

Coulomb's Law	Electric Fields	Electric Field line	Electric Flux [Nm²/C]	Enclosed charge [C]	Gaussian surface	
$F_{qQ} = \frac{1}{4\pi\epsilon_0} \frac{qQ}{r^2} \hat{r}$ $\epsilon_0 = 8.854 \cdot 10^{-12} [C^2/Nm^2]$ $k = 8.99 \cdot 10^9 [Nm^2/C^2]$	$E_Q = \frac{1}{4\pi\epsilon_0} \frac{Q}{r^2} \hat{r}$		$\phi_{\text{net}} = \oint_S E \cdot dA$ $= \oint_S E \cdot dA \cdot \cos(\theta)$	$q_{\text{enc}} = \epsilon_0 \phi_{\text{net}}$ $= \epsilon_0 \oint_S E \cdot dA$	Sphere: 1 gaussian surf Cylinder: 3 gaussian surf Cube: 6 gaussian surf $dA = dA \hat{n} (\hat{n} \perp A)$	
Isolated conductor	External elec. field	Two conducting planes	Charge Density (linear, surface, volume)		Spherical Symmetry	
$E = 0$ Cavity walls, inside isolated conductor, in metal (charges all reside at surface)	$E = \frac{\sigma}{\epsilon_0} [\text{N/C}] \text{ or } [\text{V/m}]$	$E = \frac{2\sigma_1}{\epsilon_0} = \frac{\sigma}{\epsilon_0}$	Linear density Surface density Volume density	$E_{\text{ext}} = \left(\frac{q}{4\pi\epsilon_0 R^3} \right) r$ $r - \text{radius of gauss surf}$ $R - \text{radius of sphere}$ $q - \text{charge enclosed}$ $E_{\text{int}} = 0$		
Cylindrical symmetry	Planar symmetry	Change in potential energy	Potential Energy and Electric Potential			
$E = \frac{\lambda}{2\pi\epsilon_0 r}$ $q_{\text{enc}} = \lambda h$ $= \epsilon_0 \oint_S E \cdot dA$	 Non-conducting sheet (charge density of σ)	$E = \frac{\sigma}{2\epsilon_0}$ $\phi = \phi_I + \phi_r = 2EA$	 $\Delta U > 0$ $\Delta V > 0$ Force applied	$\Delta U = U_f - U_i$ $= W_{\text{pppl}} - W_{\text{field}} [J]$ $= q(V_f - V_i) = -qE\Delta S$	$\Delta V = - \int_i^f E \cdot dS$ $= \frac{Q}{4\pi\epsilon_0 r} \left(\frac{1}{r_2} - \frac{1}{r_1} \right)$	
Voltage and Potential Energy	Equipotential surface pic	Basic Circuit with capacitor	Capacitor		Equipotential Surfaces $V_r = \frac{Q}{4\pi\epsilon_0 r}$ Same potential (+pot E)	
$V_{r>\infty} = \frac{Q}{4\pi\epsilon_0 r}$	$U = \frac{Qq}{4\pi\epsilon_0 r}$	 Voltages can be added up each other (scalar)		 *Metal plates > separation of charge *Dielectric > increase capacitance *Capacitor is charged	Capacitance $C = \frac{q}{V} [\text{F}]$ q - charge stored in one plate: not total charge!	
