frac{1}{\omega L}\right) V_0 \cos(\omega t)}$$

$V = IR$

$V_0 \cos(\omega t) = I(\omega L)$

$X_{L,C}$ inductive / capacitance

$$\boxed{X_L = 2\pi f L}$$

## IMPEDANCE Ω

(total resistance)

$Z = R + X_L + X_C$

if $Im(Z) > 1$, circuit is inductive, current is lagging

if $Im(Z) < 1$, circuit is capacitive, current is leading

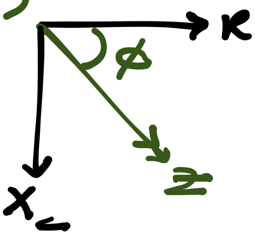
1. identify $\omega = 2\pi f$
2. identify $\phi$

## RC Circuit (Series)

$Z = R + X_C$

$= R + (-jX_C)$

$Z = R - \frac{j}{\omega C}$



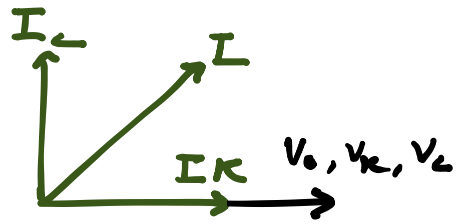

$Z = \sqrt{R^2 + X_C^2} \angle \tan^{-1}\left(-\frac{X_C}{R}\right)$

$V_0 = \sqrt{V_R^2 + V_C^2} \angle \tan^{-1}\left(-\frac{V_C}{V_R}\right)$

$V_R = IR$, $V_C = IX_C$, $V_0 = IZ$

## RC Circuit (Parallel)

$V_0 = V_C = V_R$



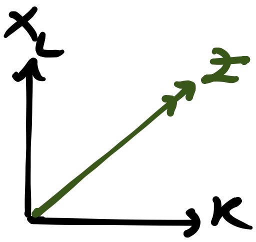

$f\uparrow$, $X_C\downarrow$, $Z\downarrow$, $\phi\downarrow$

## LR Circuit (Series)

$Z = R + X_L$

$= R + jX_L$

$Z = R + j\omega L$



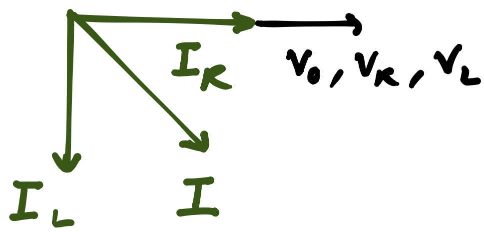

$Z = \sqrt{R^2 + X_L^2} \angle \tan^{-1}\left(\frac{X_L}{R}\right)$

$V_0 = \sqrt{V_R^2 + V_L^2} \angle \tan^{-1}\left(\frac{V_L}{V_R}\right)$

$f\uparrow$, $X_L\uparrow$, $Z\uparrow$, $\phi\uparrow$

## LR Circuit (Parallel)

$V_0 = V_L = V_R$



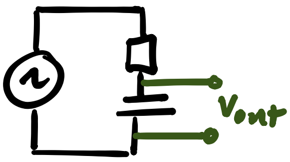
* Filters
* LRC circuits
* Series resonance
* Power in passive components (a.c.)
* Power in RC circuits
* Power in LR circuits

