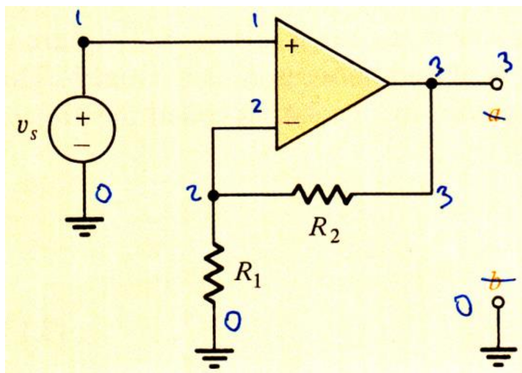
Practice problems for Lesson 5

Solved Op Amp problems

Bo2's Drill Exercise 3.11 (Thévenin)

Find the Thévenin equivalent.




```
s\th("e,1,0,vs:r1,2,0,r1:r2,2,3,r2:o,1,2,3",3,0)
```

The **th** script tells us it found the Thévenin voltage, but could not find the Norton current. This is not a surprise, since an ideal op amp has zero output resistance and a fixed voltage, an infinite current when short-circuited. So the Thévenin equivalent is given by V_{TH} and no resistance (or R_{EQ} = 0Ω). Evaluating vth results in

$$\frac{(r1 + r2)\ vs}{r1}$$

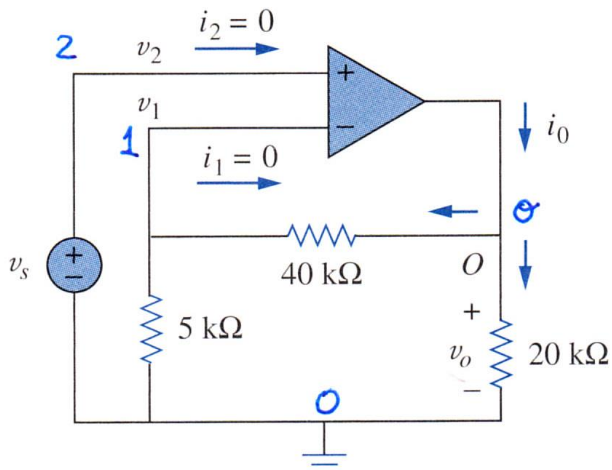
This is correct, as can be seen by comparing it to the book's answer, shown below.

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

The Thevenin resistance, as explained above, is 0Ω.

AS2's Example 5.2

Find v_o and i_o.

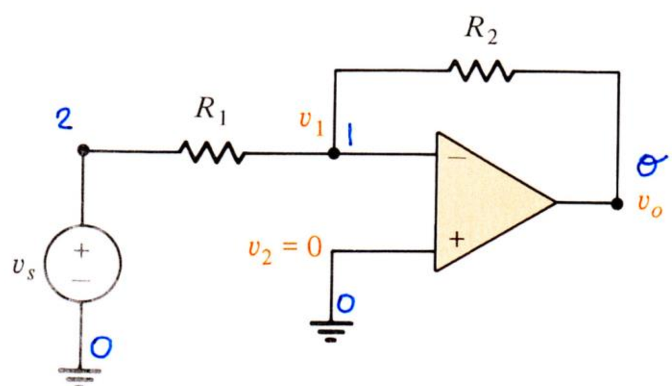



```
s\dc("e,2,0,1.:r5,1,0,5’k:r4,1,o,40’k:r2,o,0,20’k:o,2,1,o"):{vo,io}
```

The answer, **{9.,.00065}**, is correct: v_o is 9V and i_o is 0.65mA

Bo2's Figure 3.3 (Inverting)

Find the gain of the overall circuit, v_o/v_S.



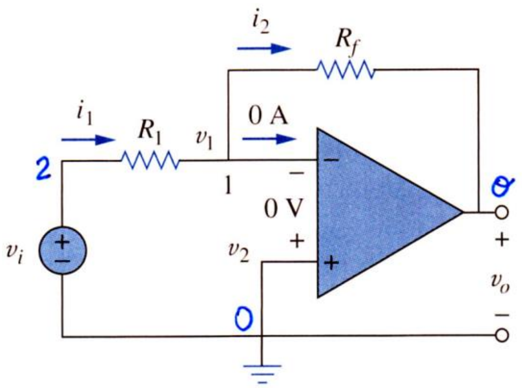
$$\frac{v_o}{v_s} = -\frac{R_2}{R_1}$$

```
s\dc("e,2,0,vs:r1,2,1,r1:r2,1,o,r2:o,1,0,o"):vo/vs
```

We get **-r2/r1**, which is correct, as can be seen in the book's answer above.