Parallel plate capacitor	Cylindrical Capacitor	Spherical capacitor	Parallel Capacitor	Series Capacitor	Energy in capacitor	
$E = \frac{Q}{A\epsilon_0}$ $V = \frac{Q}{A\epsilon_0} d$ $C_{pp} = \frac{A\epsilon_0}{d}$ (Ignore dielectric)		$E = \frac{Q}{2\pi\epsilon_0 Lr} \hat{r}$ $V = \frac{Q}{2\pi\epsilon_0 L} \ln\left(\frac{b}{a}\right)$ $C_{\text{cyl}} = \frac{2\pi\epsilon_0 L}{\ln(b/a)}$	$E = \frac{Q}{4\pi\epsilon_0 r^2} \hat{r}$ $V = \frac{Q}{4\pi\epsilon_0} \left(\frac{1}{a} - \frac{1}{b} \right)$ $C_{\text{sph}} = \frac{4\pi\epsilon_0 ab}{a-b}$ $C_{\text{single,sph}} = 4\pi\epsilon_0 r$	$Q_T = Q_1 + Q_2 + \dots$ $V_T = V_1 = V_2 = \dots$ $Q_T = C_T V$ $C_T = C_1 + C_2 + \dots$	$Q_T = Q_1 = Q_2 = \dots$ $V_T = V_1 + V_2 + \dots$ $\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \dots$	$U = \int dV = \int q dV = \int CV dV$ $U = \frac{1}{2} CV^2 = \frac{1}{2} \frac{q^2}{C}$ $= \frac{1}{2} qV$
Energy Density	Capacitance + dielectric		Ohm's Law and current	Current Density	Resistivity/Conductivity	
$U_{pp} = \frac{U}{\text{Volume}} = \frac{U}{Ad} = \frac{CV^2}{2Ad}$ $= \frac{kA\epsilon_0 E^2 d^2}{2d Ad} = \frac{1}{2} k\epsilon_0 E^2$	Increase area + decrease distance + dielectric = high capacitance	$C_{pp} = \frac{k\epsilon_0 A}{d}$ $C_{\text{cyl}} = \frac{2\pi k\epsilon_0 L}{\ln(b/a)}$ $C_{\text{sph}} = \frac{4\pi k\epsilon_0 ab}{a-b}$ k: dielectric constant ($k > 1$)	$R = \frac{V}{I} [\Omega]$ $I = \frac{dq}{dt} [A]$ $= q_0 N A v_d$ $Q = q_0 N A L [C]$ $= q_0 N A v_d t$	$I = \iint J dA = JA$ $J = n q_0 v_d [\text{A/m}^2]$	$\rho = \frac{ E }{ J } [\Omega m]$ $J = \frac{1}{\rho} E = \sigma E$	
$V_f = \frac{c_1}{c_1 + c_2} V_0$					$\sigma = \frac{1}{\rho} [1/\Omega m]$ $R = \frac{El}{JA} = \rho \frac{l}{A}$	
Power in Electric Fields	Parallel Circuit ()	Series Circuit (<>)	Magnetic Force	Magnetic Field	Magnetic field 'inside'?	
$U = qRI$ Power = $\frac{dU}{dt}$ Power = $I^2 R = \frac{V^2}{R} = VI [W]$			$F_B = q(v \times B)$ $= Bqv \sin \theta$ θ is $\angle(v, B)$	 Measured in [T]	$I_{\text{tot}} = \pi R^2 J_0$ $I_{\text{enc}} = \iint J dA = \pi r^2 J_0$ (dA = $r dr d\theta$) $\oint_C B dS = \mu_0 I_{\text{enc}} = 2\pi Br$ $B = \frac{\mu_0 I_{\text{tot}} r}{2\pi R^2}$	
Biot-Savart Law	$V_T = V_1 = V_2 = \dots$ $I_T = I_1 + I_2 + \dots$ $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \dots$ $\sum I = 0$	$V_T = V_1 + V_2 + \dots$ $I_T = I_1 = I_2 = \dots$ $R_T = R_1 + R_2 + \dots$ $\Sigma V = 0$	Magnetic force (wire) $F_B = I(L \times B)$ $= BIL \sin \theta$ θ is $\angle(L, B)$			
Ampere's Law	Magnetic field due to current			Force between two parallel currents	Solenoids	
