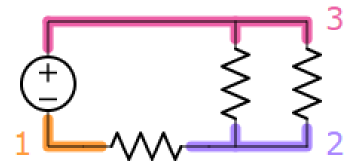
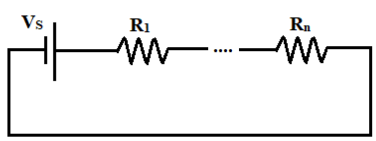
Formula	Description	Notes/Diagram
$I = \frac{Q}{t}$	I: Electric current Intensity **(Ampere A)** Q: electric charge **(Coulomb C)** t: time (sec)	Electric charge can be calculated by this formula $Q = Ne$, where: N: number of carriers e: electron charge $= 1.602 * 10^{-19}\ C$
$R = \rho \frac{l}{A}$	R: resistance **(Ohm Ω)** ρ: resistivity (property of the element) l: length of conductor (e. g. wire) (m) A: cross sectional area (m^2)	Electrical conductivity (σ or G) is the inverse of electrical resistivity. $\sigma = G = \frac{1}{\rho}$
Ohm's law $V = IR$	V: electric potential difference (voltage) between two points **(Volt V)** I: intensity of current between them. R: resistance between them.	You will use this A LOT :)
$P = IV = I^2R = \frac{V^2}{R} = \boldsymbol{\frac{dW}{dt}}$ $W = \int_{t_0}^{t_1} P(t)\,dt$	Electric power: the rate at which the electrical energy is transferred. Energy can then be calculated by integrating power.	Power is measured in **(Watt W)** Transmitted power over wires $P_T = IV$ Lost power due to transformation $P_L = I^2R = \frac{V^2}{R}$
$R_{EQ} = \sum_{k=1}^{n} R_k \qquad (1)$ $R_{EQ} = \left(\sum_{k=1}^{n} \frac{1}{R_k}\right)^{-1} \qquad (2)$	Equivalent resistance for n resistors connected in series (1) or in parallel (2).	
$\sum_{k=1}^{n} I_k = 0, \sum_{k=1}^{n} V_k = 0$	**Kirchhoff's Current Law (KCL):** sum of the currents at a node must equal zero. **Kirchhoff's Voltage Law (KVL):** sum of voltages around a loop must equal zero. (going from – to +, we add voltage) (going from + to –, we subtract voltage)	**Loop (3):** closed path in a circuit **mesh (2)**: a loop that has no other loops inside it. **Branch (4):** contains an electrical component (connects two nodes) **node (3):** connecting two or more branches (#wire segments used)

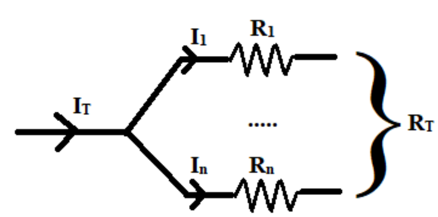
Voltage divider rule: The voltage is divided between resistors connected in series in direct proportion to their resistance (voltage is the same across parallel resistors.)

$$V_X = \frac{R_X}{\Sigma R_i} V_S$$



Current divider rule

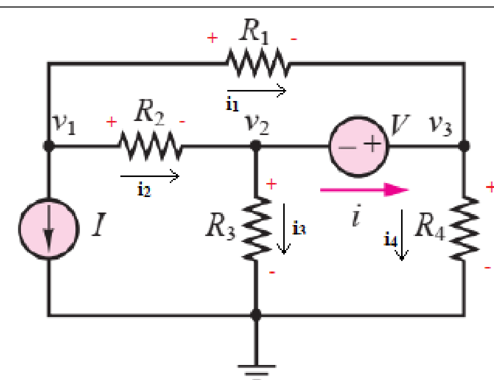
$$I_X = \frac{R_T}{R_X} I_T$$



Node Voltage Method (NVM) (useful for calculating node potential, calculating voltage across circuit elements)

1. Choose a reference ground node (has zero potential).
2. Identify currents and their direction (from + to – across resistors, from – to + across voltage sources).
3. Write Ohm's law for each pair of nodes $i_{a \to b} = \frac{v_a - v_b}{R_{ab}}$
4. For a voltage source going from node a to b, equation will become $v_{source} = v_b - v_a$
5. Write KCL equations at each node, then solve the system.

