6.24×10^{18}

$$1/(6.24 \times 10^{18}) = 1.602 \times 10^{-19}$$

f

$$f = ma, \qquad [Newton] = \frac{[kilogram][meter]}{[second]^2}$$

$$f = G\frac{m_1 m_2}{r^2}$$

$$G = 6.67384 \times 10^{-11}$$

$$[Newton\,(meter/kilogram)^2]$$

m

$$f = G\frac{Mm}{r^2} = gm$$

$$g = GM/r^2 = 9.8$$

/

$$f = k\frac{q_1 q_2}{r^2} = E q_2$$

$$k = 8.98755 \times 10^9$$

$$[Newton\,(meter/Coulumb)^2]$$

$$E = kq_1/r^2$$

q_1

q_2

g

$$f = mg$$

h_1

$$h_2$$

$$w = fl = mg(h_2 - h_1), \qquad g = \frac{w}{m(h_2 - h_1)}, \qquad \frac{[Joule]}{[kilogram][meter]} = \frac{[Newton]}{[kilogram]} = \frac{[meter]}{[s]^2}$$

E

q

l_1

l_2

$$w = fl = qE(l_2 - l_1), \qquad E = \frac{w}{q(l_2 - l_1)}, \qquad \frac{[Joule]}{[Coulomb][meter]} = \frac{[Newton]}{[Coulomb]}$$

$$i = \frac{dq}{dt}, \qquad q = \int i \; dt, \qquad [$$

$$] = \frac{[Coulomb]}{[second]}$$

$j = \lim_{A\to 0} i(A)/A$

$$q = \int i(t)\,dt = \int \mathbf{j} \cdot d\mathbf{A}\ dt$$

$$v = v - v_0 = \frac{w}{q} = \frac{Eq(l - l_0)}{q} = E(l - l_0), \quad [Volt] = \frac{[Joule]}{[Coulomb]}$$

l_0

$$v_0 = 0$$

v_1

v_2

$$q = 1$$

$$v_1 = El_1$$

$$v_2 = El_2$$

$$v = v_2 - v_1 = E(l_2 - l_1)$$

$$E = \frac{v}{l} = \frac{qv}{ql} = \frac{w}{ql} = \frac{fl}{ql} = \frac{f}{q}$$

$$E(l_2 - l_2)$$

$$v = w/q$$

$$E = f/q$$

p

$$p = \frac{dw}{dt} = \frac{dw}{dq}\,\frac{dq}{dt} = v\,i, \qquad [Watt] = \frac{[Joule]}{[second]} = \frac{[Joule]}{[Coulomb]}\frac{[Coulomb]}{[second]} = [Volt][Ampere]$$

$$w = \int p\ dt = \int vi\ dt, \quad [Joule] = [Watt][second] = [Volt][Ampere][second]$$

1

$$= 746$$

$$1000 \times 3600 = 3.6 \times 10^6$$

$$w = qv = q(v_2 - v_1) = qE(l_2 - l_1)$$

$$v = v_1 - v_2 = E(l_2 - l_1)$$

$$E = (v_2 - v_1)/l$$

gh_1

gh_2

$$w = fl = mg(h_2 - h_1)$$

$$gl = g(h_2 - h_1) = gh_2 - gh_1$$

$$g = (gh_2 - gh_1)/l$$

$$v = w/q = Eql/q = El$$

$$g = f/m$$

$$w/m = mgh/m = gh$$

$$f = GMm/r^2 = gm$$

$$(g = GM/r^2)$$

$$f = kQq/r^2 = Eq$$

$$(E = kQ/r^2)$$

$$g = (gh_1 - gh_2)/L = f/m$$

$$E = (v_2 - v_1)/L = f/q$$

$$gh_2 - gh_1$$

$$v_2 - v_1$$

$$w = mg(h_2 - h_1) = mgL$$

$$w = q(v_2 - v_1)$$

B

Φ

A

$$\Phi = \int \mathbf{B} \cdot d\mathbf{A} = |B|\ |A| \cos\alpha, \qquad [Weber] = [Tesla][meter]^2$$

