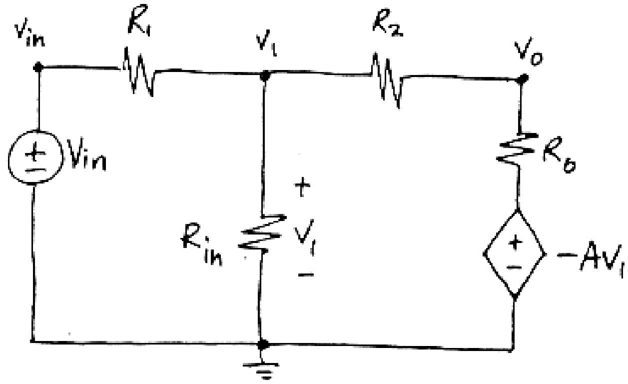
P6.7-3



$$\left.\begin{aligned}\frac{v_1-v_{in}}{R_1}+\frac{v_1}{R_{in}}+\frac{v_1-v_0}{R_2} &= 0\\ \frac{v_0+Av_1}{R_0}+\frac{v_0-v_1}{R_2} &= 0\end{aligned}\right\} \Rightarrow \frac{v_0}{v_{in}} = \frac{R_{in}(R_0-AR_2)}{(R_1+R_{in})(R_0+R_2)+R_1R_{in}(1+A)}$$

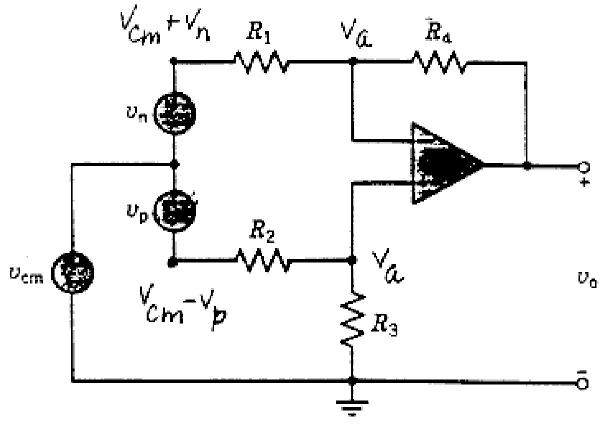
P6.7-4

a) $\frac{v_0}{v_{in}} = -\frac{R_2}{R_1} = -\frac{49\text{k}\Omega}{5.1\text{k}\Omega} = \underline{-9.6078}$

b) $$\frac{v_0}{v_{in}} = \frac{2\text{M}\Omega\left(75-(200{,}000)(50\text{k}\Omega)\right)}{(5\text{k}\Omega+2\text{M}\Omega)(75+50\text{k}\Omega)+(5\text{k}\Omega)(2\text{M}\Omega)(1+200{,}000)} = \underline{-9.9995}$$

c) $$\frac{v_0}{v_{in}} = \frac{2\text{M}\Omega(75-(200{,}000)(49\text{k}\Omega))}{(5.1\text{k}\Omega+2\text{M}\Omega)(75+49\text{k}\Omega)+(5.1\text{k}\Omega)(2\text{M}\Omega)(1+200{,}000)} = \underline{-9.6073}$$

P6.7-5



$$v_a = \frac{R_3}{R_2+R_3}(v_{cm}-v_p)$$

$$\frac{v_a-v_0}{R_4}+\frac{v_a-(v_{cm}+v_n)}{R_1} = 0$$

$$v_0 = -\frac{R_4}{R_1}(v_{cm}+v_n)+\frac{R_4+R_1}{R_1}v_a = -\frac{R_4}{R_1}(v_{cm}+v_n)+\frac{(R_4+R_1)R_3}{R_1(R_2+R_3)}(v_{cm}-v_p)$$

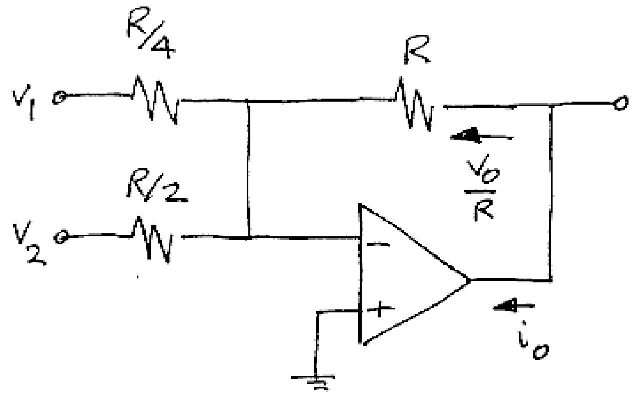
when $\frac{R_4}{R_1} = \frac{R_3}{R_2}$ then $\frac{(R_4+R_1)R_3}{R_1(R_2+R_3)} = \frac{\frac{R_4}{R_1}+1}{\frac{R_3}{R_2}+1}\times\frac{R_3}{R_2} = \frac{R_4}{R_1}$

so

$$v_0 = -\frac{R_4}{R_1}(v_{cm}+v_n)+\frac{R_4}{R_1}(v_{cm}-v_p) = -\frac{R_4}{R_1}(v_n+v_p)$$

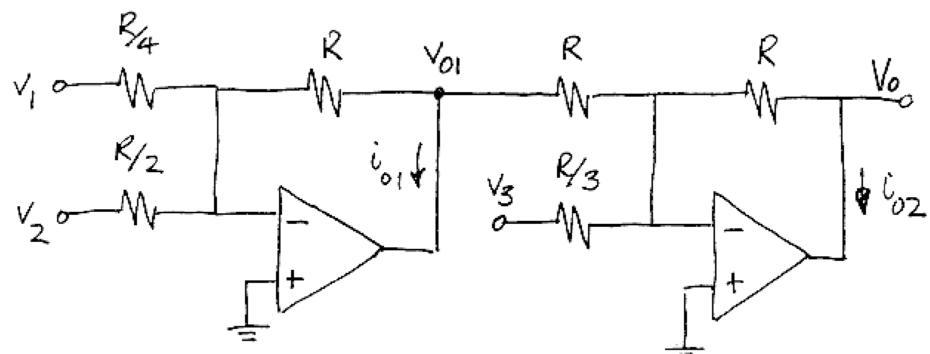
P6.7-6

(a)



$$|i_0| \le \frac{4|v_1|+2|v_2|}{R} \le \frac{6}{R} < i_{sat} \quad \text{so } R > \frac{6}{i_{sat}} = \frac{6}{2\times10^{-3}} = 3\ \text{k}\Omega \text{ is required}$$