$$\begin{cases} i_1 = \frac{v_1 - v_3}{R_1}, i_2 = \frac{v_1 - v_2}{R_2}, i_3 = \frac{v_2}{R_3}, i_4 = \frac{v_3}{R_4} \\ V = v_3 - v_2 \\ -I - i_1 - i_2 = 0, i_2 - i - i_3 = 0, i_1 + i - i_4 = 0 \end{cases}$$



Principle of superposition (useful for analyzing circuits with multiple sources)

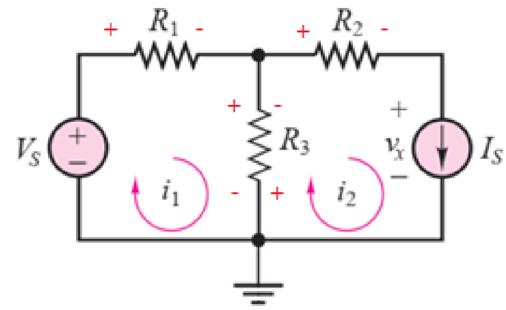
- Branch voltage/current is the sum of N voltages/currents, each of which can be computed by setting all but one source to zero and solving the circuit containing that single source.

Removing (setting sources to zero): **voltage sources** are **shortened**, **current sources** are **opened**.

Mesh Current Method (MCM) (useful for finding current through an element)

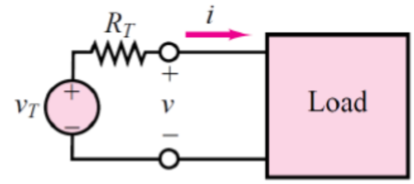
1. Identify currents at each mesh, assume clockwise direction.
2. Write KVL for each mesh, **mesh current goes from + to –** (we change signs assumptions when considering each mesh).
3. Current sources provides the current mesh (trivial).
4. Solve the system.

$$\begin{cases} V_S - i_1R_1 - (i_1 - i_2)R_3 = 0 \\ -v_x - (i_2 - i_1)R_3 - i_2R_2 = 0 \\ i_2 = I_s \end{cases}$$



Thevenin equivalent circuit:

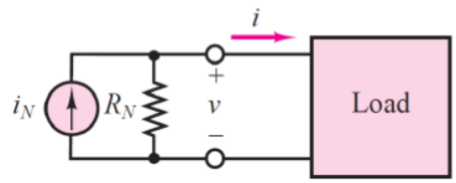
- Works for networks with voltage/current sources and linear resistors
- Assume the load is in between nodes a and b
- Remove (open) the load → ($V_{ab} = V_T$)
- Remove (short/open) all sources → $R_{a\to b} = R_T$



Norton equilvalent circuit:

- Works for networks with voltage/current sources and linear resistors
- Assume the load is in between nodes a and b
- Remove (short) the load ⟹ ($I_{ab} = I_N$)
- Remove the source ⟹ $R_{a\to b} = R_N$

Source transform: $V_T = R_T i_N,\ R_T = R_N$



AC sine wave

$$x(t) = A * \cos(\omega t + \phi)$$

In phasor notation

$$x(t) = A\angle\phi$$

A: amplitude (peak value)

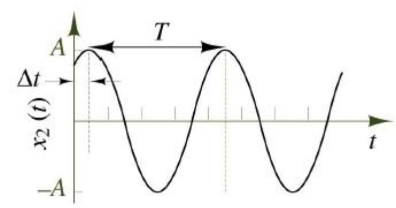
T: period (s) (after which it repeats)

$\omega = 2\pi f$: radial frequency (rad/s)

$f = 1/T$: natural frequency (Hz)

$\phi = \frac{2\pi\Delta t}{T}$: phase shift b/w v and i (rad).