α

$$\alpha = 0$$

f

u

$$\mathbf{f} = q\mathbf{u} \times \mathbf{B}, \qquad [Newton] = [Coulomb]\frac{[meter]}{[second]}[Tesla]$$

$$\mathbf{f} = q(\mathbf{E} + \mathbf{u} \times \mathbf{B})$$

I

V

$i(t)$

$$v(t)$$

i

v

$$R = \frac{V}{I} = \frac{v}{i}, \qquad [Ohm] = \frac{[Volt]}{[Ampere]}, \qquad \Omega = \frac{V}{A}$$

R

Ω

$$G = \frac{1}{R} = \frac{I}{V} = \frac{i}{v}, \qquad [Siemens] = \frac{1}{[Ohm]} = \frac{[Ampere]}{[Volt]}, \qquad S = \frac{1}{\Omega} = \frac{A}{V}$$

$$[Siemens] = 1/[Ohm]$$

$$S = 1/\Omega$$

Q

C

$$V = \frac{Q}{C}, \qquad Q = VC, \qquad C = \frac{Q}{V}$$

C_1

C_2

$$V = Q/C$$

$$i(t) = \frac{dq(t)}{dt} = \frac{dq}{dv}\,\frac{dv}{dt} = C\frac{dv(t)}{dt}, \qquad v(t) = \frac{q(t)}{C} = \frac{1}{C}\int_{-\infty}^{t} i(\tau)d\tau,$$

$$q = \int_{-\infty}^{t} i(\tau)\, d\tau$$

$$C = dq/dv$$

$$C = \frac{\epsilon A}{d} = \frac{\epsilon_0 \epsilon_r A}{d}$$

A

d

ϵ

$$\epsilon_0 = 8.854 \times 10^{-12} F/m$$

$$\epsilon_r = \epsilon/\epsilon_0$$

$$[Farad] = \frac{[Ampere][second]}{[Volt]} = \frac{[Coulomb]}{[Volt]}, \qquad F = \frac{A\ s}{V} = \frac{C}{V}$$

$$\mu F = 10^{-6} F$$

$$nF = 10^{-9}F$$

$$pF = 10^{-12}F$$

$$v(t) = sin(\omega t)$$

$$i(t) = C\frac{d\,v(t)}{dt} = C\frac{d\sin(\omega t)}{dt} = \omega C\ \ \cos(\omega t)$$

$$\omega = 2\pi f$$

$$\omega = 0$$

$$i(t) = \omega C \cos(\omega t)$$

$$\omega \to \infty$$

$$i(t) = \omega C \cos(\omega t) \to \infty$$

$$\Psi = N\Phi$$

N

$$v(t) = \frac{d\Psi(t)}{dt} = \frac{d\Psi}{di}\frac{di}{dt} = L\frac{di}{dt}, \qquad i(t) = \frac{1}{L}\int_{-\infty}^{t} v(\tau)d\tau = \frac{\Psi}{L}$$

$$\Psi = \int_{-\infty}^{t} v(\tau)\, d\tau$$

$$L = d\Psi/di$$

L

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

l

$\boldsymbol{\mu}$

$$[Henry] = \frac{[Volt][second]}{[Ampere]}, \qquad H = \frac{Vs}{A}$$

$$mH = 10^{-3} H$$

$$\mu H = 10^{-6} H$$

$$i(t) = sin(\omega t)$$

$$v(t) = L\frac{d\,i(t)}{dt} = L\frac{d\,\sin(\omega t)}{dt} = \omega L\ \cos(\omega t)$$

$$i(t) \to 0$$

$$Q = \int i \, dt$$

$$V_C = Q/C$$

$$\Psi = \int v \, dt$$

$$i = \Psi / L$$

$$\left[\sqrt{\frac{L}{C}}\right] = \sqrt{\frac{[Henry]}{[Farad]}} = \sqrt{\frac{[Volt]\ [second]}{[Ampere]}\frac{[Volt]}{[second]\ [Ampere]}} = \frac{[Volt]}{[Ampere]} = [Ohm]$$

$$\left[\sqrt{LC}\right] = \sqrt{[Henry]\ [Farad]} = \sqrt{\frac{[Volt]\ [second]}{[Ampere]}\frac{[Ampere]\ [second]}{[Volt]}} = [second]$$