**Filter** – pass/reject frequencies

**Active**
- transistors
- amplifiers

**Passive**
R, L, and C

## RC low pass

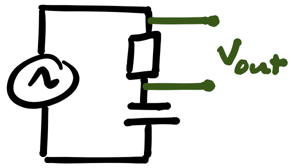



$X_C \propto \frac{1}{f}$

low $f$, $X_C \to \infty$

$V_{out} = V_{in}$

## RC high pass




$X_C \propto \frac{1}{f}$

high $f$, $X_C \to 0$

$V_C \to 0$

$V_{out} = V_{in}$

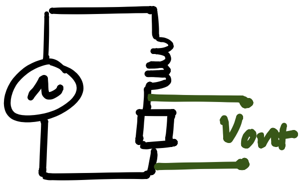
critical frequency

$f_c$

$X_C = R$

$f_c = \frac{1}{2\pi C R}$

## RL low pass




$X_L \propto f$

high $f$, $X_L \to 0$

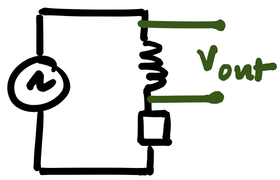
$V_L \to 0$

$V_{out} = V_{in}$

$X_L = R$

$f_c = \frac{2\pi L}{R}$

## RL high pass

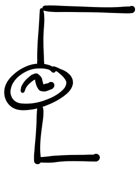



$X_L \propto f$

high $f$, $X_L \to \infty$

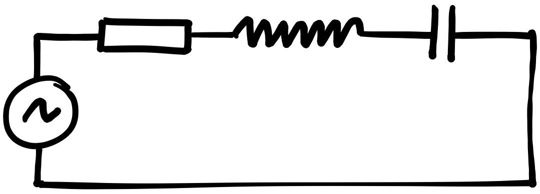
$V_{out} = V_{in}$

## Pass-Band Filter



## Stop-Band Filter

## LRC Circuit



$X_C > X_L$ (low $f$) capacitive

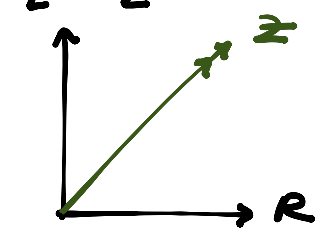
$X_L > X_C$ (high $f$) inductive

$X_L = X_C$ ($f_r$) resistive

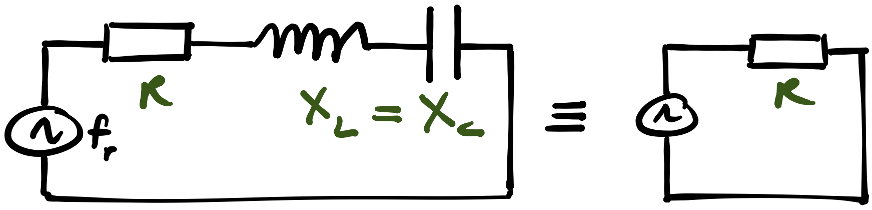
resonance

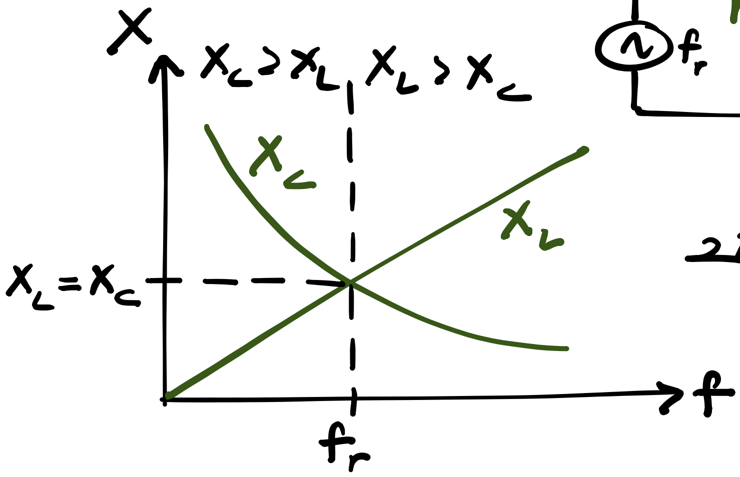
$Z = R + jX_L - jX_C$

$Z = \sqrt{R^2 + (X_L - X_C)^2} \angle \tan^{-1}\left(\frac{X_L - X_C}{R}\right)$