$\phi = 90°$ in inductor, $\phi = -90°$ in capacitor



$$Q = CV$$

$$Q = It = Ne, e = 1.602 * 10^{-19}\ C$$

Equivalent capacitance:

- For **parallel** capacitors = ΣC_i
- For **series** capacitors = $1/\Sigma C_i^{-1}$

Q: amount of electric charge stored in the capacitor (columb)

V: voltage b/w capacitor plates

C: capacitance (Farad = coulomb/volt), constant for a certain capacitor.

- Capacitor stores electric charge between its two plates separated by dielectric.
- The higher the capacitance, the more charge the capacitor can store at the same voltage.
- **These formulas work only for constant values of Q, V, I**

$$C = \varepsilon\frac{A}{d}$$

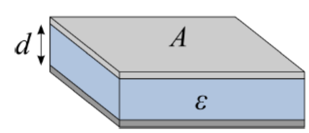
In vaccum (free space)

$$\varepsilon_0 \approx 8.854 \times 10^{-12}\ F.m^{-1}$$

A: common area b/w capacitor plates (m^2)

d: distance b/w the plates (m)

ε(permittivity): a measure of the electric polarizability of a dielectric.



$$Q(t) = C * V(t)$$

$$I(t) = \frac{dQ}{dt} = C * \frac{dV(t)}{dt}$$

$$P(t) = I(t)V(t) = \frac{dW(t)}{dt}$$

$$W(t) = \int_{-\infty}^{t} I(t')V(t')dt'$$

$$= \frac{C}{2}V^2(t) + W(0)$$

- Capacitor equations for varying voltage (and current) in AC circuits.
- Capacitor in DC circuits = Open circuit
- Capacitor in AC circuits = Short circuit
- Capacitor can consume power ($P < 0$) or deliver power ($P > 0$) that is the rate of energy consumption per unit time.
- Energy (electric charge) stored in the capacitor is the integral of power
- $W(0)$ and $V(0)$ account for initial values and can be also called $W(-\infty), V(-\infty)$

Given $i_c(t)$ we can get an expression for voltage on the capacitor

$$V_c(t) = \frac{1}{C}\int_{-\infty}^{t} I_c(t')dt'$$

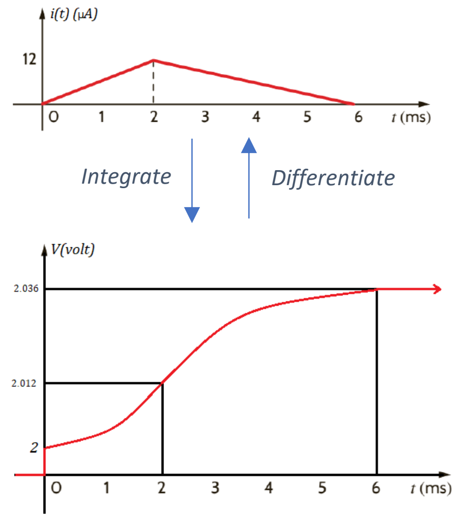
If $I_c(t)$ is a piece-wise defined function, $V_c(t)$ will also be so. **Example**

$$I(t) = \begin{cases} 1 & t \in (-\infty, 5] \\ t & t \in (5, +\infty) \end{cases} \Longrightarrow$$

$$v(t) = \begin{cases} \frac{t}{C} + v(0) & t \in (-\infty, 5] \\ \frac{\frac{t^2}{2} - \frac{5^2}{2}}{C} + v(5) & t \in (5, +\infty) \end{cases}$$

Graphing integration/differentiation relations.

1. Extract the defintion for the piecewise function from the given graph.
   a. Convert the graph and everything to standard units.
2. Integrate/differentiate functions for each case separately



Example integration problem: graph $V_c(t) = \frac{1}{C}\int_0^t I_c(t')dt' + V_0$ given the graph of $I(t)$ and $V_0 = 2\,V, C = 1\mu F = 10^{-6}F$

$$I_{\mu A}(t_{ms}) = \begin{cases} \frac{12*10^{-6}}{2*10^{-3}}t \\ \frac{-12*10^{-6}}{4*10^{-3}}t + 1.8*10^{-5} \end{cases} = \begin{cases} 6*10^{-3}t & t \in [0,2]\,ms \\ -3*10^{-3}t + 1.8*10^{-5} & t \in (2,6]\,ms \end{cases}$$

$$\Rightarrow V_{volt}(t_{ms}) = \begin{cases} \frac{6*10^{-3}t^2}{2*10^{-6}} + 2 \\ \frac{-3*10^{-3}}{2*10^{-6}}t^2 + \frac{1.8*10^{-5}}{10^{-6}}t - 0.03 + 2.012 \end{cases} = \begin{cases} 3000t^2 + 2 & t \in [0,2] \\ -1500t^2 + 18t + 1.982 & t \in (2,6] \end{cases}$$

