# CHAPTER 18

**18.1**

$$(a)\ T = Ab = \infty \quad | \quad A_v = \frac{1}{b} = 5 \quad | \quad FGE = 0$$

$$(b)\ \mathrm{A} = 10^{\frac{86}{20}} = 20000 \quad | \quad T = 20000(0.2) = 4000$$

$$A_v = \frac{A}{1+Ab} = \frac{20000}{1+4000} = 5.00 \quad | \quad FGE = \frac{100\%}{1+Ab} = \frac{100\%}{4001} = 0.025\%$$

$$(c)\ T = 10(0.2) = 2 \quad | \quad A_v = \frac{A}{1+Ab} = \frac{10}{1+2} = 3.33 \quad | \quad FGE = \frac{100\%}{1+2} = 33.3\%$$

**18.2**

$$(a)\ b = \frac{R_1}{R_1+R_2} = \frac{1k\Omega}{101k\Omega} = \frac{1}{101}$$

$$(b)\ T = Ab = 10^{\frac{80}{20}}\left(\frac{1}{101}\right) = 99.0 \quad | \quad A_v = \frac{A}{1+Ab} = \frac{10^4}{100} = 100$$

**18.3**

$$(a)\ b(s) = \frac{R_1}{R_1+R_2} = \frac{1k\Omega}{101k\Omega} = \frac{1}{101} \quad | \quad T(s) = Ab = 10^{\frac{80}{20}}\left(\frac{1}{101}\right) = 99.0$$

$$A_v = -\frac{R_2}{R_1}\frac{Ab}{1+Ab} = -\left(\frac{100k\Omega}{1k\Omega}\right)\left(\frac{99}{100}\right) = -99$$

**18.4**

$$b(s) = \frac{Z_1(s)}{Z_1(s)+Z_2(s)} = \frac{R}{R+\frac{1}{sC}} = \frac{s}{s+\frac{1}{RC}} = \frac{s}{s+10^4} \quad | \quad A = 10^{\frac{80}{20}} = 10^4$$

$$T(s) = Ab = \frac{10^4 s}{s+10^4} \quad | \quad A_v = -\frac{Z_2}{Z_1}\frac{Ab}{1+Ab} = -\left(\frac{1}{sRC}\right)\frac{\frac{10^4 s}{s+10^4}}{1+\frac{10^4 s}{s+10^4}} = -\left(\frac{1}{RC}\right)\left(\frac{1}{s+1}\right)$$

Instead of a pole at the origin, the integrator has a low-pass response with a pole a $w = 1$ rad/s.

**18.5**

$$S_A^{A_v} = \frac{A}{A_v}\frac{\P A_v}{\P A} \qquad A_v = \frac{A}{1+Ab}$$

$$\frac{\P A_v}{\P A} = \frac{(1+Ab)1 - Ab}{(1+Ab)^2} = \frac{1}{(1+Ab)^2} \qquad S_A^{A_v} = \frac{A}{\frac{A}{1+Ab}}\frac{1}{(1+Ab)^2} = \frac{1}{1+Ab} \approx \frac{1}{Ab}$$

$$S_A^{A_v} = \frac{1}{1+10^5(0.01)} = \frac{1}{1001}$$

$$\frac{\P A_v}{A_v} = S_A^{A_v}\frac{\P A}{A} = \frac{1}{1001}10\% = 9.99x10^{-3}\%$$

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**18.6**

$$A_V = \frac{A}{1+Ab} = \frac{A}{1+A} \quad | \quad \text{From Chapter 12, GE} = \frac{1}{1+Ab} = \frac{1}{1+A}$$

$$\frac{1}{1+A} \le 10^{-4} \rightarrow A \ge 9999 \quad | \quad \text{A} \ge 80 \text{ dB}$$

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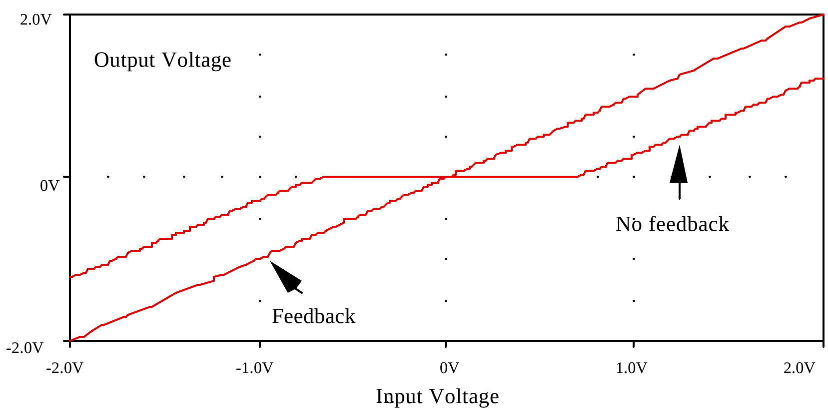
**18.7**

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*Problem 18.7 – Figure 18.74 - Class-B Amplifiers
VCC 3 0 DC 10
VEE 4 0 DC -10
VI 1 0 DC 0
Q1 3 1 2 NBJT
Q2 4 1 2 PBJT
RL1 2 0 2K
RID 1 7 100K
E1 5 0 1 7 5000
RO 5 6 100
Q3 3 6 7 NBJT
Q4 4 6 7 PBJT
RL2 7 0 2K
.MODEL NBJT NPN
.MODEL PBJT PNP
.OP
.DC VS -10 10 .01
.PROBE V(1) V(2) V(7)
.END
```

**18.8**

$$A_v = \frac{A}{1+A\beta} \quad | \quad \text{From Chapter 12, } GE = \frac{1}{1+A\beta} \cong \frac{1}{A\beta}$$

$$\frac{1}{\beta} = 200 \quad | \quad GE \cong \frac{200}{A} \le 0.002 \rightarrow A \ge \frac{200}{0.002} = 10^5 \quad | \quad A \ge 100\ dB$$

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**18.9** (a) Series-series feedback (b) Shunt-series feedback (c) Shunt-shunt feedback (d) Series-shunt feedback

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**18.10** (a) Series-shunt feedback (b) Shunt-series feedback (c) Series-series feedback (d) Shunt-shunt feedback

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**18.11** (a) Series-shunt and series-series feedback (b) Shunt-series and shunt-shunt and feedback

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**18.12** (a) Shunt-series and series-series feedback (b) Shunt-shunt and series-shunt feedback

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**18.13**

$$A = 10^{\frac{86}{20}} = 20000$$

$$(a)\ R_{\text{in}} = R_{id}(1+A\beta) \quad | \quad \text{For } \beta = 1,\ R_{\text{in}} = 40k\Omega(1+20000) = 800\ M\Omega$$

$$(b)\ R_{\text{in}} = \frac{R_{id}}{(1+A\beta)} \quad | \quad \text{For } \beta = 1,\ R_{\text{in}} = \frac{40k\Omega}{(1+20000)} = 2.00\ \Omega$$

$$(c)\ R_{\text{out}} = R_o(1+A\beta) \quad | \quad \text{For } \beta = 1,\ R_{\text{out}} = 1k\Omega(1+20000) = 20\ M\Omega$$

$$(d)\ R_{\text{out}} = \frac{R_o}{(1+A\beta)} \quad | \quad \text{For } \beta = 1,\ R_{\text{out}} = \frac{1k\Omega}{(1+20000)} = 50.0\ \text{m}\Omega$$

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**18.14**

$$(a)\ A_v = 10^{\frac{86}{20}} = 20000 \quad | \quad A_i = \frac{i_o}{i_i} \quad | \quad i_o = i_i(40k\Omega)\frac{20000}{1k\Omega} \rightarrow A_i = 8.00\ x\ 10^5$$

With resistive feedback, the closed - loop gain cannot exceed the open - loop gain.

Therefore, $A_i \le 8.00\ x\ 10^5$.

$$(b)\ A_{tr} = \frac{i_o}{v_i} = \frac{i_o}{i_i(40k\Omega)} = \frac{A_i}{(40k\Omega)} \quad | \quad A_{tr} \le \frac{8x10^5}{4x10^4\Omega} = 20\ S$$

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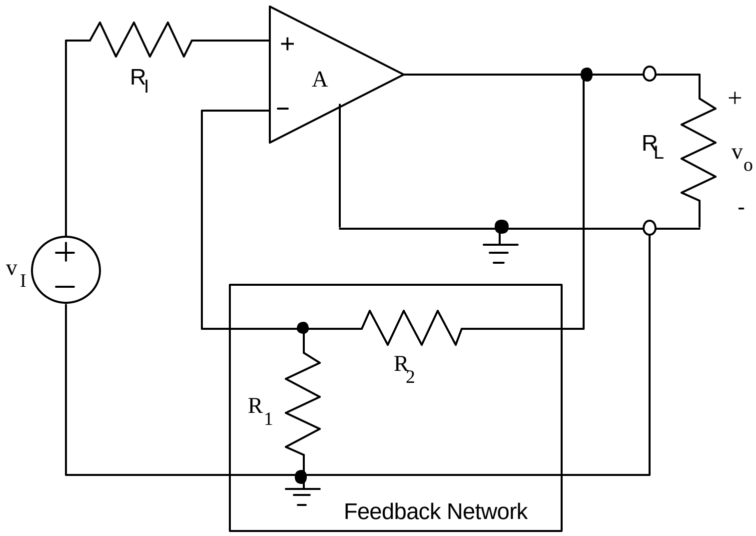
**18.15** (a)




$$(b)\ h_{11}^{A}=\left.\frac{\mathbf{v_1}}{\mathbf{i_1}}\right|_{\mathbf{v_2}=0}=15k\Omega \quad | \quad h_{11}^{F}=4.3k\Omega \| 39k\Omega=3.87k\Omega \quad | \quad h_{11}^{T}=18.9k\Omega$$

$$h_{22}^{A}=\left.\frac{\mathbf{i_2}}{\mathbf{v_2}}\right|_{\mathbf{i_1}=0}=(1k\Omega)^{-1}=(1k\Omega)^{-1} \quad | \quad h_{22}^{F}=(39k\Omega+4.3k\Omega)^{-1}=(43.3k\Omega)^{-1} \quad | \quad h_{22}^{T}=+1.02mS$$

$$h_{21}^{A}=\left.\frac{\mathbf{i_2}}{\mathbf{i_1}}\right|_{\mathbf{v_2}=0}=-\frac{15k\Omega(5000)}{1k\Omega}=-75{,}000 \quad | \quad h_{21}^{F}=\left.\frac{\mathbf{i_2}}{\mathbf{i_1}}\right|_{\mathbf{v_2}=0}=-\frac{4.3k\Omega}{39k\Omega+4.3k\Omega}=-0.0993$$

$$h_{12}^{A}=\left.\frac{\mathbf{v_1}}{\mathbf{v_2}}\right|_{\mathbf{i_1}=0}=0 \quad | \quad h_{12}^{F}=\left.\frac{\mathbf{v_1}}{\mathbf{v_2}}\right|_{\mathbf{i_2}=0}=\frac{4.3k\Omega}{39k\Omega+4.3k\Omega}=0.0993$$

$$(c)\ A=\frac{-h_{21}^{A}}{(R_I+h_{11}^{T})(h_{22}^{T}+G_L)}=\frac{-(-75000)}{(1k\Omega+15k\Omega+3.87k\Omega)\left(\frac{1}{5.6k\Omega}+\frac{1}{1k\Omega}+\frac{1}{43.3k\Omega}\right)}=3140$$

$$b=0.0993$$

$$(d)\ A_v=\frac{3140}{1+3140(0.0993)}=10.0$$

$$(\mathrm{e})\ h_{21}^{A}>>h_{21}^{F} \quad | \quad h_{12}^{F}>>h_{12}^{A} \quad | \quad \text{Note}: \left(\mathrm{R_{in}}=6.22\ M\Omega,\ R_{out}=2.66\ \Omega\right)$$

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**18.16** The circuit topology is identical to Fig. 18.8.

$$h_{11}^{F}=5k\Omega \| 45k\Omega=4.50k\Omega \quad | \quad h_{22}^{F}=(45k\Omega+5k\Omega)^{-1}=(50.0k\Omega)^{-1}$$

$$b=h_{12}^{F}=\left.\frac{v_1}{v_2}\right|_{i_2=0}=\frac{5k\Omega}{5k\Omega+45k\Omega}=\frac{1}{10} \quad | \quad R_L \left\| \frac{1}{h_{22}^{F}}=5k\Omega \| 50k\Omega=4.55k\Omega\right.$$

$$A=\frac{15k\Omega}{1k\Omega+15k\Omega+4.5k\Omega}(5000)\frac{4.55k\Omega}{1k\Omega+4.55k\Omega}=3000$$

$$A_v = \frac{A}{1+Ab} = \frac{3000}{1+3000\left(\frac{1}{10}\right)} = \frac{3000}{301} = 9.97$$

$$R_{in} = R_{in}^{A}(1+Ab) = (1k\Omega + 15k\Omega + 4.5k\Omega)(301) = 6.17\ M\Omega$$

$$R_{out} = \frac{R_{out}^{A}}{1+Ab} = \frac{5k\Omega \| 50k\Omega \| 1k\Omega}{301} = 2.72\ \Omega$$

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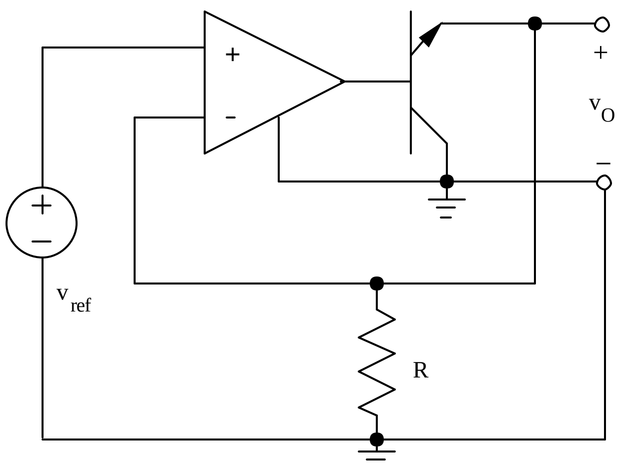
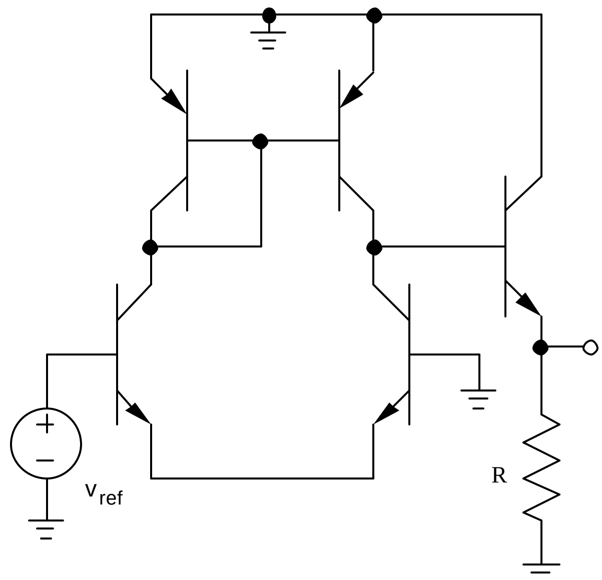
**18.17**




A-Circuit

$$h_{11}^{F} = \left.\frac{v_1}{i_1}\right|_{v_2=0} = 0 \quad | \quad h_{22}^{F} = \left.\frac{i_2}{v_2}\right|_{i_1=0} = \frac{1}{R} \quad | \quad h_{12}^{F} = \left.\frac{v_1}{v_2}\right|_{i_2=0} = 1$$

$$A = g_{m1}\left(r_{o2}\|r_{o4}\|\left[r_{p5} + (b_o+1)R\right]\right)\frac{(b_o+1)R}{r_{p5} + (b_o+1)R} = g_{m1}\frac{r_{o2}\|r_{o4}}{(r_{o2}\|r_{o4}) + r_{p5} + (b_o+1)R}(b_o+1)R$$

$$r_{o2} = \frac{50+1.4}{10^{-4}} = 514k\Omega \quad | \quad r_{o4} = \frac{50+11.3}{10^{-4}} = 613k\Omega \quad | \quad r_{o2}\|r_{o4} = 280k\Omega$$

$$I_{C5} \cong I_{E5} \cong \frac{12}{10^4} = 1.2mA \quad | \quad r_{p5} = \frac{100(.025)}{1.2mA} = 2.08k\Omega$$

$$A = 40(10^{-4})(280k\Omega)\frac{(101)10k\Omega}{280k\Omega + 2.08k\Omega + (101)10k\Omega} = 876$$

$$A_v = \frac{A}{1+T} = \frac{876}{1+876(1)} = \frac{109}{110} = 0.999$$

$$R_{in} = R_{id}(1+T) = 2r_{p1}(1+T) = 2\frac{100(0.025)}{10^{-4}}(877) = 43.9\ M\Omega$$

$$R_{out} = \frac{R \left\| \dfrac{r_{p5} + r_{o2} \| r_{o4}}{b_o + 1} \right.}{1+T} = \frac{10k\Omega \left\| \dfrac{2.08k\Omega + 280k\Omega}{101} \right.}{877} = 2.49\ \Omega$$

$$i_o = a_o i_e = a_o \frac{v_o}{R} \quad | \quad \frac{i_o}{v_{ref}} = \frac{a_o}{R}\frac{v_o}{v_{ref}} = \frac{100}{101}\left(\frac{1}{10^4}\right)(0.999) = 98.9\ mS$$

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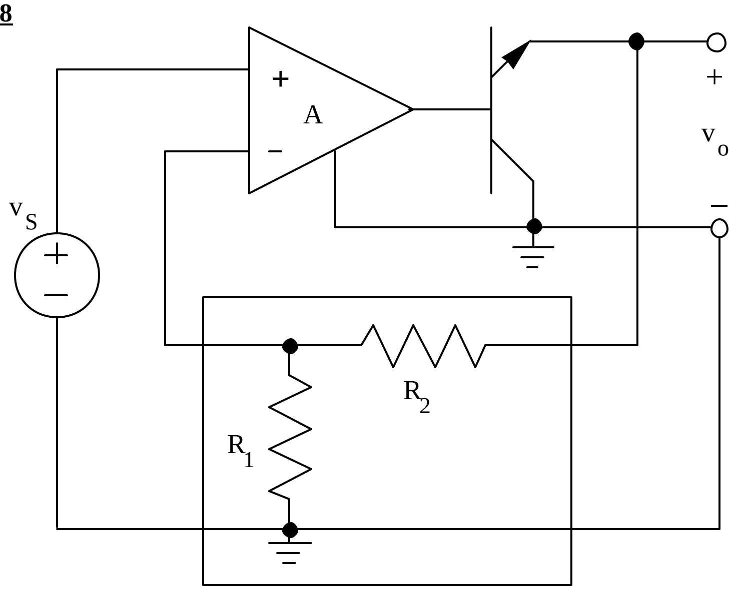
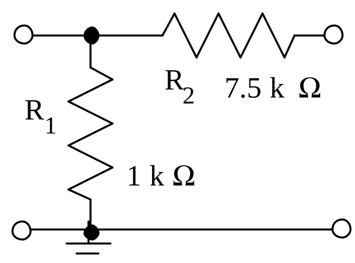
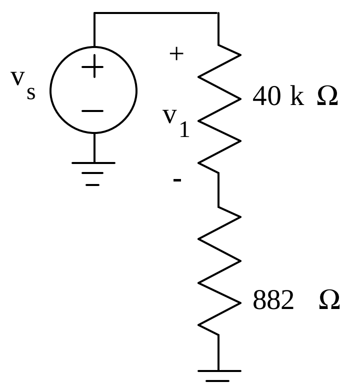
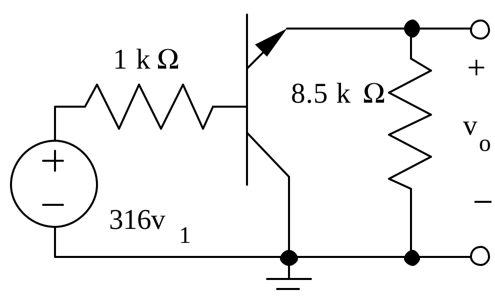
**<u>18.18</u>**




$$h_{11}^F = \left.\frac{v_1}{i_1}\right|_{v_2=0} = 1k\Omega \| 7.5k\Omega = 882\Omega \quad | \quad h_{22}^F = \left.\frac{i_2}{v_2}\right|_{i_1=0} = \frac{1}{1k\Omega + 7.5k\Omega} = \frac{1}{8.5k\Omega}$$

$$b = h_{12}^F = \left.\frac{v_1}{v_2}\right|_{i_2=0} = \frac{1k\Omega}{1k\Omega + 7.5k\Omega} = \frac{1}{8.5}$$

$$I_C = a_F I_E = \frac{100}{101}(200mA) = 198mA \quad | \quad r_p = \frac{100(.025V)}{198mA} = 12.6k\Omega$$

$$A = \frac{v_o}{v_s} = \frac{40k\Omega}{40k\Omega + 0.882k\Omega}(316)\frac{(b_o + 1)8.5k\Omega}{R_O + r_p + (b_o + 1)8.5k\Omega} = 309\frac{(101)8.5k\Omega}{1k\Omega + 12.6k\Omega + (101)8.5k\Omega} = 304$$

$$A_v = \frac{A}{1+T} = \frac{304}{1 + 304\left(\frac{1}{8.5}\right)} = \frac{304}{36.8} = 8.27$$

$$R_{in} = R_{in}^A(1+T) = 40.9k\Omega(36.8) = 1.51\ M\Omega \quad | \quad R_{out} = \frac{R_{out}^A}{1+T} = \frac{8.5k\Omega \left\| \frac{12.6k\Omega + 1k\Omega}{101} \right.}{36.8} = 3.60\ \Omega$$

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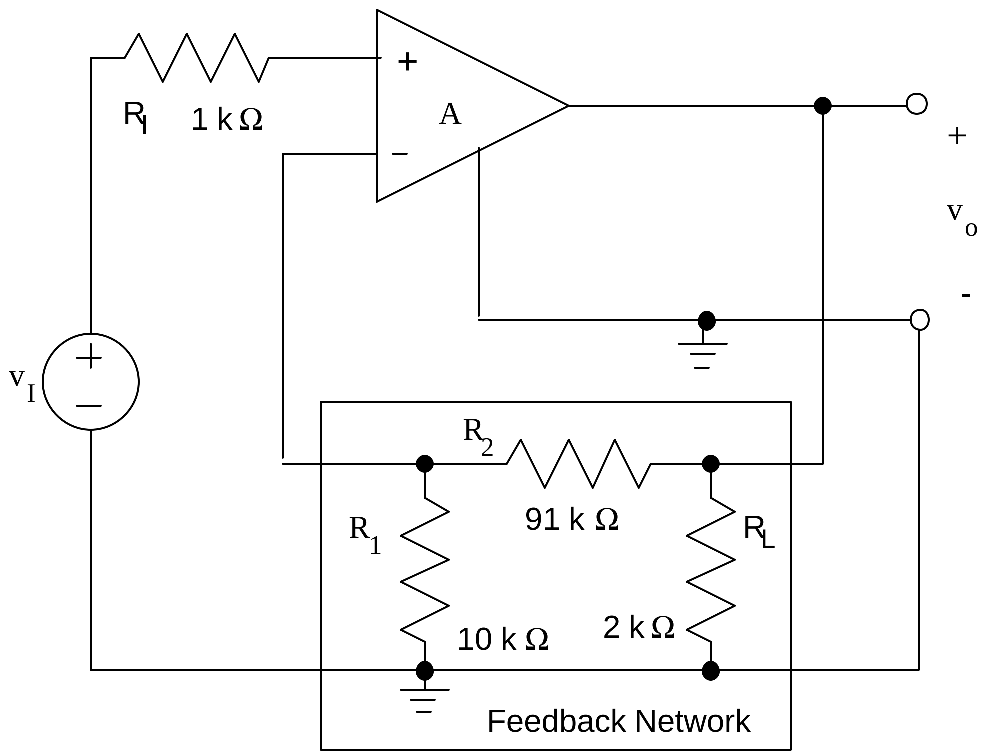
**18.19**




$$h_{11}^F = \left.\frac{v_1}{i_1}\right|_{v_2=0} = 10k\Omega \| 91k\Omega = 9.01k\Omega \quad | \quad h_{22}^F = \left.\frac{i_2}{v_2}\right|_{i_1=0} = \frac{1}{2k\Omega \| (1k\Omega + 7.5k\Omega)} = \frac{1}{1.96k\Omega}$$

$$b = h_{12}^F = \left.\frac{v_1}{v_2}\right|_{i_2=0} = \frac{10k\Omega}{10k\Omega + 91k\Omega} = \frac{1}{0.0990}$$

$$A = \frac{v_o}{v_i} = \frac{25k\Omega}{1k\Omega + 25k\Omega + 9.01k\Omega}\left(10^4\right)\frac{1.96k\Omega}{1k\Omega + 1.96k\Omega} = 4730$$

$$A_v = \frac{A}{1+Ab} = \frac{4730}{1 + 4730(0.990)} = 10.1 \quad | \quad R_{in} = R_{in}^A(1+T) = 34.0k\Omega(469) = 16.0\ M\Omega$$

$$R_{out} = \frac{R_{out}^A}{1+T} = \frac{1.96k\Omega \| 1k\Omega}{469} = 1.41\ \Omega$$

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**18.20**

$$(a)\ \ S_A^{R_{in}} = \frac{A}{R_{in}}\frac{\P R_{in}}{\P A} \quad | \quad R_{in} = R_{in}^A(1+Ab) \quad | \quad S_A^{R_{in}} = \frac{A}{R_{in}^A(1+Ab)}R_{in}^A b = \frac{Ab}{(1+Ab)} \approx 1$$

$$\frac{\P R_{in}}{R_{in}} = S_A^{R_{in}}\frac{\P A}{A} = \frac{10^5(0.01)}{1+10^5(0.01)}10\% = 9.99\%$$

$$(b)\ S_A^{R_{out}} = \frac{A}{R_{out}}\frac{\P R_{out}}{\P A} \quad | \quad R_{out} = \frac{R_{out}^A}{(1+Ab)} \quad | \quad \frac{\P R_{out}}{\P A} = -\frac{bR_{out}^A}{(1+Ab)^2}$$

$$S_A^{R_{out}} = -\frac{A(1+Ab)}{R_{out}^A}\frac{bR_{out}^A}{(1+Ab)^2} = -\frac{Ab}{(1+Ab)} \cong -1 \quad | \quad \frac{\P R_{out}}{R_{out}} = S_A^{R_{out}}\frac{\P A}{A} = -\frac{10^5(0.01)}{1+10^5(0.01)}10\% = -9.99\%$$

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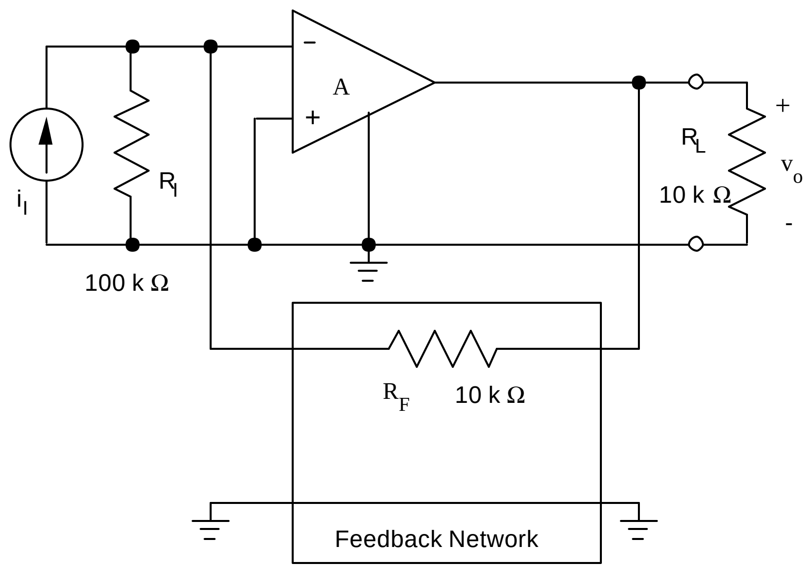
**18.21**




$$y_{11}^A = \left.\frac{i_1}{v_1}\right|_{v_2=0} = \frac{1}{15k\Omega} \quad | \quad y_{22}^A = \left.\frac{i_2}{v_2}\right|_{v_1=0} = \frac{1}{1k\Omega} \quad | \quad y_{21}^A = \left.\frac{i_2}{v_1}\right|_{v_2=0} = -\frac{(-5000)}{1k\Omega} = 5\text{S} \quad | \quad y_{12}^A = \left.\frac{i_1}{v_2}\right|_{v_1=0} = 0$$

$$y_{11}^F = \left.\frac{i_1}{v_1}\right|_{v_2=0} = \frac{1}{10k\Omega} \quad | \quad y_{22}^F = \left.\frac{i_2}{v_2}\right|_{v_1=0} = \frac{1}{10k\Omega} \quad | \quad y_{12}^F = \left.\frac{i_1}{v_2}\right|_{v_1=0} = -\frac{1}{10k\Omega} \quad | \quad y_{21}^F = \left.\frac{i_2}{v_1}\right|_{v_2=0} = -\frac{1}{10k\Omega}$$

$$y_{11}^T = \frac{1}{15k\Omega} + \frac{1}{10k\Omega} = 0.167mS \quad | \quad y_{22}^T = \frac{1}{1k\Omega} + \frac{1}{10k\Omega} = 1.10\text{mS}$$

$$A = \frac{-y_{21}^A}{(G_I + y_{11}^T)(y_{22}^T + G_L)} = \frac{-5}{(10^{-5} + 0.167x10^{-3})(1.1x10^{-3} + 10^{-4})} = -2.35x10^7\Omega \quad | \quad b = y_{12}^F = -10^{-4}$$

$$A_{tr} = \frac{A}{1+Ab} = \frac{-2.35x10^7\Omega}{1 + (-2.35x10^7\Omega)(-10^{-4}S)} = -10.0\ k\Omega \quad | \quad Ab = 2350$$

$$\text{Note: } R_{in} = \frac{100k\Omega \| 10k\Omega \| 15k\Omega}{1+2350} = 2.41\ \Omega \quad | \quad R_{out} = \frac{10k\Omega \| 1k\Omega \| 10k\Omega}{1+2350} = 0.355\ \Omega$$

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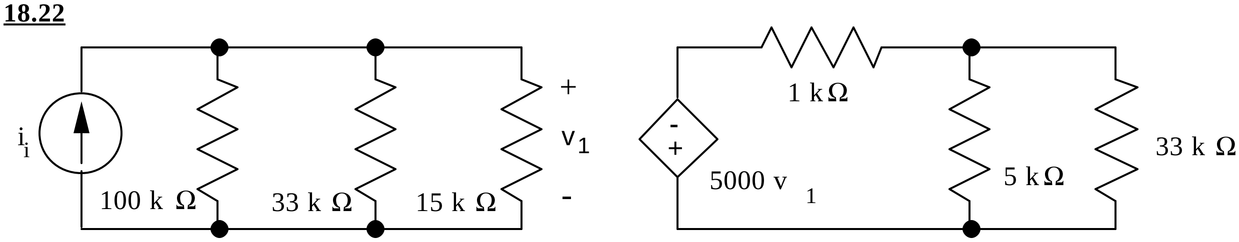
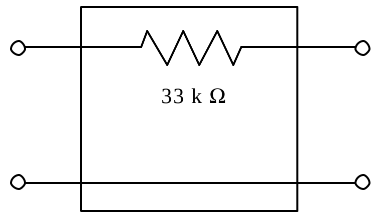
**18.22**




$$y_{11}^F = \left.\frac{i_1}{v_1}\right|_{v_2=0} = \frac{1}{33k\Omega} \quad | \quad y_{22}^F = \left.\frac{i_2}{v_2}\right|_{v_1=0} = \frac{1}{33k\Omega} \quad | \quad y_{12}^F = \left.\frac{i_1}{v_2}\right|_{v_1=0} = -\frac{1}{33k\Omega}$$

$$(15k\Omega \| 33k\Omega \| 100k\Omega) = 9.35k\Omega \quad | \quad (5k\Omega \| 33k\Omega) = 4.34k\Omega$$

$$A = \frac{v_o}{i_i} = -5000\frac{4.34k\Omega}{1k\Omega + 4.34k\Omega}(9.35k\Omega) = -3.80x10^7$$

$$A_{tr} = \frac{A}{1+Ab} = \frac{-3.80x10^7}{1+(-3.80x10^7)\left(-\frac{1}{33x10^3}\right)} = -33.0\ k\Omega$$

$$R_{in} = \frac{(15k\Omega \| 33k\Omega \| 100k\Omega)}{1+(-3.80x10^7)\left(-\frac{1}{33x10^3}\right)} = 8.11\ \Omega \quad | \quad R_{out} = \frac{(33k\Omega \| 5k\Omega \| 1k\Omega)}{1+(-3.80x10^7)\left(-\frac{1}{33x10^3}\right)} = 0.705\ \Omega$$

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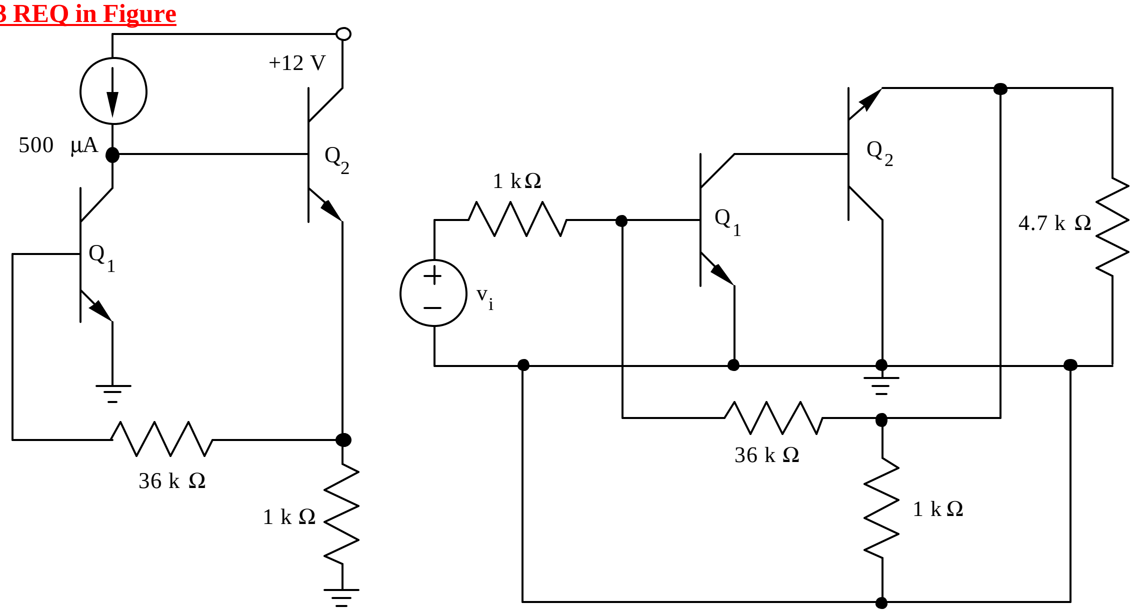
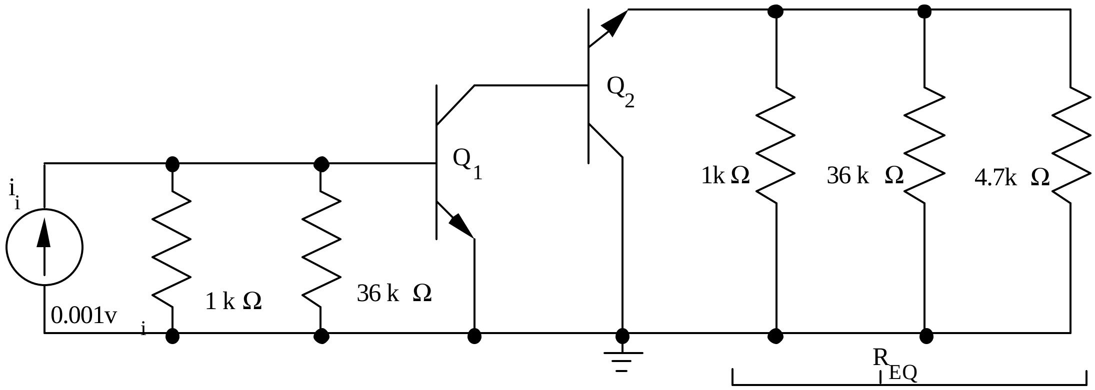
**18.23 REQ in Figure**



$$I_{C1} = 500mA - I_{B2} \quad | \quad I_{E2} = I_{B1} + \frac{36000 I_{B1} + 0.7}{1000} = 37 I_{B1} + 700mA \quad | \quad I_{B2} = \frac{I_{E2}}{101}$$

$$I_{C1} = 500mA - \frac{37 I_{B1} + 700mA}{101} = 493mA - 0.366 I_{B1} \rightarrow I_{C1} = 491.2mA$$

$$I_{E2} = 37\frac{I_{C1}}{100} + 700mA = 881.7mA \quad | \quad I_{C2} = \frac{100}{101} I_{E2} = 873mA$$




$$y_{11}^F = \left.\frac{i_1}{v_1}\right|_{v_2=0} = \frac{1}{36k\Omega} \quad | \quad y_{22}^F = \left.\frac{i_2}{v_2}\right|_{v_1=0} = \frac{1}{36k\Omega \| 1k\Omega} \quad | \quad y_{12}^F = \left.\frac{i_1}{v_2}\right|_{v_1=0} = -\frac{1}{36k\Omega}$$

$$r_{p1} = \frac{100(0.025)}{491mA} = 5.09k\Omega \;|\; r_{p2} = \frac{100(0.025)}{873mA} = 2.86\,k\Omega \;|\; r_{o1} = \frac{50 + 1.6}{493\,x10^{-6}} = 105\,k\Omega$$

$$R_E = (1k\Omega \| 36k\Omega \| 4.7k\Omega) = 807\,\Omega$$

$$A = \frac{v_o}{i_i} = (1k\Omega \| 36k\Omega \| r_{p1}) g_{m1} \left[ r_{o1} \| \left( r_{p2} + (b_o + 1) R_E \right) \right] \frac{r_{p2} + (b_o + 1) R_E}{r_{o1} + r_{p2} + (b_o + 1) R_E}$$

$$A = \frac{v_o}{i_i} = -(1k\Omega \| 36k\Omega \| 5.09k\Omega) g_{m1} \left[ r_{o1} \| \left( r_{p2} + (b_o + 1) R_{EQ} \right) \right] \frac{(b_o + 1) R_{EQ}}{r_{p2} + (b_o + 1) R_{EQ}}$$

$$(1k\Omega \| 36k\Omega \| r_{p1}) = (1k\Omega \| 36k\Omega \| 5.09k\Omega) = 817\Omega \quad | \quad g_m = 40(491mA) = 19.6mS$$

$$\left[ r_{o1} \| \left( r_{p2} + (b_o + 1) R_{EQ} \right) \right] = \left[ 105k\Omega \| \left( 2.86k\Omega + (101)806\Omega \right) \right] = 46.8k\Omega$$

$$R_{EQ} = 1k\Omega \| 36k\Omega \| 4.7k\Omega = 806\Omega \quad | \quad \frac{(b_o + 1) R_{EQ}}{r_{p2} + (b_o + 1) R_{EQ}} = \frac{(101)806\Omega}{2.86k\Omega + (101)806\Omega} = 0.966$$

$$A = -(817\Omega)(19.6mS)(46.8k\Omega)(0.966) = -724\ k\Omega \quad | \quad Ab = -724\ k\Omega \left( -\frac{1}{36k\Omega} \right) = 20.1$$

$$A_{tr} = \frac{A}{1 + Ab} = \frac{-724\,k\Omega}{1 + 20.1} = -36.0\ k\Omega$$

$$\text{Note: } R_{in} = \frac{(1k\Omega \| 36k\Omega \| 5.09k\Omega)}{1 + 20.1} = 38.7\Omega \quad | \quad R_{in} = \left( R_{EQ} \| \frac{r_{p2} + r_{o1}}{b_o + 1} \right) \frac{1}{1 + Ab} = 21.8\Omega$$

$$R_{in} = \frac{(1k\Omega \| 36k\Omega \| 5.09k\Omega)}{1+Ab} = \frac{817\Omega}{9.94} = 82.2\ \Omega$$

$$R_{out} = \frac{\left(1k\Omega \| 36k\Omega \| 4.7k\Omega \| \frac{r_{p2}+r_{o1}}{101}\right)}{1+Ab} = \frac{\left(806\Omega \| \frac{2.86k\Omega + 105k\Omega}{101}\right)}{9.94} = 46.2\ \Omega$$

$$i_i = 10^{-3} v_i \rightarrow A_v = \frac{v_o}{v_i} = \frac{v_o}{1000 i_i} = -32.4$$

Note that this amplifier can be analyzed as a shunt-series feedback amplifier. This is good for student practice - see Problem 18.32.

---

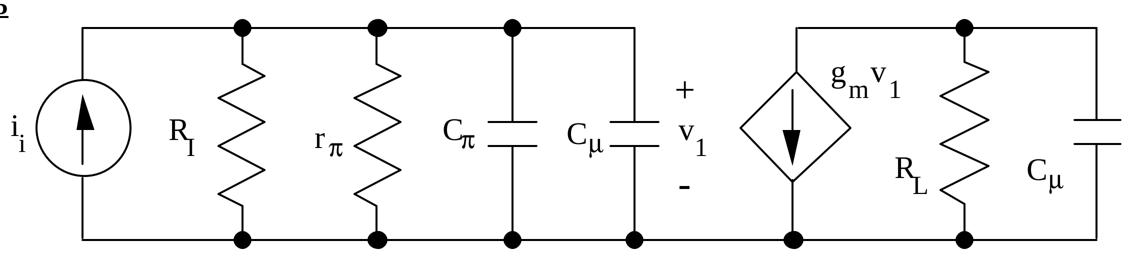
**18.24**