# Series Resonance




$X_L = X_C$

$2\pi f_r L = \frac{1}{2\pi f_r C}$

$$\boxed{f_r = \frac{1}{2\pi\sqrt{LC}}}$$

min $\searrow$ $Z = R$

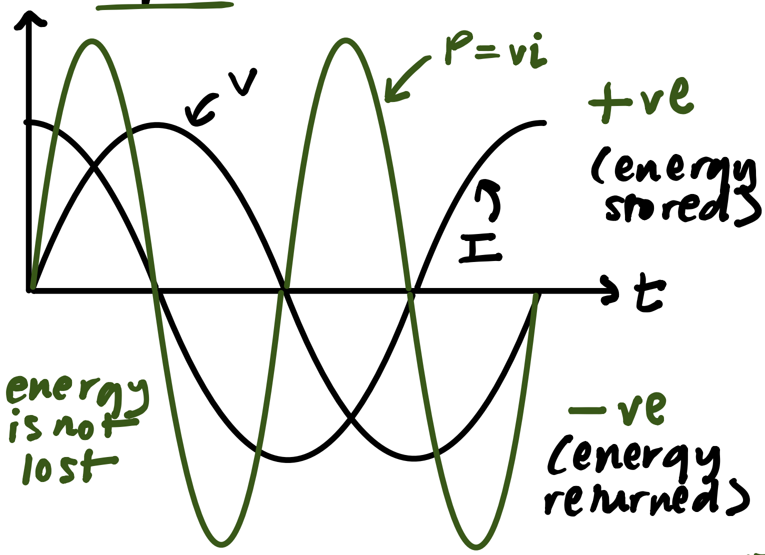
$I = \frac{V_0}{Z}$

max $\nearrow$

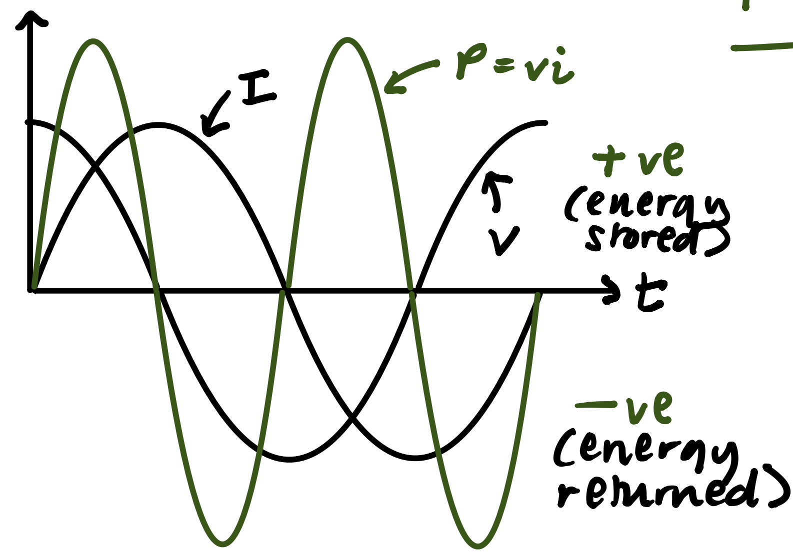
$I = \frac{V_0}{R}$

## Power in Passive Components

### Capacitor




### Inductor




## Reactive power

rate at which a capacitor stores / returns energy

$$\boxed{P_r = I_{rms}^2 X_C = \frac{V_{rms}^2}{X_C}}$$

in VAR

"furnish / deliver power" (−ve)

