Homework 1

214 2023 Hemmer sections

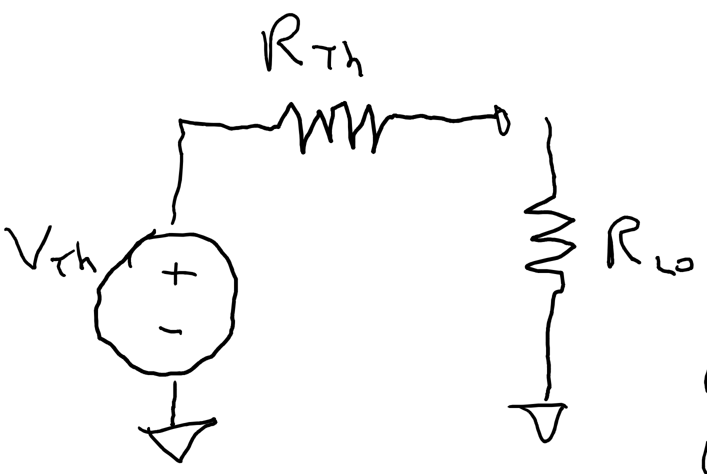
Problem 1

V_0 ϵ

- A USB power source has a nominal voltage of 5 V. The allowable voltage range is within 5 % of the nominal. Typical USB cables are in the range AWG 20—28.

P_0

- (a) Consider a 10 W USB supply. What is the smallest Thevenin equivalent voltage Vth and the largest Thevenin equivalent resistance, Rth, of this supply if it is to meet specs?
- (b) What is the smallest load resistor that can be driven by this supply without overloading?
- (c) What fraction of the supply power is dissipated in the load under this maximal load condition?
- (d) Why is this not optimized for maximum power transfer?
- (e) What is the maximum length of cable that can be used with a 5 W USB load, assuming copper AWG 20?



$V_L = V_0(1-\epsilon)$, $V_H = V_0(1+\epsilon)$

$P_0 = V_0 I_0$ $\quad V_{Th} = V_H$, $V_L = V_H - R_{Th} I_0$

$\text{rth} \to \frac{2\, e\, \text{v0}^2}{\text{p0}}$ $\quad R_{Th} = 0.25\ \Omega$ (a)

(b) $P_{Lo} = V_L I_0$, $R_{Lo} = \frac{V_L}{I_0} = 2.375\ \Omega$

(c) $P_s = V_{Th} I_0$, Fraction $= P_{Lo}/P_s = \frac{1-e}{1+e} = 90.5\%$

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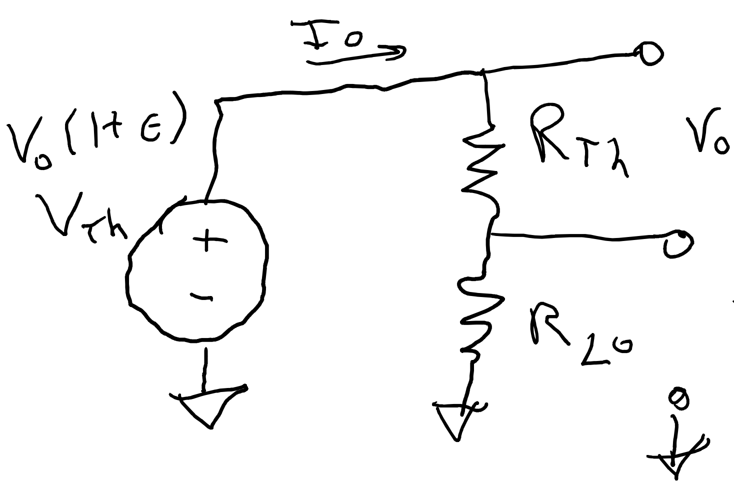
check part (c)



$$P_{V_{th}} = I_o V_o(1+\epsilon)$$

$$R_{Th} = 2\epsilon \frac{V_o^2}{P_o} = 2\epsilon \frac{V_o}{I_o}$$

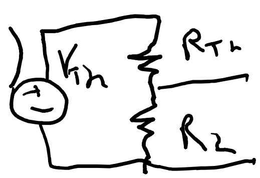
$$P_{R_{Th}} = I_o^2 R_{Th} \rightarrow 2\epsilon V_o I_o$$

$$R_{Lo} = \frac{V_o(1-\epsilon)}{I_o}$$

$$P_L = I_o^2 R_{Lo} \rightarrow V_o I_o (1-\epsilon)$$

$R_{Th} = 0.25\,\Omega$, $R_{Lo} = 2.375\,\Omega$

(d)



$V_o = V_{Th}$ — $I_o = 0$

$= \frac{1}{2} V_{Th}$ — $I_o = I_{max}$

USB voltage can only be ±5% not 50%

Problem 1

V_o $\quad\quad$ ϵ

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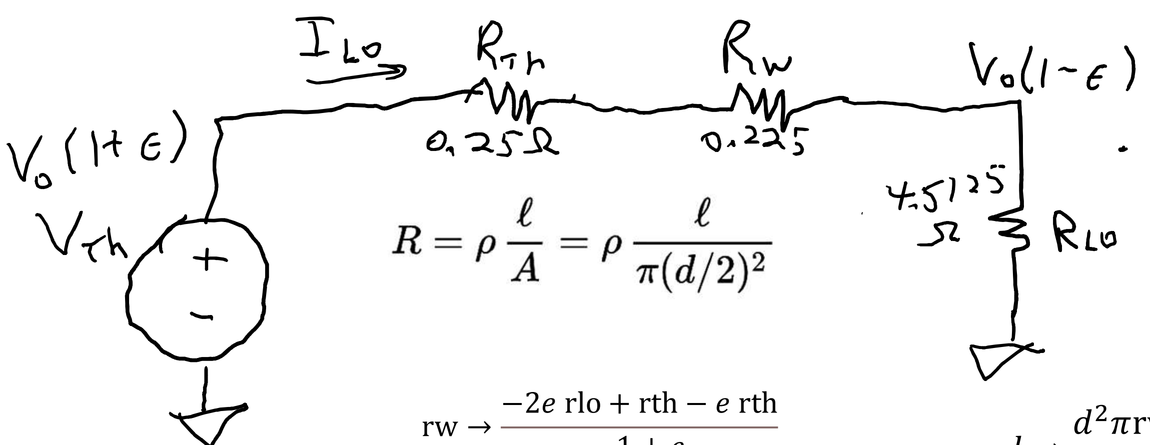

$$R = \rho \frac{\ell}{A} = \rho \frac{\ell}{\pi (d/2)^2}$$

$$\text{rw} \to \frac{-2e\ \text{rlo} + \text{rth} - e\ \text{rth}}{-1+e}$$

$$l \to \frac{d^2 \pi \text{rw}}{4p}$$

$$P_{Lo} = I_{Lo} V_o(1-\epsilon) \to I_{Lo} = \frac{P_{Lo}}{V_o(1-\epsilon)}$$

$$V_{Lo} = V_o(1-\epsilon) = \frac{R_{Lo}(V_o(1+\epsilon))}{R_{Th} + R_W + R_{Lo}}$$

$$V_o(1-\epsilon) = I_{Lo} R_{Lo} \Rightarrow R_{Lo} = \frac{V_o(1-\epsilon)}{I_{Lo}} = 4.5125\ \Omega$$