```
*Problem 18.24 – Figure 18.77
VCC 5 0 DC 12
IDC 5 4 DC 500UA
II 0 2 AC 1
*IX 0 7 AC 1
RS 2 0 1K
C1 2 3 82UF
Q1 4 3 0 NBJT
Q2 5 4 6 NBJT
RF 3 6 36K
RE 6 0 1K
C2 6 7 47UF
RL 7 0 4.7K
.MODEL NBJT NPN BF=100 VA=50 IS=1E-15
.OP
.AC DEC 100 1E2 1E7
.PRINT AC VM(7) VP(7) VM(2) VP(2)
.END
```

Results: $A_{tr}$ = -34.4 kΩ, $R_{in}$ = 36.8 Ω, $R_{out}$ = 18.6 Ω -- Note that these values are highly sensitive to the precise value of $r_{\pi?}$.

---

**18.25**




$$y_{12}^F = -sC_m \quad | \quad A = \frac{v_o}{i_i} = -\frac{r_{po}}{s(C_p + C_m)r_{po} + 1}(g_m)\frac{R_L}{sC_m R_L + 1} = -\frac{g_m r_{po} R_L}{[s(C_p + C_m)r_{po} + 1][sC_m R_L + 1]}$$

$$Z_{in}^A = \frac{r_{po}}{s(C_p + C_m)r_{po} + 1} \quad | \quad Z_{in} = \frac{Z_{in}^A}{1+Ab} = \frac{\dfrac{r_{po}}{s(C_p + C_m)r_{po} + 1}}{1 - \dfrac{g_m r_{po} R_L}{[s(C_p + C_m)r_{po} + 1][sC_m R_L + 1]}(-sC_m)}$$

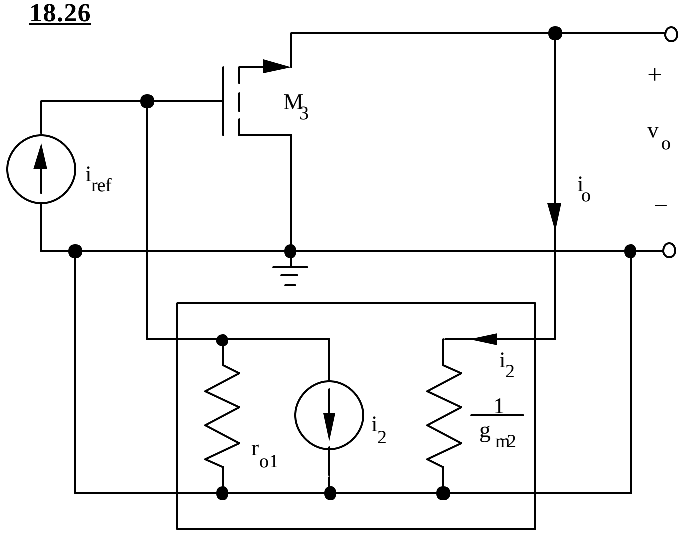
where $r_{po} = r_p \| R_I \quad | \quad Z_{in} = \dfrac{r_{po}\left(sC_m R_L + 1\right)}{\left[s\left(C_p + C_m\right)r_{po} + 1\right]\left[sC_m R_L + 1\right] + sC_m g_m r_{po} R_L}$

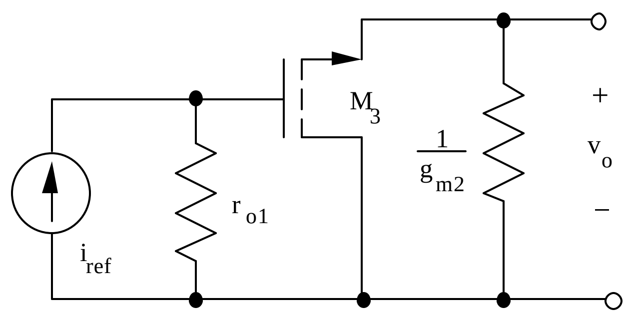
$$Z_{in} = \frac{r_{po}\left(sC_m R_L + 1\right)}{s^2\left(C_p + C_m\right)C_m r_{po} R_L + s r_{po}\left[C_p + C_m\left(1 + g_m R_L\right) + \dfrac{R_L}{r_{po}}\right] + 1} = \frac{r_{po}\left(sC_m R_L + 1\right)}{s^2\left(C_p + C_m\right)C_m r_{po} R_L + s r_{po} C_T + 1}$$

$$Z_{in} \cong \frac{r_{po}\left(sC_m R_L + 1\right)}{s r_{po}\left[C_p + C_m\left(1 + g_m R_L\right) + \dfrac{R_L}{r_{po}}\right] + 1} = \frac{r_{po}\left(sC_m R_L + 1\right)}{s r_{po} C_T + 1} \quad for \quad w << w_T$$

---

**18.26**




$$y_{11}^F = \left.\frac{i_1}{v_1}\right|_{v_2=0} = g_{o1} \quad | \quad y_{22}^F = \left.\frac{i_2}{v_2}\right|_{v_1=0} = g_{m2} \quad | \quad y_{12}^F = \left.\frac{i_1}{v_2}\right|_{v_1=0} = g_{m2}$$

$$A = \frac{v_o}{i_{ref}} = r_{o1}\frac{g_{m3}\dfrac{1}{g_{m2}}}{1 + g_{m3}\dfrac{1}{g_{m2}}} = \frac{r_{o1}}{2} \quad | \quad A_{tr} = \frac{A}{1 + Ab} = \frac{\dfrac{r_{o1}}{2}}{1 + \dfrac{r_{o1}}{2}\left(g_{m2}\right)} = \frac{r_{o1}}{2 + \mu_{f1}}$$

$$R_{in} = \frac{r_{o1}}{1 + Ab} = \frac{r_{o1}}{1 + \dfrac{\mu_{f2}}{2}} = \frac{36k\Omega}{1 + \dfrac{72}{2}} = 973\Omega \quad | \quad Note: \quad R_{in} \cong \frac{2}{g_m}$$

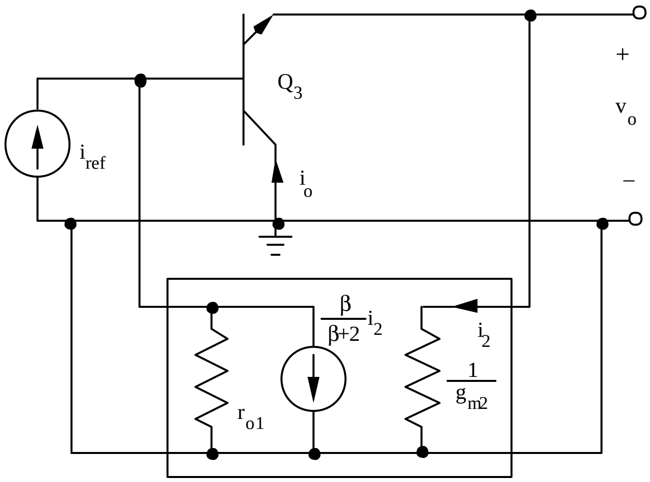
$$i_o = i_2 = g_{m2} v_o = g_{m2}\frac{r_{o1}}{\mu_{f1} + 2} i_{ref} \quad | \quad \frac{i_o}{i_{ref}} = \frac{\mu_{f1}}{\mu_{f1} + 2} = 0.973$$

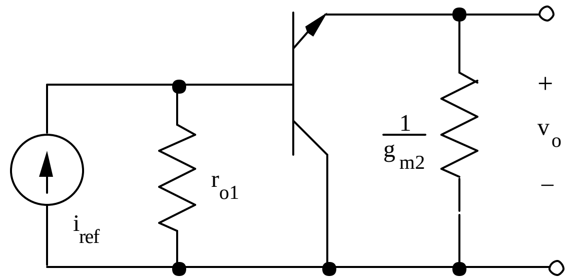
---

**18.27**

$$y_{11}^F = \left.\frac{i_1}{v_1}\right|_{v_2=0} = g_{o1} \quad | \quad y_{22}^F = \left.\frac{i_2}{v_2}\right|_{v_1=0} = g_{m2} \quad | \quad y_{12}^F = \left.\frac{i_1}{v_2}\right|_{v_1=0} = \frac{b}{b+2} g_{m2} \cong g_{m2}$$

$$i_o = a_o i_2 = a_o g_{m2} v_o \quad | \quad A = \frac{v_o}{i_{ref}} = r_{o1}\frac{(b_o+1)\frac{1}{g_{m2}}}{r_{o1}+r_{p3}+(b_o+1)\frac{1}{g_{m2}}} \cong r_{o1}\frac{(b_o+1)}{m_f+2b_o+1} \cong \frac{b_o}{m_f} r_{o1} = r_{p1}$$




$$A_{tr} = \frac{A}{1+Ab} = \frac{r_{o1}\frac{(b_o+1)}{m_f+2b_o+1}}{1+r_{o1}\frac{(b_o+1)}{m_f+2b_o+1}(g_{m2})} \cong r_{o1}\frac{b_o+1}{m_f b_o+2m_f+2b_o+2} \cong \frac{r_{o1}}{m_f} = \frac{1}{g_{m1}}$$

$$A_{tr} = \frac{1}{50mS} = 20.0\ \Omega \quad | \quad A_I = \frac{i_o}{i_{ref}} = a_o g_{m2}\frac{v_o}{i_{ref}} = a_o\frac{g_{m2}}{g_{m1}} \cong 1$$

$$R_{in}^A = r_{o1}\left\|\left[r_{p3}+(b_o+1)\frac{1}{g_{m2}}\right]\right. \cong r_{o1}\|2r_{p3} \cong 2r_{p3}$$

$$R_{in} = \frac{R_{in}^A}{1+Ab} = \frac{r_{o1}\|2r_{p3}}{1+r_{o1}\frac{(b_o+1)}{m_f+2b_o+1}(g_{m2})} \cong \frac{r_{o1}\|2r_{p3}}{1+\frac{m_f(b_o+1)}{m_f+2b_o+1}} \cong \frac{r_{o1}\|2r_{p3}}{b_o+1} \cong \frac{2r_{p3}}{b_o+1} \cong \frac{2}{g_{m3}}$$

$$R_{in} = \frac{r_{o1}\|2r_{p3}}{b_o+1} = \frac{40k\Omega\|4k\Omega}{101} = 36.0\ \Omega$$

---

**18.28**

```
*Problem 18.28 - BJT Wilson Source
*Current gain = 100
VCC 0 3 DC -6
IREF 0 1 DC 100UA
Q1 1 2 0 NBJT
Q2 2 2 0 NBJT
Q3 3 1 2 NBJT
```

```
.MODEL NBJT NPN BF=100 VA=50 IS=1E-15
.OP
.TF I(VCC) IREF
.END
```

$$\frac{b_o r_{o3}}{2} = \frac{100(55.3V)}{2(100mA)} = 27.7\ M\Omega \quad | \quad \text{SPICE}:\ 29.9\ M\Omega$$

```
*Problem 18.28 - BJT Wilson Source
*Current gain = 10K
VCC 0 3 DC -6
IREF 0 1 DC 100UA
Q1 1 2 0 NBJT
Q2 2 2 0 NBJT
Q3 3 1 2 NBJT
.MODEL NBJT NPN BF=10K VA=50 IS=1E-15
.OP
.TF I(VCC) IREF
.END
```

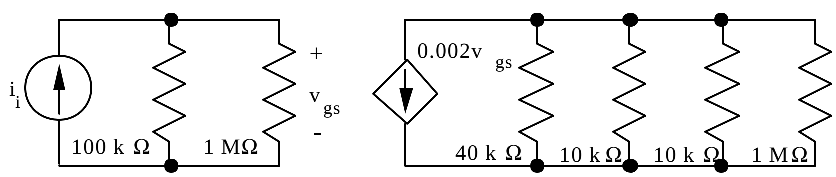
$$\text{SPICE}:\ 799\ M\Omega$$