## Average Power

power dissipated in resistor

$$\boxed{P_{avg} = V_{rms} I_{rms} = I_{rms}^2 R = \frac{V_{rms}^2}{R}}$$

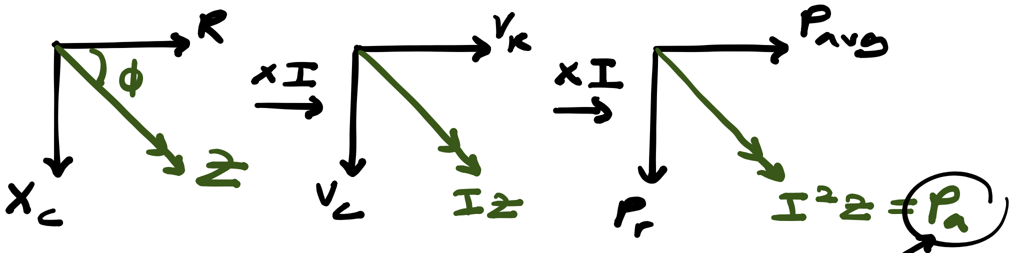
rate at which an inductor stores / returns energy

$$\boxed{P_r = I_{rms}^2 X_L = \frac{V_{rms}^2}{X_L}}$$

in VAR

"demand / absorb power" (+ve)

# RC Circuits




## Power Triangle

$\uparrow f, \downarrow P_r, \downarrow \phi$

Apparent Power
(in VA)

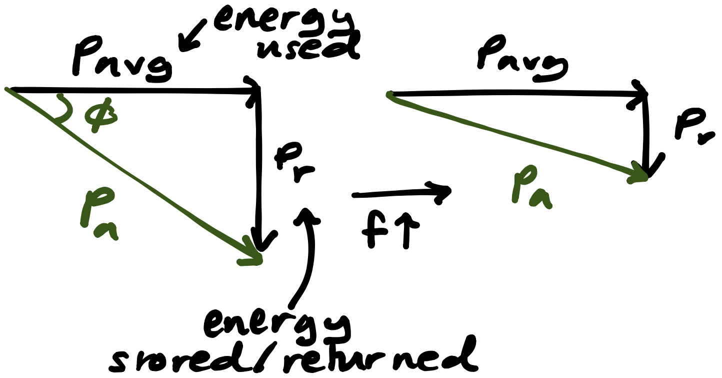
## Power Factor

$$PF = \frac{P_{avg}}{P_a}$$

$$\boxed{PF = \cos\phi}$$

$0 \leftarrow PF \rightarrow 1$

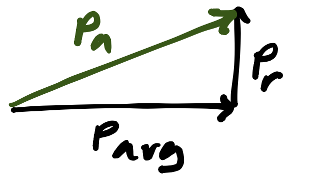
reactive resistive




$$\boxed{\begin{aligned} P_a &= I^2R \\ &= \sqrt{P_r^2 + P_{avg}^2} \\ &= \frac{P_{avg}}{\cos\phi} \end{aligned}}$$