$\oint_C B dS = \mu_0 I_{\text{enc}} = \oint_C B \cos(B, dS) dS$ $B = \frac{\mu_0 I}{2\pi R}$	Infinite wire $B = \frac{\mu_0 I}{4\pi \int_{-\infty}^{\infty} \frac{\sin \theta}{r^2} dx}$	Semi-infinite wire $B = \frac{\mu_0 I}{4\pi \int_0^{\infty} \frac{\sin \theta}{r^2} dx}$	Centre of loop $B = \frac{\mu_0 I \Phi}{4\pi R}$ $\Phi - \text{angle of loop (partial circular loop)}$	$F = \frac{\mu_0 L I_a I_b}{2\pi d}$ $\frac{\mu_0}{2\pi} = 2 \cdot 10^{-7}$	$I_{\text{enc}} = nhI$ $\mu_0 I_{\text{enc}} = \mu_0 nhI = Bh$ $B = \mu_0 nl$ (n=number of loops) (l=current on the loop)	
Magnetic flux	EMF (Faraday/Lenz)		EMF/current in loops	Power dissipated	Series Inductor	
$\Phi_B = \iint B dA [\text{Wb}]$ $\Phi_B = BA = \mu_0 nIA$	$\varepsilon = -(N) \frac{\partial \Phi_B}{\partial t} = -(N) \frac{\partial}{\partial t} \iint B dA$	Faraday's law - $\varepsilon \propto \frac{\partial \Phi_B}{\partial t}$ Lenz' law - Direction of induced I and ε against induced B	$\varepsilon = (-)(N) B v_x l$ $I = \frac{(N) B v_x l}{R}$ I is induced by induced B	$P = VI = \frac{V^2}{R} = I^2 R = \frac{N^2 B^2 v^2 l^2}{R}$	$V_T = L_T \frac{dI}{dt}$ $L_T = L_1 + L_2 + \dots$	
Inductor	Inductance	Self-induction (ε_L)	Energy in magnetic field	Ohm's law & power	Parallel inductor	
 B = $\mu_0 nI$ Solenoid is an inductor.	$L = \frac{N\Phi_B}{I} [\text{H}]$ $L = n^2 Al\mu_0$ $L = \frac{BAN}{I} = NAl\mu_0$ (N = nl)	$\varepsilon_L = -N \frac{\partial \Phi_B}{\partial t}$ $= -L \frac{d}{dt} I(t)$ $V_L = -\varepsilon_L = L \frac{d}{dt} I(t)$	$U = qV$ $dU = V dq = q dV$ Power = $\frac{dU}{dt} = IV$ $dU = IL dI$ $U = \frac{1}{2} LI^2$	$V(t) = R I(t)$ $P(t) = V(t)I(t) =$ $R(I(t))^2 = \frac{(V(t))^2}{R}$ $R=0 > V(t) = R I(t) = 0$ $R=\infty > I(t) = \frac{V(t)}{R} = 0$	$V = L \frac{dI}{dt}$ $\frac{V}{L_T} = \frac{V}{L_1} + \frac{V}{L_2} + \dots$ $\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \dots$	

Basic Quantities		Dependent voltage source		Dependent current source	
$I(t) = \frac{dq(t)}{dt}$ $q(t) = \int_{-\infty}^t I(x) dx$ $V(t) = \frac{W(t)}{q}$ $P = IV = I^2R = \frac{V^2}{R}$	2 terminal devices Resistor $V=IR$ Capacitor $I=C\frac{dV}{dt}$ Inductor $V=L\frac{di}{dt}$	Voltage-control $V = \alpha V_x$ 	Current-control $V = rI_x$ 	Voltage-control $I = gV_x$ 	Current-control $I = \beta I_x$
Independent sources		Node	Branch	Loop	Conductance
Indep. Voltage source	Indep. Current source	More than 2 elements join in one point	Section that contains only one element	Closed path: start from one node, visit other nodes (only once), return	$G = \frac{1}{R} = \frac{I}{V} [S]$ $I(t) = GV(t)$ $P(t) = \frac{(I(t))^2}{G} = G(V(t))^2$
Kirchhoff's Laws	Linearity	Voltage divider	Current divider	Open circuit	Short circuit
Current Law (node) $\sum I_{\text{enter}} = \sum I_{\text{leave}}$ Voltage Law (loop) $\sum V_{\text{drop}} = \sum V_{\text{rise}}$	$V_{\text{out}} = \alpha_1 V_1 + \alpha_2 V_2 + \dots + \beta_1 I_1 + \beta_2 I_2 + \dots$ Linear equations!	a.k.a series circuit $I = \frac{V}{\sum R}$ $V_i = V_{\text{source}} \frac{R_i}{\sum R}$	a.k.a parallel circuit $V = I_s \left(\sum \frac{1}{R} \right)^{-1}$ $I_i = I_{\text{source}} \frac{1/R_i}{(\sum 1/R)}$	- No current - Voltage exists - Disconnected wire	- No voltage across - Current goes to $R=0$ - Connected wire