G

Resistor	$i = v/R = Gv$	$v = Ri = i/G$
Inductor	$i = \int v\,dt/L$	$v = L\,di/dt$
Capacitor	$i = C\,dv/dt$	$v = \int i\,dt/C$

N_1

N_2

$$v_1(t) = \frac{d\Psi_1}{dt} = N_1 \frac{d\Phi}{dt}, \qquad v_2(t) = \frac{d\Psi_2}{dt} = N_2 \frac{d\Phi}{dt}$$

$$\frac{v_2}{v_1} = \frac{N_2}{N_1}$$

$$p_1 = v_1 i_1 = p_2 = v_2 i_2,$$

$$\frac{i_1}{i_2} = \frac{v_2}{v_1} = \frac{N_2}{N_1}$$

$$v_2 = \frac{N_2}{N_1} v_1, \qquad i_2 = \frac{N_1}{N_2} i_1$$

$$R_L$$

$$v_2/i_2 = R_2$$

$$\frac{v_1}{i_1} = \frac{(N_1/N_2)v_2}{(N_2/N_1)i_2} = \left(\frac{N_1}{N_2}\right)^2 \frac{v_2}{i_2} = \left(\frac{N_1}{N_2}\right)^2 R_L = R'_L$$

$$p(t) = \frac{dw}{dt} = \frac{dw}{dq}\ \frac{dq}{dt} = v(t)\, i(t)$$

$p(t)$

T

$$w = \int_0^T p(t)\, dt = \int_0^T v(t)\, i(t)\, dt$$

$$w > 0$$

$$w < 0$$

$$i(t) = v(t)/R$$

$$p(t) = v(t)\ i(t) = \frac{v^2(t)}{R} = i^2(t)R$$

$0 \sim T$

$$w = \int_0^T p(t)dt = \int_0^T v(t)\ i(t)dt = \frac{1}{R}\ \int_0^T v^2(t)\ dt = R\ \int_0^T i^2(t)\ dt$$

$$p(t) = d\,w/dt$$

$$v(t) = V$$

$$I = V/R$$

$$P = VI = \frac{V^2}{R} = I^2 R$$

$$w = \int_0^T P\,dt = PT = VIT = \frac{V^2}{R}\,T = I^2RT$$

$$v(t) = V_p \sin(\omega t)$$

$$i(t) = v(t)/R = V_p \sin(\omega t)/R$$

$$T = 1/f = 2\pi/\omega$$

$$w = \frac{1}{R}\int_0^T v^2(t)dt = \frac{V_p^2}{R}\int_0^T \sin^2(\omega t)dt = \frac{V_p^2}{2R}\int_0^T [1-\cos(2\omega t)]dt = \frac{V_p^2}{2R}\,T$$

$$V_{rms}$$

$$\frac{\mathbf{V}_{rms}^2}{R}T = \frac{1}{R}\int_0^T v^2(t)dt = \frac{V_p^2}{2R}T$$

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T v^2(t)dt} = \frac{V_p}{\sqrt{2}} = 0.707\, V_p$$

V_p

$$V_{rms} = V_p/\sqrt{2}$$

$$\sin\alpha\cos\alpha = \frac{1}{2}\sin 2\alpha, \quad \sin^2\alpha = \frac{1}{2}[1-\cos(2\alpha)], \quad \cos^2\alpha = \frac{1}{2}[1+\cos(2\alpha)]$$