$I_{Lo} = 1.053$ A

Solve for $R_W = 0.225\ \Omega$

Solve for $l = 6.575$ m

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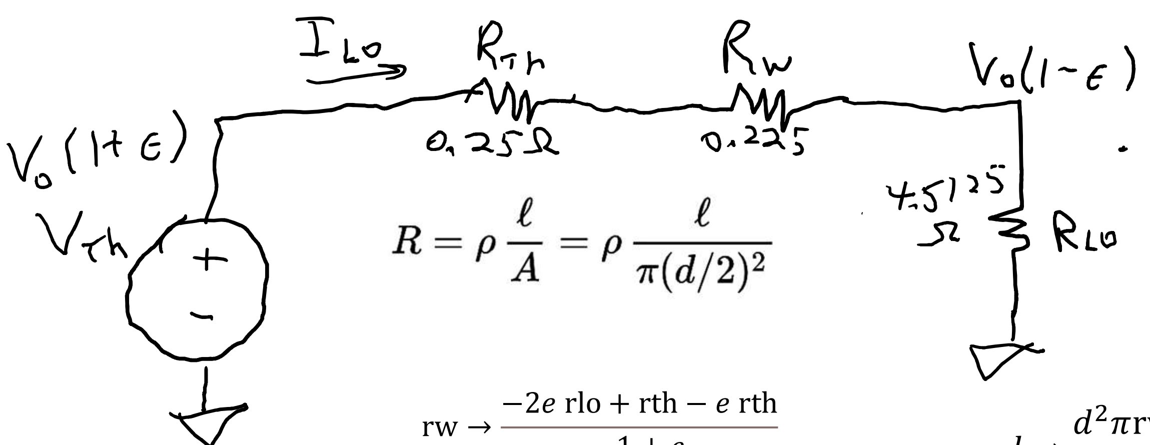

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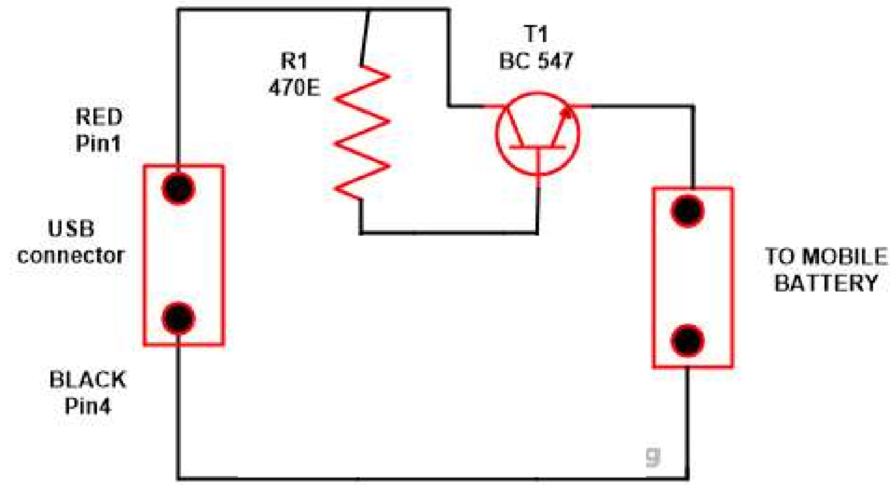
```
"problem 1"
"part a"
values={v0→5,e→0.05,p0→10,plo→5}
assign={vl->v0(1-e),vh→v0(1+e),i0→p0/v0}
as2={vth→vh}
s1=Solve[vl==vh-rth i0,rth]/.as2
Factor[s1/.assign]
s1/.assign/.values
"part b"
rlo→vl/i0/.assign/.values
"part c"
fraction→(vl i0)/(vth i0)/.as2/.assign
fraction→(vl i0)/(vth i0)/.as2/.assign/.values
"part e"
as3=rlo→v0 (1-e)/ilo/.ilo→plo/(v0 (1-e))
s2=Solve[v0(1-e)==v0(1+e)(rlo/(rlo+rw +rth)),rw]
s2=s2/.as3/.s1/.as2/.assign
Expand[Factor[s2]]
s2/.values
values2={p→1.72 10^-8,d→0.8 10^-3}
s4=Solve[rw==p l/(Pi (d/2)^2),l]
```

Problem 2

- Consider the USB-powered mobile-battery charger circuit shown below. Assume the USB power supply is the newer 10 W version but the mobile battery is the older 2.5 W version. Assume the transistor beta is 100 and V_BE = 0.7 V. Take R1 = 470 Ω.
- (a) Sketch the equivalent circuit.
- (b) What is the maximum voltage to which the mobile battery that can be charged with this circuit.
- (c) What is the charging current as a function of mobile battery voltage?
- (d) What percent of the power generated by the USB supply is being stored in the mobile battery, as a function of mobile battery voltage? Note that energy lost due to the mobile battery resistance does not count toward power stored in the battery.



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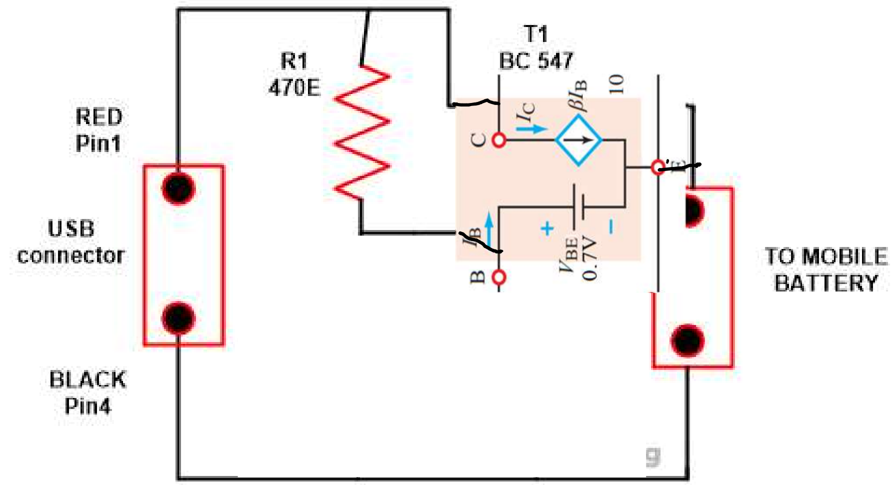
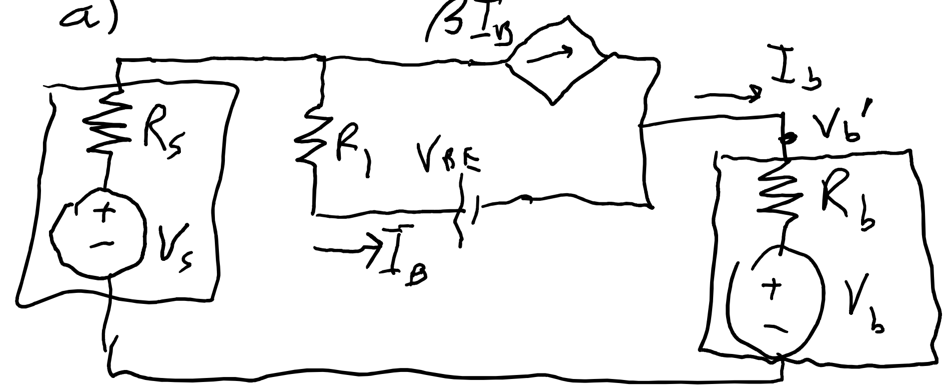


a)



b) $V_s - V_{BE} = V_b^{max} = 5.25 - 0.7 = 4.55$

c) $V_s = V_0(1+\epsilon) = V_b$, $I_s^{max} R_s = V_0(1+\epsilon) - V_0(1-\epsilon) = 2\epsilon V_0$ $\quad V_0 = 5V$, $\epsilon = 5\%$