(b)



$$v_{01} = -(4v_1 + 2v_2); \qquad v_0 = -(v_{01} + 3v_3) = 4v_1 + 2v_2 - 3v_3$$

$$i_{01} = -\frac{v_{01}}{R} - \frac{v_{01}}{R} = -\frac{2v_{01}}{R}$$

$$|i_{01}| \le \frac{2}{R}(4|v_1|+2|v_2|) \le \frac{12}{R} \le i_{sat}$$

$$\text{so } R \ge \frac{12}{i_{sat}} = \frac{12}{2\cdot10^{-3}} = 6\text{k}\Omega$$

Also

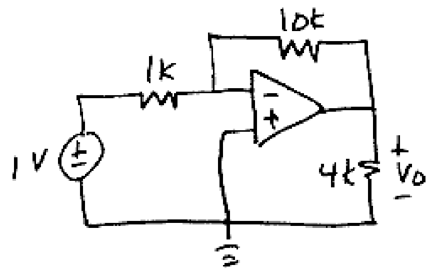
$$i_{02} = -\frac{v_0}{R} = -\frac{4v_1 + 2v_2 - 3v_3}{R}$$

$$|i_{02}| \le \frac{4|v_1|+2|v_2|+3|v_3|}{R} \le \frac{9}{R} < i_{sat}$$

$$\text{so} \quad R \ge \frac{9}{i_{sat}} = \frac{9}{2\cdot10^{-3}} = 4.5\ \text{k}\Omega$$

$\therefore$ $R \ge 6\ \text{k}\Omega$ satisfies both constraints.

P6.7-7

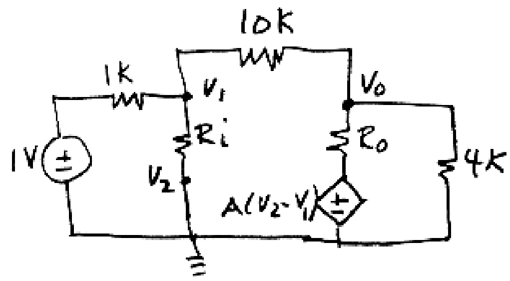


(a) Ideal op amp, KCL

$$\frac{1}{1k\Omega}+\frac{v_0}{10k\Omega}=0$$

$$\underline{v_0=-10\ V}$$

b) Finite gain op amp



$A=10^4,\ R_i=200k\Omega,\ R_0=5k\Omega$

$$\text{KCL @ } v_1\text{: } \frac{1-v_1}{1k}+\frac{v_0-v_1}{10k\Omega}-\frac{v_1}{R_i}=0$$

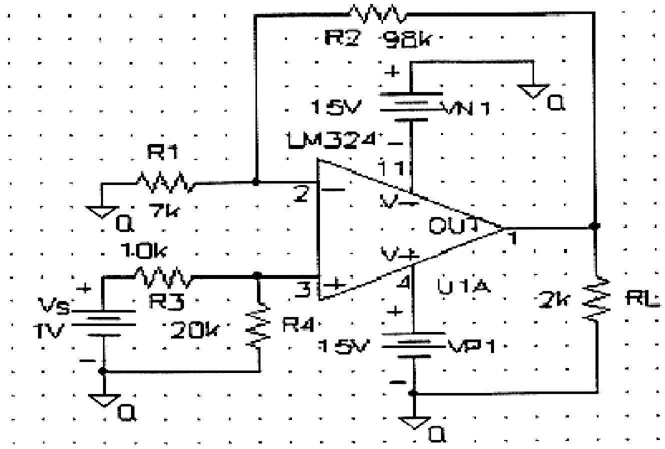
$$\text{KCL @ } v_0\text{: } \frac{v_1-v_0}{10k\Omega}+\frac{A(v_2-v_1)-v_0}{R_0}-\frac{v_0}{4k\Omega}=0$$