I_{av}

$$I_{av}T = Q = \int_0^T i(t)dt,$$

$$I_{av} = \frac{1}{T} \int_0^T i(t)dt$$

$$V_{av} = \frac{1}{T} \int_0^T v(t)dt$$

$$i(t) = I_p \sin(\omega t) = I_p \sin(2\pi f t) = I_p \sin(2\pi t/T)$$

$$T = 1/f$$

$T/2$

$$I_{av}$$

=

$$\frac{1}{T/2}\int_0^{T/2} i(t)\ dt = \frac{2}{T}\int_0^{T/2}\ I_p\ \sin(2\pi t/T)\ dt = -\frac{2}{T}\frac{T}{2\pi}I_p\ \cos(2\pi t/T)\Big|_0^{T/2}$$

$$\frac{I_p}{\pi}\left[\cos(0) - \cos(\pi)\right] = \frac{2}{\pi}\, I_p = 0.637\, I_p$$

$$w = \int_0^T p(t)dt = \int_0^T v(t)\ i(t)dt = \int_0^T v(t)\ C\frac{dv(t)}{dt}dt = C\int_0^V v\ dv = \frac{1}{2}CV^2$$

$$v(0) = 0$$

$$v(T) = V$$

$$i(t) = C\ dv(t)/dt = \omega C V_p\ \cos(\omega t)$$

$$T = 2\pi/\omega$$

$$w = \int_0^T v(t)\ i(t)dt = V_p^2 \omega C \int_0^T \sin(\omega t)\ \cos(\omega t)\,dt = \frac{V_p^2 \omega C}{2} \int_0^T \sin(2\omega t)dt = 0$$

$$w = \int_0^T p(t)dt = \int_0^T i(t)\ v(t)dt = \int_0^T i(t)\ L\frac{di(t)}{dt}dt = L\int_0^I i\ di = \frac{1}{2}LI^2$$

$$i(0) = 0$$

$$i(T) = I$$

$$i(t) = I_p \sin(\omega t)$$

$$v(t) = L\ di(t)/dt = LI_p\omega\ \cos(\omega t)$$

$$w = \int_0^T v(t)\ i(t)dt = I_p^2 \omega L \int_0^T \sin(\omega t)\ \cos(\omega t)\, dt = \frac{I_p^2 \omega L}{2} \int_0^T \sin(2\omega t) dt = 0$$

$\pi/2$

90°

$$v_C(t) = \sin(\omega t)$$

$$i_C = \omega C \cos(\omega t)$$

$$v_L(t) = \omega L \cos(\omega t)$$

$$i_L = \sin(\omega t)$$

$$w = \frac{1}{2}CV^2$$

$$[Farad][volt]^2 = \frac{[Ampere][second]}{[Volt]}[Volt]^2$$

$$[Ampere][Volt][second] = [Watt][second] = [Joule]$$

$$w = \frac{1}{2}LI^2$$

$$[Henry][Ampere]^2 = \frac{[Volt][second]}{[Ampere]}[Ampere]^2$$

$$[Volt][Ampere][second] = [Watt][second] = [Joule]$$

u

$$w = \frac{1}{2}mu^2, \qquad \frac{[kilogram][meter]^2}{[second]^2} = [Joule]$$

$$= 4.2$$

$$x = Cf = f/K$$

K

$$C = 1/K$$

$$w = \frac{1}{2} C f^2, \qquad \frac{[meter]}{[Newton]} [Newton]^2 = [meter][Newton] = [Joule]$$

$$w = \int_0^X f(x)\,dx$$

$$f(x)$$

X

$$f = Kx$$

$$x = Cf$$

$$w = \int_0^X f(x)\ dx = \int_0^F f\ C\ df = \frac{1}{2}CF^2$$

$$w = \int_0^T f\ v(t)\ dt = \int_0^T m\frac{dv}{dt}\ v(t)\ dt = m\int_0^V v\ dv = \frac{1}{2}mV^2$$