```
*Problem 18.28 - BJT Wilson Source
*Current gain = 1MEG
VCC 0 3 DC -6
IREF 0 1 DC 100UA
Q1 1 2 0 NBJT
Q2 2 2 0 NBJT
Q3 3 1 2 NBJT
.MODEL NBJT NPN BF=1MEG VA=50 IS=1E-15
.OP
.TF I(VCC) IREF
.END
```

$$m_{f1} r_{o3} = 40(51.4)\frac{55.3V}{100mA} = 1.14\ G\Omega \quad | \quad \text{SPICE}:\ 1.08\ G\Omega$$

---

**18.29**




$$y_{11}^F = \left.\frac{i_1}{v_1}\right|_{v_2=0} = 10^{-6}S \quad | \quad y_{22}^F = \left.\frac{i_2}{v_2}\right|_{v_1=0} = 10^{-6}S \quad | \quad y_{12}^F = \left.\frac{i_1}{v_2}\right|_{v_1=0} = -10^{-6}S$$

$$v_{gs} = i_i(100k\Omega \| 1M\Omega) = (90.9k\Omega)i_i \quad | \quad v_o = -\left(2x10^{-3}\right)v_{gs}\left(40k\Omega \| 10k\Omega \| 10k\Omega \| 1M\Omega\right)$$

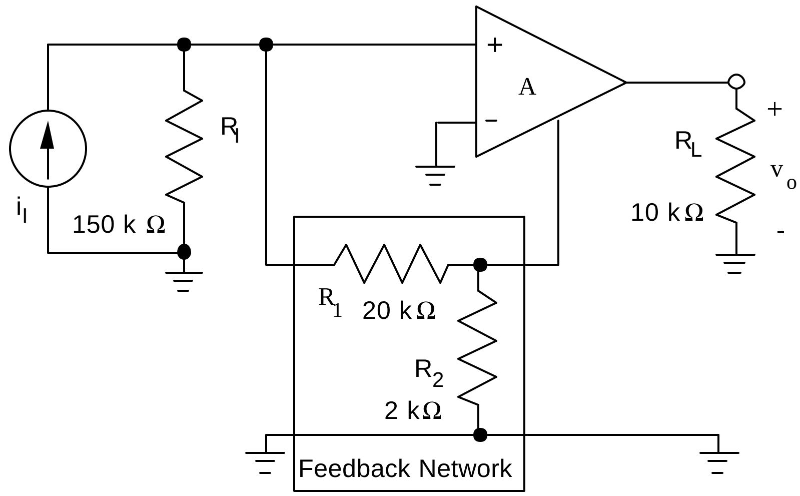
$$A = \frac{v_o}{i_i} = -(2mS)(4.44k\Omega)(90.9k\Omega) = -8.08x10^5$$

$$A_{tr} = \frac{A}{1+Ab} = \frac{-8.08x10^5}{1+\left(-8.08x10^5\right)\left(-10^{-6}\right)} = \frac{-8.08x10^5}{1.81} = -446\ k\Omega$$

$$R_{in} = \frac{(100k\Omega \| 1M\Omega)}{(1+Ab)} = \frac{90.9k\Omega}{1.81} = 50.2\ k\Omega$$

$$R_{out} = \frac{\left(40k\Omega \| 10k\Omega \| 10k\Omega \| 1M\Omega\right)}{(1+Ab)} = \frac{4.44k\Omega}{1.81} = 2.45k\Omega$$

**18.30**




$$g_{11}^F = \left.\frac{i_1}{v_1}\right|_{i_2=0} = \frac{1}{22k\Omega} \quad | \quad g_{22}^F = \left.\frac{v_2}{i_2}\right|_{v_1=0} = 2k\Omega \| 20k\Omega = 1.82k\Omega \quad | \quad g_{12}^F = \left.\frac{i_1}{i_2}\right|_{v_1=0} = -\frac{2k\Omega}{20k\Omega + 2k\Omega} = -\frac{1}{11}$$

$$g_{11}^T = \frac{1}{15k\Omega} + \frac{1}{22k\Omega} = \frac{1}{8.92k\Omega} \quad | \quad g_{22}^T = 1.82k\Omega + 1k\Omega = 2.82k\Omega \quad | \quad g_{21}^A = \left.\frac{v_2}{v_1}\right|_{i_2=0} = 5000$$

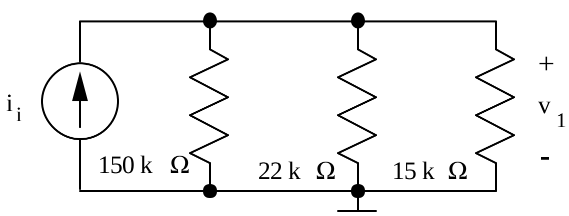
$$A = -\frac{g_{21}^A}{\left(G_I + g_{11}^T\right)\left(g_{22}^T + R_L\right)} = -\frac{5000}{\left(\frac{1}{150k\Omega} + \frac{1}{22k\Omega}\right)\left(2.82k\Omega + 10k\Omega\right)} = -3280 \quad | \quad \beta = g_{12}^F = -\frac{1}{11}$$

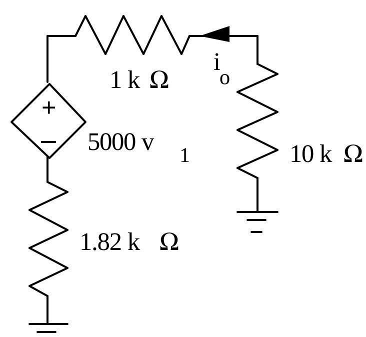
$$A_i = \frac{A}{1 + A\beta} = \frac{-3280}{1 + (-3280)\left(-\frac{1}{11}\right)} = -11.0 \quad | \quad A\beta = 298$$

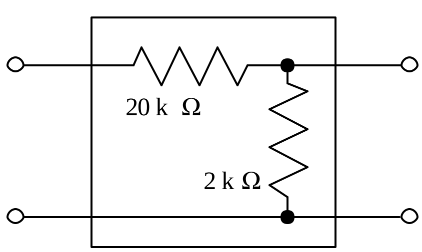
$$R_{in} = \frac{\left(150k\Omega \| 8.92k\Omega\right)}{\left(1 + A\beta\right)} = \frac{8.42k\Omega}{1 + 298} = 28.1\ \Omega$$

$$R_{out} = \left(10k\Omega + 2.82k\Omega\right)\left(1 + A\beta\right) = \left(12.8k\Omega\right)\left(299\right) = 3.83\ M\Omega$$

**18.31**



$$g_{11}^F = \left.\frac{i_1}{v_1}\right|_{i_2=0} = \frac{1}{11k\Omega} \quad | \quad g_{22}^F = \left.\frac{v_2}{i_2}\right|_{v_1=0} = 1k\Omega \| 10k\Omega = 909\Omega \quad | \quad g_{12}^F = \left.\frac{i_1}{i_2}\right|_{v_1=0} = -\frac{1k\Omega}{10k\Omega + 1k\Omega} = -\frac{1}{11}$$

$$A = \frac{i_2}{i_i} = -\left(100k\Omega \| 11k\Omega \| 15k\Omega\right)\frac{5k\Omega}{(5+1+0.909)k\Omega} = -4.32x10^3$$

$$A_i = \frac{A}{1+Ab} = \frac{-4.32x10^3}{1+\left(-4.32x10^3\right)\left(-\frac{1}{11}\right)} = -11.0$$

$$R_{in} = \frac{\left(100k\Omega \| 11k\Omega \| 15k\Omega\right)}{(1+Ab)} = \frac{5.97k\Omega}{394} = 15.2\ \Omega$$

$$R_{out} = \left(5k\Omega + 1k\Omega + 0.909k\Omega\right)(1+Ab) = (6.91k\Omega)(394) = 2.72M\Omega$$

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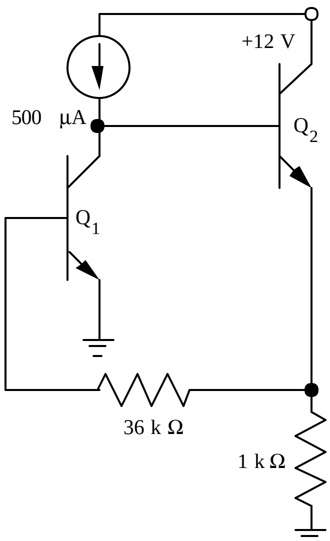
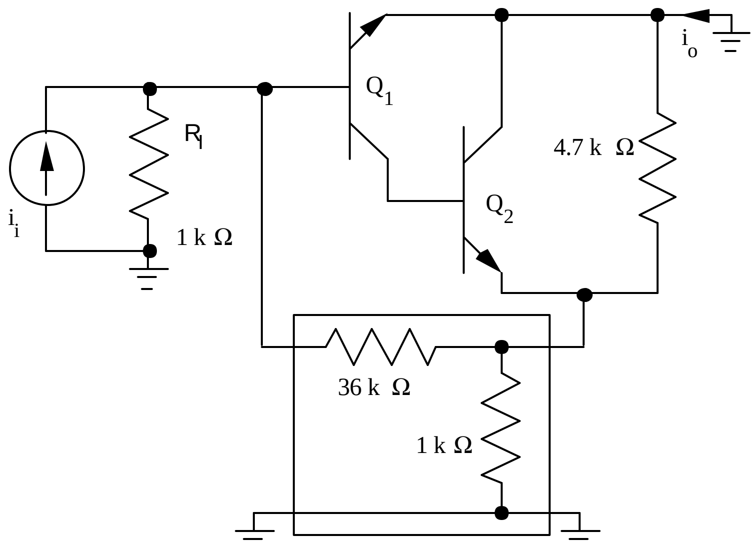
**18.32**

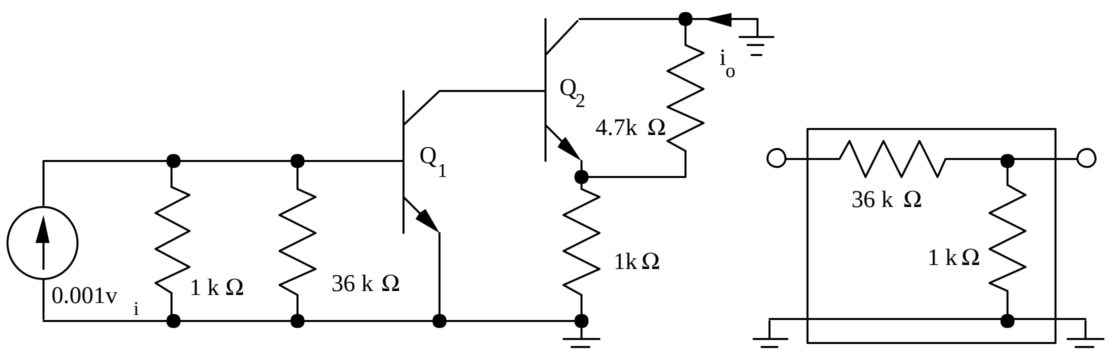



$$I_{C1} = 500mA - I_{B2} \quad | \quad I_{E2} = I_{B1} + \frac{36000I_{B1} + 0.7}{1000} = 37I_{B1} + 700mA \quad | \quad I_{B2} = \frac{I_{E2}}{101}$$

$$I_{C1} = 500mA - \frac{37I_{B1} + 700mA}{101} = 493mA - 0.366I_{B1} \rightarrow I_{C1} = 491.2mA$$

$$I_{E2} = 37\frac{I_{C1}}{100} + 700mA = 881.7mA \quad | \quad I_{C2} = \frac{100}{101}I_{E2} = 873mA$$



$$g_{11}^F=\left.\frac{i_1}{v_1}\right|_{i_2=0}=\frac{1}{37\ k\Omega}\ \ |\ \ g_{22}^F=\left.\frac{v_2}{i_2}\right|_{v_1=0}=36k\Omega\|1k\Omega=973\ \Omega\ \ |\ \ g_{12}^F=\left.\frac{i_1}{i_2}\right|_{v_1=0}=-\frac{1k\Omega}{1k\Omega+36k\Omega}=-\frac{1}{37}$$

$$1k\Omega\|37k\Omega=974\ \Omega\ \ |\ \ r_{\pi 1}=\frac{100(0.025)}{491mA}=5.09\ k\Omega\ \ |\ \ r_{\pi 2}=\frac{100(0.025)}{873mA}=2.86\ k\Omega$$

$$A=\frac{i_o}{i_i}=-\frac{974\Omega}{974\Omega+5090\Omega}(-100)(101)\left(\frac{4700\Omega}{973\Omega+4700\Omega}\right)=-1340$$

$$A_i=\frac{A}{1+A\beta}=\frac{-1340}{1+(-1340)\left(-\frac{1}{37}\right)}=\frac{-1340}{37.2}=-36.0\ \ |\ \ 1+A\beta=37.2$$

$$A_v=\frac{v_o}{v_i}=\frac{973i_o}{1000i_i}=0.973\frac{i_o}{i_i}=-35.0$$

$$R_{in}=\frac{\left(1k\Omega\|37k\Omega\|r_{\pi 1}\right)}{1+A\beta}=\frac{\left(1k\Omega\|37k\Omega\|5.09k\Omega\right)}{37.2}=22.0\ \Omega\ \ |\ \ r_{o1}=\frac{50+1.6}{493x10^{-6}}=105k\Omega$$

$$R_{out}=\frac{\left(1k\Omega\|36k\Omega\|4.7k\Omega\left\|\frac{r_{\pi 2}+r_{o1}}{101}\right.\right)}{1+A\beta}=\frac{\left(1k\Omega\|36k\Omega\|4.7k\Omega\left\|\frac{5.09k\Omega+105k\Omega}{101}\right.\right)}{37.2}=12.5\ \Omega$$

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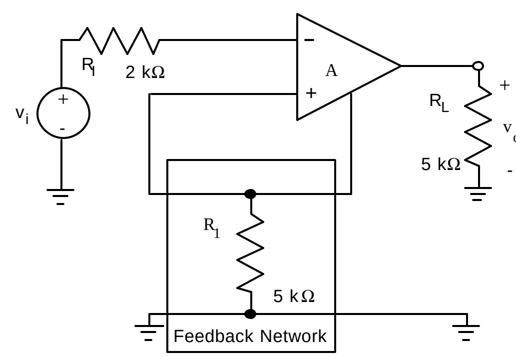
**18.33**




$$z_{11}^F=\left.\frac{v_1}{i_1}\right|_{i_2=0}=5\ k\Omega\ \ |\ \ z_{22}^F=\left.\frac{v_2}{i_2}\right|_{i_1=0}=5\ k\Omega\ \ |\ \ \beta=z_{12}^F=\left.\frac{v_1}{i_2}\right|_{i_1=0}=5\ k\Omega$$

$$z_{11}^T=5k\Omega+15k\Omega=20\ k\Omega\ \ |\ \ z_{22}^T=5k\Omega+1k\Omega=6\ k\Omega\ \ |\ \ z_{21}^A=\left.\frac{v_2}{i_1}\right|_{i_2=0}=15k\Omega(5000)=75\ M\Omega$$

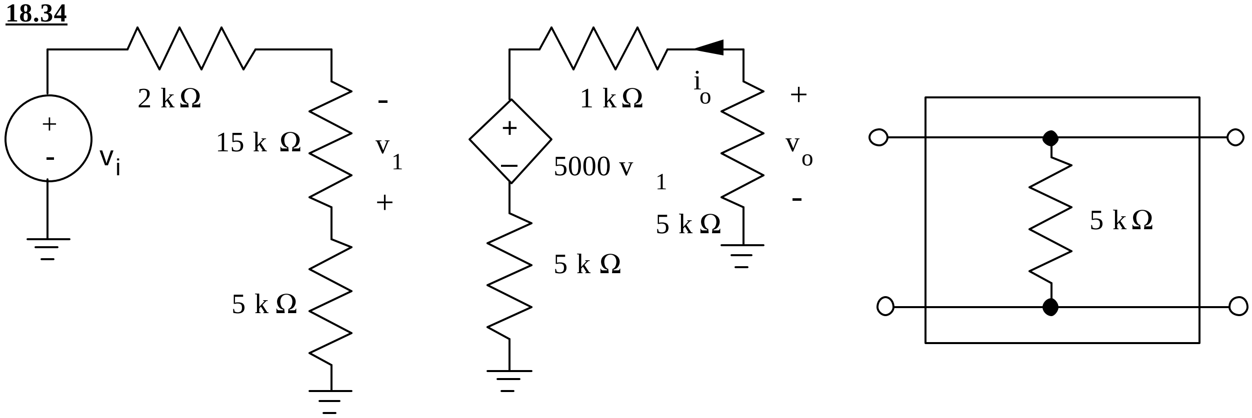
$$A=\frac{z_{21}^A}{\left(R_I+z_{11}^T\right)\left(z_{22}^T+R_L\right)}=\frac{75M\Omega}{(2k\Omega+20k\Omega)(6k\Omega+5k\Omega)}=0.310\ S$$

$$A_{tc}=\frac{A}{1+A\beta}=\frac{0.310}{1+0.310(5k\Omega)}=2.00x10^{-4}S\ \ |\ \ A\beta=1550$$

$$\text{Note: } R_{in}=\left(R_I+z_{11}^T\right)(1+A\beta)=(22k\Omega)(1551)=34.1\ M\Omega$$

$$R_{out}=\left(z_{22}^T+R_L\right)(1+A\beta)=(11k\Omega)(1551)=17.1\ M\Omega$$

**18.34**




$$z_{11}^F = \left.\frac{v_1}{i_1}\right|_{i_2=0} = 5\ k\Omega \quad | \quad z_{22}^F = \left.\frac{v_2}{i_2}\right|_{i_1=0} = 5\ k\Omega \quad | \quad b = z_{12}^F = \left.\frac{v_1}{i_2}\right|_{i_1=0} = 5\ k\Omega$$

$$A = \frac{i_o}{v_s} = \frac{15k\Omega}{2k\Omega + 15k\Omega + 5k\Omega}\left(\frac{5000}{5k\Omega + 1k\Omega + 5k\Omega}\right) = 0.310$$

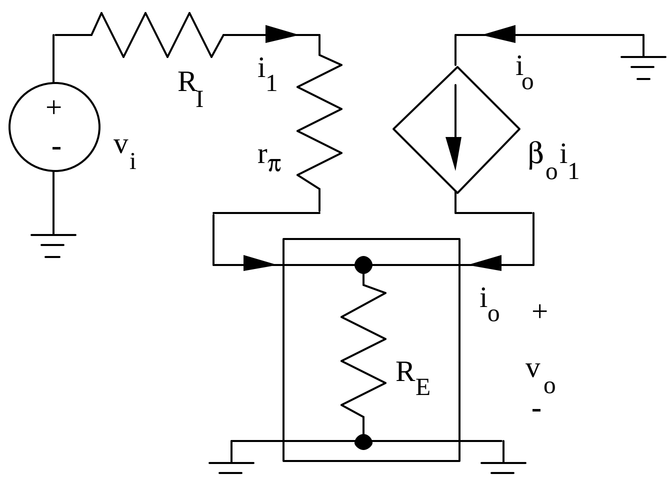
$$A_{tr} = \frac{i_o}{v_s} = \frac{A}{1+Ab} = \frac{0.310}{1+0.310(5000)} = 0.200\ mS \quad | \quad \frac{v_o}{v_s} = -5000\frac{i_o}{v_s} = -1.00 \quad | \quad 1+Ab = 1550$$

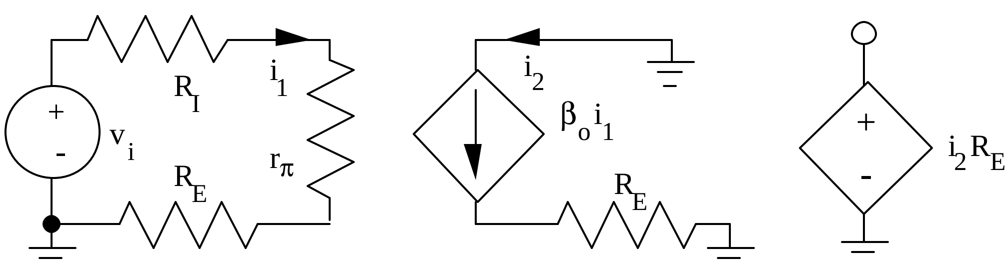
$$R_{in} = (2k\Omega + 15k\Omega + 5k\Omega)(1+Ab) = (22k\Omega)(1550) = 34.1\ M\Omega$$

$$R_{out} = (5k\Omega + 1k\Omega + 5k\Omega)(1+Ab) = (11k\Omega)(1550) = 17.1\ M\Omega$$

---

**18.35**



By carefully drawing the circuit, it can be represented as a series-series feedback amplifier. In particular, $r_\pi$ and the current generator are connected within the feedback network.

$$A = \frac{i_2}{v_s} = \frac{b_o}{R_S + r_p + R_E} \quad | \quad b = z_{12}^F = R_E$$

$$A_{tc} = \frac{i_o}{v_s} = \frac{A}{1+Ab} = \frac{\dfrac{b_o}{R_S + r_p + R_E}}{1+\dfrac{b_o}{R_S + r_p + R_E}R_E} = \frac{b_o}{R_S + r_p + (b_o+1)R_E}$$

$$A_v = \frac{v_o}{v_s} = \frac{i_o}{v_s}\frac{R_E}{a_o} = \frac{b_o}{R_S + r_p + (b_o+1)R_E}\frac{(b_o+1)R_E}{b_o} = \frac{(b_o+1)R_E}{R_S + r_p + (b_o+1)R_E}$$

$$R_{in} = R_{in}^A(1+Ab) = (R_S + r_p + R_E)\left(1+\frac{b_o}{R_S + r_p + R_E}R_E\right) = R_S + r_p + (b_o+1)R_E$$

Both answers agree with our previous direct derivations.

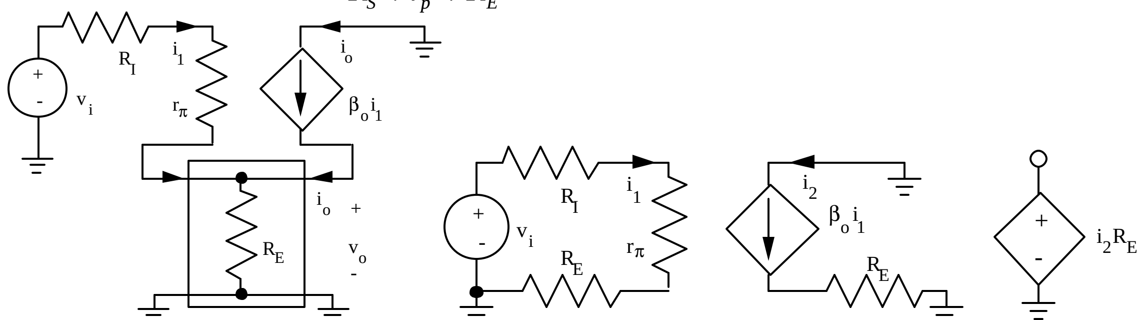
---

**18.36**

$$A_v = \frac{b_o R_L}{R_S + r_p + (b_o+1)R_E} = \frac{b_o R_L}{R_S + r_p + R_E + b_o R_E}$$

$$A_v = \frac{\dfrac{b_o}{R_S + r_p + R_E}}{1+\dfrac{b_o}{R_S + r_p + R_E}R_E}R_L = \frac{A_{tc}}{1+A_{tc}b}R_L$$

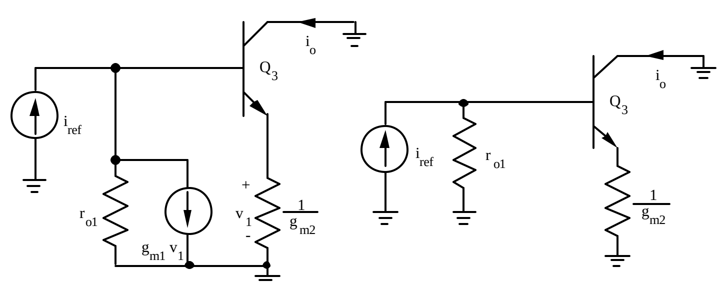
$$A_{tc} = \frac{b_o}{R_S + r_p + R_E} \quad | \quad b = R_E$$




By carefully drawing the circuit, it can be represented as a series-series feedback amplifier. In particular, $r_\pi$ and the current generator are connected within the feedback network.

---

**18.37**



$$g_{11}^F = \left.\frac{i_1}{v_1}\right|_{i_2=0} = \frac{1}{r_{o1}} \quad | \quad g_{22}^F = \left.\frac{v_2}{i_2}\right|_{v_1=0} = \frac{1}{g_{m2}} \quad | \quad g_{12}^F = \left.\frac{i_1}{i_2}\right|_{v_1=0} = \frac{g_{m1}}{g_{m2}} \cong 1$$

$$i_o = i_{ref} r_{o1} \frac{b_o}{r_{o1} + r_{p3} + (b_{o3}+1)\dfrac{1}{g_{m2}}} \approx i_{ref} \frac{b_o r_{o1}}{r_{o1} + 2r_{p3} + \dfrac{1}{g_{m2}}} \quad | \quad A = \frac{i_o}{i_{ref}} = \frac{b_o m_f}{m_f + 2b_o + 1} \approx b_o$$

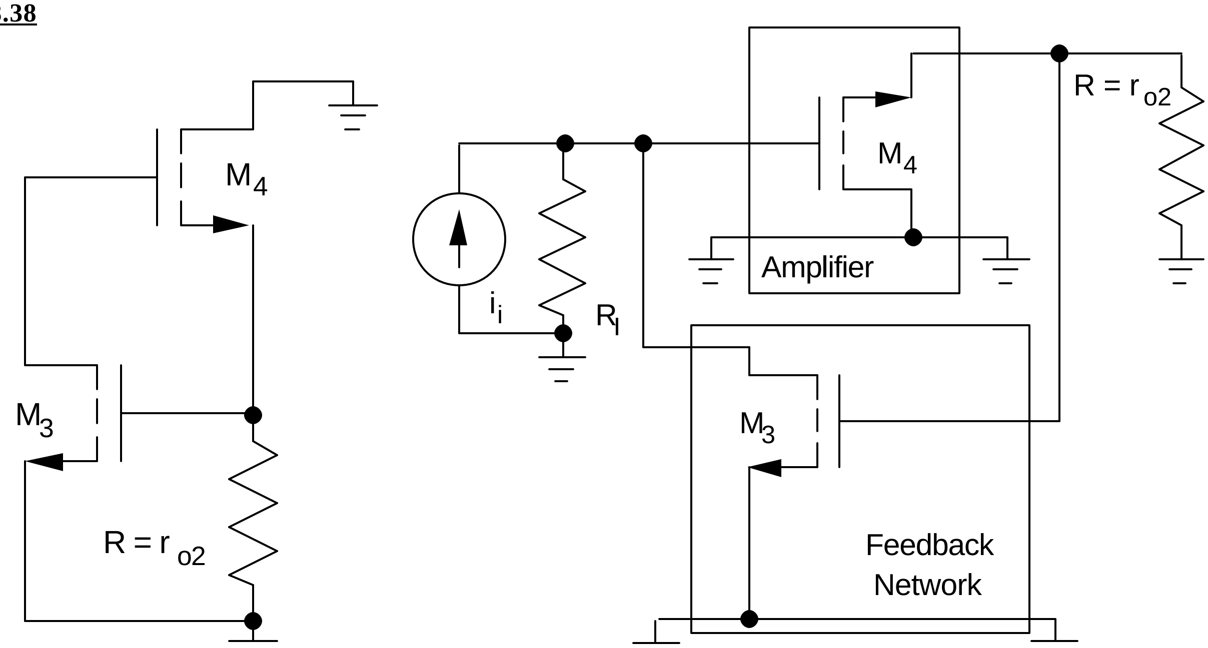
$$A_i = \frac{A}{1+Ab} = \frac{b_o}{1+b_o(1)} = a_o \approx 1 \text{ which is correct.}$$

$$R_{in} = \frac{r_{o1} \left\| \left( r_{p3} + (b_{o3}+1)\dfrac{1}{g_{m2}} \right) \right.}{1+b_o} \approx \frac{2r_p}{b_o} = \frac{2}{g_m} \quad \text{which is correct.}$$

$$R_{out} = (1+b_o) r_{o3} \left( 1 + \frac{b_{o3}\dfrac{1}{g_{m2}}}{r_{o1} + r_{p3} + \dfrac{1}{g_{m2}}} \right) = (1+b_o) r_o \left( 1 + \frac{b_o}{m_f + b_o + 1} \right) \approx b_o r_o \; - \text{ not correct!}$$

---

**18.38**




(a) (b)

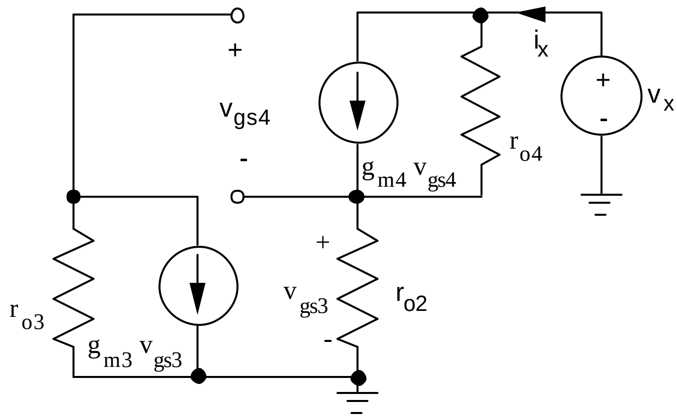
(c) Yes, see figure.

$$A_{(i)} = r_{o3} \frac{g_{m4} r_{o2}}{1 + g_{m4} r_{o2}} \frac{1}{r_{o2}} \cong \frac{r_{o3}}{r_{o2}} \quad | \quad b = g_{m3} r_{o2} \quad | \quad Ab = g_{m3} r_{o3} = m_{f3}$$

$$R_{out}^A = m_{f4} r_{o2} \quad | \quad R_{out} = R_{out}^A (1+Ab) = m_{f4}(1+m_{f3}) r_{o2}$$

$$\text{Also, } R_{in}^A = r_{o3} \quad | \quad R_{in} = \frac{R_{in}^A}{(1+Ab)} = \frac{r_{o3}}{1+m_{f3}} \cong \frac{1}{g_{m3}}$$

(d)




$$v_x = (i_x - g_{m4}v_{gs4})r_{o4} + i_x r_{o2} \quad | \quad v_{gs4} = (-m_{f3}v_{gs3} - v_{gs3}) = -i_x r_{o2}(m_{f3}+1)$$

$$v_x = i_x r_{o4} + i_x r_{o2} + g_{m4} r_{o4}(1+m_{f3})i_x r_{o2} \quad | \quad R_{out} = m_{f4}(1+m_{f3})r_{o2}$$

(e)

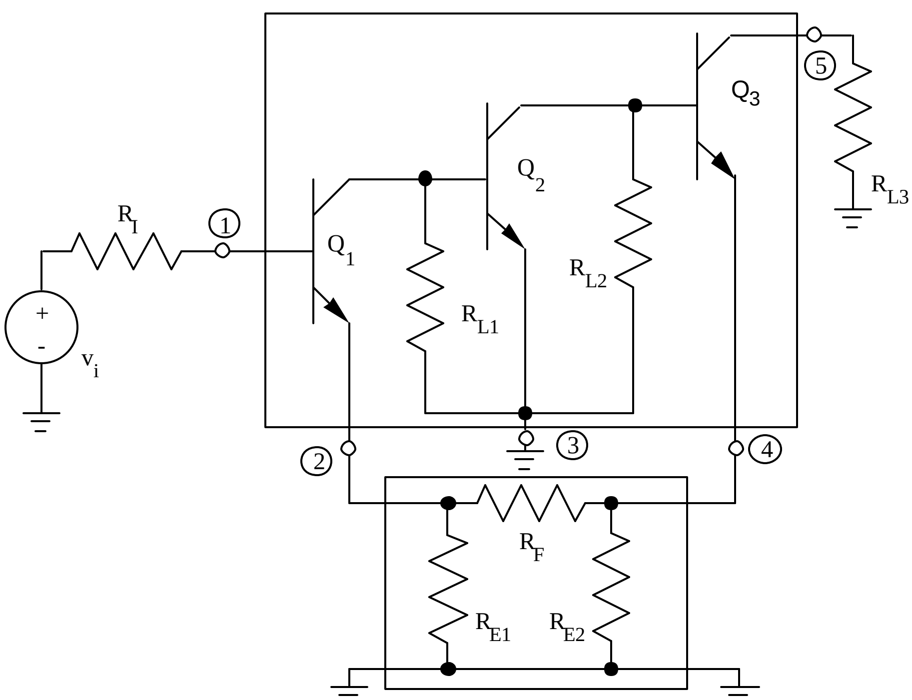
$$m_f = g_m r_o \cong \sqrt{2(0.75x10^{-3})(10^{-4})}\left[\frac{50+8}{(10^{-4})}\right] = (0.387mS)(580k\Omega) = 194$$

$$R_{out} = m_{f4}(1+m_{f3})r_{o2} = 194(195)(580k\Omega) = 21.9\ G\Omega$$

(f) SPICE yields 28.0 GΩ? ? ? ? ? ? ? ? ? ? ? with the formula above using the parameter values from SPICE.

---

**18.39**




The amplifier is not a two-port. It has five separate terminals. It can be analyzed correctly as a series-shunt configuration with the output defined at terminal 4. In the series-shunt configuration, $R_L$ is absorbed into the amplifier thereby making it a two-port.

**18.40**

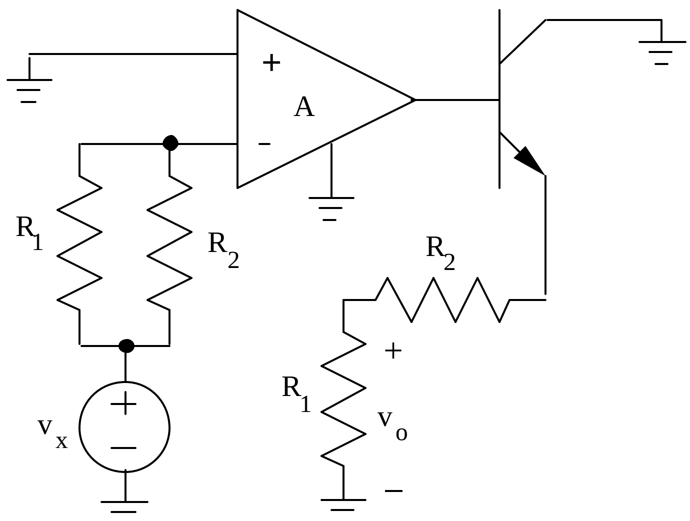
$$T = \frac{v_o}{v_x} = g_{m2}\left(r_{o2}\|r_{o4}\right)\frac{(b_o+1)R}{\left(r_{o2}\|r_{o4}\right)+r_{p3}+(b_o+1)R} \quad | \quad g_{m1} = 40\left(10^{-4}\right) = 4.00mS$$

$$r_{o2} = \frac{50+1.4}{10^{-4}} = 514k\Omega \quad | \quad r_{o4} = \frac{50+11.3}{10^{-4}} = 613k\Omega \quad | \quad r_{p3} = \frac{100(0.025)}{(12V/10k\Omega)} = 2.08k\Omega$$

$$T = \left(4x10^{-3}\right)(280k\Omega)\frac{(101)10k\Omega}{280k\Omega + 2.08k\Omega + 101(10k\Omega)} = 876 \quad (58.9\ dB)$$

---

**18.41**




Note: The loading effects of the feedback network must be carefully included.

$$R_1\|R_2 = 1k\Omega\|7.5k\Omega = 882\Omega \quad | \quad r_p = \frac{100(0.025V)}{198mA} = 12.6k\Omega$$

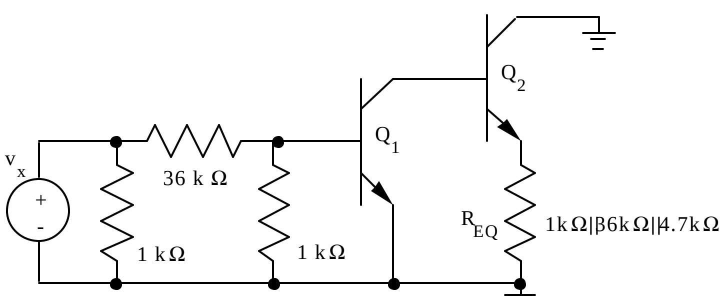
$$T = \frac{v_o}{v_x} = \frac{R_{ID}}{R_{ID}+882\Omega}(A)\frac{(b_o+1)(R_1+R_2)}{R_O+r_p+(b_o+1)(R_1+R_2)}\left(\frac{R_1}{R_1+R_2}\right)$$

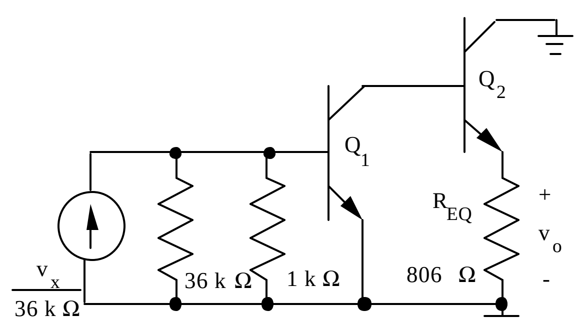
$$T = \frac{v_o}{v_x} = \frac{40k\Omega}{40k\Omega+882\Omega}(316)\frac{(101)(8.5k\Omega)}{1k\Omega+12.6k\Omega+(101)(8.5k\Omega)}\left(\frac{1k\Omega}{1k\Omega+7.5k\Omega}\right) = 35.8$$

which agrees with the result in Prob. 18.18.

---

**18.42**



$$y_{11}^F = \left.\frac{i_1}{v_1}\right|_{v_2=0} = \frac{1}{36k\Omega} \quad | \quad y_{22}^F = \left.\frac{i_2}{v_2}\right|_{v_1=0} = \frac{1}{36k\Omega \| 1k\Omega} \quad | \quad y_{12}^F = \left.\frac{i_1}{v_2}\right|_{v_1=0} = -\frac{1}{36k\Omega}$$

$$r_{\pi 1} = \frac{100(0.025)}{491mA} = 5.09k\Omega \ | \ r_{\pi 2} = \frac{100(0.025)}{873mA} = 2.86k\Omega \ | \ r_{o1} = \frac{50+1.6}{493x10^{-6}} = 105k\Omega$$

$$T = \frac{v_o}{v_s} = \frac{1}{36k\Omega}(1k\Omega \| 36k\Omega \| r_{\pi 1}) g_{m1} \left[ r_{o1} \| \left( r_{\pi 2} + (\beta_o + 1) R_{EQ} \right) \right] \frac{r_{\pi 2} + (\beta_o + 1) R_{EQ}}{r_{o1} + r_{\pi 2} + (\beta_o + 1) R_{EQ}}$$

$$\frac{(1k\Omega \| 36k\Omega \| r_{\pi 1})}{36k\Omega} = \frac{(1k\Omega \| 36k\Omega \| 5.09k\Omega)}{36k\Omega} = 0.0227 \quad | \ g_m = 40(491mA) = 19.6mS$$

$$\left[ r_{o1} \| \left( r_{\pi 2} + (\beta_o + 1) R_{EQ} \right) \right] = \left[ 105k\Omega \| \left( 2.86k\Omega + (101) 806\Omega \right) \right] = 46.8k\Omega$$

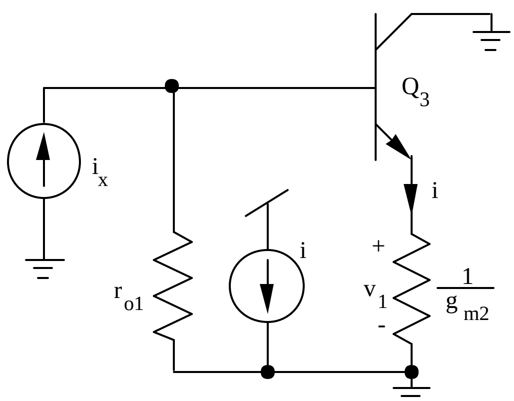
$$\frac{r_{\pi 2} + (\beta_o + 1) R_{EQ}}{r_{o1} + r_{\pi 2} + (\beta_o + 1) R_{EQ}} = \frac{2.86k\Omega + (101) 806\Omega}{105k\Omega + 2.86k\Omega + (101) 806\Omega} = 0.430$$

$$T = (0.0227)(19.6mS)(46.8k\Omega)(0.430) = 8.95$$

These results agree with those of Prob. 18.23.

---

**18.43**

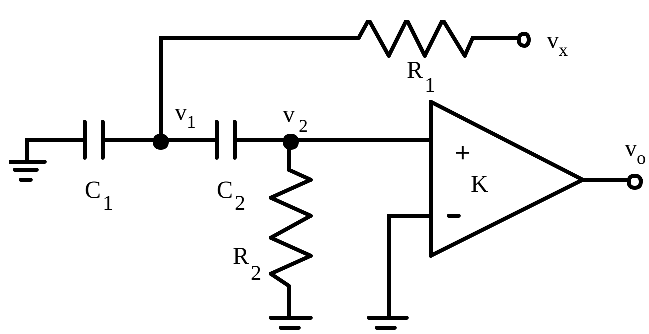



$$T = \frac{i_o}{i_x} = (\beta_o + 1) \frac{r_o}{r_o + r_\pi + (\beta_o + 1)\frac{1}{g_m}} = \frac{(\beta_o + 1)\mu_f}{\mu_f + 2\beta_o + 1} = \frac{(101)(2000)}{2000 + 200 + 1} = 91.8$$

These results agree with those of Prob. 18.27.

---

**18.44**



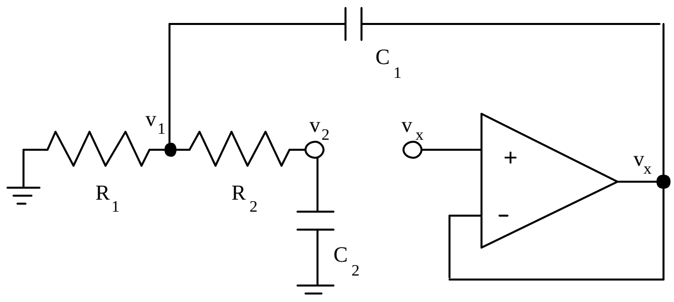
$$\begin{bmatrix} G_1V_x \\ 0 \end{bmatrix} = \begin{bmatrix} s(C_1+C_2)+G_1 & -sC_2 \\ -sC_2 & sC_2+G_2 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \qquad V_o = KV_2$$

$$\Delta = s^2C_1C_2 + s\left[C_1G_2 + C_2(G_1+G_2)\right] + G_1G_2$$

$$T = \frac{V_o}{V_x} = K\frac{s\dfrac{1}{R_1C_1}}{s^2 + s\left[\dfrac{1}{R_2C_2} + \dfrac{1}{(R_1\|R_2)C_1}\right] + \dfrac{1}{R_1R_2C_1C_2}}$$

---

**18.45**




$$\begin{bmatrix} sC_1V_x \\ 0 \end{bmatrix} = \begin{bmatrix} sC_1+G_1+G_2 & -G_2 \\ -G_2 & sC_2+G_2 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \qquad V_2 = \frac{sC_1G_2}{\Delta}V_x$$

$$\Delta = s^2C_1C_2 + s\left[C_1G_2 + C_2(G_1+G_2)\right] + G_1G_2$$

$$T = \frac{V_2}{V_x} = \frac{\dfrac{s}{R_2C_2}}{s^2 + s\left[\dfrac{1}{R_2C_2} + \dfrac{1}{(R_1\|R_2)C_1}\right] + \dfrac{1}{R_1R_2C_1C_2}}$$

---

**18.46**