Solving yields $\underline{v_0=-10.03\ V}$

PSpice Problems

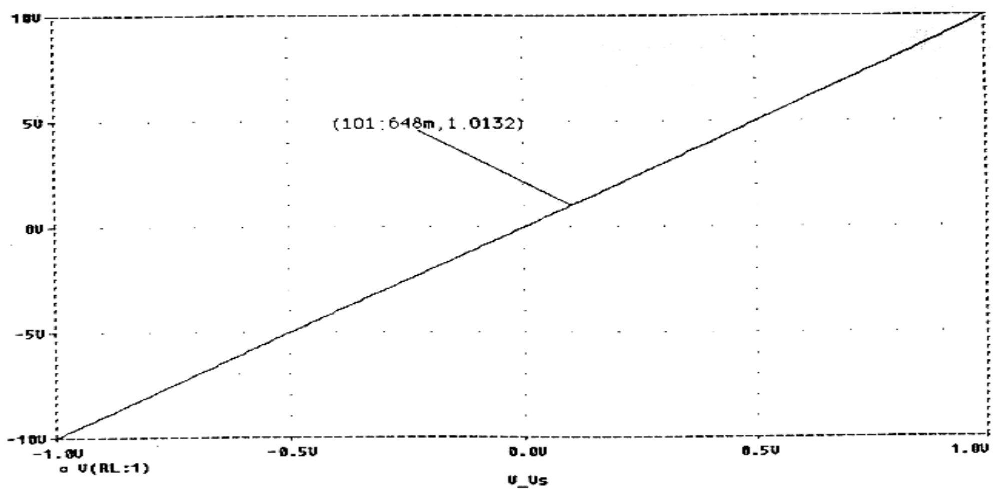
SP 6-1

From the PROBE plot shown below



$v_0 \simeq 1$ V when $v_s \simeq 0.1$ V

Then $i_0 = \dfrac{v_0}{2000} \simeq 0.5$ mA



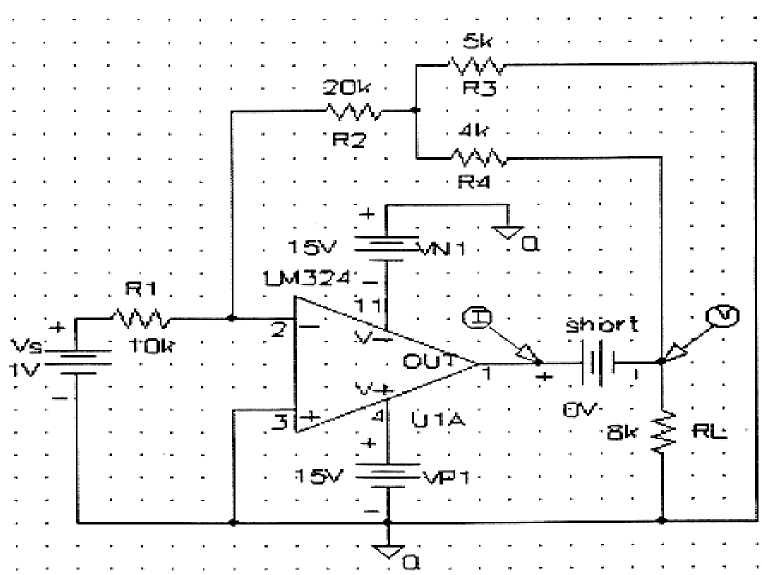
SP 6-2

These PROBE plots indicates that

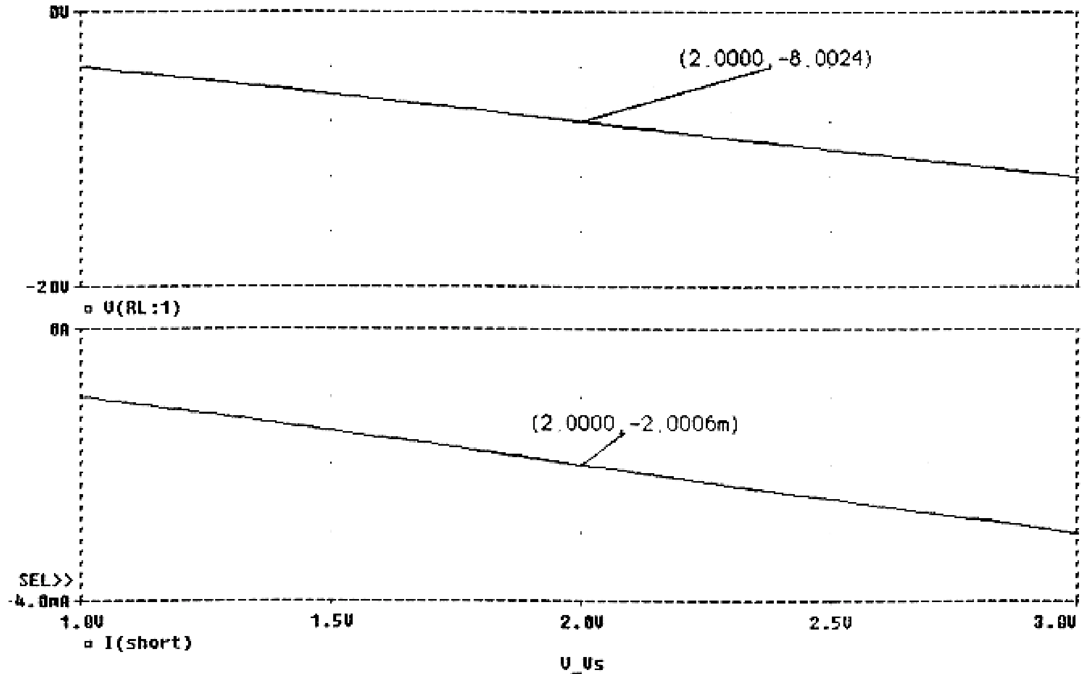
$v_0 = -8.0024\text{V}$ and

$i_0 = -2.0006\text{mA}$

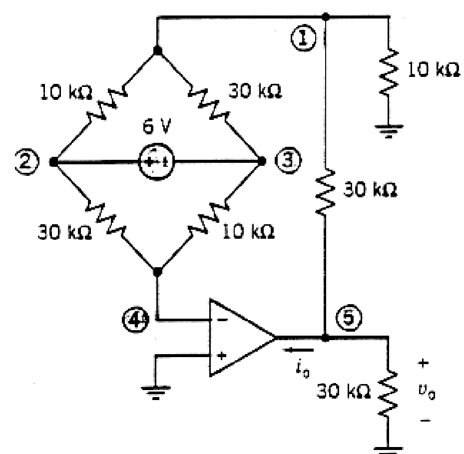
Notice that a model of the LM324 op amp was used instead of an ideal op amp



SP 6-2 (continued)

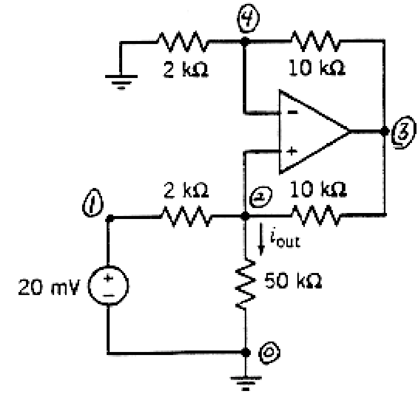



```
SP 6-3 Spice deck corresponding to SP 6-3
R1 1  0 10K
R2 1  5 30K
R3 1  2 10K
R4 1  3 30K
R5 2  4 30K
R6 3  4 10K
VS 2  3 DC   6
RI 4  0 10MEG
X0A1  4 0  5 IDEAL
R7 5  0 30K

.SUBCKT IDEAL 1 2 3
E 3 0 1 2 -1G
.ENDS IDEAL
.END
```




```
 NODE    VOLTAGE       NODE     VOLTAGE       NODE    VOLTAGE
(    1)     3.0000    (     2)      4.5000   (     3)   -1.5000
(    4)-12.00E-09    (     5)     12.0000

VOLTAGE SOURCE CURRENTS
NAME         CURRENTS
VS          -3.000E-04
```

```
SP 6-4 Spice deck corresponding to Problem SP 6-4(a)
V1    1 0   DC .02
R1    1 2   2K
R2    2 0   50K
R3    2 3   10K
R4    3 4   10K
R5    4 0   2K
X0A   1 4   2 3  IDEAL

.SUBCKT IDEAL 1 2 3
E 3 0 1 2 -1G
.ENDS IDEAL
.END
```

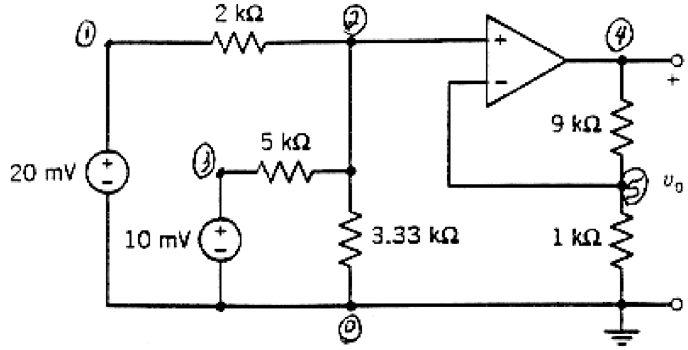



```
NODE     VOLTAGE       NODE    VOLTAGE       NODE   VOLTAGE
(    1)    .0200     (     2)      .5000    (     3)   3.0000
(    4)    .5000

VOLTAGE SOURCE CURRENTS
NAME          CURRENTS
VS            2.400E-04
```

```
SP 6-4b Spice deck corresponding to Problem SP 6-4(b)
VS    1 0   DC .02
R1    1 2   2K
R2    2 0   50K
R3    2 3   10K
R4    3 4   10K
R5    4 0   2K
X0A   1 4   2  3  UA741

.SUBCKT UA741 1 2 5
IB1 1 0 70nA
Ib2 2 0 90nA
VOS 3 2 1mV
RI 1 3 2MEG
E 4 0 1 3 -200000
RO 4 5 75
.ENDS UA741
.END
```

```
 NODE   VOLTAGE      NODE     VOLTAGE     NODE    VOLTAGE
(    1)    .0200    (     2)      .5285   (     3)    3.1777
(    4)    .5295    (X0A1.3)      .5295  (X0A1.4)     3.2174

VOLTAGE SOURCE CURRENTS
NAME         CURRENT
VS           2.543E-04
X0A1.VOS     -8.044E-12
```