$I_s^{max} = P_0 / V_0$, $R_s = \frac{2\epsilon V_0}{P_0/V_0} = 2\epsilon \frac{V_0^2}{P_0}$, $P_{0s} = 10\,W$, $P_{0b} = 2.5\,W$

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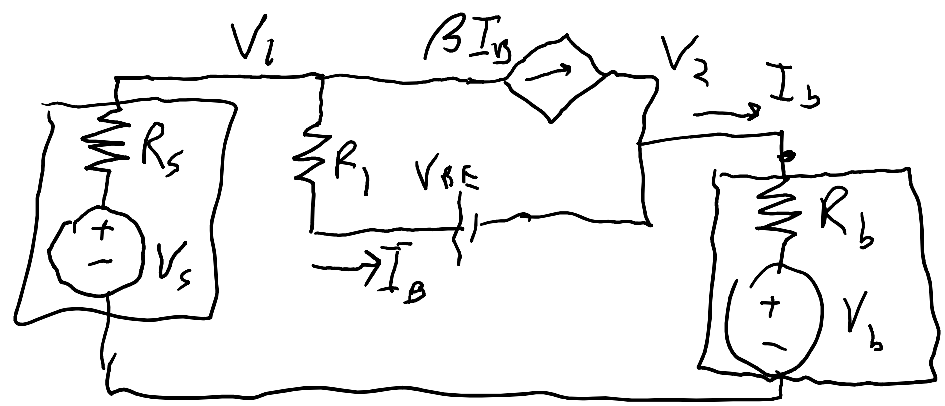
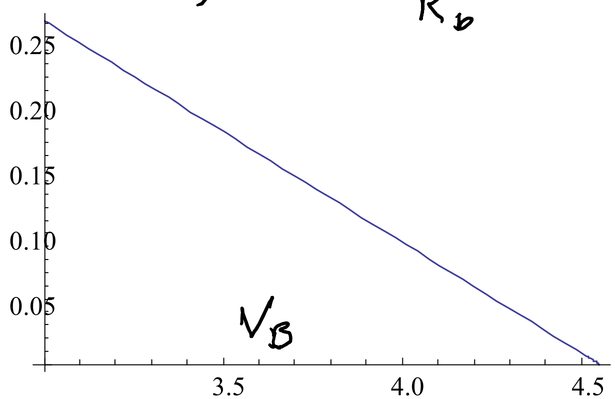


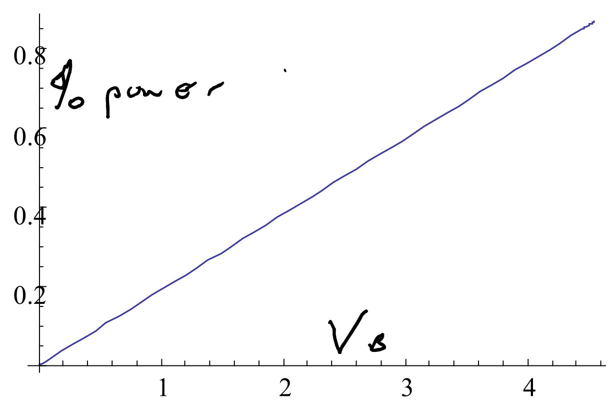
$$\frac{V_1 - V_s}{R_s} + \frac{V_1 - (V_{BE} + V_2)}{R_1} + \beta I_B = 0, \quad I_B = \frac{V_1 - (V_{BE} + V_2)}{R_1}, \quad I_b = \frac{V_2 - V_b}{R_b}$$

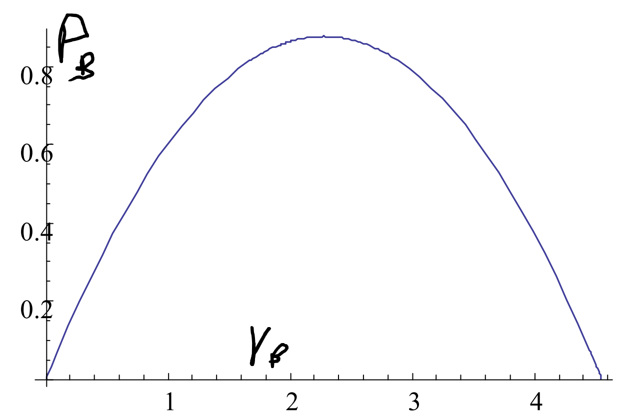
$$-\beta I_B - I_B + \frac{V_2 - V_b}{R_b} = 0$$

(d) $I_b V_b / I_s V_s$ - $I_s = \frac{V_1 - V_s}{R_s}$

(c)







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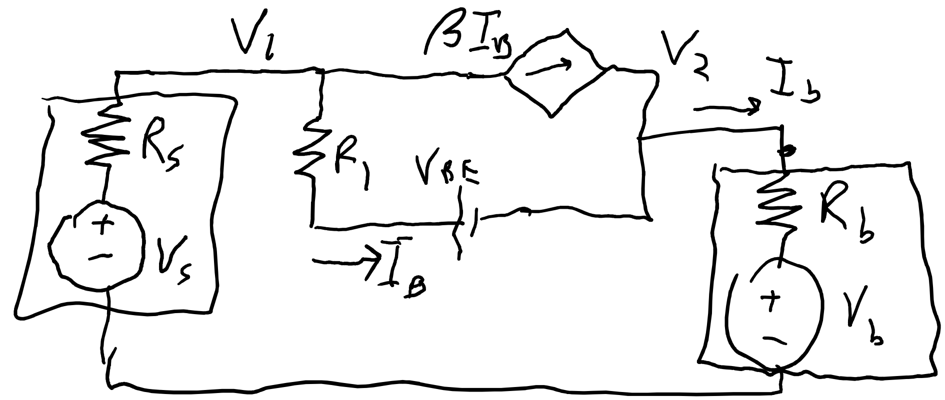


```
"problem 2"
values={v0→5,e→0.05,ps→10,pb→2.5,b→100,vbe→0.7,r1→470}
assign={rs→2 e v0^2/ps,rb→2 e v0^2/pb,vs→v0(1+e)}
resistances->{rs,rb}/.assign/.values
e1=(v1-vs)/rs+ibb+b ibb==0
e2=ibb==(v1-(vbe+v2))/r1
e3=(v2-vb)/rb-ibb-b ibb==0
eqn={e1,e2,e3}
vec={v1,v2,ibb}
s1=Solve[eqn,vec]
e5=ib==(v2-vb)/rb/.s1
e5=ib==(v2-vb)/rb/.s1/.assign
s2=Solve[e5,ib]
s2=s2/.values
Plot[ib/.s2,{vb,3,4.55}]
"power check"
c1={prs→(v1-vs)^2/rs,prb→(v2-vb)^2/rb,pr1->(v1-(vbe+v2))^2/r1}
c2={pvs→-vs (vs-v1)/rs,pvb→vb (v2-vb)/rb,pt→-(v2-v1)b ibb}
c3={c1,c2}/.s1/.assign/.values
-(pvb/pvs)/.Flatten[c3]
Plot[-(pvb/pvs)/.Flatten[c3],{vb,0,4.55}]
Plot[pvb/.Flatten[c3],{vb,0,4.55}]
Manipulate[{c1,c2}/.s1/.assign/.values/.vb→vbm,{{vbm,4},0,4.55}]
Manipulate[{(prs+prb+pr1),(pvs+pvb+pt)}/.Flatten[{c1,c2}]/.s1/.assign/.values/.vb→vbm,{{
vbm,4},0,4.55}]
```