Nodal Analysis	Mesh Analysis		Supernode		Supermesh
(#Eq) = (#Node) - 1 - N_v N_v is independent or dependent voltage sources	- Voltages at nodes - Kirchhoff's current law - One ground node set	(#Eq) = (#Loop) - N_l = Branch - Node + 1 - N_l N_l is independent or dependent current sources	- Voltages surround loops - Kirchhoff's voltage law - Calculate for each loop	- Two nodes connected by voltage source - None of them are reference node	- Used when current source is shared between two loops
Superposition		Source transformation	Equivalence		
Deactivate all sources except one source - Holds for I , V but not power Deactivate source? - Voltage source > short - Current source > open	I_1 - current through R due to V_1 only I_2 - current through R due to V_2 only $I_{\text{tot}} = I_1 + I_2 + \dots$ $P_{\text{tot}} = I_{\text{tot}}^2 R$ $= R(I_1 + I_2 + \dots)^2$ $V_L = V_S \frac{R_L}{R_L + R_S}$	 	To make this equivalent, $V_S = I_s \times R_s$ $R_s = R_p$	$R_1 \leftrightarrow R_2$ $R_1 + R_2$ $R_1 \parallel R_2$ $\frac{R_1 R_2}{R_1 + R_2}$ $V_1 \leftrightarrow \pm V_2$ $V_1 \pm V_2$ $I_1 \parallel \pm V_2$ $I_1 \pm I_2$	
Thevenin Theorem	Norton Theorem	Multiple Thevenin usage	Dependent sources in thevenin	Maximum power transfer	Efficiency
1) $R_L >$ open ckt \rightarrow get V_{OC} 2) $R_L >$ short ckt \rightarrow get I_{SC} $R_{Th} = \frac{V_{OC}}{I_{SC}}$ $V_{Th} = V_{OC}$	If sources independent 1) Get V_{OC} 2) Deactivate sources 3) Replace R_L into virtual voltage source, find R_{eq} 4) $R_{eq} = R_N$, $I_N = I_{SC}$	1) Divide circuit into two+ 2) Get V_{OC} , R_{Th} for one side 3) Substitute linear ckt in 2) to V_{OC} - R_{Th} connection 4) Repeat 2) and 3) to get R_{Th} , V_{OC} and I_{SC}	1) $R_L >$ open ckt \rightarrow get V_{OC} 2) $R_L >$ short ckt \rightarrow get I_{SC} 3) Do not remove dependent sources in 1) and 2) $R_{Th} = \frac{V_{OC}}{I_{SC}}$	$I_L = \frac{V_{Th}}{R_{Th} + R_L}$ $P_L = I_L^2 R_L = \left(\frac{V_{Th}}{R_{Th} + R_L} \right)^2 R_L$ $\frac{dP_L}{dR_L} = V_{Th}(R_L + R_{Th})(R_L - R_{Th})$ $P_{L\max} = P_{out\max}$ $= \frac{V_{Th}^2 R_{Th}}{4R_{Th}^2}$	$\text{Efficiency} = \frac{P_{out}}{P_{in}}$ $P_{in} = \frac{V_{Th}^2}{R_L + R_{Th}}$ $P_{out} = \frac{V_{Th}^2 R_L}{(R_L + R_{Th})^2}$
Capacitors	Inductors		Series		Parallel
$q(t) = C v_c(t)$ $i_c(t) = C \frac{dv_c(t)}{dt}$ $v(t) = v(t_0) + \frac{1}{C} \int_{t_0}^t i(\tau) d\tau$	$P = \frac{dW}{dt} = v(t) i(t)$ $W_c(t) = \frac{1}{2} C [v(t)]^2$ - v_c must be continuous - DC signal > capacitor looks like open circuit	$L = \frac{N\Phi_B}{i}$ $V_L(t) = L \frac{di_L(t)}{dt}$ $i(t) = i(t_0) + \frac{1}{C} \int_{t_0}^t v(\tau) d\tau$	$P = \frac{dW}{dt} = v(t) i(t)$ $W_L(t) = \frac{1}{2} L [i(t)]^2$ - i_L must be continuous - DC signal > inductor looks like short circuit	Inductor $L_T = \sum_i L_i$ Capacitor $\frac{1}{C_T} = \sum_i \frac{1}{C_i}$ Resistor $R_T = \sum_i R_i$	Inductor $\frac{1}{L_T} = \sum_i \frac{1}{L_i}$ Capacitor $C_T = \sum_i C_i$ Resistor $\frac{1}{R_T} = \sum_i \frac{1}{R_i}$