```
*Problem 18.46 - Fig. 18.75 BJT Op-amp
VCC 8 0 DC 12
VEE 9 0 DC -12
IS 2 9 DC 200U
VS 1 0 DC 0
Q1 4 1 2 NBJT
Q2 5 3 2 NBJT
Q3 4 4 8 PBJT
Q4 5 4 8 PBJT
Q5 8 5 6 NBJT
R 6 9 10K
VB 7 3 DC 0
VX 7 6 AC 0
IX 0 7 AC 1
*VX 7 6 AC 1
*IX 0 7 AC 0
.MODEL NBJT NPN BF=100 VA=50 IS=1E-15
.MODEL PBJT PNP BF=100 VA=50 IS=1E-15
.OP
```

```
.AC LIN 1 10 10
.PRINT AC IM(VX) IP(VX) IM(VB) IP(VB) VM(7) VP(7) VM(6) VP(6)
```

Results: I(VX) = 1.000 A, I(VB) = 3.703 x $10^{-5}$ A, V(7) = 1.188 mV, V(6) = -1.000 V

$$T_v = -\frac{-.9988V}{1.188mV} = 841 \quad | \quad T_i = \frac{1.000A}{37.03mA} = 2.70x10^4$$

$$T = \frac{T_vT_i - 1}{2 + T_v + T_i} = \frac{841\left(2.70x10^4\right) - 1}{2 + 841 + 2.70x10^4} = 816 \quad | \quad \frac{R_2}{R_1} = \frac{1 + T_v}{1 + T_i} = \frac{1 + 841}{2.70x10^4} = 0.0312$$

---

**18.47**

```
*Problem 18.47 - Fig. 18.76
VCC 4 0 DC 10
IS 5 0 DC 200U
VS 1 0 DC 0
Q1 4 3 5 NBJT
RID 1 8 40K
RO 2 3 1K
E1 2 0 1 8 316.2
R2 6 5 7.5K
R1 8 0 1K
VB 7 8 DC 0
VX 7 6 AC 0
IX 0 7 AC 1
*VX 7 6 AC 1
*IX 0 7 AC 0
.MODEL NBJT NPN BF=100 VA=50 IS=1E-15
.OP
.AC LIN 1 10 10
.PRINT AC IM(VX) IP(VX) IM(VB) IP(VB) VM(7) VP(7) VM(6) VP(6)
.END
```

Results: I(VX) = 0.9759 A, I(VB) = 0.0241 A, V(7) = 3.078 mV, V(6) = -0.9969 V

$$T_v = -\frac{-.9969V}{3.078mV} = 324 \quad | \quad T_i = \frac{0.9759A}{0.0241A} = 40.5x10^4$$

$$T = \frac{T_vT_i - 1}{2 + T_v + T_i} = \frac{324(40.5) - 1}{2 + 324 + 40.5} = 35.8 \quad | \quad \frac{R_2}{R_1} = \frac{1 + T_v}{1 + T_i} = \frac{1 + 324}{1 + 40.5} = 7.83$$

---

**18.48** The circuit description is the same as Problem 18.47 except for the change in the values of $R_1$ and $R_2$.

```
R2 6 5 300K
R1 8 0 40K
```

Results: I(VX) = 0.9548 A, I(VB) = 45.19 mA, V(7) = 3.011 mV, V(6) = -0.9970 V

$$T_v = -\frac{-.9970V}{3.011mV} = 331 \quad | \quad T_i = \frac{0.9548A}{45.19mA} = 21.1$$

$$T = \frac{T_vT_i - 1}{2 + T_v + T_i} = \frac{331(21.1) - 1}{2 + 331 + 21.1} = 19.7 \quad | \quad \frac{R_2}{R_1} = \frac{1 + T_v}{1 + T_i} = \frac{1 + 331}{1 + 21.1} = 15.0$$

---

**18.49**

```
*Problem 18.49 - Fig. 18.73(b)
IS 0 1 DC 0
RS 1 0 1K
RID 1 0 15K
RO 2 3 1K
E1 3 4 1 0 5000
RL 2 0 4.7K
R2 4 0 1K
R1 4 6 36K
VB 7 1 DC 0
VX 7 6 AC 0
IX 0 7 AC 1
*VX 7 6 AC 1
*IX 0 7 AC 0
.OP
.AC LIN 1 10 10
.PRINT AC IM(VX) IP(VX) IM(VB) IP(VB) VM(7) VP(7) VM(6) VP(6)
.END
```

Results: I(VX) = 0.9500 A, I(VB) = 49.97 mA, V(7) = 1.271 mV, V(6) = -0.9987 V

$$T_v = -\frac{-.9987V}{1.271mV} = 786 \quad | \quad T_i = \frac{0.9500A}{49.97mA} = 19.0$$

$$T = \frac{T_v T_i - 1}{2 + T_v + T_i} = \frac{786(19.0) - 1}{2 + 786 + 19.0} = 18.5 \quad | \quad \frac{R_2}{R_1} = \frac{1 + T_v}{1 + T_i} = \frac{1 + 786}{1 + 19.0} = 39.4$$

---

**18.50**

```
*Problem 18.50
VCC 5 0 DC 6
IREF 0 1 DC 100UA
Q1 1 4 0 NBJT
Q2 4 4 0 NBJT
Q3 5 3 4 NBJT
IX 0 2 DC 0
VX1 2 1 DC 0
VX2 2 3 DC 0
.MODEL NBJT NPN BF=100 VA=50 IS=1E-15
.OP
.TF I(VX1) IX                       ---> 0.9910
*.TF I(VX2) IX                      ---> 9.043 x 10^-3
.END
*Problem 18.50
VCC 5 0 DC 6
IREF 0 1 DC 100UA
Q1 1 4 0 NBJT
Q2 4 4 0 NBJT
Q3 5 3 4 NBJT
IX 0 2 DC 0
VX1 2 1 DC 0
VX2 2 3 DC 0
.MODEL NBJT NPN BF=100 VA=50 IS=1E-15
.OP
.TF V(1) VX1                        ---> -0.9990
*.TF V(2) VX1                       ---> 1.012 x 10^-3
.END
```

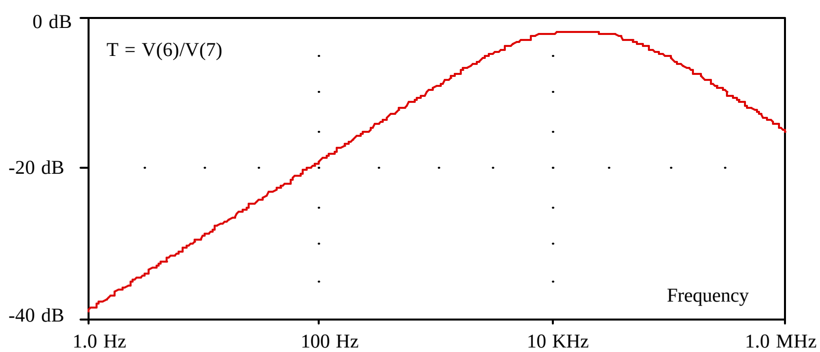
$$T_v = -\frac{-0.9990}{1.012x10^{-3}} = 987 \quad | \quad T_i = \frac{0.9910}{9.043x10^{-3}} = 110$$

$$T = \frac{987(110)-1}{2+987+110} = 98.8 \quad | \quad \frac{R_2}{R_1} = \frac{1+987}{1+110} = 8.90$$

---

**18.51** Since the output resistance of the amplifier is zero ($R_2 = 0$), the simplified method can be used: $T = T_V$.