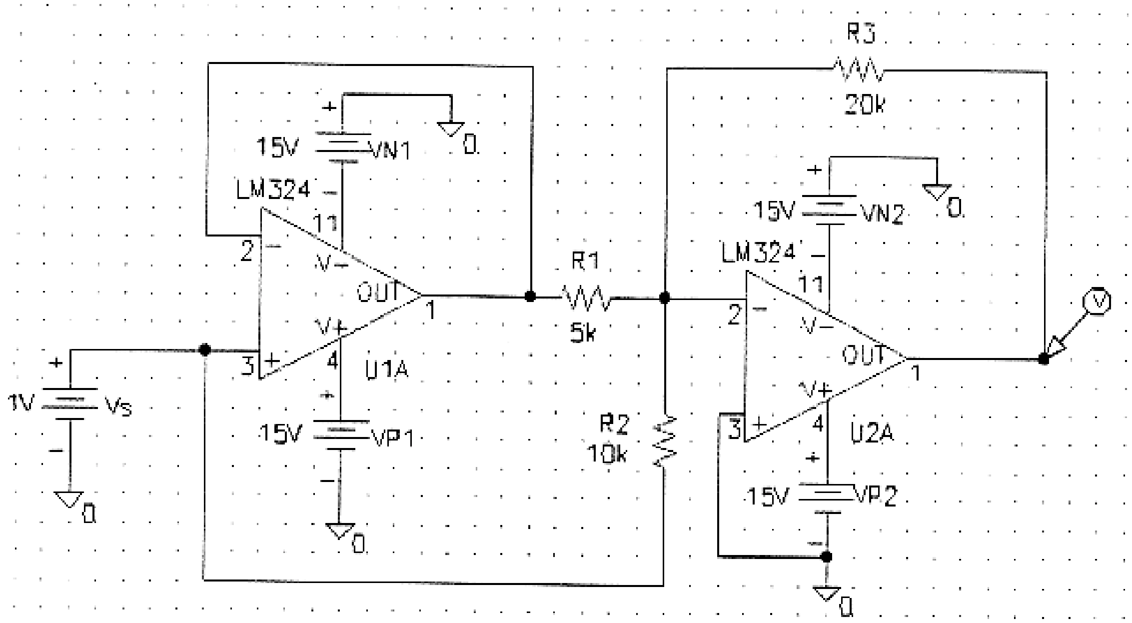
```
SP 6-5 Spice deck corresponding to Problem SP 6-5(a)
V1    1 0   DC .02
R1    1 2   2K
R2    2 3   5K
R3    2 0   3.33K
V2    3 0   DC .01
X0A   1 5   2  4 IDEAL
R4    4 5   9K
R5    5 0   1K

.SUBCKT IDEAL 1 2 3
E 3 0 1 2 -1G
.ENDS IDEAL
.END
```



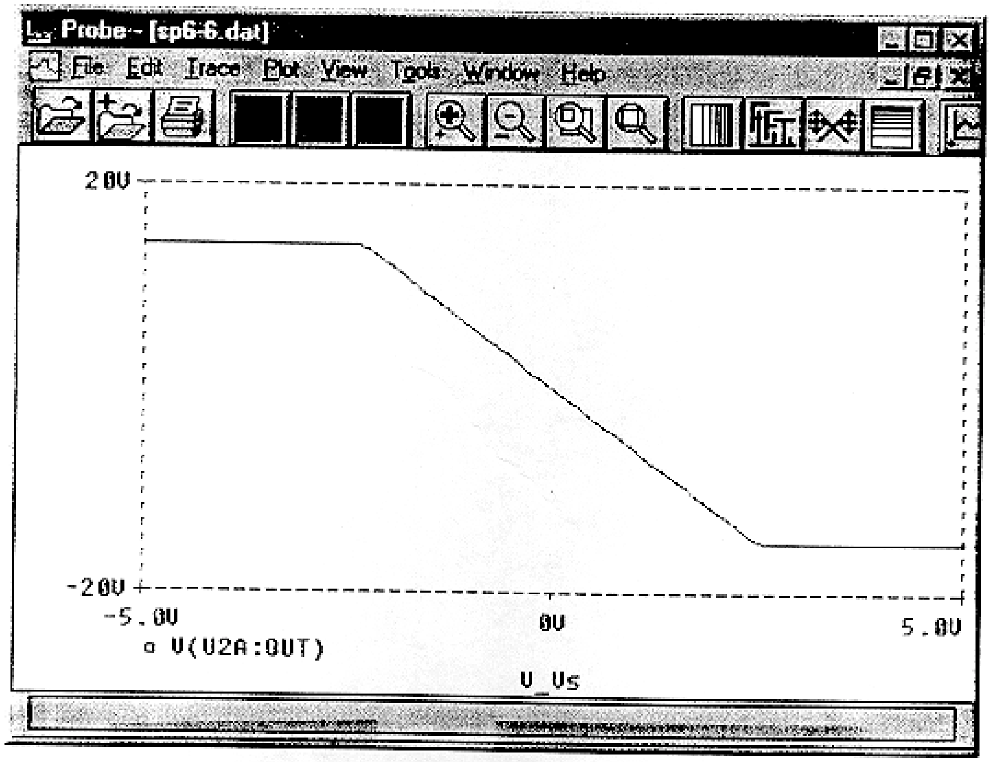

```
NODE     VOLTAGE       NODE     VOLTAGE       NODE     VOLTAGE
(    1)     .0200     (     2)       .0120   (     3)       .0100
(    4)     .1200     (     5)       .0120

VOLTAGE SOURCE CURRENTS
NAME          CURRENTS
V1            -4.002E-06
V2             3.993E-07
```

```
SP 6-5 Spice deck corresponding to Problem SP 6-5(b)
V1    1 0   DC .02
R1    1 2   2K
R2    2 3   5K
R3    2 0   3.33K
V2    3 0   DC .01
X0A   1 5   2  4 UA741
R4    4 5   9K
R5    5 0   1K

.SUBCKT UA741 1 2 5
IB1 1 0 70nA
IB2 2 0 90nA
VOS 3 2 1mV
RI 1 3 2MEG
E 4 0 1 3 -200000
RO 4 5 75
.ENDS UA741
.END

 NODE   VOLTAGE       NODE     VOLTAGE      NODE    VOLTAGE
(    1)     .0200    (     2)      .0119   (     3)     .0100
(    4)     .1297    (     5)      .0129   (X0A1.3)     .0129
(X0A1.4)     .1307

VOLTAGE SOURCE CURRENTS
NAME          CURRENT
V1            -4.047E-06
V2             3.813E-07
X0A1.VOS      -3.267E-13
```