AS2's Figure 5.10 (Inverting)

Find v_o.



$$v_o = -\frac{R_f}{R_1} v_i$$

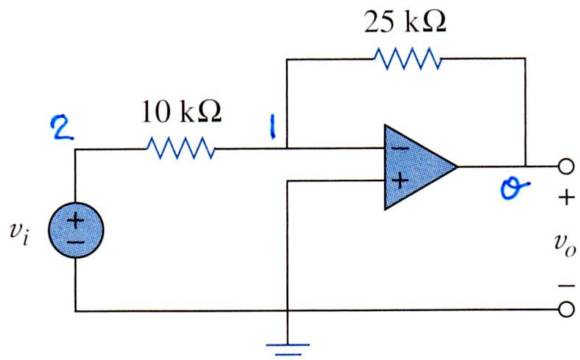
```
s\dc("e,2,0,vi:r1,2,1,r1:rf,1,o,rf:o,0,1,o"):vo
```

This problem is almost identical to the one above. The answer we get is correct:

$$-\frac{\mathrm{rf}}{\mathrm{r1}}\mathrm{vi}$$

AS2's Example 5.3 (Inverting)

If v_i is 0.5V, calculate the output voltage v_o and the current in the 10'kΩ resistor.

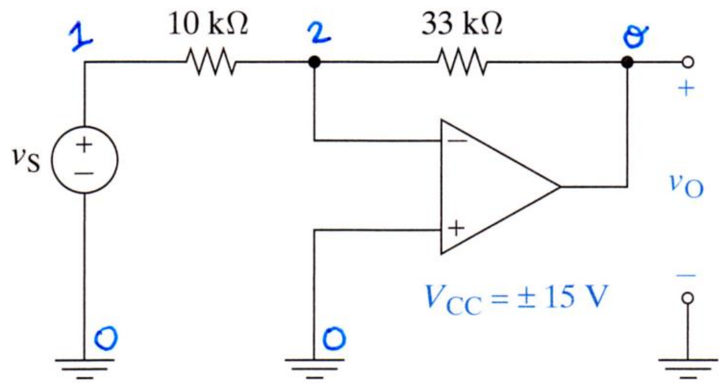



```
s\dc("e,2,0,.5:r1,2,1,10'k:rf,1,o,25'k:o,0,1,o"):{vo,ir1}
```

The answer, **{-1.25,5.E-5}**, is correct.

TR5's Exercise 4-11 (Inverting)

Find v_O when v_S is 2V, -4V and 6V. Notice the output of the op amp is limited to ±15V.



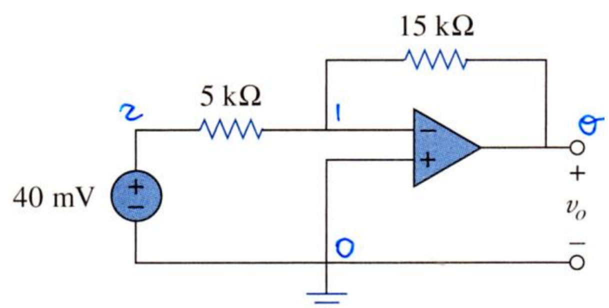
This may be the only non-linear problem you will see in this book, because I solved it before I realized it included the ±15V constraint. But anyway, here it goes.

```
s\dc("e,1,0,vs:r1,1,2,10'k:r2,2,o,33'k:o,0,2,o"):
{vo|vs=2.,vo|vs=-4.,vo|vs=6.}
```

The answer, **{-6.6,13.2,-19.8}**, is correct within the linear realm, but since the output is constrained to no more than 15V or less than -15V, the answer is v_O=**-15**V for v_S = 6V.

AS2's Practice Problem 5.3 (Inverting)

Find the output voltage of the op amp (e.g. v_o) and calculate the current through the feedback resistor (e.g. the 15'kΩ resistor).