More curves for Power ($P(t) = I(t)V(t)$) or Energy $W_L(t) = L\int_{-\infty}^t IdI$ or $W_C = C\int_{-\infty}^t VdV$ can be constructed and drawn in the same manner.

Note: integration graph for 0 ⇒ constant, constant ⇒ line, line ⇒ parabola, etc.

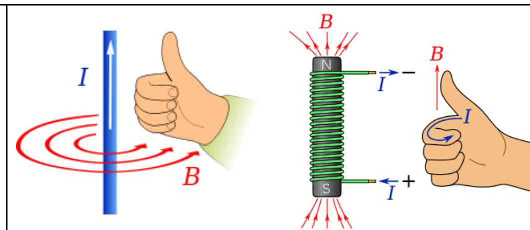
Faraday law

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

- Magnetic flux is measured in weber (Wb = V.S)

Induced EMF is given by the rate of change of the magnetic flux.

Inductance (Henry = V/A): a propery of incuctor, measures the amount of induced EMF per unit change in currect



$$V_L(t) = L\frac{dI}{dt}$$

$$I_L = \frac{1}{L}\int_{-\infty}^t V_L(t')dt'$$

$$P(t) = I(t)V(t) = \frac{dW(t)}{dt}$$

Voltage on an inductor

Current flowing through inductor

- Inductor in DC circuits = Short circuit

- Inductor in AC circuits = Open circuit

Same equations for power and energy apply

Equivalent inductance:

- For **series** inductors = ΣL_i
- For **parallel** inductors = $1/\Sigma L_i^{-1}$

$$W(t) = \int_{-\infty}^t I(t')V(t')dt'$$

$$= L\int_{-\infty}^t IdI = \frac{L}{2}I^2(t) + W(0)$$

$$A + Bj = L\big(cos(\theta) + jsin(\theta)\big) = Le^{j\theta} = L\angle\theta$$

$$L = \sqrt{a^2+b^2}, \theta = \arctan\left(\frac{b}{a}\right)$$

$$A = L*\cos(\theta), B = L*\sin(\theta)$$

$$\frac{L_1\angle\theta_1}{L_2\angle\theta_2} = \frac{L_1}{L_2}\angle(\theta_1 - \theta_2)$$

$$L_1\angle\theta_1 * L_2\angle\theta_2 = L_1L_2\angle(\theta_1 + \theta_2)$$

Complex number formulas for phasor calculations.

$$\sin\left(\frac{\pi}{2} - x\right) = \cos x$$

$$\cos\left(\frac{\pi}{2} - x\right) = \sin x$$

$$\sin\left(\frac{\pi}{2} + x\right) = \cos x$$

$$\cos\left(\frac{\pi}{2} + x\right) = -\sin x$$

<u>**Recall**</u>

$$\sin(A \pm B) = \sin A\cos B \pm \cos A \sin B$$

$$\cos(A \pm B) = \cos A\cos B \mp \sin A\sin B$$

$$\tan A \pm B = \frac{\tan A \pm \tan B}{1 \mp \tan A \tan B}$$

$$\sin A\cos B = 0.5(\sin(A+B) + \sin(A-B))$$

$$\cos A\cos B = 0.5(\cos(A+B) + \cos(A-B))$$

$$\sin A\sin B = 0.5(\cos(A-B) - \cos(A+B))$$

$$Z_R = R$$

$$Z_C = \frac{1}{j\omega C} = -\frac{j}{\omega C}$$

$$Z_L = j\omega L$$

$$Z = R + jX$$

- Re(Z) = Resistance
- Im(Z) = Reactance

- Impedance of Resistor, Capacitor, and Inductor.
- Equivalent impenance can be found in the same way as equivalent resistance.