k

$$f = ma$$

$$m\frac{d^2}{dt^2}x(t) + kx(t) = 0,$$

$$\frac{d^2}{dt^2}x(t) + \frac{k}{m}x(t) = \ddot{x} + \omega_n^2 x(t) = 0$$

$$x(t)$$

$$\omega_n = \sqrt{k/m} = 1/\sqrt{cm}$$

$$c = 1/k$$

$$i_C(t) = C\frac{dv(t)}{dt}, \quad v(t) = L\frac{di_L(t)}{dt}$$

$i_C(t)$

$$i_L(t)$$

$$i_C(t) + i_L(t) = 0$$

$$i_C(t) = -i_L(t)$$

$$v(t) = L\frac{d}{dt}i_L(t) = L\frac{d}{dt}\ (-C\frac{dv}{dt}),$$

$$\frac{d^2v(t)}{dt^2} + \frac{1}{LC}v(t) = \ddot{v}(t) + \omega_n^2 v(t) = 0$$

$$v(t) = e^{st}$$

$$\ddot{v}(t) = s^2 e^{st}$$

$$(s^2 + \omega_n^2)e^{st} = 0,$$

$$s^2 + \omega_n^2 = 0$$

$$s = \pm j\omega_n$$

$$v(t) = e^{j\omega_n t} = \cos \omega t \pm j \sin \omega_n t$$

$$x(t) = \sin(\omega_n t) = 0$$

$$\dot{x}(t) = \omega_n \ \cos(\omega_n t) = \pm\omega_n$$

$$x(t) = \sin(\omega_n t) = \pm 1$$

$$\dot{x}(t) = \omega_n \ \cos(\omega_n t) = 0$$

$$v(t) = \sin(\omega_n t) = 0$$

$$W_C = Cv^2/2 = 0$$

$$i(t) = C\dot{v}(t) = \omega_n C \ \cos(\omega_n t) = \pm\omega_n C$$

$$W_L = Li^2/2$$

$$v(t) = \sin(\omega_n t) = \pm 1$$

$$i(t) = C\dot{v}(t) = \omega_n C \ \cos(\omega_n t) = 0$$

$\dot{x}$

$$\frac{d^2x}{dt^2} + \frac{b}{m}\frac{dx}{dt} + \frac{k}{m}x = 0$$

$$\frac{d^2v}{dt^2} + \frac{R}{L}\frac{dv}{dt} + \frac{1}{LC}v = 0$$

$$p(t) = v(t)i(t) = v(t)\frac{d}{dt}Q(t)$$

$$w = \int_0^t P(\tau) d\tau = v(t)[Q(t) - Q(0)] = Cv^2(t)$$

$$Q(0) = 0$$

$$Q(t) = Cv(t)$$

$$W_C = Cv^2/2$$

$$Li^2/2 = 0$$

$$R = 0$$

$$\sum_k I_k = 0$$

$$\sum_k w_k = \sum_k V_k Q = 0, \qquad \sum_k V_k = 0$$

$$4 + 5 - 3 - 4 - 2 = 0$$

$$-12 + 3 + 4 + 5 = 0$$

$$V_2$$

V_0

I_2

R_1

R_2

$$I_2 = 3/2 = 1.5A$$

$$V_2 - 5 + 3 = 0, \qquad V_2 = 2V$$

$$R_2 = V_2/I_2 = 2V/1.5A = 1.33\Omega$$

$$2 - I_1 - I_2 = 2 - I_1 - 1.5 = 0, \qquad I_1 = 0.5A$$

$$R_1 = 5V/0.5A = 10\Omega$$

$$3 \times 2 + 5 - V_0 = 0, \qquad V_0 = 11V$$

$$V = V_1 + \cdots + V_n$$

$$IR_1 + \cdots + IR_n = I(R_1 + \cdots + R_n) = IR_s$$

$$\frac{I}{G_1} + \cdots + \frac{I}{G_n} = I\left(\frac{1}{G_1} + \cdots + \frac{1}{G_n}\right) = \frac{I}{G_s}$$

$$R_s = \frac{V}{I} = R_1 + \cdots + R_n$$

$$G_s = \frac{1}{R_s} = \frac{I}{V} = \frac{1}{1/G_1 + \cdots + 1/G_n}$$

V_k

R_k

$$V_k = IR_k = \frac{V}{R_s} R_k = V \frac{R_k}{R_1 + R_2 + \cdots + R_n}$$

$n = 2$

$$V_1 = V\frac{R_1}{R_1 + R_2}, \qquad V_2 = V\frac{R_2}{R_1 + R_2}$$

$$I = I_1 + \cdots + I_n$$

$$\frac{V}{R_1} + \cdots + \frac{V}{R_n} = V\left(\frac{1}{R_1} + \cdots + \frac{1}{R_n}\right) = \frac{V}{R_p}$$