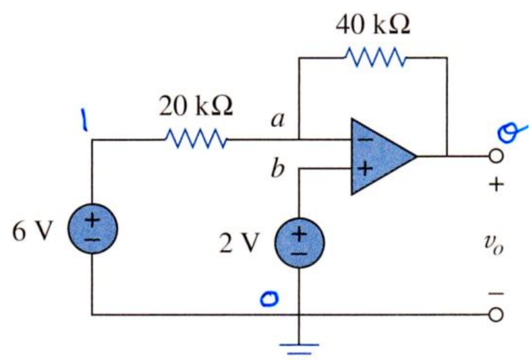
My answer below. Notice we used the m for milli in the value of the voltage source.

```
s\dc("e,2,0,40'm:r1,2,1,5'k:rf,1,o,15'k:o,0,1,o"):approx({vo,irf})
```

The answer, **{-.12,8.E-6}**, is correct.

AS2's Example 5.4 (Inverting)

Determine v_o.

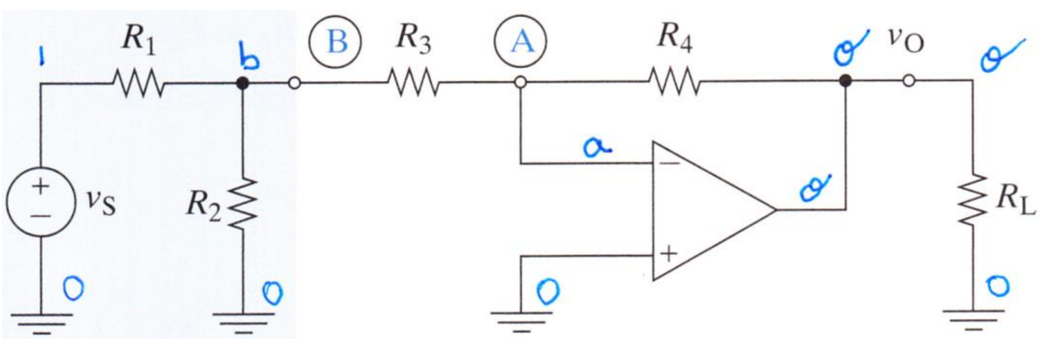


s\dc("e6,1,0,6:r1,1,a,20’k:e2,b,0,2:rf,a,o,40’k:o,a,b,o"):vo

The answer, **-6**, is correct.

TR5's Example 4-14 (Inverting)

Find the input-output relationship of the circuit below.



The 'formal' way to *symbulate* this circuit would be as described below.

s\dc("e,1,0,**vs**:r1,1,b,r1:r2,b,0,r2:r3,b,a,r3:r4,a,o,r4:o,0,a,o:rl,o,0,**rl**")

However, since we are only interested in the ratio of the input to the output, a smarter (and faster – as in 49 seconds instead of 55 seconds) way to *symbulate* it is this:

s\dc("e,1,0,**1**:r1,1,b,r1:r2,b,0,r2:r3,b,a,r3:r4,a,o,r4:o,0,a,o:rl,o,0,**1**")

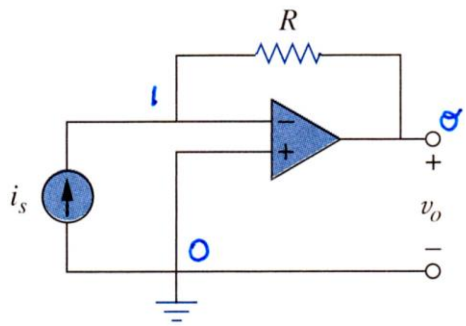
When we evaluate vo/v1, both approaches get the same answer, shown left below:

$$\frac{-\ r2\ r4}{r1\ (r2 + r3) + r2\ r3} \qquad -\frac{R_2R_4}{R_1R_2 + R_1R_3 + R_2R_3}$$

which is correct, as can be seen by comparing it to the book's answer, shown right.

AS2's Practice Problem 5.4a (Transresistance)

This is a current-to-voltage converter, also called a *transresistance amplifier*. Find v_o/i_S.

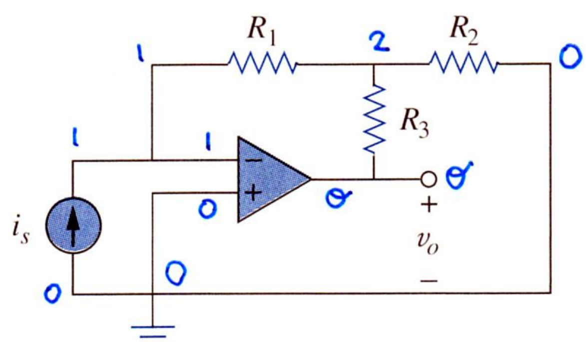


s\dc("j,0,1,is:r,1,o,r:o,0,1,o"):vo/is

The answer, **-r**, is correct.