SP 6-6

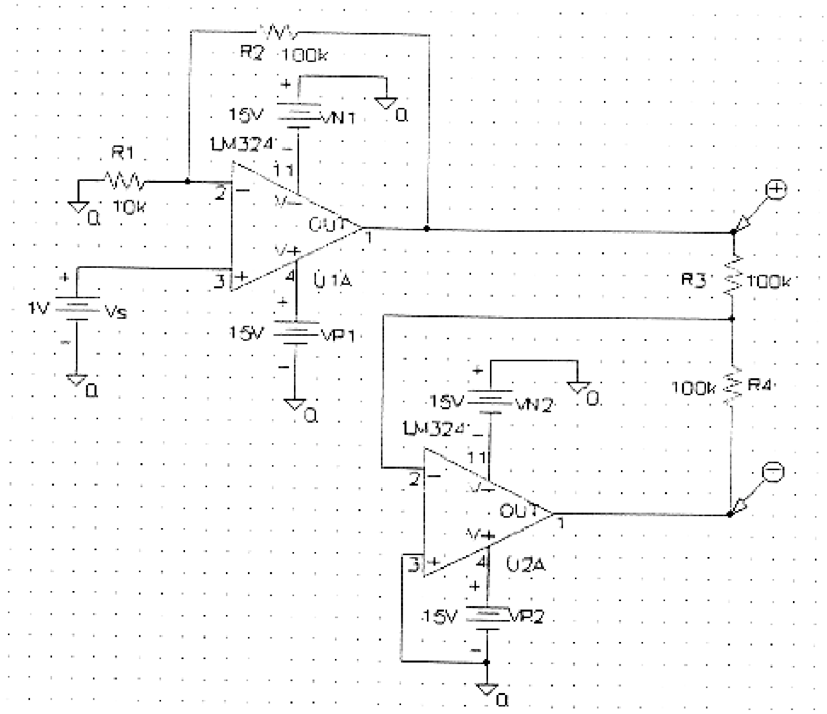


R3
20k
15V
VN1
0
LM324
11
2
V-
OUT
1
V+
3
4
U1A
1V
Vs
15V
VP1
0
R1
5k
R2
10k
15V
VN2
0
LM324
11
2
V-
OUT
1
V+
3
4
U2A
15V
VP2
0

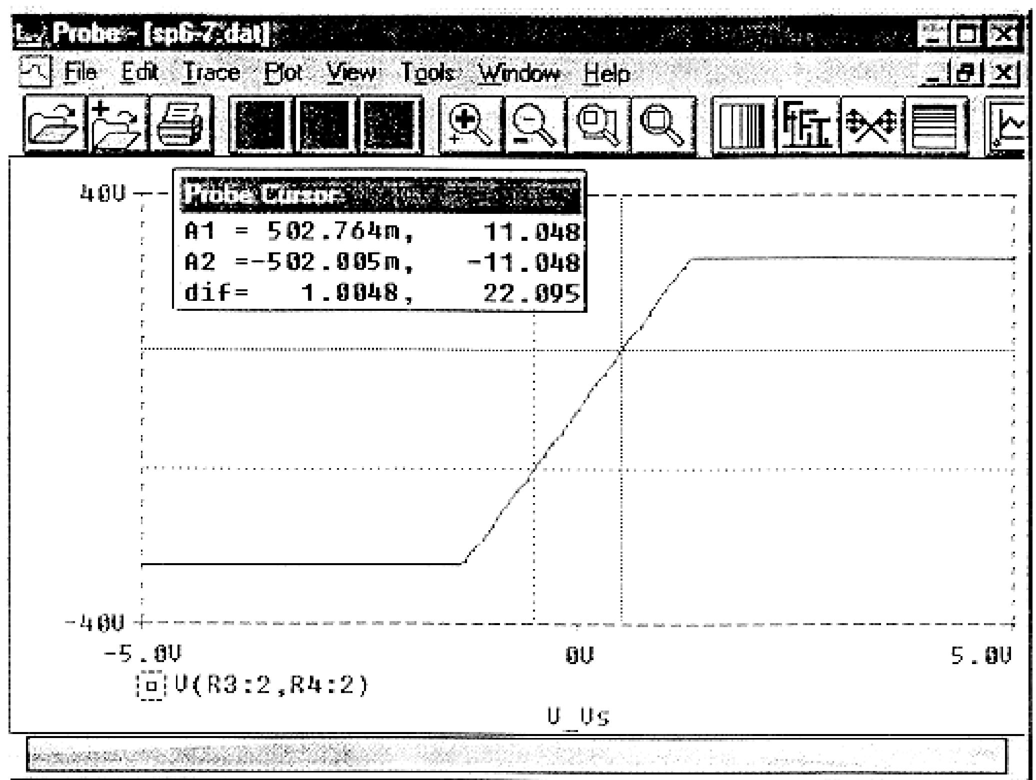


Probe - [sp6-6.dat]
File Edit Trace Plot View Tools Window Help
20V
-20V
-5.0V
0V
5.0V
V(U2A:OUT)
V_Vs