$$VG_1 + \cdots + VG_n = V(G_1 + \cdots + G_n) = VG_p$$

$$R_p = \frac{V}{I} = \frac{1}{1/R_1 + \cdots + 1/R_n} = R_1||R_2||\cdots||R_n$$

$$G_p = \frac{1}{R_p} = \frac{I}{V} = G_1 + \cdots + G_n = \frac{1}{R_p} = \frac{1}{R_1} + \cdots + \frac{1}{R_n}$$

$$R_p = R_1||R_2 = \frac{1}{1/R_1 + 1/R_2} = \frac{R_1\ R_2}{R_1 + R_2}$$

I_k

$$I_k = \frac{V}{R_k} = \frac{IR_p}{R_k} = I\frac{1/R_k}{1/R_1 + 1/R_2 + \cdots + 1/R_n} = I\frac{G_k}{G_1 + G_2 + \cdots + G_n}$$

$$I_1 = I\frac{G_1}{G_1 + G_2} = I\frac{1/R_1}{1/R_1 + 1/R_2} = I\frac{R_2}{R_1 + R_2}$$

$$I_2 = I\frac{G_2}{G_1 + G_2} = I\frac{1/R_2}{1/R_1 + 1/R_2} = I\frac{R_1}{R_1 + R_2}$$

$$v = v_1 + v_2 + \cdots + v_n = L_1 \frac{di}{dt} + \cdots + L_n \frac{di}{dt} = (L_1 + L_2 + \cdots + L_n) \frac{di}{dt} = L_s \frac{di}{dt}$$

$$L_s = L_1 + L_2 + \cdots + L_n$$

$$i = i_1 + i_2 + \cdots + i_n = \frac{1}{L_1} \int v \, dt + \cdots + \frac{1}{L_n} \int v \, dt = \left(\frac{1}{L_1} + \cdots + \frac{1}{L_n} \right) \int v \, dt = \frac{1}{L_p} \int v \, dt$$

$$\frac{1}{L_p} = \frac{1}{L_1} + \cdots + \frac{1}{L_n}$$

$$i = i_1 + i_2 + \cdots + i_n = C_1 \frac{dv}{dt} + \cdots + C_n \frac{dv}{dt} = (C_1 + C_2 + \cdots + C_n) \frac{dv}{dt} = C_p \frac{dv}{dt}$$

$$C_p = C_1 + C_2 + \cdots + C_n$$

$$v = v_1 + v_2 + \cdots + v_n = \frac{1}{C_1} \int i \, dt + \cdots + \frac{1}{C_n} \int i \, dt = \left(\frac{1}{C_1} + \cdots + \frac{1}{C_n} \right) \int i \, dt = \frac{1}{C_s} \int i \, dt$$