$X > 0 \Rightarrow$ Inductive impedance

$X < 0 \Rightarrow$ Capacitive Impedance

<u>**Recall**</u>

Angular frequency (rad/s) = $2\pi *$ natural frequency (Hz)

$$\omega = 2\pi f = \frac{2\pi}{T}$$

$$\tau\frac{dx}{dt}+x=K_s f(t)$$

General form of a differential equation for a 1st order circuit (with 1 capacitor or 1 inductor)

x: some variable, current/voltage through/on the capacitor/inductor.
τ: transient time (growth/decay until steady state)
$f(t)$: input to the system (from current/volatage source)
K_s: DC gain, final output at the steady state (when $t\to\infty$ and the input became constant)

Voltage and current on/through capacitor or inductor cannot change immediately because this will require infinite power.

$$V_{C|L}(0^-)=V_{C|L}(0^+)=V_{C|L}(0)$$
$$I_{C|L}(0^-)=I_{C|L}(0^+)=I_{C|L}(0)$$

Recall: in DC circuits (in steady state, circuit has been closed for a long time), capacitor acts as an open circuit, inductor – closed.

Solution:

$$x(t)=x(\infty)+\big(x(0^+)-x(\infty)\big)e^{-t/\tau}$$
$$x(t)=x_F+x_N$$

Transient response = Forced (steady state) response + Natural response

Recall: capacitor discharging acts as a voltage source with voltage $V=V_C(0)$, inductor discharging acts as a current source with $I_S=I_L(0)$
$x_F=$ particular solution to the ODE
$x_N=$ homogeneous solution

$\tau=R_TC$ for single capacitor circuit
$\tau=\frac{L}{R_T}$ for single inductor circuit
- R_T is the thevenin equivalent resistance looking from capacitor(inductor) terminals.

Thevenin ODE: $V_T=CR_T\frac{dV_c}{dt}+V_c$
Norton ODE: $i_N=\frac{L}{R_N}\frac{di_L}{dt}+i_L$

$$H(j\omega)=\frac{V_{out}}{V_{in}}=|H|\angle-\text{atan}\left(\frac{\omega}{\omega_0}\right)$$

Frequency response: how the output changes in response to a sinusoidal input.

Recall:

$$|H|=\sqrt{\big(Re(H)\big)^2+\big(Im(H)\big)^2},\angle H=\text{atan}\left(\frac{Im(H)}{Re(H)}\right)$$

Cutoff angular frequency of the filter ω_0: the value after which the filter effect begins to be visible.
- RC filters $\omega_0=1/RC$
- RL filters $\omega_0=R/L$

Low(high)-pass filter: passes low(high)-frequency singals only and block other freqs (low=below cutoff, high=above cutoff)
Bandpass filter: passes signals with frequencies only in some range $[\omega_1,\omega_2]$
Bode-plot for filters: two plots, first $(\omega,|H|)$, second $(\omega,\angle H)$, usually logarithmic scaled.

Frequency response for filters

(a) Low-pass RC filter $H(j\omega)=\frac{1}{1+j\omega RC}=\frac{1}{\sqrt{1+(\omega RC)^2}}\angle\text{atan}(-\omega RC)$

(b) High-pass RL filter $H(j\omega)=\frac{j\omega L}{R+j\omega L}=\frac{1}{\sqrt{1+\left(\frac{R}{\omega L}\right)^2}}\angle\text{atan}\left(\frac{R}{\omega L}\right)$

(c) High-pass RC filter $H(j\omega)=\frac{j\omega RC}{j\omega RC+1}=\frac{1}{\sqrt{1+\left(\frac{1}{\omega RC}\right)^2}}\angle\text{atan}\left(\frac{1}{\omega RC}\right)$

(d) Low-pass RL filter $H(j\omega)=\frac{R}{R+j\omega L}=\frac{1}{\sqrt{1+\left(\frac{\omega L}{R}\right)^2}}\angle\text{atan}\left(-\frac{\omega L}{R}\right)$