SP 6-7

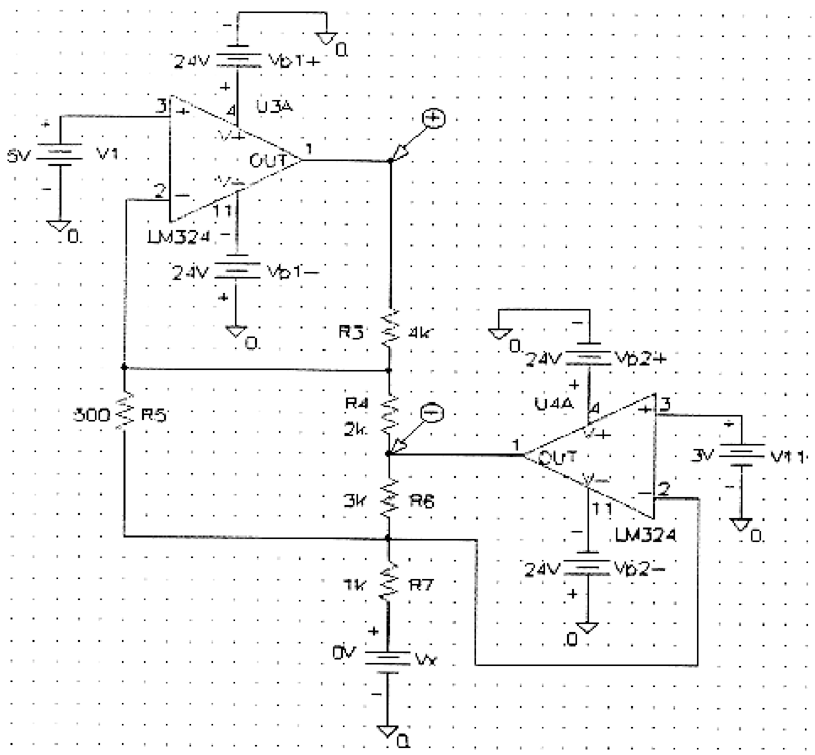


R2 100k
15V
VN1
LM324
R1
10k
1V
Vs
15V
VP1
U1A
OUT
R3 100k
100k R4
15V
VN2
LM324
U2A
OUT
15V
VP2

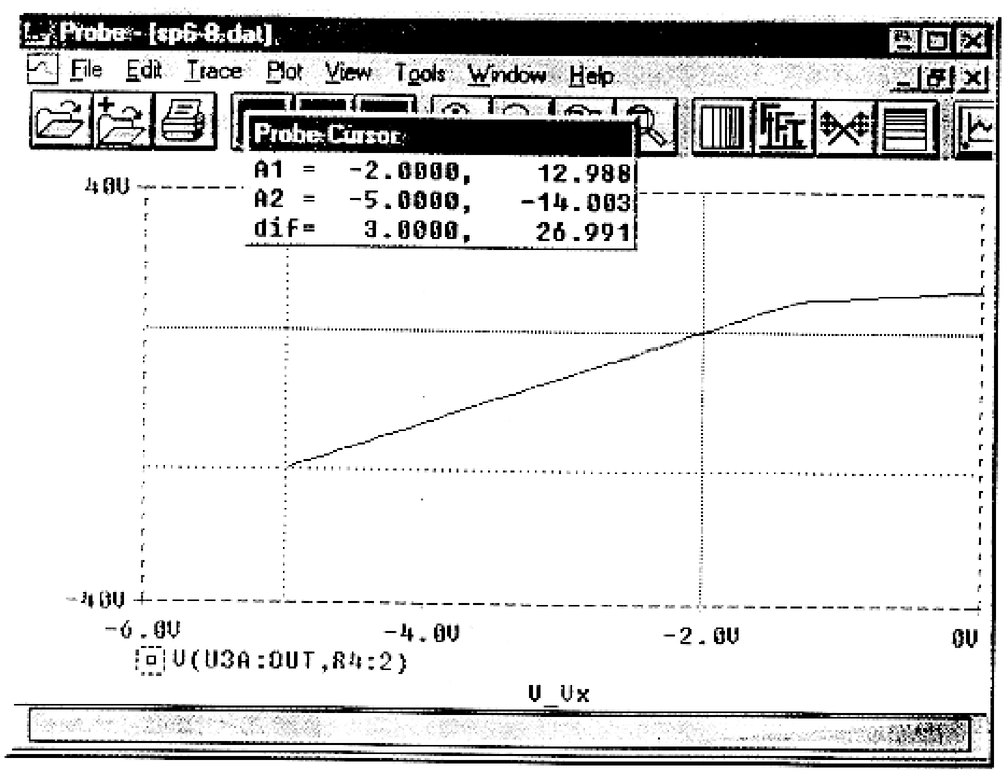


Probe - [sp6-7.dat]
File Edit Trace Plot View Tools Window Help
Probe Cursor
A1 = 502.764m, 11.048
A2 =-502.005m, -11.048
dif= 1.0048, 22.095
40V
-40V
-5.0V
0V
5.0V
V(R3:2,R4:2)
V_Vs

SP 6-8



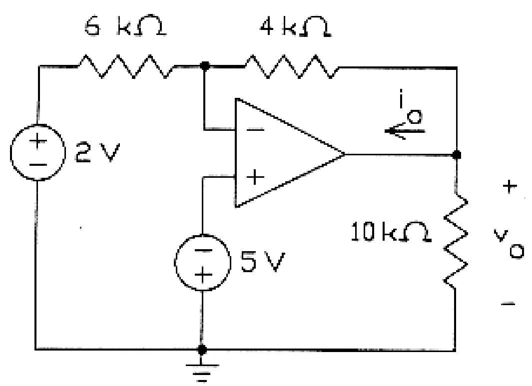
24V
Vb1+
U3A
5V
V1
OUT
LM324
24V
Vb1−
R3
4k
24V
Vb2+
U4A
R4
2k
300
R5
3V
V11
3k
R6
LM324
24V
Vb2−
1k
R7
0V
Vx



Probe - [sp6-8.dat]
File Edit Trace Plot View Tools Window Help
Probe Cursor
A1 = -2.0000, 12.988
A2 = -5.0000, -14.003
dif= 3.0000, 26.991
40V
-40V
-6.0V
-4.0V
-2.0V
0V
V(U3A:OUT,R4:2)
V_Vx

Verification Problems

VP 6-1



Apply KCL at the ouput node of the op amp to get

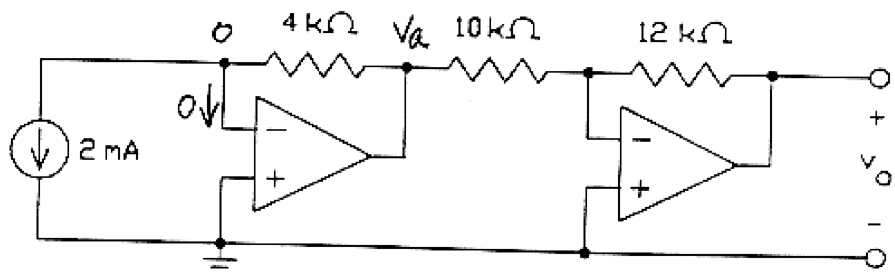
$$i_0+\frac{v_0}{10,000}+\frac{v_0-(-5)}{4000}=0$$

or, when $v_o = 7$ V and $i_o = -1$mA,

$$-10^{-3}+\frac{7}{10,000}+\frac{12}{4000}=2.7\times10^{-3}\neq 0$$

KCL is not satisfied, so the analysis cannot be correct.

VP 6-2



$$v_a=\left(4\times10^3\right)\left(2\times10^{-3}\right)=8\text{ V}$$

$$v_0=-\frac{12\times10^3}{10\times10^3}v_a=-1.2\ (8)=-9.6\text{ V}$$

So $v_0 = -9.6$ V instead of 9.6 V.