Problem 3

- The transistor circuit shown below is known as a Darlington pair. In this device the input transistor has a high beta but a low power rating. The second transistor has a lower beta but a higher power rating. For simplicity assume both transistors have V_BE = 0.7 V. Take β1 = 100 and β2 = 10. Choose Rs = 1 kΩ and R_L = 100 Ω, R_E = 10 Ω. Assume V0 > Vin and Vin > V_BE
- (a) What is the voltage gain of the circuit?
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- (c) For an input voltage of Vin = 5 V and supply voltage V0 = 10 V, what is the power dissipated in each resistor?
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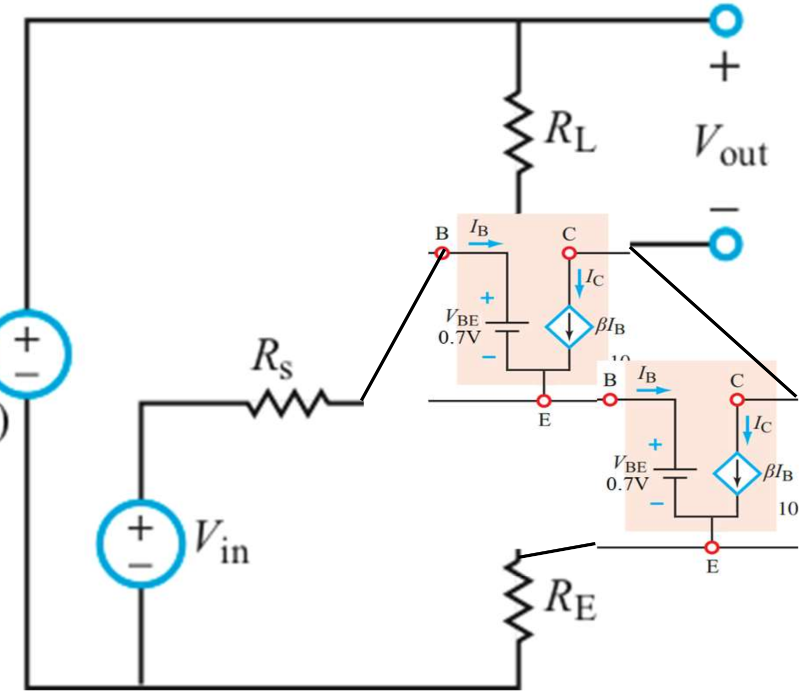

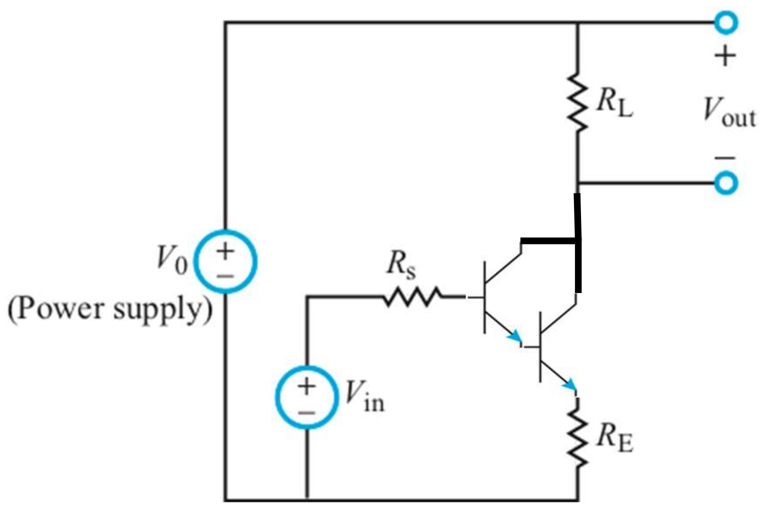

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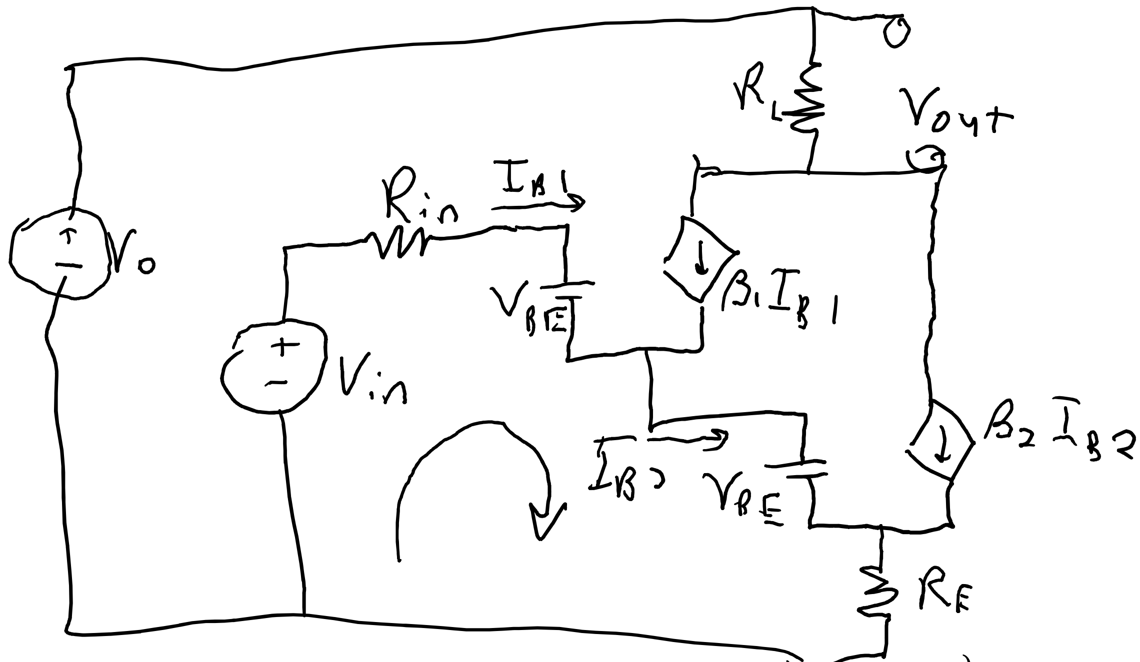