(e) Series RLC bandpass filter

$$H(j\omega)=\frac{j\omega RC}{j\omega RC-\omega^2LC+1}=\frac{\omega RC}{\sqrt{(1-\omega^2LC)^2+(\omega RC)^2}}\angle\frac{\pi}{2}-\text{atan}\left(\frac{\omega RC}{1-\omega^2LC}\right)=$$

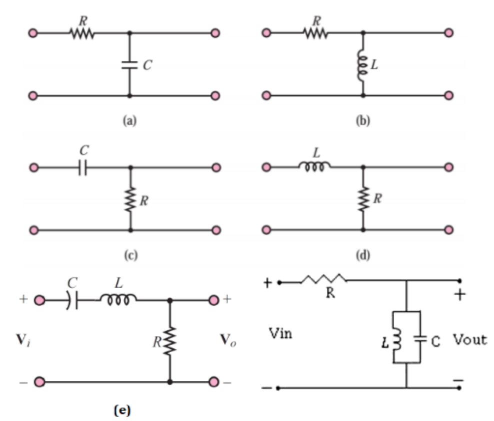
$$=\frac{j\omega A}{\left(\frac{j\omega}{\omega_1}+1\right)\left(\frac{j\omega}{\omega_2}+1\right)}\Rightarrow\begin{cases}A=RC\\ \omega_1=\dfrac{2}{CR+\sqrt{C^2R^2-4LC}}\\ \omega_2=\dfrac{CR+\sqrt{C^2R^2-4LC}}{2LC}\end{cases}$$

$$|H|=\frac{A\omega}{\sqrt{\left(\frac{\omega}{\omega_1}^2+1\right)\left(\frac{\omega}{\omega_2}^2+1\right)}},$$

$$\angle H=\frac{\pi}{2}-\text{atan}\left(\frac{\omega}{\omega_1}\right)-\text{atan}\left(\frac{\omega}{\omega_2}\right)$$

$\omega_n=\sqrt{\frac{1}{LC}}=$ natural or resonant frequency
$Q=\frac{1}{2\zeta}=\frac{1}{\omega_nCR}=\frac{1}{R}\sqrt{\frac{L}{C}}=$ quality factor
$\zeta=\frac{1}{2Q}=\frac{R}{2}\sqrt{\frac{C}{L}}=$ damping ratio
$B=\frac{\omega_n}{Q}=$ bandwidth

(f) Parallel RLC bandpass filter $H(j\omega)=\frac{j\omega L}{R-RLC\omega^2+j\omega L}$



Cramer's rule:

$$\begin{cases}a_1x+b_1y=c_1\\ a_2x+b_2y=c_2\end{cases}\Rightarrow\begin{cases}x=\dfrac{c_1b_2-b_1c_2}{a_1b_2-b_1a_2}\\ y=\dfrac{a_1c_2-c_1a_2}{a_1b_2-b_1a_2}\end{cases}$$

Operator method: write n 1st order ODEs, substitute $s=\frac{d}{dt}$ then solve for any of the variables and substitute s back to get the n^{th} order ODE

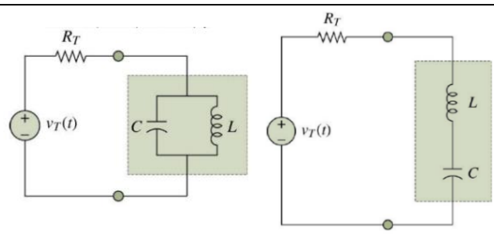
$$\frac{1}{\omega_n^2}\frac{d^2x(t)}{dt^2}+\frac{2\zeta}{\omega_n}\frac{dx(t)}{dt}+x(t)=K_sf(t)$$

General form of 2nd order circuit ODE

ζ: the damping ratio
ω_n: natural frequency
$f(t)$: input
K_s: DC gain

Solution $x(t)=x_F+x_N=K_sf+(\alpha_1e^{s_1t}+\alpha_2e^{s_2t})$

$$s_{1,2}=\begin{cases}-\zeta\omega_n\pm\omega_n\sqrt{\zeta^2-1} & \zeta>1 & \text{Overdamped response}\\ -\omega_n & \zeta=1 & \text{Critically damped response}\\ -\zeta\omega_n\pm j\omega_n\sqrt{1-\zeta^2} & 0<\zeta<1 & \text{Underdamped response}\end{cases}$$