$$P_{avg} = V_0 I_0 \cos\phi$$

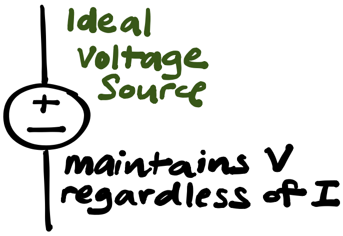
## LR Circuits

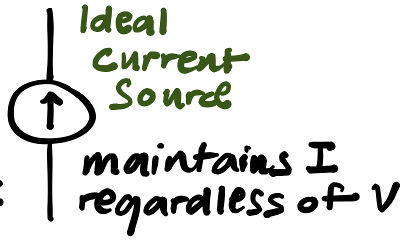



$\uparrow f, \uparrow P_r, \uparrow \phi$

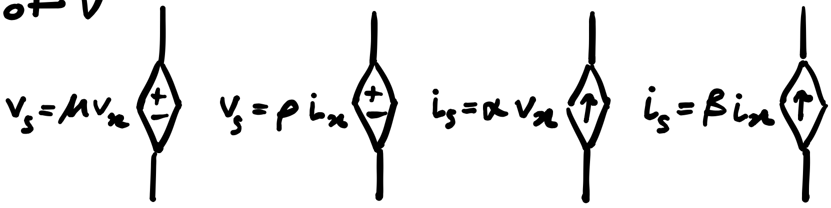
# NODE VOLTAGE METHOD AND SUPERPOSITION THEOREM

* Node voltage method
* Superposition theorem

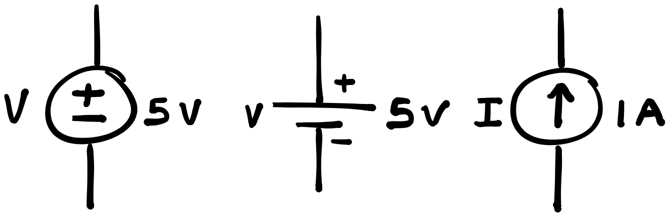


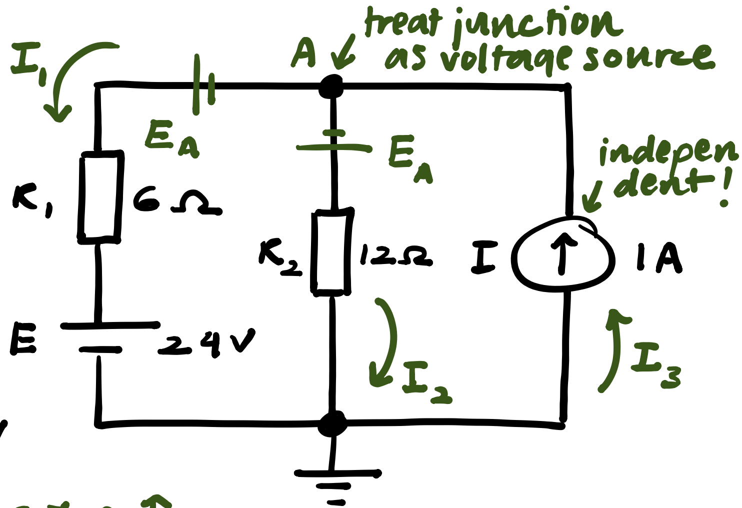

## Dependent Source




## Independent Source




## NODE VOLTAGE METHOD




KCL:

$$I_1 + I_2 = I_3 = 1A$$

$$I = \frac{\Delta V}{R}$$

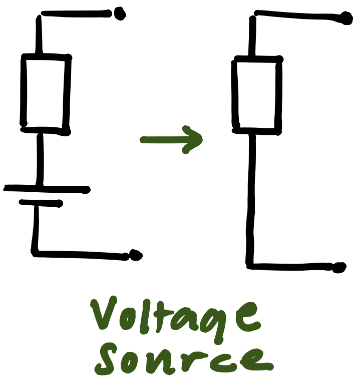
$$\frac{E_A - 24}{6} + \frac{E_A}{12} = 1$$