$$\frac{V_{out}}{R_L} = \beta_1 I_{B1} + \beta_2 I_{B2}$$

$$\left\{-\frac{\text{vout}}{\text{rl}} == \text{b1ib1} + \text{b2ib2}, (1+\text{b2})\text{ib2re} + \text{ib1rin} + 2\text{vbe} - \text{vin} == 0, \text{ib2} == (1+\text{b1})\text{ib1}\right\}$$

$$-V_{in} + R_{in} I_{B1} + V_{BE} + V_{BE} + R_E(1+\beta_2) I_{B2}$$

$$\text{vout} \to \frac{(\text{b1rl} + \text{b2rl} + \text{b1b2rl})(2\text{vbe} - \text{vin})}{\text{re} + \text{b1re} + \text{b2re} + \text{b1b2re} + \text{rin}}$$

$$I_{B2} = (1+\beta_1) I_{B1}$$

(a) $V_{out} = -9.1566(V_{in} - 1.4)$

(b) $V_{out} = -\dfrac{R_L(\beta_1+\beta_2+\beta_1\beta_2)(V_{in} - 2V_{BE})}{R_E(1+\beta_1+\beta_2+\beta_1\beta_2) + R_{in}} \xrightarrow{\beta \text{ large}} -\dfrac{R_L}{R_E}$

$V_{in} \gg V_{BE}$

$R_E > \dfrac{R_{in}}{\beta_1 \beta_2}$

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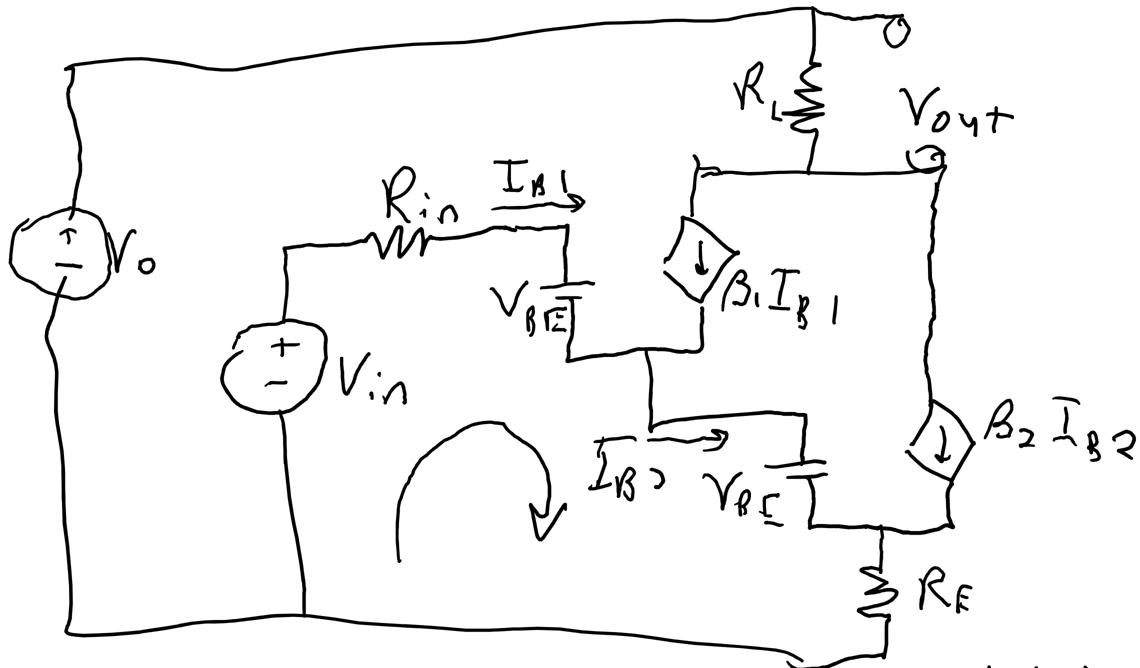

$$\left\{\left\{\left\{\begin{array}{c}\text{prin}\to 0.0000883724133510532 8,\\ \text{prl}\to 10.888365048983275,\\ \text{pre}\to 1.0907992561988544\end{array}\right\},\left\{\begin{array}{c}\text{pvin}\to -0.0014863748967795212,\\ \text{pv0}\to -3.299752270850537,\\ \text{pt1c}\to -0.8026498086287207,\\ \text{pt2c}\to -7.896589656745457\end{array}\right\},\\ \text{pt1v}\to 0.00020809248554913294,\\ \text{pt2v}\to 0.0210173410404624 27\right\}\right\}.$$

(c) & (d)