$$\frac{1}{C_s} = \frac{1}{C_1} + \cdots + \frac{1}{C_n}$$

$$v = Ri = i/G$$

$$i = v/R = Gv$$

$$v = L\ di/dt$$

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

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

$$i = C\ dv/dt$$

$$R_s = R_1 + R_2$$

$$1/G_s = 1/G_1 + 1/G_2$$

$$L_s = L_1 + L_2$$

$$1/C_s = 1/C_1 + 1/C_2$$

$$1/R_p = 1/R_1 + 1/R_2$$

$$G_p = G_1 + G_2$$

$$1/L_p = 1/L_1 + 1/L_2$$

$$C_p = C_1 + C_2$$

i_1

i_2

$$i_1 = \frac{R_2}{R_1 + R_2} i, \quad i_2 = \frac{R_1}{R_1 + R_2} i$$

$$i_1 = \frac{C_1}{C_1 + C_2} i, \quad i_2 = \frac{C_2}{C_1 + C_2} i$$

$$i_1 = \frac{L_2}{L_1 + L_2} i, \quad i_2 = \frac{L_1}{L_1 + L_2} i$$

$$v_1 = \frac{R_1}{R_1 + R_2} v, \quad v_2 = \frac{R_2}{R_1 + R_2} v$$

$$v_1 = \frac{C_2}{C_1 + C_2} v, \quad v_2 = \frac{C_1}{C_1 + C_2} v$$

$$v_1 = \frac{L_1}{L_1 + L_2} v, \quad v_2 = \frac{L_2}{L_1 + L_2} v$$

I_0

$$I = V_0/R_L$$

$$V = I_0 R_L$$

$$R_L = 0$$

$$V = R_L I = 0 \neq V_0$$

$$R_L = \infty$$

$$I = V/R_L = V/\infty = 0 \neq I_0$$

R_0

$$IR_0$$

$$V = V_0 - IR_0 < V_0$$

(V_0, R_0)

$$\begin{cases} \text{Source:} \quad V = V_0 - IR_0 \qquad (I = 0, \;\; V = V_0), \qquad (V = 0, \;\; I = V_0/R_0) \\ \text{load:} \quad V = R_L I \end{cases}$$

$$\begin{cases} I = V_0/(R_0 + R_L) \\ V = R_L I = V_0\, R_L/(R_0 + R_L) \end{cases}$$

$$R_0 = 0$$

$$V = V_0$$

$$R_0 > 0$$

$$R_L \downarrow \Longrightarrow I \uparrow \Longrightarrow R_0 I \uparrow \Longrightarrow V \downarrow$$

$$V_0 = 1.5V$$

V/R_0

$$I = I_0 - V/R_0 < I_0$$

(I_0, R_0)

$$\begin{cases} \text{Source:} \quad I = I_0 - V/R_0 \qquad (I = 0, \ \ V = R_0 I_0), \qquad (V = 0, \ \ I = I_0) \\ \text{Load:} \quad I = V/R_L \end{cases}$$

$$\begin{cases} V = I_0 R_0 R_L/(R_0 + R_L) = I_0 \ R_0 || R_L \\ I = V/R_L = I_0 R_0/(R_0 + R_L) \end{cases}$$

$$R_0 = \infty$$

$$I = I_0$$

$$R_0 < \infty$$

I_L

$$R_L \uparrow \Longrightarrow V \uparrow \Longrightarrow V/R_0 \uparrow \Longrightarrow I \downarrow$$

V_0, R_0

$$V = V_0 - R_0 I = R_0(V_0/R_0 - I)$$

$$(I_0, R_0')$$

$$V = R_0'(I_0 - I) = R_0' I_0 - R_0' I$$

$$R_0 = R_0'$$

$$V_0 = I_0 R_0$$

$$(I_0 = V_0/R_0,\ R_0)$$

$(V_0 = I_0 R_0',\ R_0')$

$$I_0 = V_0/R_0$$

$$R_0 = \frac{|\Delta V|}{|\Delta I|}$$

$$\Delta V$$

ΔI

	Open circuit ($I = 0$)	Short circuit ($V = 0$)
Voltage Source	$V_{oc} = V_0$	$I_{sc} = V_0/R_0$
Current Source	$V_{oc} = I_0 R_0$	$I_{sc} = I_0$

$$\frac{\text{open-circuit voltage}}{\text{short-circuit current}} = \frac{V_{oc}}{I_{sc}} = \left\{ \begin{array}{cc} V_0/(V_0/R_0) & \text{(voltage source)} \\ (I_0R_0)/I_0 & \text{(current source)} \end{array} \right\} = R_0$$

V_i

I_i

$$i = 1, 2$$

$$(V_1, I_1)$$

(V_2, I_2)