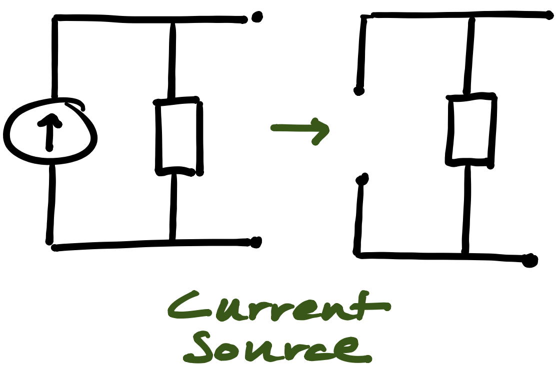
$E_A = 20V$

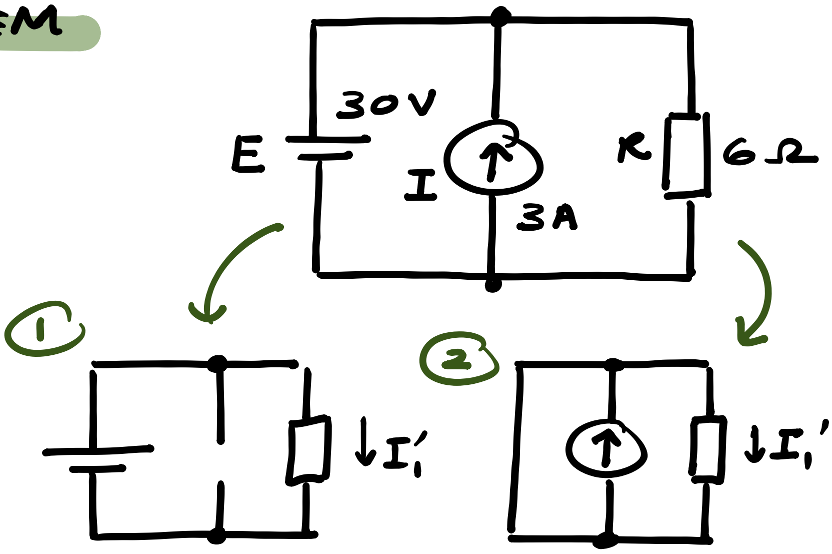
$I_1 = -0.67A \uparrow$

$I_2 = 1.67A \downarrow$

## SUPERPOSITION THEOREM




$$I_1' = \frac{E}{R} = 5A \qquad I_1' = 0 \text{ (short circuit)}$$

$$I_1 = 5 + 0 = 5A$$

- Sensors
- The operational amplifier
- Open-loop configuration
- Negative feedback
- The inverting amplifier
- The non-inverting amplifier

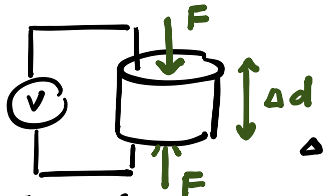
## Electronic sensor

Sensing device → Processor → Output device

change of physical quantity

1. **Force**

Piezo-Electric Transducers
ie. microphone, touchpad

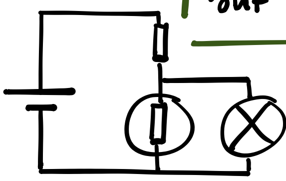



$$\Delta E = \frac{\Delta V}{\Delta d}$$

2. **Light intensity**

Light-Dependent Resistor
↑light, ↓resistance

$$\boxed{V_{out} = \frac{R_L}{R+R_L} V_0}$$



Voltage Divider Circuit

3. **Temperature**

Thermistor

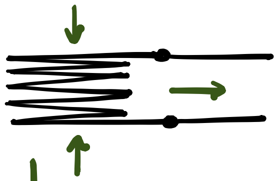
$$\boxed{V_{out} = \frac{R_T}{R+R_T} V_0}$$

1. Positive Temperature Coefficient, PTC
↑temp, ↑resistance

2. Negative Temperature Coefficient, NTC
↑temp, ↓resistance

4. **Surface changes** (expansion / contraction)

Metal-wire Strain Gauge

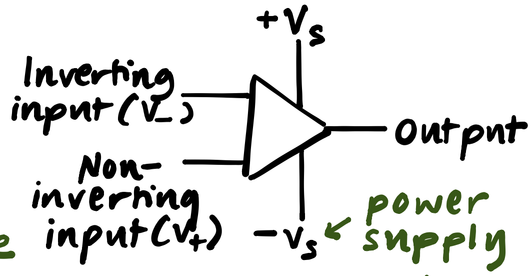


From $\delta R = \frac{\rho \, \delta L}{A}$, $\boxed{\frac{\delta R}{R} = \frac{\delta L}{L}}$

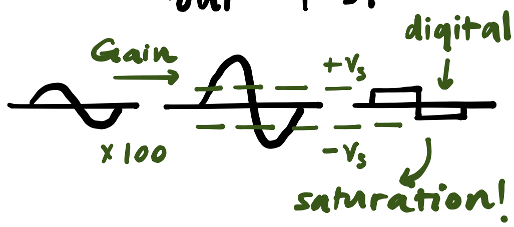
or $\boxed{\frac{\Delta R_1}{\Delta R_2} = \frac{\Delta L_1}{\Delta L_2}}$