Intro to transient circuits	First-order transient ckt	Resistor-Capacitor	Resistor-Inductor		
$C \frac{dv_c(t)}{dt} + \frac{v_c(t)}{R} = 0$ $\frac{dV_c(t)}{dt} + \frac{V_c(t)}{RC} = 0$ $V_c(t) = V_0 e^{-\frac{t}{RC}}$	$v(t) = v(\infty) + (v(t_0) - v(\infty)) e^{-\frac{t}{\tau}}$ $\tau = R_{Th} C = \frac{L}{R_{Th}}$	$V_c(t) = V_s \frac{R}{R+R_g} \left(1 - e^{-\frac{t}{\tau}} \right)$ $V_{c\text{-charge}} = V_m \left(1 - e^{-\frac{t}{\tau}} \right)$ $V_{c\text{-discharge}} = V_m \left(e^{-\frac{t}{\tau}} \right)$		$\frac{V_L + i_L R_{Th}}{R_{Th} dt} + i_L = \frac{V_{Th}}{R_{Th}}$ $\tau = \frac{L}{R_{Th}}$	
Complex Number Identities ($j = \sqrt{-1} = 1\angle(\pi/2)$)	Sinusodials (Fourier)		Lead/Lag		
$Z = x + jy$ = $r(\cos\theta + j\sin\theta)$ = $e^{j\theta}$ ($\theta = \tan^{-1}\frac{y}{x}$) $\text{Re}(Z) = x$, $\text{Im}(Z) = y$ $\bar{Z} = x - jy$	$Z_1 \pm Z_2 = (x_1 + x_2) \pm j(y_1 + y_2)$ $Z_1 Z_2 = (x_1 x_2 - y_1 y_2) + j(x_2 y_1 + x_1 y_2)$ $\frac{z_1}{z_2} = \frac{z_1 z_2}{z_2 z_2} = \frac{ z_1 }{ z_2 } \angle(\theta_1 - \theta_2)$	$v(t) = V_m \cos(wt + \theta)$ $w = 2\pi f = \frac{2\pi}{T}$ $T = \frac{1}{f}$	 2V_m peak-to-peak amplitude	$ t $ $ t $ $ t-l $ Lead \rightarrow Lag	- Same Frequency - All functions should be cosine or sine - All amplitudes should be positive or negative - $0 \leq$ separation $< 180^\circ$
Phasor Relationships	Impedance - Inductor		Impedance - Capacitor		
$v(t) = V_m \cos(wt + \theta_v)$ = $Re[V e^{j\omega t}]$ $V = V_m e^{j\theta_v} = V_m \angle \theta_v$	$i(t) = I_m \cos(wt + \theta_i)$ = $Re[I e^{j\omega t}]$ $I = I_m e^{j\theta_i} = I_m \angle \theta_i$	$V_L(t) = L \frac{di_L(t)}{dt}$ $\text{Re}[V e^{j\omega t}]$ = $Re[L \frac{d}{dt} V e^{j\omega t}]$ = $Re[L j\omega V e^{j\omega t}]$	$Z_L = jwL [\Omega]$ $I_m = \frac{V_m}{wL}$ $i(t) = \frac{V_m}{wL} \cos(wt + \theta_v - \frac{\pi}{2})$	$i_c(t) = C \frac{dv_c(t)}{dt}$ $\text{Re}[I e^{j\omega t}]$ = $Re[C \frac{d}{dt} V e^{j\omega t}]$ = $Re[C j\omega V e^{j\omega t}]$	$Z_C = \frac{1}{jwC} = -\frac{j}{wC} [\Omega]$ $I_m = wC V_m$ $i(t) = I_m \cos(wt + \theta_v + \frac{\pi}{2})$
Impedance - Resistor	Impedance and admittance	Parallel/series impedance	Resonance frequency	Trigonometric Identities	
$Z_R = R [\Omega]$ $V_R(t) = I_R(t) R$	$Z = \frac{V}{I} = R + jX$ $Y = \frac{1}{Z} = G + jB$ Z - impedance Y - Admittance G - Conductance B - Susceptance	series $Z_{eq} = \sum_i Z_i$ Parallel $\frac{1}{Z_{eq}} = \sum_i \frac{1}{Z_i}$	$w_0 = \frac{1}{\sqrt{CL}}$ 	$\sin(wt + \theta)$ $= \cos(wt + \theta - \frac{\pi}{2})$ $\cos(wt + \theta)$ $= \sin(wt + \theta + \frac{\pi}{2})$	- $\sin(wt + \theta)$ = $\cos(wt + \theta - \pi)$ - $\cos(wt + \theta)$ = $\cos(wt + \theta + \pi)$