$P_{Rin} \sim 0$ $\quad P_{vin} \sim 0$

$P_{RL} = 10.9\ W$ $\quad P_{V0} = -3.3\ W$

$P_{RE} = 1.1\ W$ $\quad P_{T1} = -0.8\ W$

$P_{T2} = -7.9\ W$

Total power

Resistors 12 W, Sources −12 W

$\{11.97925267759548, -12.000061926150396\}$

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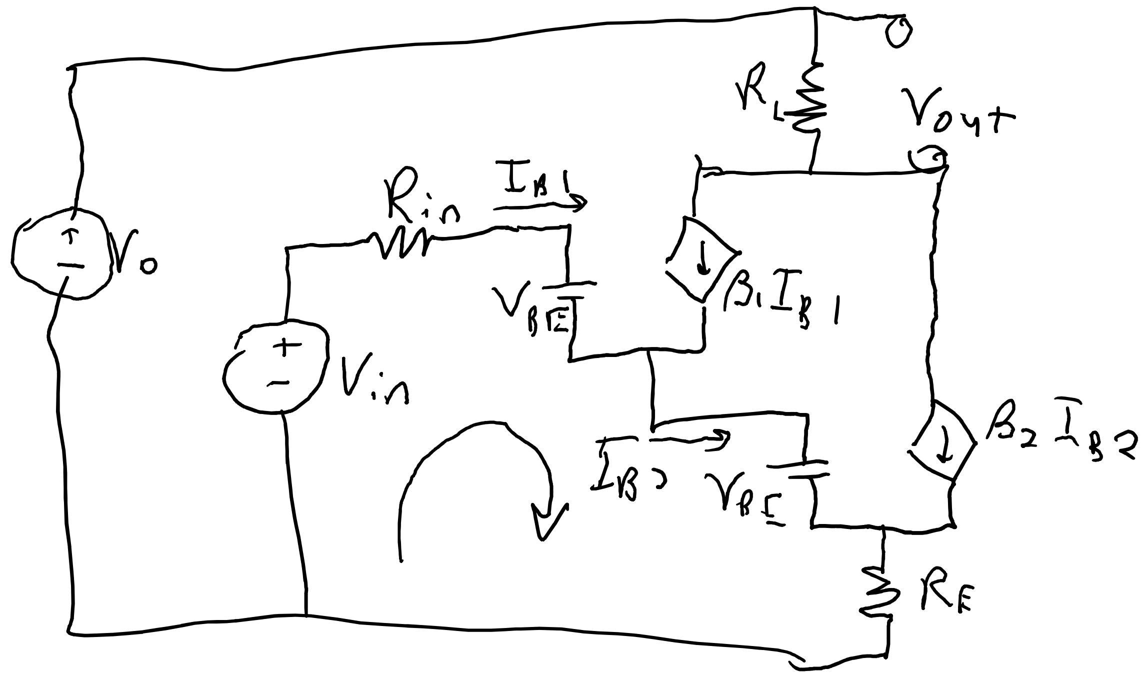
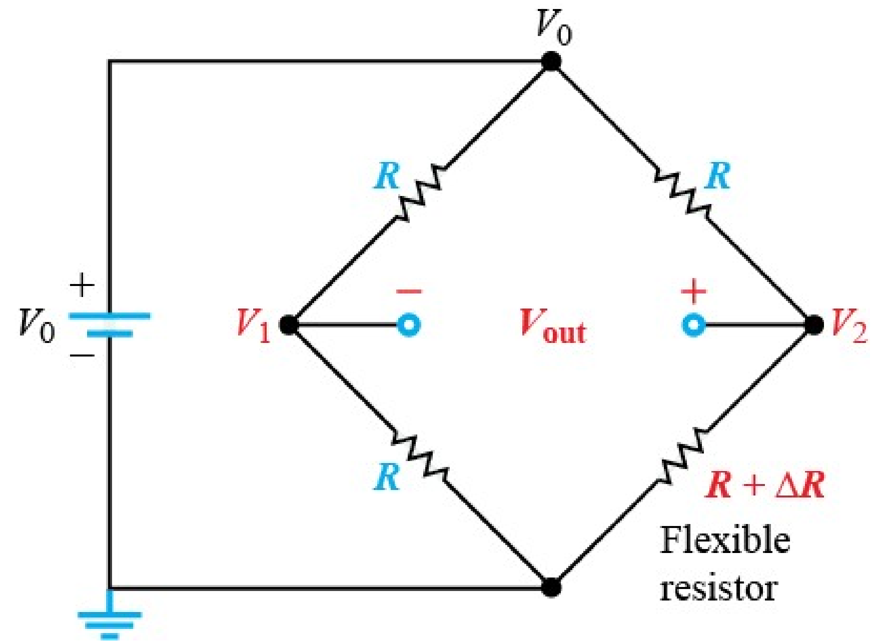



```
 "problem 3"
values={b1→100,b2→10,vbe→0.7,rin→1000,rl→100,re→10}
values2={vin→5,v0→10}
e1=vout /rl==b1 ib1+b2 ib2
e2=-vin+rin ib1+vbe+vbe+re ib2(1+b2)==0
e3=ib2==ib1(1+b1)
eqn={e1,e2,e3}
vec={ib1,ib2,vout}
s1=Solve[eqn, vec]
s1/.values
N[vout/.s1/.values]
p1={{prin→rin ib1^2,prl→rl (b1 ib1 +b2 ib2)^2,pre→re ((1+b2)ib2)^2},
  {pvin→-vin ib1,pv0→-v0 (b1 ib1+b2 ib2),pt1c→((v0-vout)-(vin-rin ib1-vbe))b1 ib1,pt2c→((v0-vout)-(vin-rin ib1-vbe-vbe))b2
ib2},pt1v→vbe ib1,pt2v→vbe ib2}
p2=p1/.s1/.values/.values2
{prin+prl+pre,pvin+pv0+pt1c+pt2c+pt1v+pt1v}/.Flatten[p2]
```

Problem 4

- Consider the Wheatstone bridge circuit shown below. Suppose you have a voltmeter that can measure in the range of 1 mV to 100 V, with an accuracy of 1 % from 10 mV to 100 V and 10 % from 1 to 10 mV.
- (a) What is the smallest percentage change you can measure in the flexible resistor?
- (b) Assuming you can measure the resistance directly with the voltmeter to 1 %, how much improvement do you get for V0 = 100 V.
- (c) If you treat the Vout terminal as a power supply, what is its Thevenin equivalent voltage and resistance as a function of the fractional change in the flexible resistor?
- (d) What is the power consumed in each resistor, the Thevenin equivalent resistor, and in the source when R = 100 Ω and the fractional resistor change is 1 %?



$$\frac{(V_1 - V_0)}{R} + \frac{V_1}{R} = 0$$

$$\frac{d\,v0}{2(2+d)} = V_{out} = \frac{V_0}{2}\left(\frac{\Delta}{2+\Delta}\right) \quad \text{equate to } V_{min}$$

$$\frac{(V_2 - V_0)}{R} + \frac{V_2}{R(1+\Delta)} = 0$$

$V_{min} = 0.1\,mV$ (1 − 10 mV)

0.1 mV (10 mV − 100 V)

$$d \to \frac{4\text{vmin}}{\text{v0} - 2\text{vmin}}$$

(a) $\Delta = \frac{4 V_{min}}{V_0 - 2V_{min}} \to 4\frac{V_{min}}{V_0}$

(b) $\frac{\Delta d}{\Delta} = \frac{0.01}{4 V_{min}/V_0} = 2500$

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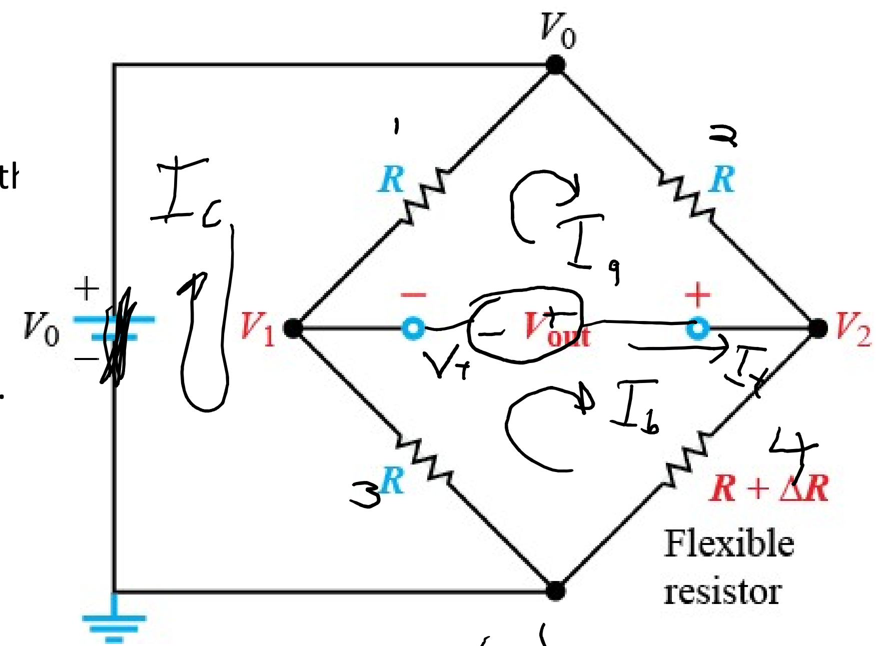