VP 6-3

When $v_0 = -12$ V, the current in the 4 kΩ resistor is

$$i=\frac{-12-2}{4000}=-3.5\text{ mA}$$

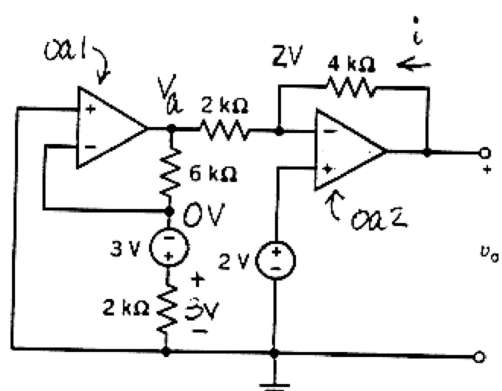
Then

$$i=\frac{2-v_a}{2000}$$

or

$$2-v_a=2000\left(-3.5\cdot10^{-3}\right)$$

$$v_a=2+2(3.5)=9\text{V}$$



Finally, apply KCL at the inverting node of oal to get

$$-\frac{9}{6000}+\frac{3}{2000}=0$$

Since KCL is satisfied, this analysis appears to be correct.

VP 6-4

First notice that $v_e = v_f = v_e$ is required by the ideal op amp. (There is zero current into the input lead of an ideal op amp so there is zero current in the 10 kΩ connected between nodes e and f, hence zero volts across this resistor. Also, the node voltages at the input nodes of an ideal op amp are equal.)

The node equations at nodes b, c and d are all satisfied by the given voltages:

node b: $$\frac{0-(-5)}{10000}+\frac{0}{40000}+\frac{0-2}{4000}=0$$

node c: $$\frac{0-2}{4000}=\frac{2-5}{6000}+0$$

node d: $$\frac{2-5}{6000}=\frac{5}{5000}+\frac{5-11}{4000}$$

Therefore, the analysis is correct.

VP 6-5

The node equations at nodes b and e are satisfied by the given voltages:

node b: $$\frac{-.25-2}{20000}+\frac{-.25}{40000}+\frac{-.25-(-5)}{40000}=0$$

node e: $$\frac{-2.5-(-0.25)}{9000}=\frac{-0.25}{1000}+0$$

Therefore, the analysis is correct.

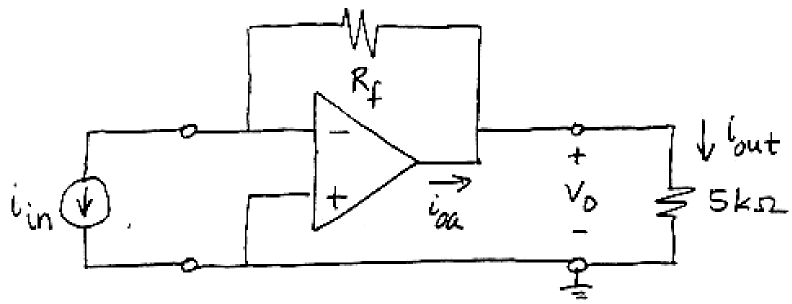
Also, the circuit is an noninverting summer with R_a = 10 kΩ and R_b = 1 kΩ, K_1 =1/ 2, K_2 = 1/ 4 and K_4 = 9. The given node voltages satisfy the equation

$$-2.5=v_d=K_4\left(K_1 v_a+K_2 v_c\right)=10\left(\frac{1}{2}(2)+\frac{1}{4}(-5)\right)$$

Again, we see that the analysis is correct.

Design Problems

DP 6-1 From Figure 6.6-1(g), this circuit



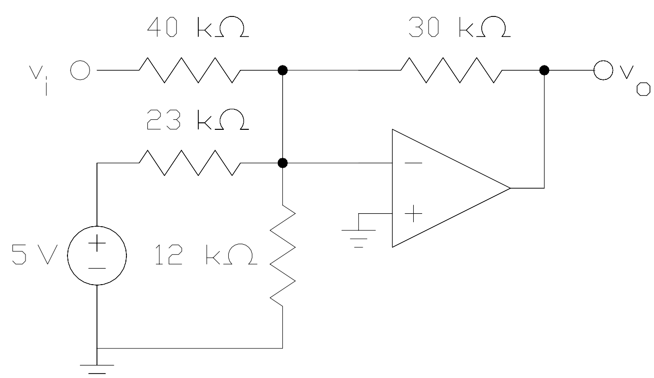
is described by $v_0 = R_f i_{in}$. Since $i_{out} = \frac{v_0}{5k\Omega}$

we require $\frac{1}{4} = \frac{i_{out}}{i_{in}} = \frac{R_f}{5k\Omega}$

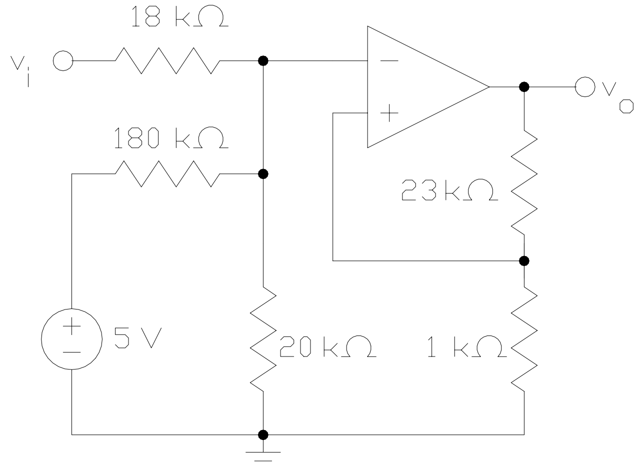
or $R_f = 1250\ \Omega$

Notice that $i_{oa} = i_{in} + \frac{1250 \cdot i_{in}}{5000} = \frac{5}{4} i_{in}$. To avoid current saturation of the op amp $\frac{5}{4} i_{in} < i_{sat}$ or $i_{in} < \frac{4}{5} i_{sat}$. For example, if $i_{sat} = 2\text{mA}$, then $i_{in} < 1.6\text{mA}$ to avoid current saturation.

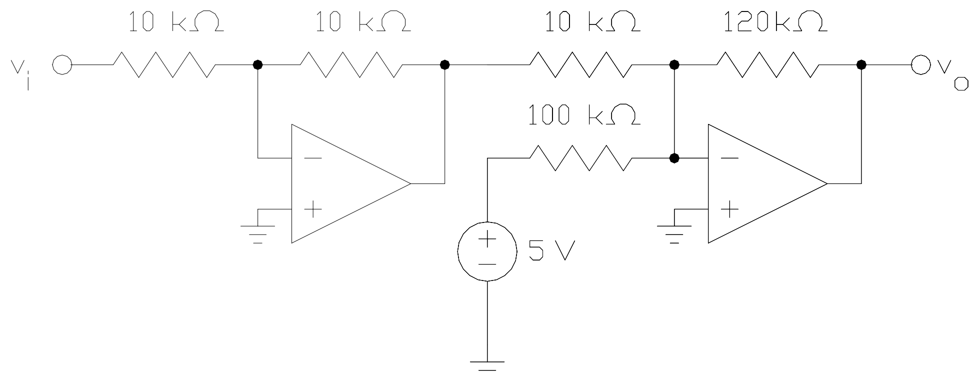
DP 6-2 $v_o = -\frac{3}{4} v_i + 3 = -\frac{3}{4} v_i + \left(1 + \frac{3}{4}\right)\left(\frac{12}{35}\right)5$