## Operational Amplifier (op-amp)

to perform math operations




$$V_{out} \leq |V_s|$$




Inverting Input $V_-$
+ve input, -ve output
-ve input, +ve output

Non-inverting Input $V_+$
+ve input output
-ve input output

compared! (unless one is grounded)

---

## Voltage Gain (G)

$$\boxed{G = \frac{V_{out}}{V_{in}}}$$

Default: $10^5$

## Impedance

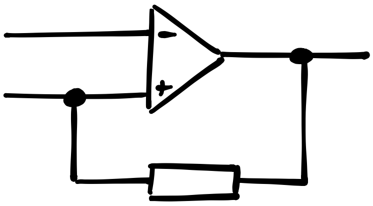
$R_{in}$ is infinite ⇒ small current
$R_{out}$ is zero ⟹ large current

**Ideal**
- infinite $R_{in}$
- zero $R_{out}$
- infinite bandwidth & slew rate

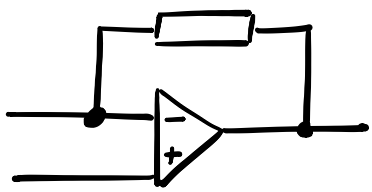
**Practical**
- high $R_{in}$
- low $R_{out}$
- limited bandwidth & slew rate

## Feedback

increase amp
**Positive**



reduce amplification



**Negative**

# OPEN LOOP CONFIG
(no feedback)

$V_{out} \propto V_{in}$

$V_{out} \propto (V_+ - V_-)$

$$\boxed{V_{out} = G(V_+ - V_-)}$$

if $V_{out} > V_s$

$\Rightarrow V_{out} = V_s$ (saturated)

if $V_+ > V_-$, $+V_s$

if $V_+ < V_-$, $-V_s$

# NEGATIVE FEEDBACK
(reduce gain to 1)

$V_{out} = G(V_+ - V_-)$

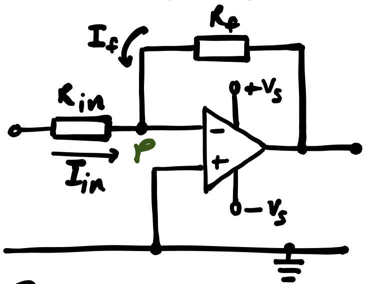
$V_{out} = G(V_{in} - V_{out})$

$V_{out}(1+G) = G V_{in}$

$$\frac{V_{out}}{V_{in}} = \frac{G}{1+G}$$

$$\boxed{G' = \frac{G}{1+G}}$$

## ① Inverting Amplifier




$I_{in} + I_f = I_p$

$I_{in} + I_f = 0$ ← virtual ground

$$\frac{V_{in} - V_-}{R_{in}} + \frac{V_{out} - V_-}{R_f} = 0$$

$V_- \approx 0$

$$\frac{V_{in}}{R_{in}} + \frac{V_{out}}{R_f} = 0$$

$$\boxed{\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_{in}}}$$

$G \rightarrow \infty$ ← very large

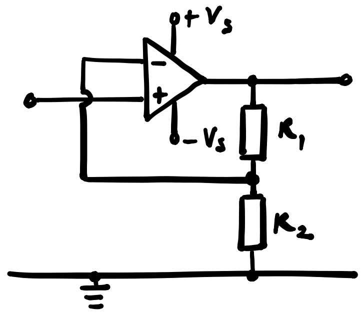
$$\frac{V_{out}}{V_+ - V_-} \rightarrow \frac{1}{0}$$

$V_+ - V_- \approx 0$

$V_+ \approx V_-$

$V_+ = 0$, $V_- \approx 0$, $V_p \approx 0$ ← virtual ground

## ② Non-inverting Amp.




$$G = 1 + \frac{R_1}{R_2}$$

$G \rightarrow \infty$

$V_+ \approx V_-$

$V_- \approx V_{in}$

$$V_{in} = \frac{R_2}{R_1 + R_2} V_{out}$$

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