(c)

$$\frac{d\ \text{v0}}{2(2+d)} = V_{out} = \frac{V_0}{2}\left(\frac{\Delta}{2+\Delta}\right) = V_{Th}$$

$$R_{Th} = \frac{V_t}{I_t} \qquad \text{rth} \rightarrow \frac{(4+3d)r}{2(2+d)} \qquad R_{th} = R\,\frac{1+\frac{3}{4}\Delta}{1+\frac{1}{2}\Delta}$$

$$R(I_a - I_c) + R I_a + V_t = 0$$

$$R(I_b - I_c) - V_t + I_b R(1+\Delta) = 0$$

$$(I_c - I_a)R + (I_c - I_b)R = 0$$

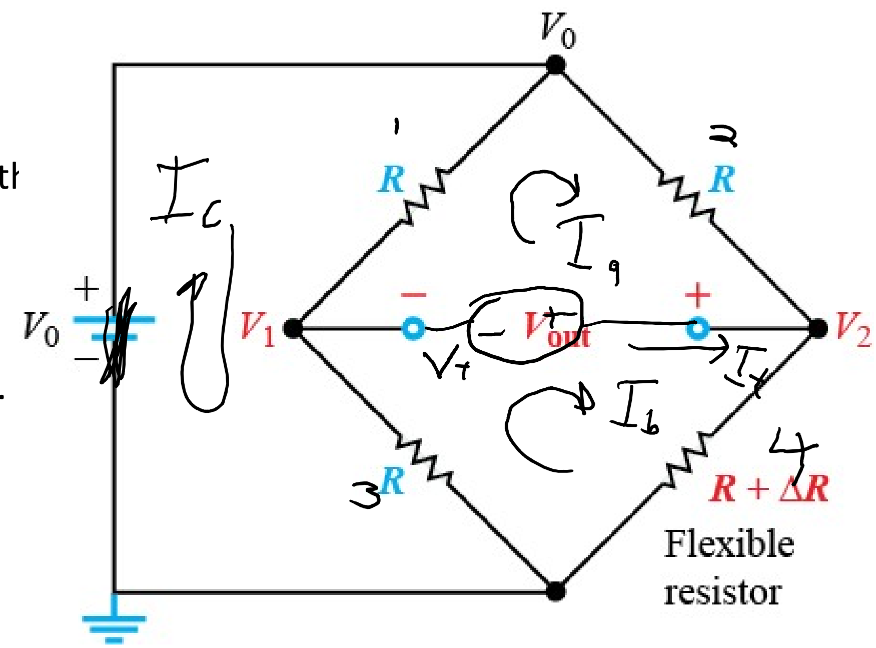
$$\left\{\left\{\left\{\begin{array}{l} \text{pr1} \rightarrow 0.024876084453447772, \\ \text{pr2} \rightarrow 0.025124223411264152, \\ \text{pr3} \rightarrow 0.024876084453447772, \\ \text{pr4} \rightarrow 0.024875468724023908 \end{array}\right\}, \begin{array}{l} \text{"psum"} \rightarrow 0.0997518610421836, \\ \text{"prth"} \rightarrow 0.09975186104218361, \\ \{\text{pt} \rightarrow 0.09975186104218361\} \end{array}\right\}\right\}$$

(d)

$P_1 = 24.9$ mW
$P_2 = 25.1$
$P_3 = 24.9$
$P_4 = 24.9$
$P_{sum} = P_{Th} = 10$ mV
$P_t = 10$ mW

Problem 4

- Consider the Wheatstone bridge circuit shown below. Suppose you have a voltmeter that can measure in the range of 1 mV to 100 V, with an accuracy of 1 % from 10 mV to 100 V and 10 % from 1 to 10 mV.
- (a) What is the smallest percentage change you can measure in the flexible resistor?
- (b) Assuming you can measure the resistance directly with the voltmeter to 1 %, how much improvement do you get for V0 = 100 V.
- (c) If you treat the Vout terminal as a power supply, what is its Thevenin equivalent voltage and resistance as a function of the fractional change in the flexible resistor?
- (d) What is the power consumed in each resistor, the Thevenin equivalent resistor, and in the source when R = 100 Ω and the fractional resistor change is 1 %?




```
"problem 4"
values={vmin→0.1/1000,v0→100,dd→0.01}
e1=(v1-v0)/r+v1/r==0
e2=(v2-v0)/r+v2/(r(1+d))==0
eqn={e1,e2}
vec={v1,v2}
s1=Solve[eqn,vec]
s2=(v2-v1)/.s1
Factor[s2]
s3=Solve[s2==vmin,d]
dd/d/.s3/.values
values2={r→10,vt→1,v0→100,d→0.01}
e3=(ia-ic)r+ia r+vt==0
e4=(ib-ic)r-vt+ib r (1+d)==0
e5=(ic-ia)r+(ic-ib) r==0
eqn={e3,e4,e5}
vec={ia,ib,ic}
s3=Solve[eqn,vec]
```

Useful tables

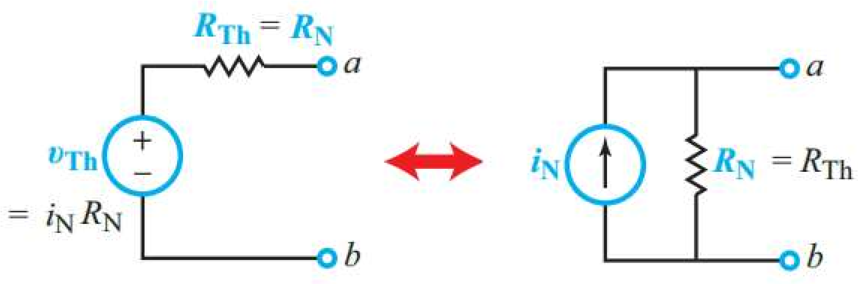
Material	Conductivity σ (S/m)	Resistivity ρ (Ω-m)
Conductors:		
Silver	6.17×10^{7}	1.62×10^{-8}
Copper	5.81×10^{7}	1.72×10^{-8}
Gold	4.10×10^{7}	2.44×10^{-8}
Aluminum	3.82×10^{7}	2.62×10^{-8}
Iron	1.03×10^{7}	9.71×10^{-8}
Mercury (liquid)	1.04×10^{6}	9.58×10^{-7}
Semiconductors:		
Carbon (graphite)	7.14×10^{4}	1.40×10^{-5}
Pure germanium	2.13	0.47
Pure silicon	4.35×10^{-4}	2.30×10^{3}
Insulators:		
Paper	$\sim 10^{-10}$	$\sim 10^{10}$
Glass	$\sim 10^{-12}$	$\sim 10^{12}$
Teflon	$\sim 3.3 \times 10^{-13}$	$\sim 3 \times 10^{12}$
Porcelain	$\sim 10^{-14}$	$\sim 10^{14}$
Mica	$\sim 10^{-15}$	$\sim 10^{15}$
Polystyrene	$\sim 10^{-16}$	$\sim 10^{16}$
Fused quartz	$\sim 10^{-17}$	$\sim 10^{17}$
Common materials:		
Distilled water	5.5×10^{-6}	1.8×10^{5}
Drinking water	$\sim 5 \times 10^{-3}$	~ 200
Sea water	4.8	0.2
Graphite	1.4×10^{-5}	71.4×10^{3}
Rubber	1×10^{-13}	1×10^{13}
Biological tissues:		
Blood	~ 1.5	~ 0.67
Muscle	~ 1.5	~ 0.67
Fat	~ 0.1	~ 10