```
*Problem 18.51
VS 1 0 DC 0
C1 1 2 0.005UF
C2 2 3 0.005UF
R1 2 7 2K
R2 3 0 2K
E1 4 0 3 0 1
R 4 5 31.83
C 5 0 1NF
E2 6 0 5 0 2
VX 7 6 AC 1
.OP
.AC DEC 100 1 1E6
.PROBE V(6) V(7)
.END
```

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**18.52** (a) For Fig. 18.73(a), use values from Problem 18.15.
(b) For Fig. 18.73(b), use values from Problem 18.30.
(c) For Fig. 18.73(c), use values from Problem 18.33.
(d) For Fig. 18.73(a), use values from Problem 18.21.

(a) With gain $A = 0$, $R_{inD} = R_I + R_{id} + R_1 \| [R_2 + R_o \| R_L]$

$$R_{inD} = 1k\Omega + 15k\Omega + 4.3k\Omega \| [39k\Omega + 1k\Omega \| 5.6k\Omega] = 19.9k\Omega$$

With the input open - circuited, the current in $R_{id}$ is zero, and so $T_{OC} = 0$.

With the input set to zero, The Thevenin equivalent looking back into $R_1$ is

$$V_{th} = \left[5000\left(\frac{5.6k\Omega}{5.6k\Omega + 1k\Omega}\right)\right]\left[\frac{4.3k\Omega}{4.3k\Omega + 39k\Omega + (5.6k\Omega \| 1k\Omega)}\right] = 413 \text{ and}$$

$$R_{th} = R_1 \| [R_2 + R_o \| R_L] = 4.3k\Omega \| [39k\Omega + 1k\Omega \| 5.6k\Omega] = 3.88k\Omega$$

$$T_{SC} = 413 \frac{15k\Omega}{3.88k\Omega + 15k\Omega + 1k\Omega} = 312 \quad | \quad R_{in} = 19.9k\Omega\left(\frac{1+312}{1+0}\right) = 6.22\ M\Omega$$

With gain $A = 0$,

$$R_{outD} = R_L \| R_o \| \left[R_2 + \left(R_1 \| (R_{id} + R_I)\right)\right] = 5.6k\Omega \| 1k\Omega \| \left[39k\Omega + \left(4.3k\Omega \| (15k\Omega + 1k\Omega)\right)\right] = 832\Omega$$

With the output shorted, $T_{SC} = 0$. With the output open - circuited, $T_{OC} = 312$

$R_{out} = 832\Omega\left(\dfrac{1+0}{1+312}\right) = 2.66\ \Omega$ | $R_{in}$ and $R_{out}$ agree with both Prob. 18.18 and SPICE.

(b) With gain $A = 0$,

$$R_{inD} = R_I \| R_{id} \| \left[R_1 + R_2 \| (R_o + R_L)\right] = 150k\Omega \| 15k\Omega \| \left[20k\Omega + 2k\Omega \| (1k\Omega + 10k\Omega)\right] = 8.37k\Omega$$

With the input short - circuited, $T_{SC} = 0$.

With the input open - circuited, $T_{OC} = \dfrac{5000}{R_L + R_o + R_2 \| \left[R_1 + \left(R_I \| R_{id}\right)\right]} \dfrac{R_2}{R_2 + R_1 + \left(R_I \| R_{id}\right)} R_I \| R_{id}$

$$T_{OC} = -\frac{5000}{10k\Omega + 1k\Omega + 2k\Omega \| \left[20k\Omega + \left(150k\Omega \| 15k\Omega\right)\right]} \left[\frac{2k\Omega}{2k\Omega + 20k\Omega + \left(150k\Omega \| 15k\Omega\right)}\right] \left(150k\Omega \| 15k\Omega\right) = -297$$

$R_{in} = 8.37k\Omega\left(\dfrac{1+0}{1+297}\right) = 28.1\ \Omega$ | Since the circuit is series feed back at the output,

we look into the circuit between ground and the bottom of $R_L$. With gain $A = 0$,

$$R_{outD} = R_L + R_o + R_2 \| \left[R_1 + \left(R_I \| R_{id}\right)\right] = 10k\Omega + 1k\Omega + 2k\Omega \| \left[20k\Omega + \left(150k\Omega \| 15k\Omega\right)\right] = 12.9k\Omega$$

With the output open, $i_o = 0$, and $T_{OC} = 0$. With the output short - circuited, $T_{SC}$ is

$$T_{SC} = -\frac{5000}{R_L + R_o + R_2 \| \left[R_1 + \left(R_I \| R_{id}\right)\right]} \frac{R_2}{R_2 + R_1 + \left(R_I \| R_{id}\right)} \left(R_I \| R_{id}\right) = 297$$

$R_{out} = 12.9k\Omega\left(\dfrac{1+297}{1+0}\right) = 3.84\ \text{M}\Omega$ | $R_{in}$ and $R_{out}$ agree with both Prob. 18.30 and SPICE.

- - - - - - -

We can instead choose to look at the shunt output. With gain $A = 0$,

$$R_{outD} = R_L \| \left\{R_o + R_2 \| \left[R_1 + \left(R_I \| R_{id}\right)\right]\right\} = 10k\Omega \| \left\{1k\Omega + 2k\Omega \| \left[20k\Omega + \left(150k\Omega \| 15k\Omega\right)\right]\right\} = 2.24k\Omega$$

With the output shorted, $T_{SC} = -\dfrac{5000}{R_o + R_2 \| \left[R_1 + \left(R_I \| R_{id}\right)\right]} \dfrac{R_2}{R_2 + R_1 + \left(R_I \| R_{id}\right)} R_I \| R_{id} = -1325$

With the output open - circuited,

$$T_{OC} = -\frac{5000}{R_L + R_o + R_2 \| \left[R_1 + \left(R_I \| R_{id}\right)\right]} \frac{R_2}{R_2 + R_1 + \left(R_I \| R_{id}\right)} \left(R_I \| R_{id}\right) = -297$$

$R_{out} = 2.24k\Omega\left(\dfrac{1+1325}{1+297}\right) = 9.967\ \text{k}\Omega$ and removing the 10k $\Omega$ resistor yields $R_{out} = 3.04 M\Omega$.

The error is due to loss of significance in the calculations.

If we remove $R_L$ from across the output, $R_{outD} = 2.89k\Omega$, $T_{SC} = -1325$, and $T_{OC} = 0$.

$R_{out} = 2.89k\Omega\left(\dfrac{1+1325}{1+0}\right) = 3.83\ \text{M}\Omega$ | $R_{out}$ again agrees with both Prob. 18.30 and SPICE.

(c) With gain $A = 0$,

$$R_{inD} = R_I + R_{id} + R_1 \| (R_o + R_L) = 2k\Omega + 15k\Omega + 5k\Omega \| (1k\Omega + 5k\Omega) = 19.7k\Omega$$

When the input is open - circuited, zero current exists in $R_{id}$ and $T_{OC} = 0$.

With the input short - circuited,

$$|T_{SC}| = \frac{5000}{R_L + R_o + [R_1 \| (R_{id} + R_I)]} \left( \frac{R_1}{R_1 + R_{id} + R_I} \right) R_{id}$$

$$|T_{SC}| = \frac{5000}{5k\Omega + 1k\Omega + [5k\Omega \| (15k\Omega + 2k\Omega)]} \left( \frac{5k\Omega}{5k\Omega + 15k\Omega + 2k\Omega} \right) 15k\Omega = 1730$$

$$R_{in} = 19.7k\Omega \left( \frac{1 + 1730}{1 + 0} \right) = 34.1\ M\Omega$$

With gain $A = 0$, (remember, this is series feedback and we look into the bottom of $R_L$)

$$R_{outD} = R_L + R_o + [R_1 \| (R_{id} + R_I)] = 5k\Omega + 1k\Omega + [5k\Omega \| (15k\Omega + 2k\Omega)] = 9.86k\Omega$$

With the output open - circuited, $T_{OC} = 0$. With the output shorted,

$|T_{SC}| = 1730$, the same as above, and $R_{out} = 9.86k\Omega \left( \frac{1 + 1730}{1 + 0} \right) = 17.1\ \mathrm{M}\Omega$

$R_{in}$ and $R_{out}$ agree with both Prob. 18.33 and SPICE.

If we take the output as the voltage at $v_o$, then $|T_{SC}| = \frac{5000}{R_o + [R_1 \| (R_{id} + R_I)]} \left( \frac{R_1}{R_1 + R_{id} + R_I} \right) R_{id}$

$$|T_{SC}| = \frac{5000}{1k\Omega + [5k\Omega \| (15k\Omega + 2k\Omega)]} \left( \frac{5k\Omega}{5k\Omega + 15k\Omega + 2k\Omega} \right) 15k\Omega = 3500$$

$$R_{outD} = R_L \| \{R_o + [R_1 \| (R_{id} + R_I)]\} = 5k\Omega \| \{1k\Omega + [5k\Omega \| (15k\Omega + 2k\Omega)]\} = 2.47k\Omega$$

$$R_{out} = 2.47k\Omega \left( \frac{1 + 3500}{1 + 1730} \right) = 4.99\ \mathrm{k}\Omega \quad (= 5k\Omega \| (1731) 4.86k\Omega)$$

(d) With gain $A = 0$,

$$R_{inD} = R_I \| R_{id} \| [R_F + (R_L \| R_o)] = 100k\Omega \| 15k\Omega \| [10k\Omega + (10k\Omega \| 1k\Omega)] = 5.94k\Omega$$

With the input short - circuited, $T_{SC} = 0$.

When the input is open - circuited,

$$|T_{OC}| = \left( \frac{5000}{R_o} \right) \frac{(R_L \| R_o)}{(R_L \| R_o) + R_F + (R_I \| R_{id})} (R_I \| R_{id})$$

$$|T_{OC}| = \left( \frac{5000}{1k\Omega} \right) \frac{(10k\Omega \| 1k\Omega)}{(10k\Omega \| 1k\Omega) + 10k\Omega + (100k\Omega \| 15k\Omega)} (100k\Omega \| 15k\Omega) = 2480$$

$$R_{in} = 5.94k\Omega \left( \frac{1 + 0}{1 + 2480} \right) = 2.39\ \Omega$$

With gain $A = 0$,

$$R_{outD} = R_L \| R_o \| \left[R_F + \left(R_I \| R_{id}\right)\right] = 10k\Omega \| 1k\Omega \| \left[10k\Omega + \left(100k\Omega \| 15k\Omega\right)\right] = 875\Omega$$

With the output short - circuited, $T_{SC} = 0$. With the output open,

$\left|T_{OC}\right| = 2480$, the same as above, and $R_{out} = 875\Omega\left(\dfrac{1+0}{1+2480}\right) = 0.353\ \Omega$

$R_{in}$ and $R_{out}$ agree with both Prob. 18.21 and SPICE.

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**18.53**

With gain $A = 0$, $R_{inD} = R_{id} + R_1 \left\| \left[R_2 + \dfrac{r_p + R_o}{b_o + 1}\right]\right.$ | $r_p = \dfrac{100(0.025V)}{200mA} = 12.5k\Omega$

$$R_{inD} = 40k\Omega + 1k\Omega \left\| \left[7.5k\Omega + \frac{12.5k\Omega + 1k\Omega}{101}\right]\right. = 40.9k\Omega$$

With the input open - circuited, the current in $R_{id}$ is zero, and so $T_{OC} = 0$.

With the input set to zero, the load on the emitter follower is

$$R_{LEQ} = R_2 + \left(R_1 \| R_{id}\right) = 7.5k\Omega + \left(1k\Omega \| 40k\Omega\right) = 8.48k\Omega$$

$$T_{SC} = A\frac{(b_o+1)R_{LEQ}}{R_o + r_p + (b_o+1)R_{LEQ}}\frac{\left(R_1 \| R_{id}\right)}{R_2 + \left(R_1 \| R_{id}\right)} = 316\frac{101(8.48k\Omega)}{1k\Omega + 12.5k\Omega + 101(8.48k\Omega)}\left(\frac{0.976k\Omega}{8.48k\Omega}\right) = 35.8$$

$$R_{in} = 40.9k\Omega\left(\frac{1+35.8}{1+0}\right) = 1.51\ M\Omega$$

With gain $A = 0$, $R_{outD} = \left[R_2 + \left(R_1 \| R_{id}\right)\right] \left\| \left(\dfrac{r_p + R_o}{b_o + 1}\right)\right. = 8.48k\Omega \| 134\Omega = 132\Omega$

With the output shorted, $T_{SC} = 0$. With the output open - circuited, $T_{OC} = 32.0$.

$R_{out} = 132\Omega\left(\dfrac{1+0}{1+35.8}\right) = 3.59\ \Omega$ | $R_{in}$ and $R_{out}$ agree with both Prob. 18.18 and SPICE.

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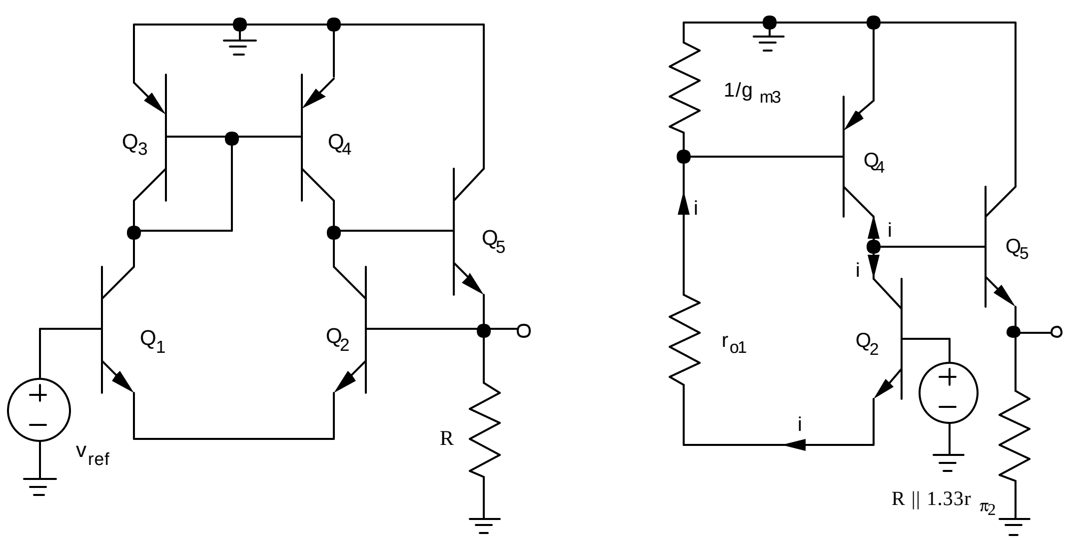
**18.54**



$R_{inD} = 4r_{p1} = 100k\Omega$ (See analysis below **.)

With the input shorted, $T_{SC} = g_{m2}\left[r_{o2}\|r_{o4}\|(b_{o5}+1)(R\|1.33r_{p2})\right]\Omega\left[\dfrac{(b_{o5}+1)(R\|1.33r_{p2})}{r_{p5}+(b_{o5}+1)(R\|1.33r_{p2})}\right]$

$$A_{vef} = \frac{(b_{o5}+1)(R\|1.33r_{p2})}{r_{p5}+(b_{o5}+1)(R\|1.33r_{p2})} = \frac{(101)(10k\Omega\|33.3k\Omega)}{2.08k\Omega+(101)(10k\Omega\|33.3k\Omega)} = 0.997$$

$$T_{SC} = 40(100mA)\left[500k\Omega\|500k\Omega\|(101)(10k\Omega\|33.3k\Omega)\right](0.997) = 757$$

With the input open, $T_{OC} \cong -\dfrac{2i}{v_i}(r_{o2}\|r_{o4})A_{vef} \cong -\dfrac{2}{r_{o1}+\dfrac{1}{g_{m3}}}(r_{o2}\|r_{o4})A_{vef} \cong -\dfrac{2}{r_{o1}}(r_{o2}\|r_{o4})(0.997) \cong -0.997$

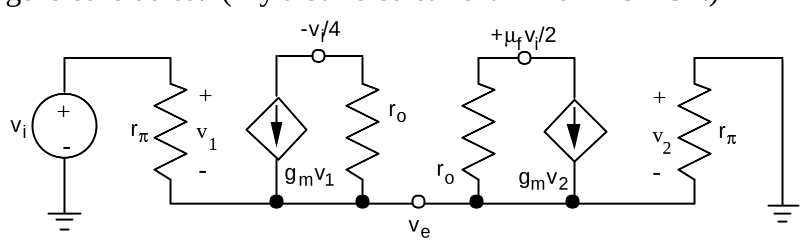
$$R_{in} = 100k\Omega\left(\frac{1+757}{1+0.997}\right) = 38.0M\Omega$$

$$R_{outD} = R\|1.33r_{p1}\|\frac{r_{p5}+(r_{o2}\|r_{o4})}{b_{o5}+1} = 10k\Omega\|33.3k\Omega\|\frac{2.08k+(500k\Omega\|500k\Omega)}{101} = 1.88k\Omega$$

With the output open, $T_{OC} = 757$. With the output shorted, $T_{SC} = 0$

$$R_{in} = 1.88k\Omega\left(\frac{1+0}{1+757}\right) = 2.48\ \Omega.$$

The values of $R_{in}$ and $R_{out}$ agree well with simulation when the effect of imbalance due to offset voltage is considered. (Try a buffered current mirror in SPICE.)




** The input resistance to the differential pair with active load is $4r_p$ rather than the $2r_p$ that one might expect. Because of the high gain ($m_f/2$) to the output node, a significant current is fed back through $r_{o2}$. At the emitter node :

$$g_p(v_i - v_e) + g_m(v_i - v_e) + g_m(0 - v_e) + g_p(0 - v_e) + g_o\left(\frac{m_f}{2}v_i - v_e\right) + g_o\left(-\frac{v_i}{4} - v_e\right) = 0$$

$$\left(\frac{3}{2}g_m + g_p - \frac{g_o}{4}\right)v_i = (2g_m + 2g_p + 2g_o)v_e \quad | \quad \frac{v_e}{v_i} = \frac{\left(\frac{3}{2}g_m + g_p + \frac{g_o}{2}\right)}{(2g_m + 2g_p + 2g_o)} \cong \frac{3}{4}$$

The voltage across $r_p$ of the input transistor is $\dfrac{v_i}{4}$, so $R_{in} \cong 4r_p$. If an input is applied to the right side instead of the left, the sign changes on the $g_o\dfrac{m_f}{2}v_i$ term, and $R_{in} \cong \dfrac{4}{3}r_p$.

**18.55**

$$I_{C1} = 500mA - I_{B2} \quad | \quad I_{E2} = I_{B1} + \frac{36000 I_{B1} + 0.7}{1000} = 37 I_{B1} + 700mA \quad | \quad I_{B2} = \frac{I_{E2}}{101}$$

$$I_{C1} = 500mA - \frac{37 I_{B1} + 700mA}{101} = 493mA - 0.366 I_{B1} \rightarrow I_{C1} = 491.2mA$$

$$I_{E2} = 37\frac{I_{C1}}{100} + 700mA = 881.7mA \quad | \quad I_{C2} = \frac{100}{101} I_{E2} = 873mA \quad | \quad g_{m1} = 40(491.2mA) = 19.6mS$$

$$r_{p1} = \frac{100(0.025)}{491mA} = 5.09k\Omega \quad | \quad r_{p2} = \frac{100(0.025)}{873mA} = 2.86k\Omega \quad | \quad r_{o1} = \frac{50 + 1.6}{493x10^{-6}} = 105k\Omega$$

After replacing $v_i$ and $R_I$ with their Norton equivalent, and with $g_{m1} = 0$,

$$R_{inD} = R_I \| r_{p1} \| \left[ R_F + R_E \| R_L \| \left( \frac{r_{p2} + r_{o1}}{b_{o2} + 1} \right) \right]$$

$$R_{inD} = 1k\Omega \| 5.09k\Omega \| \left[ 36k\Omega + 1k\Omega \| 4.7k\Omega \| \left( \frac{2.86k\Omega + 105k\Omega}{101} \right) \right] = 817\Omega$$

With the input shorted, $T_{SC} = 0$. With the input open and starting at the output of $Q_1$,

$$T_{OC} = (-g_{m1} r_{o1}) \left\{ \frac{(b_{o2}+1)\left[R_E \| R_L \| (R_F + R_I \| r_{p1})\right]}{r_{o1} + r_{p2} + (b_{o2}+1)\left[R_E \| R_L \| (R_F + R_I \| r_{p1})\right]} \right\} \left[ \frac{(R_I \| r_{p1})}{R_F + (R_I \| r_{p1})} \right]$$

$$T_{OC} = (-2062) \left\{ \frac{(101)\left[1k\Omega \| 4.7k\Omega \| (36k\Omega + 1k\Omega \| 5.09k\Omega)\right]}{105k\Omega + 2.86k\Omega + (101)\left[1k\Omega \| 4.7k\Omega \| (36k\Omega + 1k\Omega \| 5.09k\Omega)\right]} \right\} \left[ \frac{1k\Omega \| 5.09k\Omega}{36k\Omega + (1k\Omega \| 5.09k\Omega)} \right]$$

$$T_{OC} = (-2062)(0.403)(0.0227) = -18.9$$

$$R_{in} = 817\Omega \left( \frac{1+0}{1+18.9} \right) = 41.2\Omega$$

$$R_{outD} = R_E \| R_L \| (R_F + R_I \| r_{p1}) \| \frac{r_{p2} + r_{o1}}{(b_{o2}+1)} = 1k\Omega \| 4.7k\Omega \| (36k\Omega + 1k\Omega \| 5.09k\Omega) \| \frac{2.86k\Omega + 105k\Omega}{(101)} = 460\Omega$$

$T_{SC} = 0,\ T_{OC} = 18.9,\ R_{out} = 460\Omega \left( \dfrac{1+0}{1+18.9} \right) = 23.1\Omega$ | The results agree with SPICE.

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**18.56**

$$R_{inD} = 100k\Omega \| \left[1M\Omega + (10k\Omega \| 10k\Omega \| 40k\Omega)\right] = 91.0k\Omega \quad | \quad T_{SC} = 0$$

$$T_{OC} \cong g_m (10k\Omega \| 10k\Omega \| 40k\Omega) \frac{100k\Omega}{100k\Omega + 1M\Omega} = 0.808 \quad | \quad R_{in} = 91.0k\Omega \frac{1+0}{1+0.808} = 50.3\ k\Omega$$

$$R_{outD} = 10k\Omega \| 10k\Omega \| 40k\Omega \| 1.1M\Omega = 4.43k\Omega \quad | \quad T_{SC} = 0$$

$$T_{OC} \cong g_m (10k\Omega \| 10k\Omega \| 40k\Omega) \frac{100k\Omega}{100k\Omega + 1M\Omega} = 0.808 \quad | \quad R_{out} = 4.43k\Omega \frac{1+0}{1+0.808} = 2.45\ k\Omega$$

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**18.57**

$$R_{outD} = m_{f4} r_{o2} \quad | \quad T_{OC} = 0 \quad | \quad T_{SC} = (g_{m3} r_{o3}) \frac{g_{m4}\left(r_{o2} \| r_{o4}\right)}{1 + g_{m4}\left(r_{o2} \| r_{o4}\right)} \cong m_{f3} \frac{m_{f4}}{2 + m_{f4}} \cong m_{f3}$$

$$R_{out} = m_{f4} r_{o2} \frac{1 + m_{f3}}{1 + 0} = m_{f4} r_{o2}\left(m_{f3} + 1\right)$$