$$R_1 = \infty$$

$$R_2 = 0$$

$$V_0 = 10V$$

$$R_0 = 10\Omega$$

$$I_0 = V_0/R_0 = 1A$$

$$R_L = 40\Omega$$

$$V_L = 8V$$

$$I_L = 0.2A$$

$$I_0 = 1mA$$

$$R_0 = 8K\Omega$$

$$V_0 = I_0 R_0 = 8V$$

$$R_L = 2K\Omega$$

$$V_L = 1.6V$$

$$I_L = 0.8mA$$

$$W = VI$$

$$W = -VI$$

$$V_0 = 5\,V$$

$$R = 5\Omega$$

$$I = V/R = 1\,A$$

$$W_R = I^2 R = V^2/R = IV = 5$$

$$W_V = -IV = -5$$

$$W_V$$

$$I_0 = 1A$$

$$V_0 = 2V$$

$$R = 3\Omega$$

$$2V/3\Omega = 2/3A$$

$$I_v = 1 - 2/3 = 1/3A$$

$$P_R = V_0^2/R = 4/3\ W$$

$$P = V_0 I_V = 2/3\ W$$

$$P = V_0 I_0 = 2\ W$$

$$(2/3 + 4/3 = 2)$$

$$I_0 = 1$$

$R_0 = 1\ M\Omega$

$$V_0 = 1000\ V$$

V_{oc}

$$V_0 = V_{oc}$$

I_{sc}

$$R_0 = \frac{V_{oc}}{I_{sc}}$$

$$R_v$$

R_a

$$V_0 = 6V, R_0 = 100\Omega, R_v = 10,000\Omega, R_a = 200\Omega$$

V_L

$$R_v \to \infty$$

$$R_L = 1k\Omega$$

$$V_L = 9.09V$$

$$R_L = 2k\Omega$$

$$V_L = 9.52V$$

$$V_0 \frac{1}{R_0 + 1} = 9.09, \qquad V_0 \frac{2}{R_0 + 2} = 9.52$$

$$V_0 = 9.09\, R_0 + 9.09, \qquad V_0 = 4.76\, R_0 + 9.52$$

$$R_0 = \frac{9.52 - 9.09}{9.09 - 4.76} = \frac{0.43}{4.33} \approx 0.1\ k\Omega$$

$$V_0 = 9.09\,R_0 + 9.09 = 9.09 \times 0.1 + 9.09 = 10\,V$$

R_{in}

$$v_{out}$$

R_{out}

$$v_{out} = Av_{in}$$

v_{in}

$$R_0 = R_{out}$$

$$R_L = R_{in}$$

$$P_L = I^2 R_L = \left(\frac{V_0}{R_0 + R_L} \right)^2 R_L = V_0^2 \frac{R_L}{(R_0 + R_L)^2}$$

P_L

$$P_L = V_0^2 \frac{R_L}{(R_0 + R_L)^2} \stackrel{R_0 \to 0}{\Longrightarrow} \frac{V_0^2}{R_L}$$

$$\frac{d}{dR_L}P_L(R_L) = V_0^2\frac{(R_0+R_L)^2 - 2R_L(R_0+R_L)}{(R_0+R_L)^4} = V_0^2\frac{R_0-R_L}{(R_0+R_L)^3} = 0$$

$$R_L = R_0$$

$$P_L = \frac{V_0^2}{(R_0 + R_L)^2} R_L \bigg|_{R_L = R_0} = \frac{V_0^2}{4R_0}$$

$$I = \frac{V_0}{R_0 + R_L} = \frac{V_0}{2R_0}$$

$$P_0 = V_0 I = \frac{V_0^2}{2R_0} = 2P_L$$

$$R_0 = R_L$$

$$R_L = x$$

$$R_0 = 2$$

P_0

$$\eta = \frac{P_L}{P_0} = \frac{I^2 R_L}{I^2(R_0 + R_L)} = \frac{R_L}{R_0 + R_L}$$

50%

η

$$R_L \gg R_0$$

$$R_L = 2R_0$$

$$\eta = \left. \frac{R_L}{R_0 + R_L} \right|_{R_L = 2R_0} = \frac{2}{3} > \frac{1}{2}$$

$$P_L = I^2 R_L = \frac{V_0^2}{(R_0 + R_L)^2} R_L = V_0^2 \frac{2R_0}{(R_0 + 2R_0)^2} = \frac{2V_0^2}{9R_0} < \frac{V_0^2}{4R_0}$$

R_T

$$P_L = V_L I$$

$$I = \frac{P_L}{V_L}$$

$$P_T = R_T I^2 = R_T \left(\frac{P_L}{V_L} \right)^2 = \frac{R_T \, P_L^2}{V_L^2}$$

P_T

kV