Parallel RLC circuit: $LCi_L''+\frac{L}{R}i_L'+i_L=\frac{1}{R}V_T$
Series RLC circuit: $LCv_c''+RCv_c'+v_c=V_T$

Analogies b/w Series RLC circuit and Mass-Spring-Damper mechanical system

$$Lv_c''+Rv_c'+1/C\,v_c=V_T$$
$$my''+by'+ky=u$$

Electrical System	Mechanical System
Inductance L	Mass m
Resistance R	Damping coeff. b
Capacitance C	Compliance $1/k$

$n = p = n_i$

Intrinsic concentration of electrons and holes for some **pure** material are equal to the intrinsic carrier concentration.

$n_i = 1.5 * 10^{16}\ m^{-3}$ (electrons per cubic meters) for silicon at room temperature.

$n_{\text{p\_side}} p_{\text{p\_side}} = n_{\text{n\_side}} p_{\text{n\_side}} = n_i^2$

Mass action law: for any (doped) semiconductor: **electrons con. * holes con.** remains constant and is equal to the carrier con. squared, this can be used with p-side, or n-side.

n-type: $n > n_i, p < p_i$
p-type: $n < n_i, p > p_i$

The number of electrons for an n-type semiconductor is greater than the intrinsic concentration for pure material.

n-type: doped with an element of group 15 (e.g., Arsenic)
p-type: doped with an element of group 13 (e.g., Indium)

$$V_0 = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

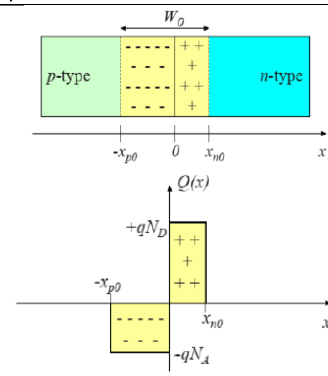
$$x_n = \sqrt{\frac{2\epsilon_s}{q} \frac{N_a}{N_d} \frac{1}{N_a + N_d} V_0}$$

$$x_p = \sqrt{\frac{2\epsilon_s}{q} \frac{N_d}{N_a} \frac{1}{N_a + N_d} V_0}$$

$$W_0 = x_n + x_p, \qquad Q(x) = -qN_A$$

$$E(x) = -\frac{dV(x)}{dx}, \frac{dE(x)}{dx} = \frac{Q(x)}{\varepsilon}, \kappa = \frac{\varepsilon}{\varepsilon_0}$$

N_A = acceptor concentration.
N_D = donor concentration
V_0 = Built-in potential for the semi-conductor.
x_n = n-side width of depletion region.
x_p= p-side width of depletion region.
W_0 = total width of depletion region.
$Q(x)$ = electric charge
$E(x)$ = strength of electric field
ε = permittivity of substance
ε_0 = permittivity of vaccum
κ = dielectric constant.

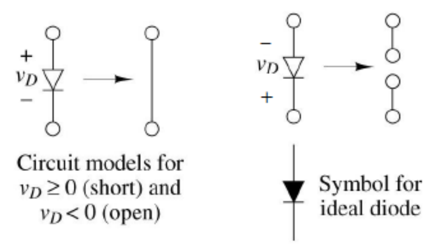


$$i_D = -I_0 = I_s$$

$$i_D = I_0 e^{\frac{qv_D}{kT}} - I_0 \cong I_0 e^{38.67 v_D}$$

Diffusion current for reverse-biased and forward-biased diode.
Diffusion current i_D: holes moving from p to n (conventional direction)
Drift current: electrons flowing from n to p.

$q \cong 1.602 * 10^{-19}\ C$ electron charge
$k \cong 1.381 * 10^{-23} \frac{J}{K}$ boltzmann const.
T: material temprature in kelvins (room temp ≅ 300 K)
I_s reverse saturation current:
very small current (10^{-12} to 10^{-15} A) resulting from minority charge carriers flowing through the depletion region.