$$R_{inD} = r_{o3} \quad | \quad T_{SC} = 0 \quad | \quad T_{OC} = m_{f3} \frac{g_{m4}\left(r_{o2} \| r_{o4}\right)}{1 + g_{m4}\left(r_{o2} \| r_{o4}\right)} \cong m_{f3} \quad | \quad R_{in} = r_{o3} \frac{1+0}{1 + m_{f3}} = \frac{1}{g_{m3}}$$

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**18.58**

Using Wq. (14.28), $R_{outD} = r_o\left[1 + \frac{b_o R_E}{R_{th} + r_p + R_E}\right] = r_{o4}\left[1 + \frac{b_o\left(r_{o2} \| r_{p3}\right)}{r_{o3} + r_{p4} + \left(r_{o2} \| r_{p3}\right)}\right] \cong r_{o4} \frac{b_o r_{p3}}{r_{o3}} = r_{o4} \frac{b_o^2}{m_f}$

$$T_{OC} = (g_{m3} r_{o3}) \frac{r_{o2} \| r_{p3}}{r_{o3} + r_{p4} + r_{o2} \| r_{p3}} \cong (g_{m3} r_{o3}) \frac{r_{p3}}{r_{o3}} = b_o$$

$$T_{SC} \cong (g_{m3} r_{o3}) \frac{(b_o + 1)\left(r_{o2} \| r_{p3}\right)}{r_{o3} + r_{p4} + (b_o + 1)\left(r_{o2} \| r_{p3}\right)} \cong m_f \quad | \quad R_{out} \cong r_{o4} \frac{b_o^2}{m_f} \frac{1 + m_f}{1 + b_o} \cong b_o r_{o4}$$

We cannot exceed the $b_o r_{o4}$ limit as long as the base current of $Q_4$ reaches ground!

$$R_{inD} = r_{o3} \| \left[r_{p4} + (b_o + 1)\left(r_{o2} \| r_{p3}\right)\right] \cong r_{o3} \| b_o r_{p3} \cong r_{o3} \quad | \quad T_{SC} = 0$$

$$T_{OC} = m_{f3} \frac{g_{m4}\left(r_{o2} \| r_{o4}\right)}{1 + g_{m4}\left(r_{o2} \| r_{o4}\right)} \cong m_{f3} \quad | \quad R_{in} = r_{o3} \frac{1+0}{1 + m_{f3}} \cong \frac{1}{g_{m3}}$$

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**18.59**

$$(a) \quad A(s) = \frac{\dfrac{2x10^{14} p^2}{\left(2p\,x10^3\right)\left(2p\,x10^5\right)}}{\left(1 + \dfrac{s}{2p\,x10^3}\right)\left(1 + \dfrac{s}{2p\,x10^5}\right)} = \frac{5x10^5}{\left(1 + \dfrac{s}{2p\,x10^3}\right)\left(1 + \dfrac{s}{2p\,x10^5}\right)}$$

$A(s)$ represents a low-pass amplifier with two widely-spaced poles

*Open − loop* : $A_o = 5x10^5 = 114 dB \quad | \quad f_L = 0 \quad | \quad f_H \cong f_1 = 1000\ Hz$

$(b)$ *A* common mistake would be the following :

Closed − loop : $f_H = 1000 Hz\left[1 + 5x10^5(0.01)\right] = 5 MHz$

*Oops*! - This exceeds $f_2 = 100\ kHz$! This is a two-pole low-pass amplifier.

$$A_v(s) = \frac{\dfrac{2x10^{14} p^2}{\left(s + 2p\,x10^3\right)\left(s + 2p\,x10^5\right)}}{1 + \dfrac{2x10^{14} p^2}{\left(s + 2p\,x10^3\right)\left(s + 2p\,x10^5\right)}(0.01)} = \frac{2x10^{14} p^2}{s^2 + 1.01\left(2p\,x10^5\right)s + 2x10^{12} p^2}$$

Using dominant-root factorization : $f_1 = 101\ kHz, \quad f_2 = 4.95\ MHz$

So the closed-loop values are $f_H = 101\ kHz \quad and \quad f_L = 0.$

**18.60**

$$(a)\ \ A(s) = \frac{\dfrac{2p\, x10^{10} s}{\left(2p\, x10^{6}\right)}}{\left(s+2p\, x10^{3}\right)\left(1+\dfrac{s}{2p\, x10^{6}}\right)} = \frac{10^{4}\, s}{\left(s+2p\, x10^{3}\right)\left(1+\dfrac{s}{2p\, x10^{6}}\right)}$$

$A(s)$ represents a band - pass amplifier with two widely - spaced poles

Open – loop : $A_o = 10^4$ or 80 $dB$ | $f_L = 1$ kHz | $f_H = 1$ M$Hz$

$$(b)\ \ A_v(s) = \frac{\dfrac{2p\, x10^{10} s}{\left(s+2p\, x10^{3}\right)\left(s+2p\, x10^{6}\right)}}{1+\dfrac{2p\, x10^{10} s}{\left(s+2p\, x10^{3}\right)\left(s+2p\, x10^{6}\right)}(0.01)} = \frac{6.28\, x10^{10} s}{s^{2}+1.01\left(2p\, x10^{8}\right)s+4p^{2} x10^{9}}$$

Using dominant - root factorization :

$$f_H = \frac{1.01\left(2p\, x10^{8}\right)}{2p} = 101\ MHz, \quad f_L = \frac{1}{2p}\left(\frac{4p^{2} x10^{9}}{1.01\left(2p\, x10^{8}\right)}\right) = 9.90\ Hz$$

$$(c)\ \ A_v(s) = \frac{\dfrac{2p\, x10^{10} s}{\left(s+2p\, x10^{3}\right)\left(s+2p\, x10^{6}\right)}}{1+\dfrac{2p\, x10^{10} s}{\left(s+2p\, x10^{3}\right)\left(s+2p\, x10^{6}\right)}(0.025)} = \frac{6.28\, x10^{10} s}{s^{2}+2.51\left(2p\, x10^{8}\right)s+4p^{2} x10^{9}}$$

Using dominant - root factorization :

$$f_H = \frac{2.51\left(2p\, x10^{8}\right)}{2p} = 251\ MHz, \quad f_L = \frac{1}{2p}\left(\frac{4p^{2} x10^{9}}{2.51\left(2p\, x10^{8}\right)}\right) = 3.98\ Hz$$

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**18.61**

$$(a)\ \ A(s) = \frac{\dfrac{4p^{2}\, x10^{18} s^{2}}{\left(2p\, x10^{6}\right)\left(2p\, x10^{7}\right)}}{\left(s+200p\right)\left(s+2000p\right)\left(1+\dfrac{s}{2p\, x10^{6}}\right)\left(1+\dfrac{s}{2p\, x10^{7}}\right)}$$

$$A(s) = \frac{10^{5} s^{2}}{\left(s+200p\right)\left(s+2000p\right)\left(1+\dfrac{s}{2p\, x10^{6}}\right)\left(1+\dfrac{s}{2p\, x10^{7}}\right)}$$

$A(s)$ represents a band - pass amplifier with four widely - spaced poles

Open – loop : $A_o = 10^5$ or 100 $dB$ | $f_L \cong 1$ kHz | $f_H \cong 1$ M$Hz$

$$(b)\ \ A_v(s) = \frac{\dfrac{4p^{2}\, x10^{18} s^{2}}{\left(s+200p\right)\left(s+2000p\right)\left(s+2p\, x10^{6}\right)\left(s+2p\, x10^{7}\right)}}{1+\dfrac{4p^{2}\, x10^{18} s^{2}}{\left(s+200p\right)\left(s+2000p\right)\left(s+2p\, x10^{6}\right)\left(s+2p\, x10^{7}\right)}(0.01)}$$

Using MATLAB : $D(s) = s^4 + 6.9122x10^7 s^3 + 3.9518x10^{17} s^2 + 2.7288x10^{18} s + 1.5585x10^{21}$

The closed loop amplifier has complex roots :

$$\frac{1}{2p}(-3.45 \pm j62.7) = (-0.637 \pm j9.98)\text{ Hz} \quad \text{and} \quad \frac{10^8}{2p}(-0.346 \pm j6.28) = (-0.0637 \pm j1)\text{ x}10^8\text{ Hz}$$

Note that the amplifier is stable since all the poles are in the left half plane. See Problem 18.67.

$$(c)\ A_v(s) = \frac{\dfrac{2p\,x10^{10}s}{(s+2p\,x10^3)(s+2p\,x10^6)}}{1+\dfrac{2p\,x10^{10}s}{(s+2p\,x10^3)(s+2p\,x10^6)}(0.025)}$$

Using MATLAB : $D(s) = s^4 + 6.9122x10^7 s^3 + 9.909x10^{16} s^2 + 2.7288x10^{18} s + 1.5585x10^{21}$

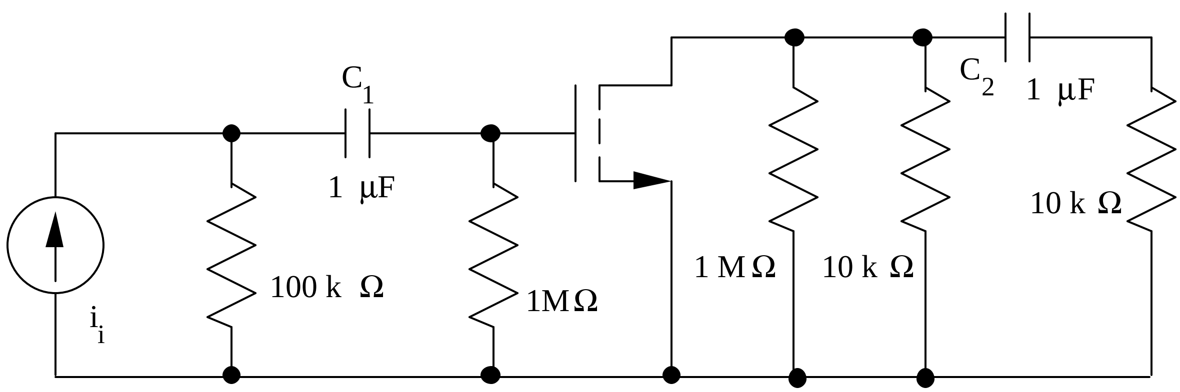
The closed loop amplifier has complex roots :

$$\frac{1}{2p}(-13.8 \pm j124.7) = (-2.20 \pm j19.9)\text{ Hz} \quad \text{and} \quad \frac{10^8}{2p}(-0.346 \pm j3.13) = (-0.637 \pm j4.98)x10^7\text{ Hz}$$

Note that the amplifier is stable since all the poles are in the left half plane.

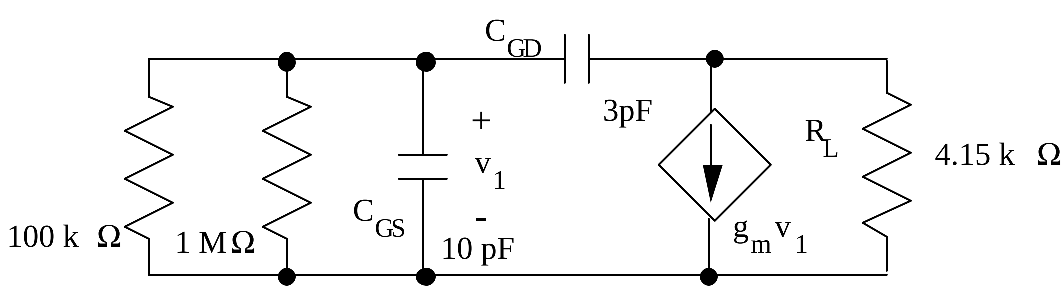
---

**18.62**




$$w_1 = \frac{1}{10^{-6}(100k\Omega + 1M\Omega)} = 0.909\frac{rad}{s} \quad | \quad w_2 = \frac{1}{10^{-6}(10k\Omega + 25k\Omega \| 10k\Omega \| 1M\Omega)} = 58.5\frac{rad}{s}$$

$$\text{Separate, widely-spaced, poles} \rightarrow f_L^A = f_2 = \frac{58.5}{2p} = 9.31\ Hz$$




25k Ω||1M Ω||10k Ω||10k Ω

$$w_H^A = \frac{1}{r_{po}C_T} = \frac{1}{(100k\Omega \| 1M\Omega)\left[10pF + 3pF\left(1 + 2mS(4.15k\Omega) + \frac{4.15k\Omega}{100k\Omega \| 1M\Omega}\right)\right]}$$

$$f_H^A = \frac{1}{2p}\frac{1}{(90.9k\Omega)(38.0pF)} = 46.1\ kHz$$

$$v_{gs} = i_s(100k\Omega \| 1M\Omega) = (90.9k\Omega)i_s \quad | \quad v_o = -(2x10^{-3})v_{gs}(25k\Omega \| 10k\Omega \| 10k\Omega \| 1M\Omega)$$

$$A = \frac{v_o}{i_s} = -(2mS)(4.15k\Omega)(90.9k\Omega) = -7.55x10^5\Omega \quad | \quad y_{12}^F = -10^{-5}S$$

$$1 + Ab = 1 + (-7.55x10^5\Omega)(-10^{-6}S) = 1.76$$

$$f_L = \frac{9.31}{1.76} = 5.29\ Hz \qquad f_H = 46.1kHz(1.76) = 81.0\ kHz$$

---

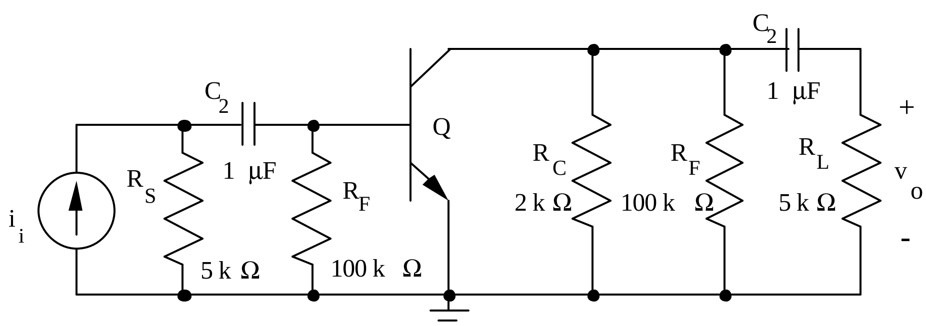
**18.63**

$$S_{A_o}^{w_H^F} = \frac{A_o}{w_H^F}\frac{\P w_H^F}{\P A_o} \quad | \quad w_H^F = w_H^A(1 + Ab) \quad | \quad S_{A_o}^{w_H^F} = \frac{A_o}{w_H^A(1 + A_o b)} w_H^A b = \frac{A_o b}{(1 + A_o b)} \cong +1$$

$$\frac{\P w_H^F}{w_H^F} = S_{A_o}^{w_H^F}\frac{\P A_o}{A_o} = \frac{10^5(0.01)}{1 + 10^5(0.01)}10\% = 9.99\%$$

---

**18.64**




From the Exercise : $g_m = 40.3\ mS \quad | \quad r_p = 3.72\ k\Omega \quad | \quad r_o = 50.8\ k\Omega \quad | \quad 1 + Ab = 2.19$

$$r_{o2} = \frac{50 + 1.4}{10^{-4}} = 514k\Omega \quad | \quad r_{o4} = \frac{50 + 11.3}{10^{-4}} = 613k\Omega \quad | \quad r_{p5} = \frac{100(0.025)}{0.0012} = 2.08k\Omega$$

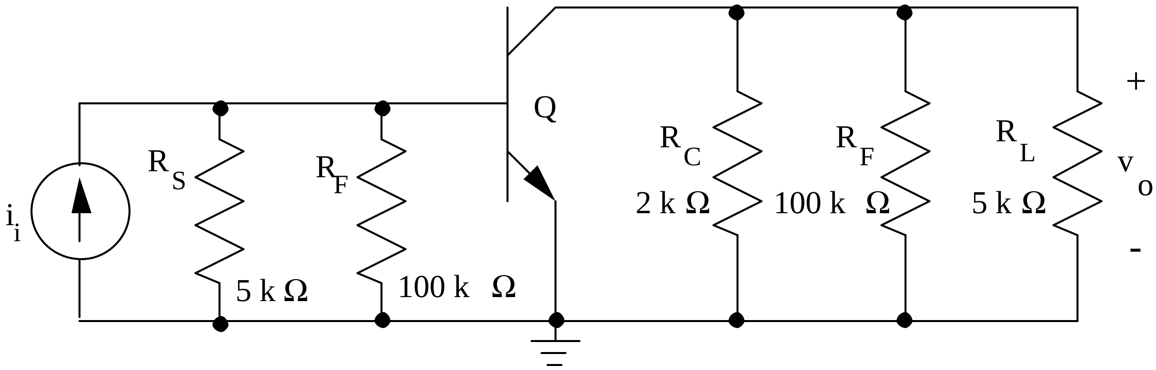
$$C_{p1} = \frac{40.3mS}{2p(500MHz)} - 0.75pF = 12.1pF$$

Using the open - circuit time constant approach with $C_1 = C_2 = 1\ mF$ :

$$R_{1O} = 5k\Omega + 100k\Omega \| r_p\ 5k\Omega + 100k\Omega \| 3.72k\Omega = 8.59k\Omega$$

$$R_{2O} = 5k\Omega + 50.8k\Omega \| 2k\Omega \| 100k\Omega = 6{,}89k\Omega$$

$$f_L = \frac{1}{2p}\left[\frac{1}{1mF(8.59k\Omega)} + \frac{1}{1mF(6.89k\Omega)}\right] = 41.6\ Hz \quad | \quad f_L^F = \frac{f_L}{1 + Ab} = 19.0\ Hz$$




$$r_{po} = 3.72k\Omega \| 100k\Omega \| 5k\Omega = 2.09k\Omega \quad | \quad R_L = 50.8k\Omega \| 2k\Omega \| 100k\Omega \| 5k\Omega = 1.37k\Omega$$

$$C_T = 12.1pF + 0.75pf\left[1 + 40.3mS(1.37k\Omega) + \frac{1.37k\Omega}{2.09k\Omega}\right] = 54.8pF$$

$$f_H = \frac{1}{2\pi r_{po} C_T} = \frac{1}{2\pi(1.37k\Omega)(54.8pF)} = 1.39\ MHz \quad | \quad f_H^F = f_H(1 + A\beta) = 3.04\ MHz$$

---

**18.65**

$$A(s) = \frac{2\pi\ x\ 10^7}{s + 2000\pi} \quad | \quad A = \frac{25k\Omega}{1k\Omega + 25k\Omega + 9.01k\Omega}\left(\frac{2\pi\ x\ 10^7}{s + 2000\pi}\right)\frac{1.96k\Omega}{1.96k\Omega + 1k\Omega} = \frac{2.97\ x\ 10^7}{s + 2000\pi}$$

$$A_V(s) = \frac{\dfrac{2.97\ x\ 10^7}{s + 2000\pi}}{1 + \dfrac{2.97\ x\ 10^7}{s + 2000\pi}(0.0990)} = \frac{2.97x10^7}{s + 2.95x10^6} = \frac{10.1}{1 + \dfrac{s}{2.95x10^6}} \quad | \quad f_H = \frac{2.95x10^6}{2\pi} = 470\ kHz$$

---

**18.66**

(a) At high frequencies with $\beta = 0.01$, $A\beta = \dfrac{(2x10^{14}\pi^2)(0.01)}{(s + 2000\pi)(s + 2\pi x10^5)} \cong \dfrac{(2x10^{12}\pi^2)}{s(s + 2\pi x10^5)}$

$$|A\beta| = \frac{(2x10^{12}\pi^2)}{\omega\sqrt{\omega^2 + (2\pi x10^5)^2}} = 1 \quad | \quad \text{Using MATLAB,} \quad \omega = 4.42x10^6$$

$$\angle A\beta = -90 - \tan^{-1}\left(\frac{4.42x10^6}{2\pi x10^5}\right) = 171.9^o \quad | \quad \Phi_M = 8.1^o$$

(b) At high frequencies with $\beta = 0.025$, $A\beta = \dfrac{(2x10^{14}\pi^2)(0.025)}{(s + 2000\pi)(s + 2\pi x10^5)} \cong \dfrac{(5x10^{12}\pi^2)}{s(s + 2\pi x10^5)}$

$$|A\beta| = \frac{(5x10^{12}\pi^2)}{\omega\sqrt{\omega^2 + (2\pi x10^5)^2}} = 1 \quad | \quad \text{Using MATLAB,} \quad \omega = 7.01x10^6$$

$$\angle A\beta = -90 - \tan^{-1}\left(\frac{7.01x10^6}{2\pi x10^5}\right) = 174.9^o \quad | \quad \Phi_M = 5.1^o$$

**18.67**

$$(a)\ \text{At high frequencies with}\quad b=0.01,\quad Ab=\frac{s\left(2p\ x10^{10}\right)(0.01)}{(s+2000p)\left(s+2p\ x10^{6}\right)}\cong\frac{2p\ x10^{8}}{\left(s+2px10^{6}\right)}$$

$$|Ab|=\frac{2p\ x10^{8}}{\sqrt{w^{2}+\left(2px10^{6}\right)^{2}}}=1\quad|\quad w\cong 2p\ x10^{8}$$

$$\angle Ab=-\tan^{-1}\left(\frac{2p\ x10^{8}}{2px10^{6}}\right)=-89.4^{o}\quad|\quad \Phi_{M}=90.6^{o}$$

$$(b)\ \text{At high frequencies with}\quad b=0.025,\quad Ab=\frac{s\left(2p\ x10^{10}\right)(0.025)}{(s+2000p)\left(s+2p\ x10^{6}\right)}\cong\frac{5p\ x10^{8}}{\left(s+2px10^{6}\right)}$$

$$|Ab|=\frac{5p\ x10^{8}}{w\sqrt{w^{2}+\left(2px10^{6}\right)^{2}}}=1\quad|\quad w\cong 5p\ x10^{8}$$

$$\angle Ab=-\tan^{-1}\left(\frac{5p\ x10^{8}}{2p\ x10^{6}}\right)=-89.8^{o}\quad|\quad \Phi_{M}=90.2^{o}$$

---

**18.68**

$$(a)\ \text{At high frequencies with}\quad b=0.01,\quad Ab=\frac{s^{2}\left(4p^{2}\ x10^{18}\right)(0.01)}{(s+200p)(s+2000p)\left(s+2p\ x10^{6}\right)\left(s+2p\ x10^{7}\right)}$$

$$Ab\cong\frac{s^{2}\left(4p^{2}\ x10^{18}\right)(0.01)}{s^{2}\left(s+2p\ x10^{6}\right)\left(s+2p\ x10^{7}\right)}\cong\frac{4p^{2}\ x10^{16}}{\left(s+2p\ x10^{6}\right)\left(s+2p\ x10^{7}\right)}$$

$$|Ab|=\frac{4p^{2}\ x10^{16}}{\sqrt{w^{2}+\left(2px10^{6}\right)^{2}}\sqrt{w^{2}+\left(2px10^{6}\right)^{2}}}=1\quad|\quad\text{Using MATLAB,}\quad w\cong 6.2673x10^{8}$$

$$\angle Ab=-\tan^{-1}\left(\frac{6.2673x10^{8}}{2px10^{6}}\right)-\tan^{-1}\left(\frac{6.2673x10^{8}}{2px10^{7}}\right)=-173.7^{o}\quad|\quad \Phi_{M}=6.3^{o}$$

$$(b)\ \text{At high frequencies with}\quad b=0.025,\quad Ab=\frac{s^{2}\left(4p^{2}\ x10^{18}\right)(0.025)}{(s+200p)(s+2000p)\left(s+2p\ x10^{6}\right)\left(s+2p\ x10^{7}\right)}$$

$$Ab\cong\frac{s^{2}\left(4p^{2}\ x10^{18}\right)(0.025)}{s^{2}\left(s+2p\ x10^{6}\right)\left(s+2p\ x10^{7}\right)}\cong\frac{p^{2}\ x10^{17}}{\left(s+2p\ x10^{6}\right)\left(s+2p\ x10^{7}\right)}$$

$$|Ab|=\frac{p^{2}\ x10^{17}}{\sqrt{w^{2}+\left(2px10^{6}\right)^{2}}\sqrt{w^{2}+\left(2px10^{6}\right)^{2}}}=1\quad|\quad\text{Using MATLAB,}\quad w\cong 9.9246x10^{8}$$

$$\angle Ab=-\tan^{-1}\left(\frac{9.9246x10^{8}}{2px10^{6}}\right)-\tan^{-1}\left(\frac{9.9246x10^{8}}{2px10^{7}}\right)=-176.0^{o}\quad|\quad \Phi_{M}=4.0^{o}$$

---

**18.69**

$$(a)\ T(s) = \frac{4\ x\ 10^{19}\pi^3}{(s+2\pi\ x\ 10^4)(s+2\pi\ x\ 10^5)^2}\beta \quad | \quad \angle T(j\omega) = -\tan^{-1}\frac{f}{10^4} - 2\tan^{-1}\frac{f}{10^5} = -180^o$$

For $f >> 10^4$, $-2\tan^{-1}\frac{f}{10^5} = -90^o \rightarrow f = 10^5\ Hz$. Using this as a starting point for iteration, we find $f = 110\ kHz\ or\ \omega = 2.2\ x\ 10^5\pi$

$$(b)\ \left|A(j2.2x10^5\pi)\right| = \frac{4\ x\ 10^{19}\pi^3}{\sqrt{(2.2x10^5\pi)^2 + (2\pi\ x\ 10^4)^2}\left[(2.2x10^5\pi)^2 + (2\pi\ x\ 10^5)^2\right]} = 2048$$

The amplifier will oscillate for closed - loop gains $\leq 2048$ (66.2 dB).

---

**18.70**

$$T(s) = A\beta = \left(\frac{10^7}{s+50}\right)\frac{\frac{1}{sC_L}}{R_O + \frac{1}{sC_L}} = \left(\frac{10^7}{s+50}\right)\frac{1}{sC_LR_O+1} = \left(\frac{10^7}{s+50}\right)\frac{1}{500sC_L+1}$$

Assume that the unity - gain occurs at $\omega_1 >> 50$ : $\angle T(j\omega_1) = \angle A + \angle\beta = -90^o - \tan^{-1}(500\omega_1C_L)$

$-90^o - \tan^{-1}(500\omega_1C_L) = -180^o + 60^o \quad | \quad \tan^{-1}(500\omega_1C_L) = 30^o \quad | \quad 500\omega_1C_L = 0.5774$

$$\left|T(j\omega_1)\right| = 1 \quad | \quad \frac{10^7}{\omega_1\sqrt{1+(500\omega_1C_L)^2}} = \frac{10^7}{\omega_1\sqrt{1+\left[\tan(30^o)\right]^2}} = 1 \rightarrow \omega_1 = 8.66\ x\ 10^6$$

$$C_L = \frac{\tan(30^o)}{500(8.66x10^6)} = 133\ pF$$

---

**18.71**

$$(a)\ T = A\beta = \frac{2x10^{14}\pi^2}{(s+2x10^3\pi)(s+2x10^5\pi)}\left(\frac{1}{5}\right)$$ | Yes, it is a second - order system and will have some phase margin, although $\Phi_M$ may be vanishingly small.

(b) For $\omega >> 2\pi\ x\ 10^5$, $\left|T(j\omega)\right| \approx \frac{4x10^{13}\pi^2}{\omega^2}$ and $\left|T(j\omega)\right| = 1$ for $\omega = 1.987x10^7\ \frac{rad}{s}$

$\angle T(j1.987x10^7) = -\tan^{-1}\frac{1.987x10^7}{2000\pi} - \tan^{-1}\frac{1.987x10^7}{2x10^5\pi} = 178.2^o \rightarrow \Phi_M = 1.83^o$ | A very small phase margin.

---

**18.72** (a)

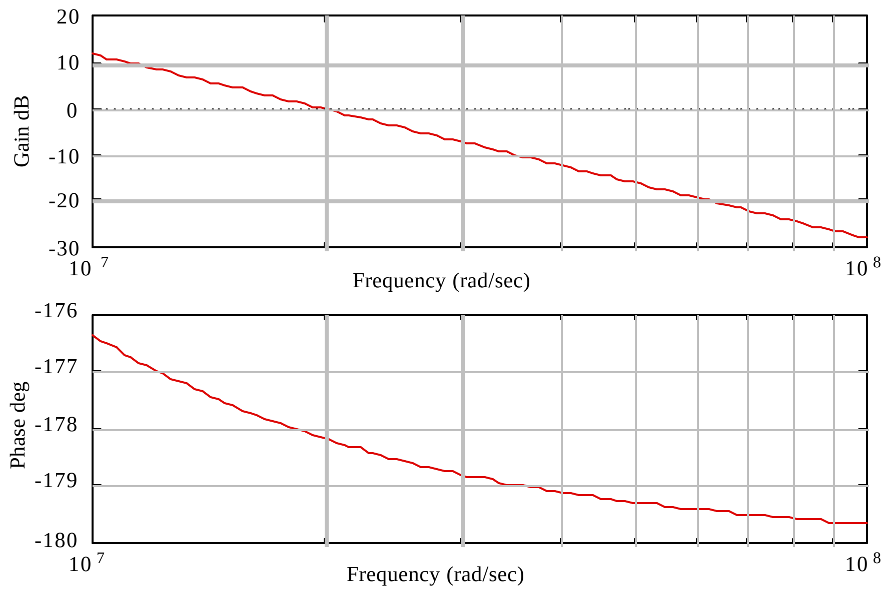
The following command line will generate the complete bode plot:

```
w=logspace(3,8,400);  bode((2e14*pi^2/5),conv([1 2000*pi],[1 2e5*pi]),w)
```

The following command line will generate the bode plot between $10^7$ and $10^8$rad/s:

```
w=logspace(7,8,100);  bode((2e14*pi^2/5),conv([1 2000*pi],[1 2e5*pi]),w)
```

The second plot agrees with the results calculated in the previous problem.

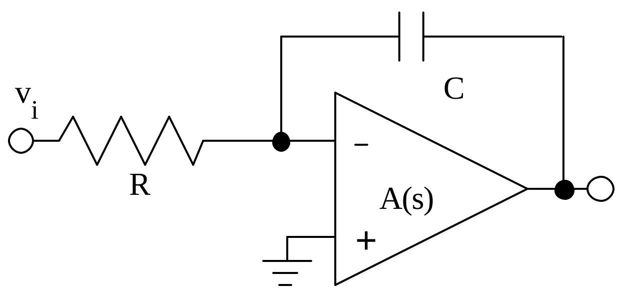



(b) w=logspace(7,8,100); bode((2e14*pi^2),conv([1 2000*pi],[1 2e5*pi]),w)

yields a phase margin of only 0.75 degrees

---

**18.73**




$$b = \frac{R}{R + \frac{1}{sC}} = \frac{sRC}{sRC+1} \quad | \quad T = \frac{2p\ x\ 10^6}{s+20p}\frac{sRC}{(sRC+1)} \quad | \quad For\ wRC >> 1,\ \ T \cong \frac{2p\ x\ 10^6}{s+20p}$$

and $|T| = 1$ for $w = 2p\ x\ 10^6$. Given $RC = 10^{-8}\left(10^5\right) = 10^{-3},\ b = \dfrac{s}{s+1000}$

$$\angle T = 90^o - \tan^{-1}\frac{2p\ x\ 10^6}{20p} - \tan^{-1}\frac{2p\ x\ 10^6}{1000} = -90.0^o \quad | \quad \Phi_M = 90.0^o$$

---

**18.74**

$$b=\frac{R}{R+\frac{1}{sC}}=\frac{sRC}{sRC+1}=\frac{s10^5\left(10^{-8}\right)}{s10^5\left(10^{-8}\right)+1}=\frac{s}{s+1000}$$

$$A(s)=\frac{10^5}{\left(1+\frac{s}{2000p}\right)\left(1+\frac{s}{200000p}\right)}=\frac{4p^2\ x\ 10^{13}}{(s+2000p)(s+200000p)}$$

$$T=\frac{4p^2\ x\ 10^{13}}{(s+2000p)(s+200000p)}\ \frac{s}{(s+1000)}\quad |\quad \text{At high frequencies,}\quad T\cong\frac{4p^2\ x\ 10^{13}}{s^2}$$

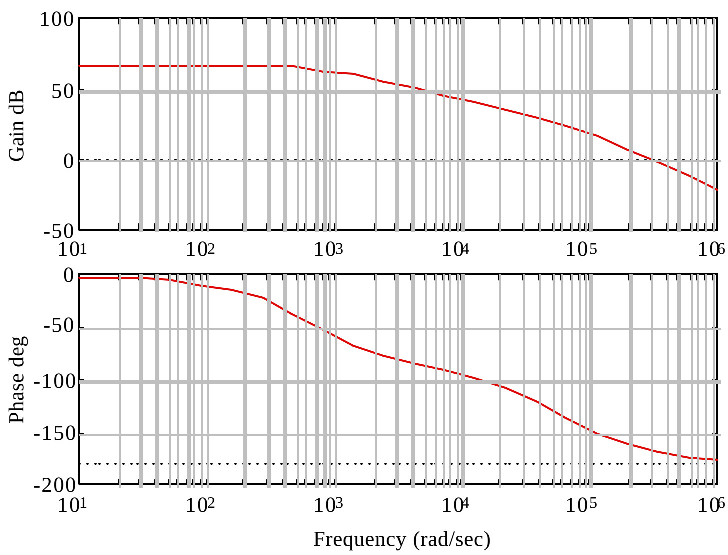
and the integrator will have a positive phase margin, although $\Phi_M$ may be very small.

$$\text{For } w>>2p\ x\ 10^5,\ \left|T(jw_1)\right|\approx\frac{4p^2\ x\ 10^{13}}{w_1^2}=1\Rightarrow w=1.987\ x\ 10^7\ \frac{rad}{s}>>2p\ x\ 10^5$$

$$\angle T=90^o-\tan^{-1}\frac{1.987\ x\ 10^7}{2000p}-\tan^{-1}\frac{1.987\ x\ 10^7}{200000p}-\tan^{-1}\frac{1.987\ x\ 10^7}{1000}\quad |\quad \Phi_M=1.83^o$$

---

**18.75**




$$(a)\quad b=\frac{R_1}{R_1+\frac{R_2\frac{1}{sC_C}}{R_2+\frac{1}{sC_C}}}=\frac{R_1}{R_1+\frac{R_2}{sC_CR_2+1}}=\frac{R_1}{R_1+R_2}\frac{sC_CR_2+1}{sC_C\left(R_1\|R_2\right)+1}$$

$$\text{For } C_C=0,\quad T=\frac{2x10^{11}p^2}{(s+200p)(s+20000p)}\frac{1}{21}$$

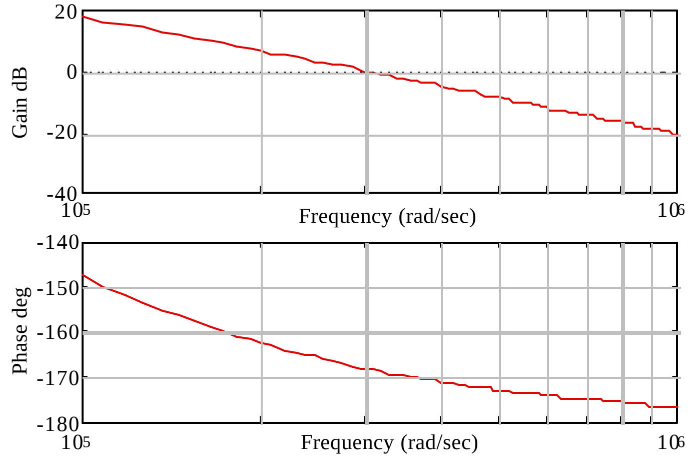
The graphs above were generated using

bode(2e11*pi^2/21,[1 2.02e4*pi 4e6*pi^2])

Blowing up the last decade:

w=linspace(1e5,1e6);   bode(2e11*pi^2/21,[1 2.02e4*pi 4e6*pi^2],w)

and the phase margin is approximately $12^{o}$




Setting the zero to cancel the second pole,

$$b(s) = \frac{R_1}{R_1 + R_2} \frac{sC_C R_2 + 1}{sC_C (R_1 \| R_2) + 1} = \frac{s + \dfrac{1}{C_C R_2}}{s + \dfrac{1}{C_C (R_1 \| R_2)}}$$

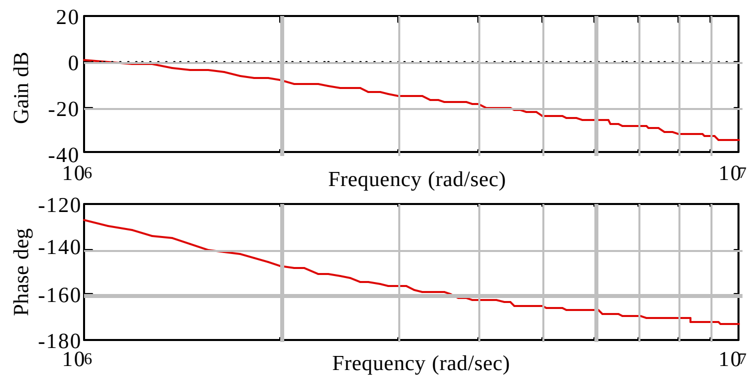
$$T = \frac{2x10^{11} p^2}{(s + 200p)(s + 20000p)} \frac{(s + 20000p)}{s + 1.319x10^6} = \frac{2x10^{11} p^2}{s^2 + 1.320x10^6 s + 8.288x10^6}$$

Using MATLAB:

bode(2e11*pi^2,[1 1.320e6 8.288e8])

and then

w=linspace(1e6,1e7);  bode(2e11*pi^2,[1 1.320e6 8.288e8],w)




The phase margin is now approximately $50^{o}$

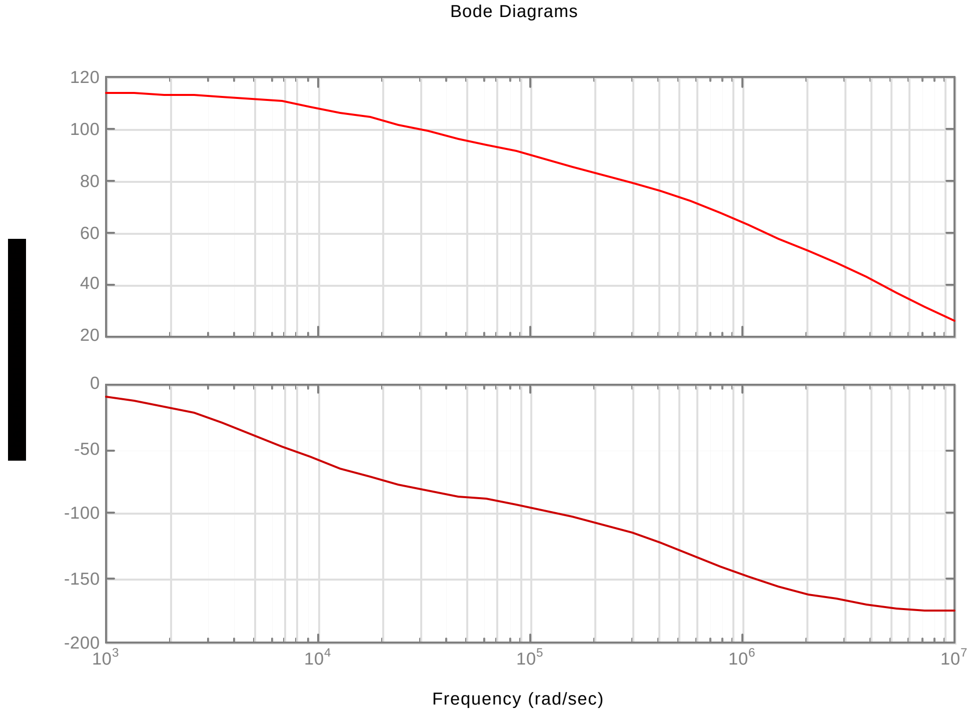
---

**18.76**

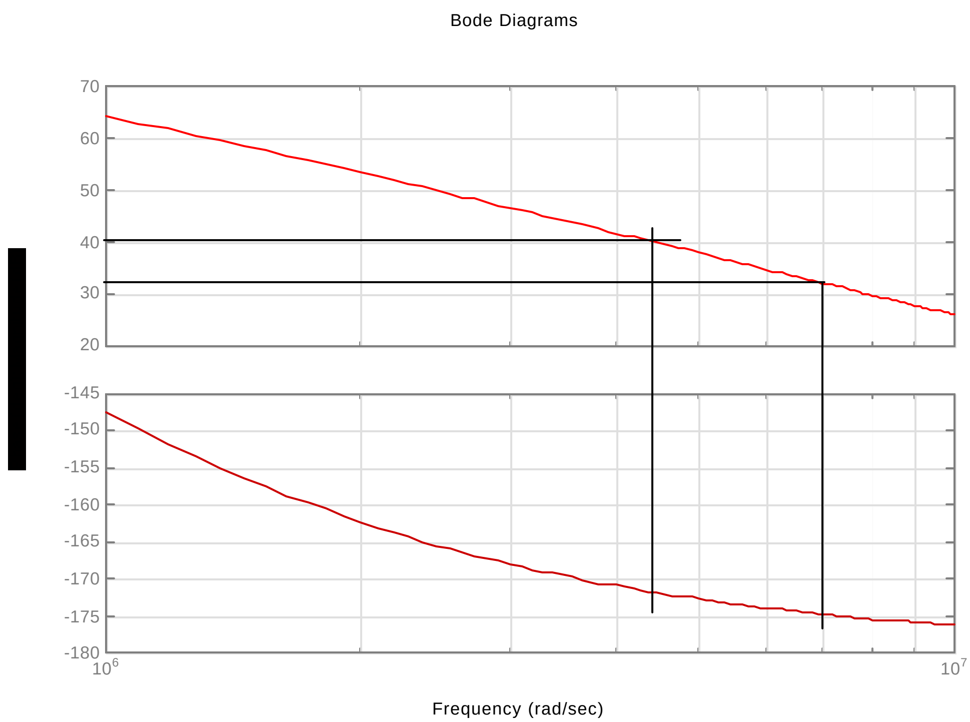
```
num=4e19*pi^3;
p=conv([1 2e5*pi],[1 2e5*pi]);
den=conv([1 2e4*pi],p];
bode(num,den)
```

Results:   Frequency = 6.9 x$10^5$ rad/s and approximately 66 dB which agree with the hand calculations in Problem 18.47.

**18.77**

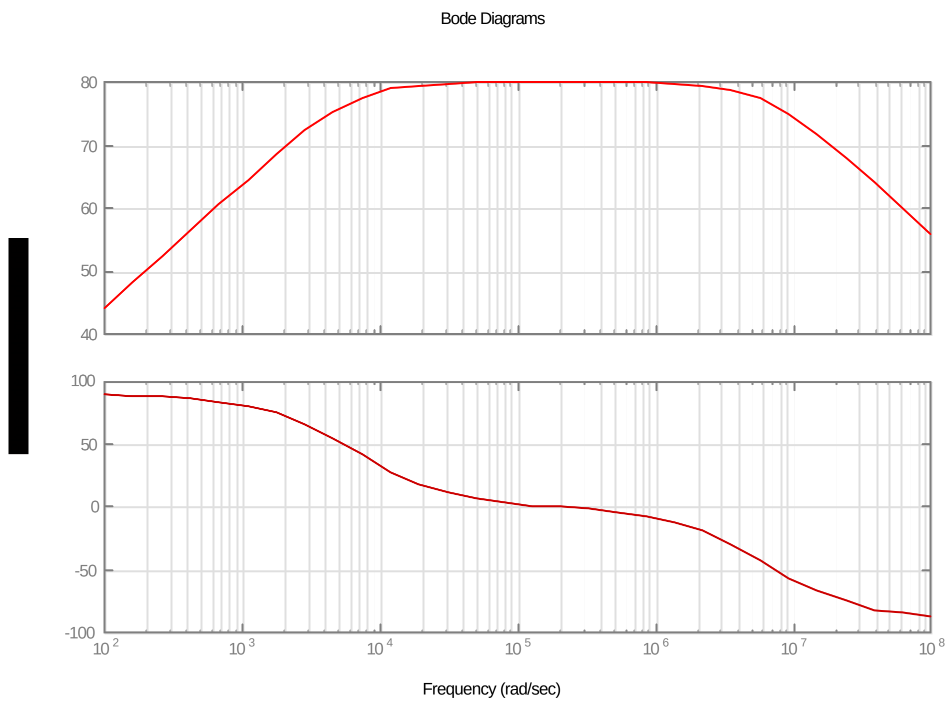



Expanded view:



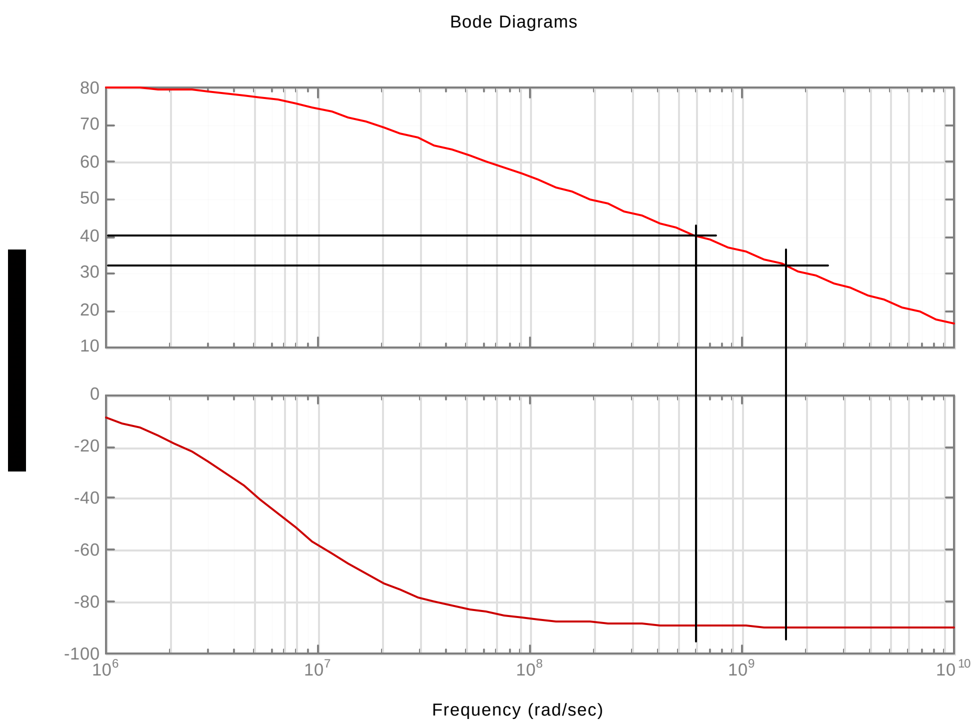

For a gain of 100 (40 dB), the phase margin is approximately $8^\circ$. For a gain of 40 (32 dB), the phase margin is approximately $5^\circ$. The gain margin is infinite in both cases since the phase shift never reaches $180^\circ$. These values agree with the calculations in Problem 18.66. (b) The amplifier will not oscillate.

**18.78**

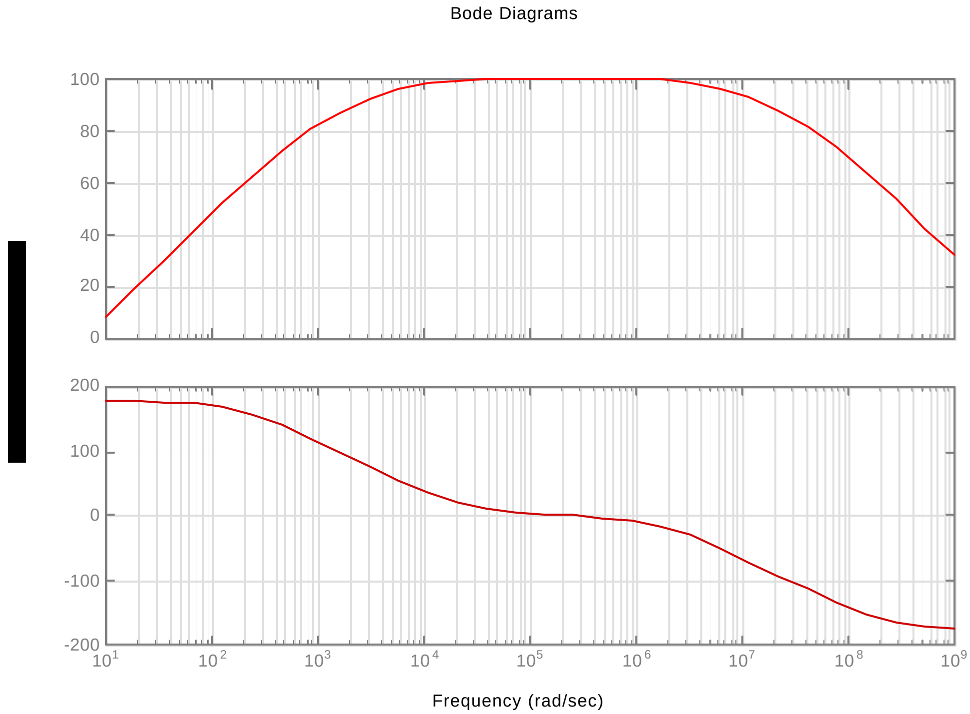


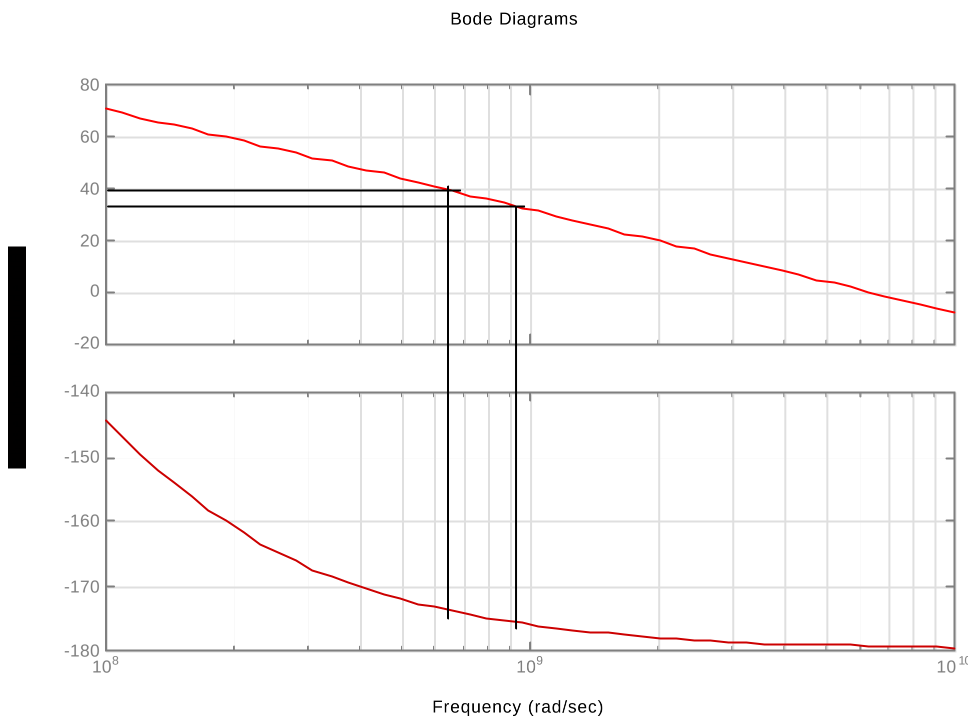

The phase shift ranges from +90° at low frequencies to –90° at high frequencies. The phase margin for both gains of 100 and 40 is 90° at the high frequency intersection and 270° at the low end. These values agree with the calculations in Problem 18.67. (b) The amplifier will not oscillate.

Expanded view at high frequencies:



**18.79**



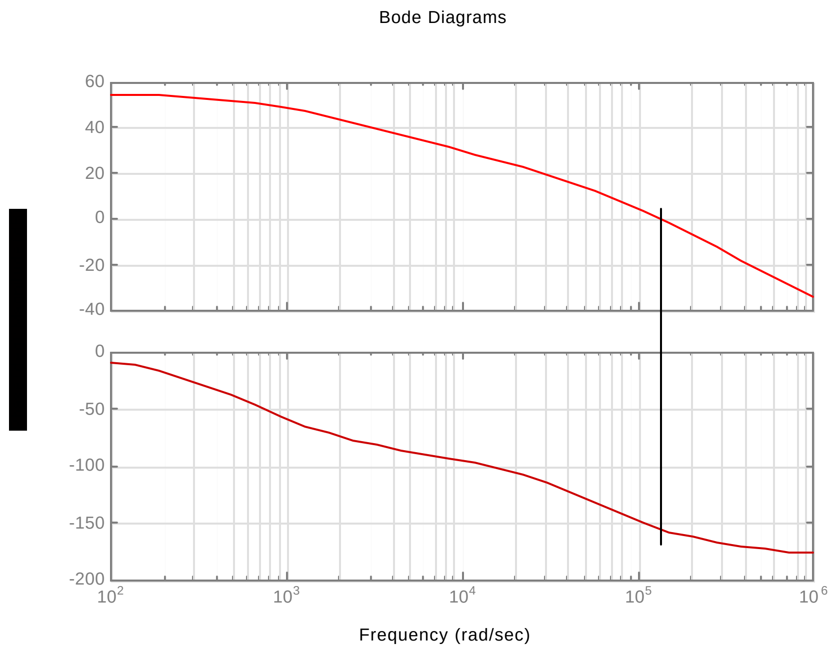

The phase margin is approximately 6° and 4° for gains of 40 dB and 32 dB respectively. The gain margin is infinite in both cases. These values agree with the calculations in Problem 18.68. (b) The amplifier will not oscillate.

**18.80**

```
num=2e11*pi^2
den=conv([1 200*pi],[1 20000*pi]);
bode(num/100,den)

w=logspace(5,6,100);  bode(num/100,den,w)
```

Results:   Yes, the amplifier is stable with a phase margin of approximately 26$^{o}$.

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**18.81**

$$A_v(s) = \frac{\dfrac{A_o w_o}{s+w_o}}{1+\dfrac{A_o w_o}{s+w_o}} = \frac{w_T}{s+(1+A_o)w_o} \cong \frac{w_T}{s+w_T} = \frac{2p\ x\ 10^6}{s+2p\ x\ 10^6}$$

$$\text{From problem 18.45 : } b(s) = \frac{5x10^4 s}{s^2+7x10^4 s+5x10^8}$$

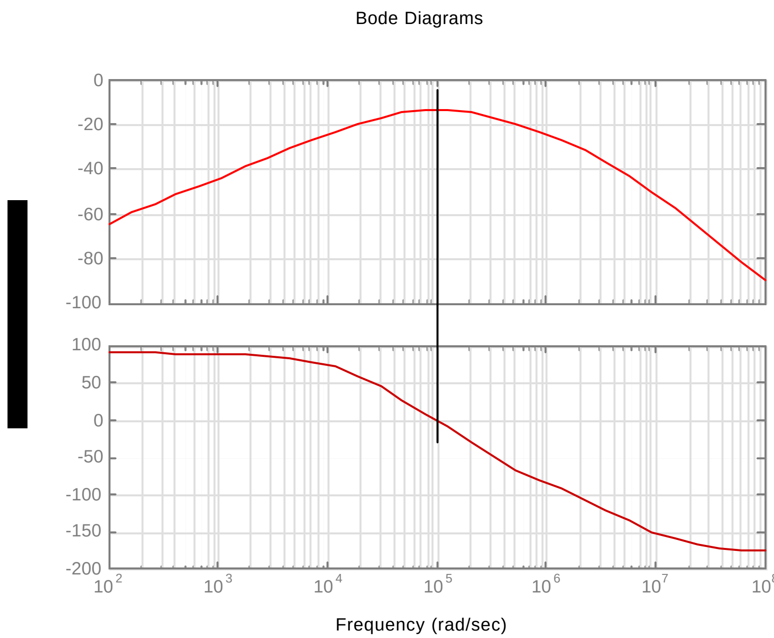
$$T(s) = A_v(s)b(s) = \frac{10^{11}ps}{\left(s+2p\ x\ 10^6\right)\left(s^2+7x10^4 s+5x10^8\right)}$$

Using MATLAB:

```
num=[pi*1e11 0]
den=conv([1 3e5 1e10],[1 5e6])
bode(num,den)
```

It is also instructive to use:  nyquist(num,den)

One finds that |T(jω)| < 1 for all ω, so the phase margin is undefined.  The filter is stable. Note that this is a positive feedback system so the point of interest is +1.   The gain of the filter is approximately -3 dB.  So the filter has a gain margin of 3 dB.




**18.82**

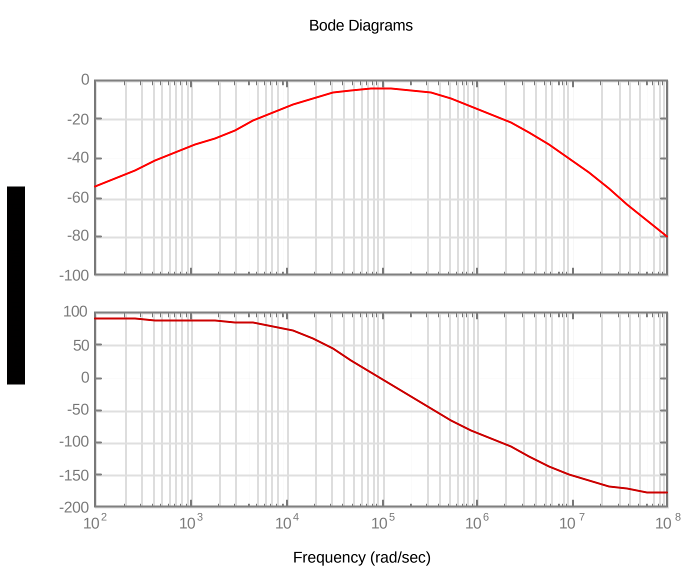
$$T(s)=K(s)b(s)=\left(\frac{10^7}{s+5\ x\,10^6}\right)\left(\frac{10^5 s}{s^2+3x10^5 s+10^{10}}\right)=\frac{10^{12} s}{\left(s+5\ x\,10^6\right)\left(s^2+3x10^5 s+10^{10}\right)}$$

Using MATLAB:

```
num=[1e12 0]
den=conv([1 3e5 1e10],[1 5e6])
bode(num,den)
```

It is also instructive to use: nyquist(num,den)

One finds that $|T(j\omega)| < 1$ for all $\omega$, so the phase margin is undefined. The filter is stable. Note that this is a positive feedback system so the point of interest is +1. The gain of the filter is approximately -3 dB. So the filter has a gain margin of 3 dB.



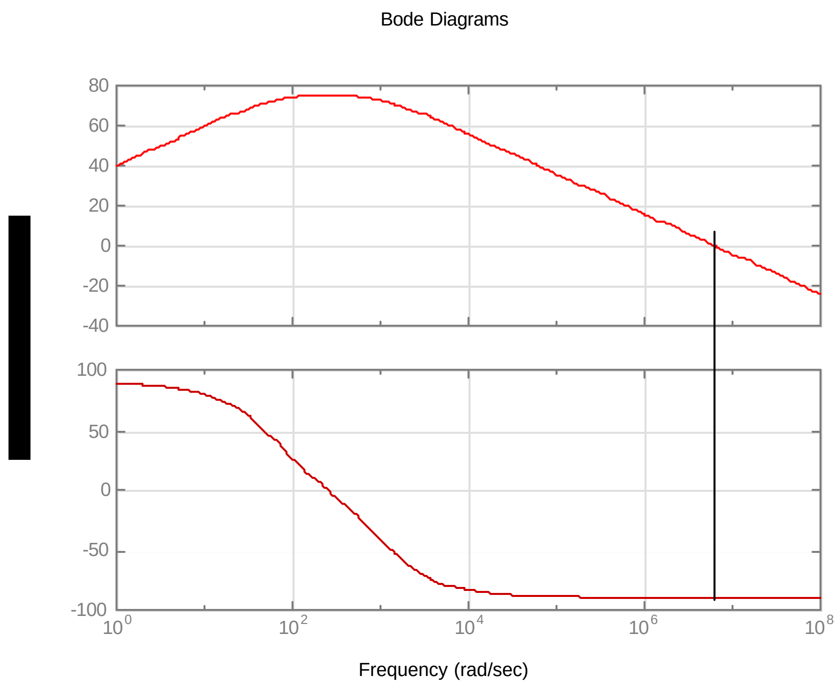
**18.83**

$$b = \frac{sRC}{sRC+1} = \frac{s}{s+1000} \quad | \quad T = \frac{2p\ x\ 10^{6} s}{(s+20p)(s+1000)}$$

Using MATLAB:

```
num=[2e6*pi 0]; den=conv([1 20*pi],[1 1000]);
w=logspace(0,8,400);
bode(num,den,w)
```

The phase margin is 90$^{o}$ which agrees with Problem 18.73.




**18.84**

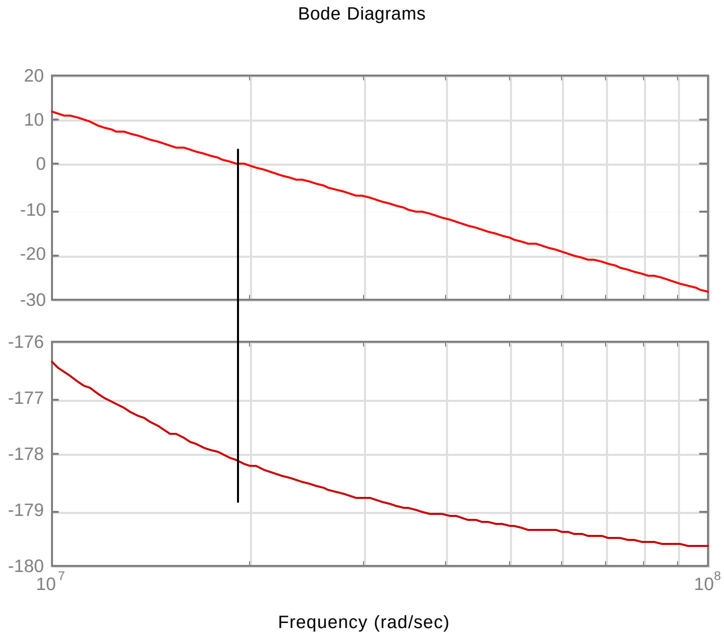
$$b = \frac{sRC}{sRC+1} = \frac{s}{s+1000} \quad | \quad A(s) = \frac{10^{5}}{\left(1+\frac{s}{2000p}\right)\left(1+\frac{s}{200000p}\right)} = \frac{4p^{2}\ x\ 10^{13}}{(s+2000p)(s+200000p)}$$

$$T = \frac{4p^{2}\ x\ 10^{13} s}{(s+2000p)(s+200000p)(s+1000)}$$

Using MATLAB:

```
num=[4e13*pi^2 0];   den=conv([1 1000],conv([1 2000*pi],[1 200000*pi]));
w=logspace(7,8,100);   bode(num,den,w)
```

The phase margin is 1.8$^{o}$ which agrees with Problem 18.74.




---

**18.85**

$$b(s)=\frac{\dfrac{R_1}{sC_SR_1+1}}{\dfrac{R_1}{sC_SR_1+1}+R_2}=\frac{R_1}{R_1+R_2}\frac{1}{sC_S\left(R_1\|R_2\right)+1}=\frac{1}{9.30\left(1.89x10^{-6}s+1\right)}$$

$$b(s)=\frac{5.69x10^4}{s+5.29x10^5}\qquad A_v(s)=\frac{10^7}{s+50}\qquad T(s)=A_v(s)b(s)$$

$$For\ w>>50,\ \left|T(jw)\right|\cong\frac{5.69x10^{11}}{w\sqrt{w^2+\left(5.29x10^5\right)^2}}\rightarrow\left|T(jw)\right|=1\ for\ w=6.68x10^5$$

$$\Phi_M=180-\tan^{-1}\frac{6.68x10^5}{50}-\tan^{-1}\frac{6.68x10^5}{5.29x10^5}=38.4^o$$

---

**18.86**

$$A_{v1}=\frac{V_{o1}}{V_{o2}}=-\frac{1}{sRC}\qquad V_{o2}=\left(1+\frac{2R}{2R}\right)V_+=2V_+$$

$$\left(V_+-V_{o1}\right)\frac{G}{2}+sCV_++\left(V_+-V_{o2}\right)G_F=0\quad \text{Combining these yields}$$

$$A_{v2}=\frac{V_{o2}}{V_{o1}}=\frac{G}{sC+\left(\dfrac{G}{2}-G_F\right)}\quad\text{and}\quad T(s)=A_{v1}A_{v2}=\frac{1}{sRC\left(sRC+\dfrac{1}{2}-\dfrac{R}{R_F}\right)}$$

$$\angle T(jw_o)=0\rightarrow R_F=2R\ \text{ and }\ \left|T(jw_o)\right|=1\rightarrow w_o=\frac{1}{RC}$$

**18.87**

Define $V_1$ as the output of the inverting amplifier and $V_2$ as the output of the right - hand non - inverting amplifier.

$$V_1 = -V_2 \frac{Z_2}{Z_1} = -V_2 \frac{R}{R+\frac{1}{sC}} = -V_2 \frac{sCR}{SCR+1} \quad | \quad V_2 = V_1 \left( \frac{R}{R+\frac{1}{sC}} \right) \left( 1+\frac{R_2}{R_1} \right) \left( \frac{R}{R+\frac{1}{sC}} \right) \left( 1+\frac{R_2}{R_1} \right)$$

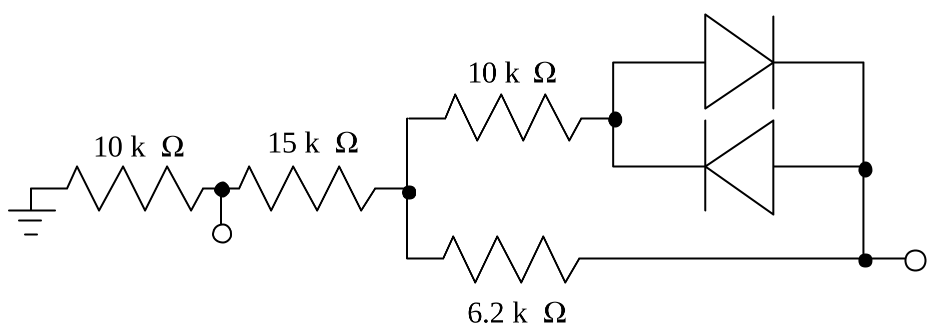
$$V_2 \left[ 1 + \left( \frac{sCR}{SCR+1} \right)^3 \left( 1+\frac{R_2}{R_1} \right)^2 \right] = 0 \quad | \quad \left( \frac{jwCR}{jwCR+1} \right)^3 \left( 1+\frac{R_2}{R_1} \right)^2 = -1$$

$$3\left[ 90^o - \tan^{-1}(wCR) \right] = 180^o \quad | \quad \tan^{-1}(wCR) = 30^o \quad | \quad wCR = \tan\left(30^o\right) = 0.5774$$

$$\left( 1+\frac{R_2}{R_1} \right)^2 \left( \frac{wCR}{\sqrt{1+(wCR)^2}} \right)^3 = \left( 1+\frac{R_2}{R_1} \right)^2 \left[ \frac{\tan\left(30^o\right)}{\sqrt{1+\tan^2\left(30^o\right)}} \right]^3 = 1 \rightarrow \frac{R_2}{R_1} = \sqrt{8} - 1 = 1.83$$

---

**18.88**




$$f_o = \frac{1}{2p(5k\Omega)(500\,pF)} = 63.7\ kHz \quad | \quad |v_O| = \frac{3(0.7V)}{\left( 2 - \frac{15k\Omega}{10k\Omega} \right)\left( 1+\frac{10k\Omega}{6.2k\Omega} \right) - \frac{10k\Omega}{10k\Omega}} = 6.85\ V$$

---

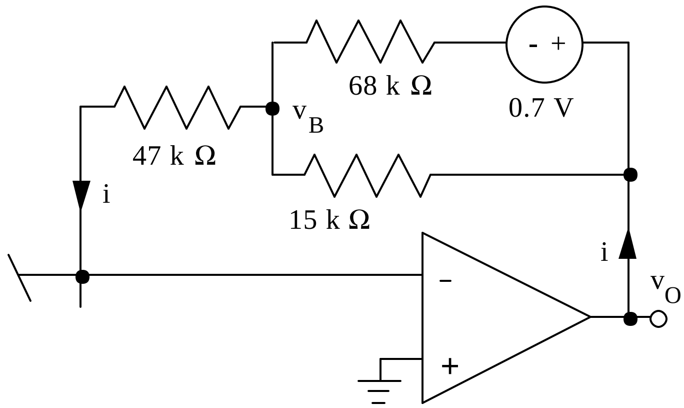
**18.89**

```
*Problem 18.89 - Wien-Bridge Oscillator
C1 1 0 500PF IC=1
RA 1 0 5K
C2 1 2 500PF
RB 2 3 5K
E1 3 0 1 6 1E6
R1 6 0 10K
R2 5 6 15K
R3 3 5 6.2K
R4 4 5 10K
D1 3 4 DMOD
D2 4 3 DMOD
.MODEL DMOD D
.TRAN 10U 10M UIC
.PROBE V(1) V(2) V(3) V(4) V(5) V(6)
.END
```

Results: f = 60.0 kHz, amplitude = 6.8 V

---

**18.90**




Using Eq. (18.124), $f_o = \dfrac{1}{2p\sqrt{3}(5000)(10^{-9})} = 18.4\ kHz$

Using Eq. (18.125), the total feedback resistance should be $R_1 = 12R = 60k\Omega.$

The current in R $_1$ is $I = \dfrac{V_O}{R_1} = \dfrac{V_O}{12R} = \dfrac{V_O}{60k\Omega}$. The voltage at V $_B$ is

$V_B = I(47k\Omega) = \dfrac{47k\Omega}{60k\Omega}V_O$ | In the diode network, $I = \dfrac{V_O}{60k\Omega} = \dfrac{V_O - V_B}{15k\Omega} + \dfrac{V_O - 0.7 - V_B}{68k\Omega}$

$$\frac{\frac{13}{60}V_O}{15k\Omega} + \frac{\frac{13}{60}V_O}{68k\Omega} - \frac{V_O}{60k\Omega} = \frac{0.7}{68k\Omega} \rightarrow V_O = 10.7\ V$$

---

**18.91**

```
*Problem 18.91 - Phase Shift Oscillator
C1 1 6 1000PF IC=1
RA 1 0 5K
C2 1 2 1000PF
RB 2 0 5K
C3 2 3 1000PF
E1 3 0 0 6 1E6
R2 6 5 47K
R3 5 3 15K
R4 5 4 68K
D1 3 4 DMOD
D2 4 3 DMOD
.MODEL DMOD D
.TRAN 10U 20M UIC
.PROBE V(1) V(2) V(3) V(4) V(5) V(6)
.END
```

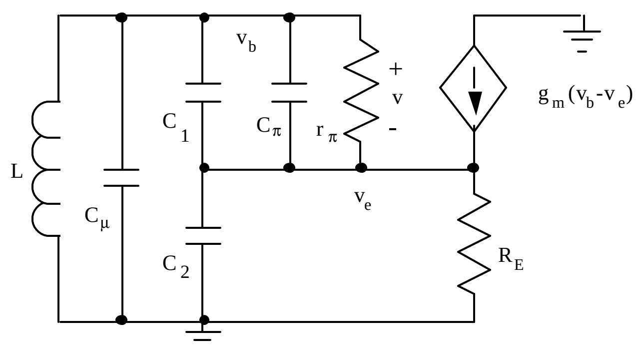
Results: f = 17.5 kHz, amplitude = 11.5 V

---

**18.92** Note that the presence of $r_\pi$ makes the analysis more complex than the FET case. $C_4$ is a coupling capacitor, and its impedance is neglected in the analysis. $C_5 = C_1 + C_\pi$. However, the effect of $r_\pi$ can usually be neglected in the $f_o$ calculation as shown below.

$$\begin{bmatrix} s(C_5 + C_m) + g_p + \dfrac{1}{sL} & -(sC_5 + g_p) \\ -(sC_5 + g_m + g_p) & s(C_2 + C_5) + g_m + g_p + G_E \end{bmatrix} \begin{bmatrix} V_b \\ V_e \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

$$\Delta(s) = s^2\left[C_5C_2 + C_m(C_2 + C_5)\right] + s\left[C_2g_p + C_m(g_m + g_p + G_E) + C_5G_E\right]$$
$$+ \frac{g_m + g_p + G_E}{sL} + g_pG_E + \frac{(C_2 + C_5)}{L}$$




$$\Delta(jw_o) = 0 \quad | \quad w_o^2 = \frac{1}{C_{TC}}\left[\frac{1}{L} + \frac{1}{r_pR_E(C_2 + C_5)}\right] = \frac{1}{C_{TC}}\left[\frac{1}{L} + \frac{g_m}{b_oR_E(C_2 + C_5)}\right] \quad | \quad C_{TC} = C_m + \frac{C_2C_5}{C_2 + C_5}$$

$$w_o\left[C_2g_p + C_m(g_m + g_p + G_E) + C_5G_E\right] = \frac{g_m + g_p + G_E}{w_oL}$$

$$w_o^2L\left[C_m + \frac{C_2}{b_o + 1 + \dfrac{r_p}{R_E}} + \frac{C_5}{1 + g_mR_E + \dfrac{R_E}{r_p}}\right] = 1 \quad | \quad w_o^2L\left[C_m + \frac{C_2}{b_o + 1 + \dfrac{b_o}{g_mR_E}} + \frac{C_5}{1 + g_mR_E + \dfrac{g_mR_E}{b_o}}\right] = 1$$

$$(a)\ C_{TC} = \frac{100pF(20pF)}{100pF + 20pF} = 16.7pF \quad | \quad w_o^2 = \frac{1}{16.7pF}\left[\frac{1}{5mH} + \frac{10mS}{100(1k\Omega)(100pF + 20pF)}\right]$$

$$w_o^2 = \frac{1}{16.7pF}\left[2x10^5 + 833\right] \rightarrow f_o = 17.5\ MHz$$

Note that the correction term is negligible $: w_o \cong \dfrac{1}{LC_{TC}}$ $\quad (b)\ C_{TC} = \dfrac{1}{\dfrac{1}{C_2} + \dfrac{1}{C_5} + \dfrac{1}{C_3}}$

$$C_{TC}^{\min} = \frac{1}{\frac{1}{100\,pF} + \frac{1}{20\,pF} + \frac{1}{5\,pF}} = 3.85\,pF \quad | \quad f_o \cong \frac{1}{2p\sqrt{LC_{TC}}} = \frac{1}{2p\sqrt{(5mH)(3.85\,pF)}} = 36.3\ MHz$$

$$C_{TC}^{\max} = \frac{1}{\frac{1}{100\,pF} + \frac{1}{20\,pF} + \frac{1}{50\,pF}} = 12.5\,pF \quad | \quad f_o \cong \frac{1}{2p\sqrt{(5mH)(12.5\,pF)}} = 20.1\ MHz$$

$$(c)\ w_o^2 L\left[\frac{C_2}{b_o + 1 + \frac{b_o}{g_m R_E}} + \frac{C_5}{1 + g_m R_E + \frac{g_m R_E}{b_o}}\right] \cong \frac{1}{C_{TC}}\left[\frac{C_2}{b_o + 1 + \frac{b_o}{g_m R_E}} + \frac{C_5}{1 + g_m R_E + \frac{g_m R_E}{b_o}}\right] = 1$$

$$\frac{1}{16.7\,pF}\left[\frac{100\,pF}{101 + \frac{100}{g_m(1k\Omega)}} + \frac{20\,pF}{1 + g_m(1k\Omega) + \frac{g_m(1k\Omega)}{100}}\right] = 1 \quad | \quad \text{MATLAB yields} \quad g_m = 0.211\,mS$$

$$I_C = (0.211mS)(0.025V) = 5.28\ mA$$

---

**<u>18.93</u>** Assuming the effect of $r_\pi$ is negligible:

$$(a)\ f_o \cong \frac{1}{2p}\sqrt{\frac{1}{C_{EQ}L}} \quad | \quad C_{EQ} = \frac{1}{\frac{1}{C_4} + \frac{1}{C_m + \frac{1}{\frac{1}{C_1 + C_p} + \frac{1}{C_2}}}} \quad | \quad C_p = \frac{40(5mA)}{10^9 p} - 3\,pF = 60.7\,pF$$

$$C_{EQ} = \frac{1}{\frac{1}{0.01uF} + \frac{1}{3pF + \frac{1}{\frac{1}{(20 + 60.7)pF} + \frac{1}{100\,pF}}}} = 47.4\,pF \quad | \quad f_o \cong \frac{1}{2p}\sqrt{\frac{1}{47.4\,pF(20mH)}} = 5.17MHz$$

$$(b)\ C_p = \frac{40(10\,mA)}{10^9 p} - 3\,pF = 124\,pF \quad | \quad C_{EQ} = \frac{1}{\frac{1}{0.01uF} + \frac{1}{3\,pF + \frac{1}{\frac{1}{20\,pF + 124\,pF} + \frac{1}{100\,pF}}}} = 61.6\,pF$$

$$f_o \cong \frac{1}{2p}\sqrt{\frac{1}{61.6\,pF(20mH)}} = 4.53MHz$$

---

**18.94**

$$C_{TC} = \frac{1}{w_o^2 L} = \frac{1}{\left(4x10^7 p\right)^2 (3mH)} = 21.1pF \quad | \quad C_{TC} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}} \quad | \quad g_m R \geq \frac{C_1}{C_2} \rightarrow \frac{2I_{DS}R}{V_{GS} - V_P} \geq \frac{C_1}{C_2}$$

$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 = 10mA\left(1 + \frac{V_{GS}}{4}\right)^2 \quad | \quad -4 \leq V_{GS} \leq 0.$ Suppose we pick $V_{GS}$ in the middle of this range : $V_{GS} = -2V \rightarrow I_D = 10mA\left(1 - \frac{2}{4}\right)^2 = 2.50mA \quad | \quad R = \frac{2V}{2.5mA} = 800\Omega \rightarrow 820\ \Omega$

$\frac{C_1}{C_2} \leq \frac{2I_D R}{V_{GS} - V_P} = \frac{2(2)}{-2-(-4)} = 2 \quad | \quad C_1 \leq 2C_2 \quad |$ Select $C_1 \cong C_2 \cong 42p\text{F}$ | Choosing

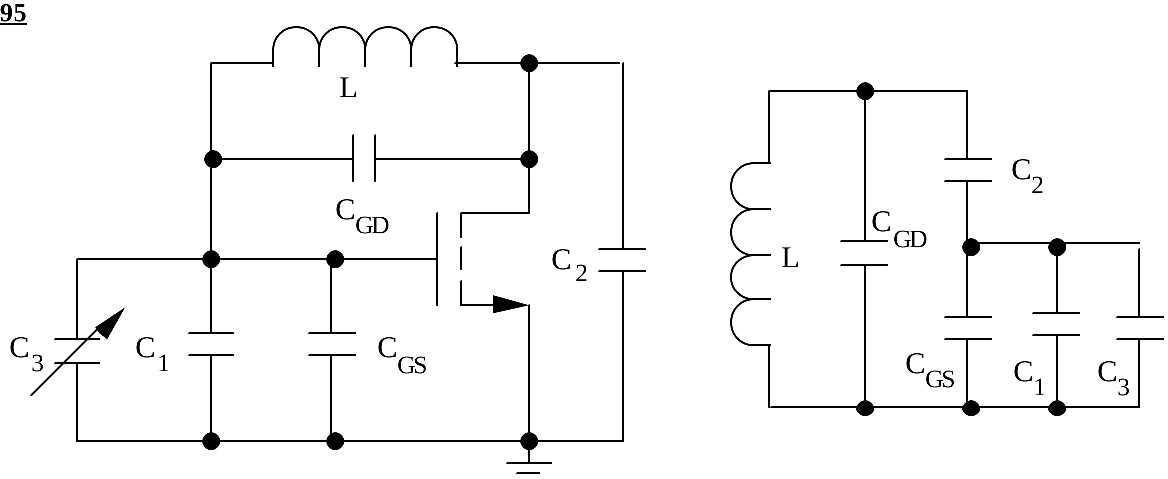
$C_1 = 47pF$ from Appendix C, $C_2 = \frac{1}{\frac{1}{21.1pF} - \frac{1}{47pF}} = 38.3pF$ which is close to 39 pF.

If 47pF and 39pF are used : $f_o = \frac{1}{2p\sqrt{(21.3pF)(3mH)}} = 19.9\ MHz$

In order to obtain an exact frequency of oscillation, a 33-pF capacitor in parallel with a small variable capacitor could be used. Note that including the FET capacitances would modify the design values.

---

**18.95**




$$C_{TC} = C_{GD} + \frac{1}{\frac{1}{C_2} + \frac{1}{C_1 + C_3 + C_{GS}}} = 4pF + \frac{1}{\frac{1}{50pF} + \frac{1}{50pF + 0 + 10pF}} = 31.27pF$$

$$f_o = \frac{1}{2p\sqrt{LC_{TC}}} = \frac{1}{2p\sqrt{\left(10^{-5}H\right)\left(31.27x10^{-12}F\right)}} = 9.00\,MHz$$

$g_m r_o \geq \frac{C_1 + C_3 + C_{GS}}{C_2} = \frac{50pF + 0 + 10pF}{50pF} = 1.20$ which is easily met.

---

**18.96**

$$(a)\ C_{TC} = C_{GD} + \frac{1}{\dfrac{1}{C_2} + \dfrac{1}{C_1 + C_3 + C_{GS}}} \quad | \quad C_{TC}^{\max} = 4pF + \frac{1}{\dfrac{1}{50pF} + \dfrac{1}{50pF + 5pF + 10pF}} = 32.3pF$$

$$f_o = \frac{1}{2p\sqrt{LC_{TC}}} = \frac{1}{2p\sqrt{(10mH)(32.3pF)}} = 8.87\ MHz$$

$$C_{TC}^{\min} = 4pF + \frac{1}{\dfrac{1}{50pF} + \dfrac{1}{50pF + 50pF + 10pF}} = 38.4pF \quad | \quad f_o = \frac{1}{2p\sqrt{(10mH)(38.4pF)}} = 8.12\ MHz$$

$$(b)\ g_m r_o \ge \frac{C_1 + C_3 + C_{GS}}{C_2} \quad | \quad g_m r_o \ge \frac{50pF + 5pF + 10pF}{50pF} = 1.30\ and$$

$$g_m r_o \ge \frac{50pF + 50pF + 10pF}{50pF} = 2.20 \quad | \quad \therefore\ g_m r_o \ge 2.20 \text{ which is easily met.}$$

---

**18.97**

$$(a)\ C_D = \frac{C_{jo}}{\sqrt{1 + \dfrac{V_{TUNE}}{f_j}}} \quad | \quad C_D = \frac{20pF}{\sqrt{1 + \dfrac{2V}{0.8V}}} = 10.7pF \quad | \quad C_{TC} = \frac{1}{\dfrac{1}{75pF + 10.7pF} + \dfrac{1}{75pF}} = 40.0pF$$

$$C_D = \frac{20pF}{\sqrt{1 + \dfrac{20V}{0.8V}}} = 3.92pF \quad | \quad C_{TC} = \frac{1}{\dfrac{1}{75pF + 3.92pF} + \dfrac{1}{75pF}} = 38.5pF$$

$$f_o^{\min} = \frac{1}{2p\sqrt{(10mH)(40.0pF)}} = 7.96\ MHz \quad | \quad f_o^{\max} = \frac{1}{2p\sqrt{(10mH)(38.5pF)}} = 8.11\ MHz$$

$$(b) \text{ In this circuit,} \quad R = r_o: \ m_f = g_m r_o \ge \frac{C_1 + C_D}{C_2} \quad | \quad m_f \ge \frac{78.9pF}{75pF} = 1.05$$

---

**18.98**

$$C_{TC} = \frac{1}{\dfrac{1}{470pF} + \dfrac{1}{220pF}} = 150pF \quad | \quad f_o = \frac{1}{2p\sqrt{(10mH)(150pF)}} = 4.11\ MHz$$

$$\text{The required} \quad g_m R \ge \frac{C_2}{C_1} = \frac{220pF}{470pF} = 0.468 \text{ is met :}$$

$$g_m R = \frac{2I_D R}{V_{GS} - V_P} \cong \frac{2(2.5mA)(820\Omega)}{-2-(-4)} = 1.03$$

This analysis is borne out by the SPICE simulation below.

```
VDD 3 0 DC 10
R 1 0 820
C1 1 0 470PF IC=2
C2 2 1 220PF IC=0
*C1 1 0 220PF IC=2
*C2 2 1 470PF IC=0
```

```
L 2 0 10UH
J1 3 2 1 NFET
.MODEL NFET NJF VTO=-4 BETA=0.625MA
.OP
.TRAN 10N 30U UIC
.PROBE
.END
```

$(b)$ For this case, the required $g_m R \geq \frac{C_2}{C_1} = \frac{470\,pF}{220\,pF} = 2.14$ is not met.

and the circuit fails to oscillate.

This analysis is borne out by the SPICE simulation below. The circuit does not oscillate.

---

**18.99**

$$C_{TC} = 3pF + \frac{1}{\frac{1}{50\,pF + 10pF} + \frac{1}{50\,pF}} = 30.3pF \quad | \quad f_o = \frac{1}{2p\sqrt{(10mH)(30.3\,pF)}} = 9.15\ MHz$$

```
*Problem 18.99 NMOS Colpitts Oscillator
VDD 3 0 DC 12
LRFC 3 2 20MH
C1 1 0 50PF
C2 2 0 50PF
L 2 1 10UH
M1 2 1 0 0 NFET
CGS 1 0 10PF
CGD 1 2 4PF
.MODEL NFET NMOS VTO=1 KP=10MA LAMBDA=0.02
.OP
.TRAN 50N 40U UIC
.PROBE
.END
```

Results: f = 7.5 MHz, amplitude = 80 V peak-peak. There is little to set the amplitude in this circuit, and the frequency of oscillation is significantly in error. Also, $\mu_f$ of the transistor greatly exceeds the gain required for oscillation and the waveform at the drain is highly nonlinear. The voltage at the gate is filtered by the LC network and is more sinusoidal in character. A diode from ground to gate could be employed to help limit the amplitude of the oscillation.

---

**18.100**

$$f_o = \frac{1}{2p\sqrt{(10mH + 10mH)(20\,pF)}} = 7.96\ MHz$$

---

**18.101**

$$f_o = \frac{1}{2\pi\sqrt{LC_{TC}}} \quad | \quad C_{TC} = \frac{1}{\frac{1}{C}+\frac{1}{C_D}} \quad | \quad C = 220\,pF \quad | \quad C_D = \frac{20\,pF}{\sqrt{1+\frac{V_{TUNE}}{0.8V}}} \quad | \quad L = L_1 + L_2 = 20\mu H$$

$$(a)\ \ C_D = \frac{20pF}{\sqrt{1+\frac{2V}{0.8V}}} = 10.7pF \quad | \quad C_{TC} = \frac{1}{\frac{1}{220\,pF}+\frac{1}{10.7\,pF}} = 10.2pF$$

$$f_o = \frac{1}{2\pi\sqrt{20\mu H(10.2\,pF)}} = 11.1\,MHz$$

$$C_D = \frac{20\,pF}{\sqrt{1+\frac{20V}{0.8V}}} = 3.92\,pF \quad | \quad C_{TC} = \frac{1}{\frac{1}{220PF}+\frac{1}{3.92\,pF}} = 3.85\,pF$$

$$f_o = \frac{1}{2\pi\sqrt{20\mu H(3.85\,pF)}} = 18.1\,MHz \quad (b)\ \ m_f \geq \frac{L_1}{L_2} = 1.00$$

---

**18.102**

$$\omega_S = \frac{1}{\sqrt{LC_S}} \quad | \quad L = \frac{RQ}{\omega_S}$$

$$(a)\ \ L = \frac{40(25000)}{2x10^7\pi} = 15.915\ mH \quad | \quad C_S = \frac{1}{\omega_S^2 L} = \frac{1}{(2x10^7\pi)^2 15.915mH} = 15.916\,fF$$

$$(b)\ \ C_P = \frac{1}{\frac{1}{15.915\,fF}+\frac{1}{10\,pF}} = 15.890\,fF \quad | \quad f_P = \frac{1}{2\pi\sqrt{15.915mH(15.890\,fF)}} = 10.008\ MHz$$

$$(c)\ \ C_P = \frac{1}{\frac{1}{15.915\,fF}+\frac{1}{32\,pF}} = 15.907\,fF \quad | \quad f_P = \frac{1}{2\pi\sqrt{15.915mH(15.907\,fF)}} = 10.003\ MHz$$

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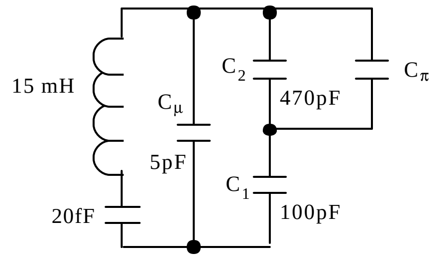
**18.103**




$$(a)\ \ C_{TC} = \frac{1}{\frac{1}{20\,fF}+\frac{1}{470\,pF}+\frac{1}{100\,pF}} = 19.995\,fF \ \ | \ \ f_P = \frac{1}{2p\sqrt{15mH(19.995\,fF)}} = 9.190\ MHz$$

$$(b)\ \ I_C = 100\frac{5-0.7}{100k\Omega+101(1k\Omega)} = 2.14mA \ \ | \ \ C_p = \frac{40(2.14\,mA)}{2p\left(2.5x10^8\,Hz\right)} - 5\,pF = 49.5\,pF$$

$$C_{TC} = \frac{1}{\frac{1}{20\,fF}+\frac{1}{5pF+\frac{1}{100\,pF}+\frac{1}{470\,pF+49.5\,pF}}} = 19.996\,fF$$

$$f_P = \frac{1}{2p\sqrt{15mH(19.996\,fF)}} = 9.190\ MHz$$

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**18.104**

$$C_{TC}^{\max} = \frac{1}{\frac{1}{20\,fF}+\frac{1}{1pF}+\frac{1}{100\,pF}+\frac{1}{470\,pF}} = 19.60\,fF \ \ | \ \ f_P = \frac{1}{2p\sqrt{15mH(19.60\,fF)}} = 9.28\ MHz$$

$$C_{TC}^{\max} = \frac{1}{\frac{1}{20\,fF}+\frac{1}{35\,pF}+\frac{1}{100\,pF}+\frac{1}{470\,pF}} = 19.98\,fF \ \ | \ \ f_P = \frac{1}{2p\sqrt{15mH(19.98\,fF)}} = 9.19\ MHz$$

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**18.105**

```
*Problem 18.105 BJT Colpitts Crystal Oscillator
VCC 1 0 DC 5
VEE 4 0 DC -5
Q1 1 2 3 NBJT
RE 3 4 1K
RB 2 0 100K
C1 3 0 100PF
C2 2 3 470PF
LC 2 6 15M
CC 6 5 20FF IC=5
RC 5 0 50
.MODEL NBJT NPN BF=100 VA=50 TF=1N CJC=5PF
.OP
.TRAN 2N 20U UIC
.PROBE
.END
```

In the period of time used in the simulation results, node 6 at the interior of the crystal oscillates vigorously, but the oscillation is not coupled well to the other nodes.