AWG size designation	Diameter d (mm)
0	8.3
2	6.5
4	5.2
6	4.1
10	2.6
14	1.6
18	1.0
20	0.8

Useful equations – chapter 3

$$I = \frac{V}{R} = GV. \qquad RI = V_t,$$

$$R_{\mathrm{Th}} = \frac{v_{\mathrm{Th}}}{i_{\mathrm{sc}}} \qquad i_N = \frac{v_{\mathrm{Th}}}{R_{\mathrm{Th}}} \qquad R_N = R_{\mathrm{Th}}$$

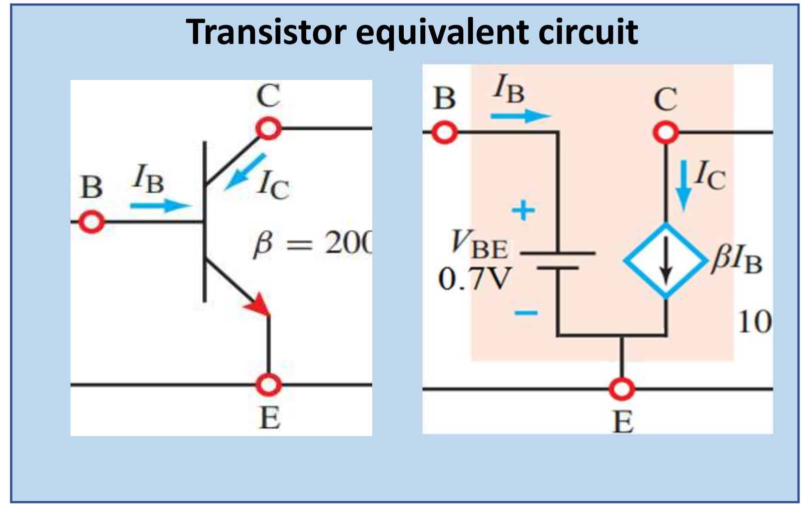


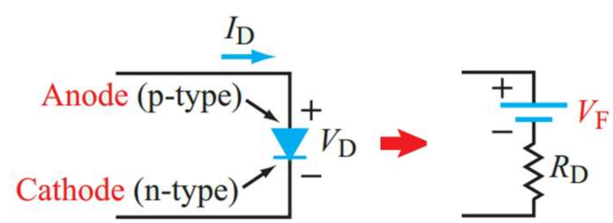
Thévenin equivalent circuit

Norton equivalent circuit

$i_{\mathrm{N}} = v_{\mathrm{Th}} / R_{\mathrm{Th}}$

$$R_L = R_s \qquad \text{(maximum power transfer).}$$





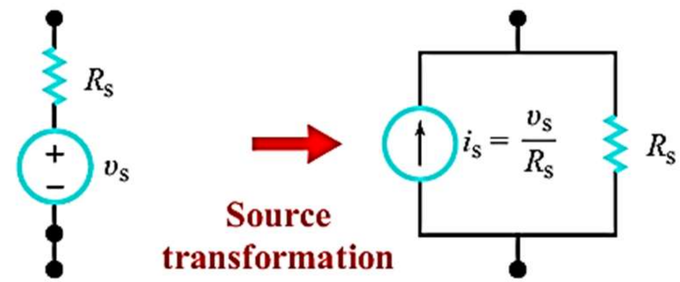
Useful equations – chapter 2 part 2

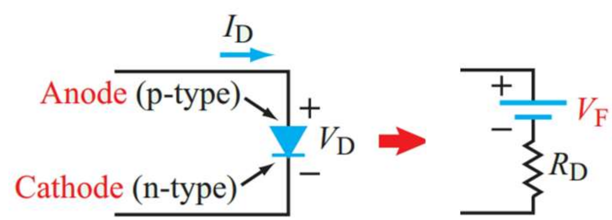
$$R_{eq} = \sum_{i=1}^{N} R_i \qquad \text{(resistors in series)},$$

$$\frac{1}{R_{eq}} = \sum_{i=1}^{N} \frac{1}{R_i} \qquad \text{(resistors in parallel)}.$$

$$G_{eq} = \sum_{i=1}^{N} G_i \qquad \text{(conductances in parallel)}.$$

$$v_i = \left(\frac{R_i}{R_{eq}} \right) v_s \qquad \text{(voltage division)}$$

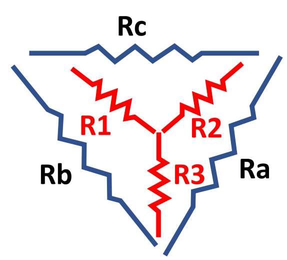




$$R_1 = \frac{R_b R_c}{R_a + R_b + R_c} \qquad R_a = \frac{R_1 R_2 + R_2 R_3 + R_1 R_3}{R_1}$$

$$R_2 = \frac{R_a R_c}{R_a + R_b + R_c} \qquad R_b = \frac{R_1 R_2 + R_2 R_3 + R_1 R_3}{R_2}$$

$$R_3 = \frac{R_a R_b}{R_a + R_b + R_c} \qquad R_c = \frac{R_1 R_2 + R_2 R_3 + R_1 R_3}{R_3}$$



$$R_1 = R_2 = R_3 = \frac{R_a}{3} \quad (\text{if } R_a = R_b = R_c),$$

$$R_a = R_b = R_c = 3R_1 \quad (\text{if } R_1 = R_2 = R_3).$$

Useful equations – chapter 2 part 1

$$i = \frac{v_a - v_b}{R} \qquad v = iR, \qquad G = \frac{1}{R} \quad \text{(S)}, \qquad i = \frac{v}{R} = Gv,$$

$$R = \frac{\ell}{\sigma A} \qquad R = \rho\frac{\ell}{A} = \rho\frac{\ell}{\pi(d/2)^2}$$

$$p = iv = i^2R = \frac{v^2}{R} \quad \text{(W)}. \qquad p = iv = Gv^2 \quad \text{(W)}.$$

$R=R_0(1+\alpha T)$, $\qquad R_D \approx \Delta V_D/\Delta I. \qquad R = \frac{dv}{di}$

$$\sum_{n=1}^{N} i_n = 0$$ **(KCL)** $$\sum_{n=1}^{N} v_n = 0 \quad \text{(KVL)},$$

Useful equations– chapter 1

$$p(t) = v(t) \cdot i(t)$$

$$i = \frac{dq}{dt} \text{ (A).}$$

$$W = \int_0^{\infty} p(t)dt$$

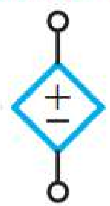
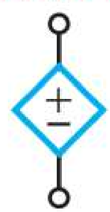
$$dq = i \ dt.$$

$$\sum_{k=1}^{n} p_k = 0,$$

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

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

$$W = \int_0^{\infty} \left(\frac{v^2}{R}\right) \mathrm{d}t$$

Dependent Sources	
Voltage-Controlled Voltage Source (VCVS)  $v_s = \alpha v_x$	Voltage-Controlled Current Source (VCCS)  $i_s = g v_x$
Current-Controlled Voltage Source (CCVS)  $v_s = r i_x$	Current-Controlled Current Source (CCCS)  $i_s = \beta i_x$