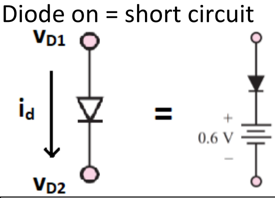


Two methods to determine whether the diode is conducting or not.

- Assume it's not conducting, replace it with open circuit, calculate potential around its terminals using NVM (V_{D1}, V_{D2}). If $V_{D1} < V_{D2} \Rightarrow V_D < 0$, then our assumption was correct.
- Assume it's conducting, replace it with short circuit, calculate current through the short circuit using MCM (i_d). If $i_d > 0$ then our assumption was correct.

* Non-ideal diode is equivalent to an ideal diode in series with a battery of offset volatage (silicon diodes, $v_\gamma = 0.6V$, germanium $v_\gamma = 0.3V$) - Diode starts to conduct when $V_{D1} > V_{D2}$ or $i_d > 0$

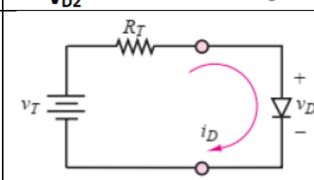
Diode off = open circuit
Diode on = short circuit



$$v_T = i_D R_T + v_D$$

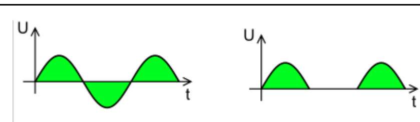
$$i_D = I_0\left(e^{\frac{qv_D}{kT}} - 1\right)$$

Diode (quiescent/operating/Q) point represents the actual current and voltage of the diode and can be calculated by solving the two equations simultaneously for v_D, i_D (approx. graphical solution is used) The first equation comes from the Thevenin equivalent of the circuit being analyzed with the diode treated as the load.



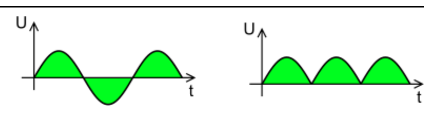
Half-wave rectifier (using diode and resistor):

$$v_{peak} = 2v_{rms}^{rectifier} = \sqrt{2}\, v_{rms}^{source}, \qquad v_{dc}^{avg} = \frac{v_{peak}}{\pi}$$



Full-wave rectifier (using bridge rectifier):

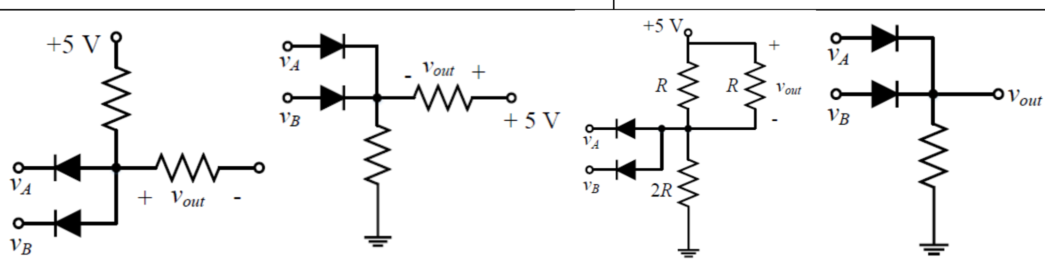
$$v_{peak} = \sqrt{2}\, v_{rms}, \qquad v_{dc}^{avg} = \frac{2v_{peak}}{\pi}$$



Adding a capacitor in parallel with R_{Load} results in a peak-rectified voltage.

$$v_{rms} = \sqrt{\frac{1}{T}\int_0^T v_s^2(t)\, dt}$$

$$1\ Hz = 2\pi\ rad/sec$$



Logic gates using diodes (from left to right):
AND, NOR, NAND, OR

Diode clamp with forward diode (in picture, -) or reverse diode (+) shifted by v_{DC}

$$v_{out} = v_s \pm V_{peak}, \qquad v_{out} = v_s \pm V_{peak} - v_{DC}$$