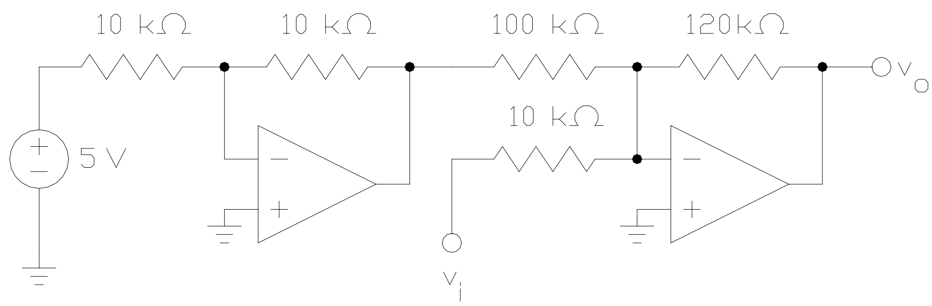
DP 6-3 (a) $12v_i + 6 = 24\left(\frac{1}{2}v_i + \frac{1}{20}(5)\right) \quad \Rightarrow \quad K_4 = 24,\ K_1 = \frac{1}{2}, \text{ and } K_2 = \frac{1}{20}.$ Take R_a = 18 kΩ and R_b = 1 kΩ to get



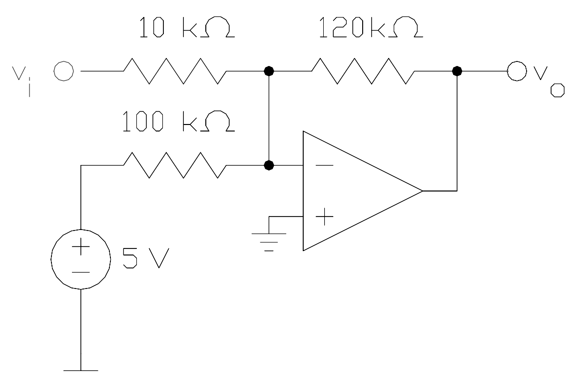
(b)



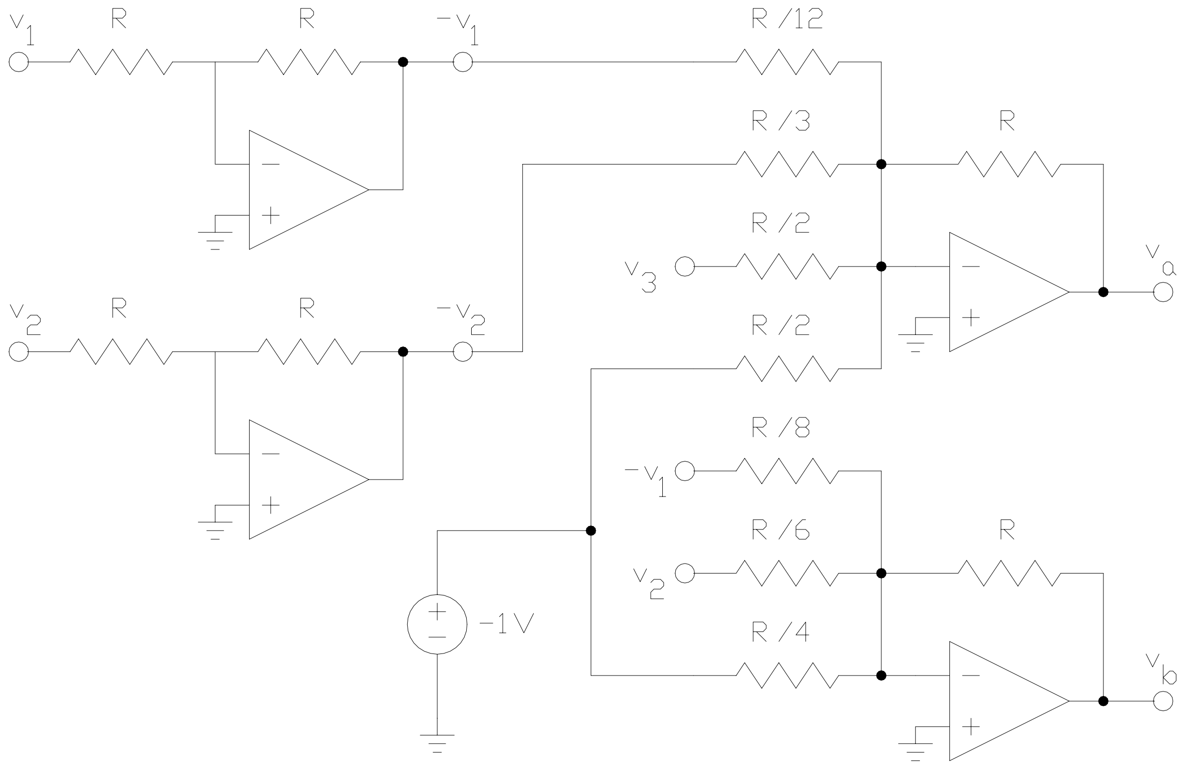
(c)



(d)



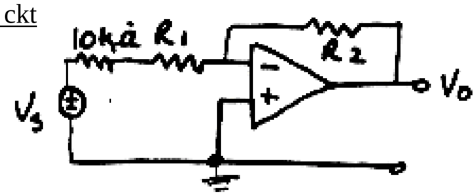
DP6-4



DP 6-5

Need gain $v_o/v_s = \dfrac{4}{20\times10^{-3}} = 200$

<u>Inverting ckt</u>

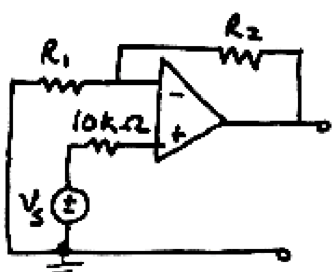


$$\frac{v_0}{v_s} = -\frac{R_2}{R_1+R_s}$$

Use $R_2 = 2\ \text{M}\Omega,\ R_1 = 0$

$R_s = 10\text{k}\Omega$

<u>Noninverting ckt</u>



$$\frac{v_0}{v_s} = \left(1+\frac{R_2}{R_1}\right)v_s$$

R_{IN} = <u>higher</u> for noninverting compared to inverting

Choose $\left(1+R_2/R_1\right) = 200$ use $R_1 = 1\text{k}\Omega,\ R_2 = 199\text{k}\Omega$

So use noninverting for higher R_{IN} for microphone.