AS2's Practice Problem 5.4b (Transresistance)

This is another *transresistance amplifier*. Again, find v_o/i_S.



s\dc("j,0,1,is:r1,1,2,r1:r2,2,0,r2:r3,2,o,r3:o,0,1,o")

Asking:

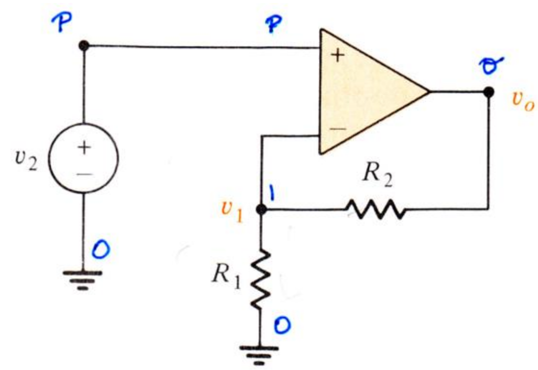
expand(vo/is)

gets **-r1*r3/r2-r1-r3**, which is equivalent to the book's answer.

$$\frac{v_o}{i_s} = -R_1\left(1 + \frac{R_3}{R_1} + \frac{R_3}{R_2}\right)$$

Bo2's Example 3.1 (Non-Inverting Amplifier)

Find v_o/v_1.

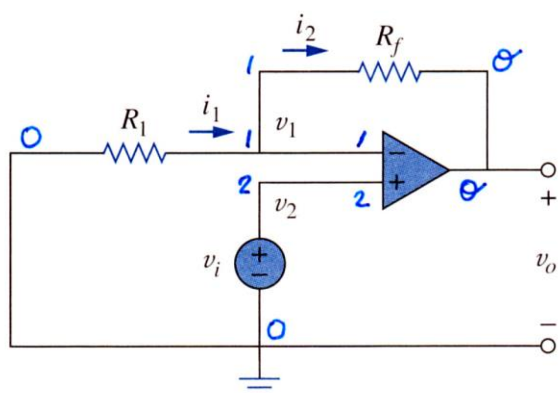



```
s\dc("e,p,0,v2:r1,1,0,r1:r2,1,o,r2:o,p,1,o"):vo/v1
```

We get **1+r2/r1**, which is correct.

AS2's Figure 5.16 (Non-Inverting Amplifier)

Find v_o.



$$v_o = \left(1 + \frac{R_f}{R_1}\right) v_i$$

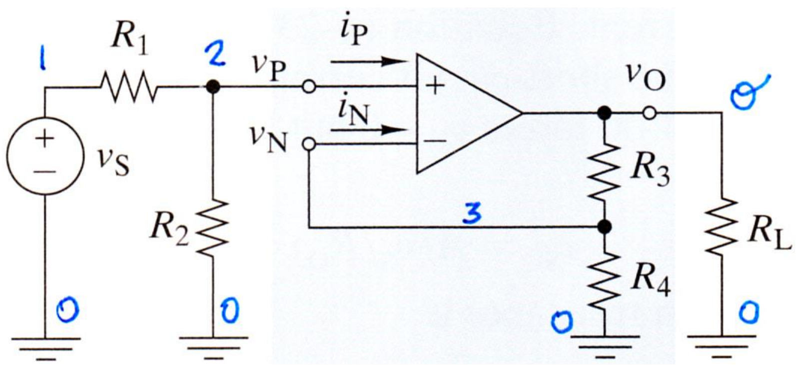
```
s\dc("e,2,0,vi:r1,0,1,r1:rf,1,o,rf:o,2,1,o"):vo
```

We get the right answer (below), an expression equivalent to the book's answer.

$$\frac{(\mathrm{r1} + \mathrm{rf})}{\mathrm{r1}}\mathrm{vi}$$

TR5's Example 4-13 (Non-Inverting Amplifier)

Find Vo/Vs.



We can solve this problem in one simulation, as shown below.

```
s\dc("e,1,0,vs:r1,1,2,r1:r2,2,0,r2:o,2,3,o:r3,o,3,r3:r4,3,0,r4"):vo/vs
```

$$\frac{r2\ (r3 + r4)}{(r1 + r2)\ r4}$$

which is correct, as can be seen by comparing it to the book's answer, shown below:

$$\left[\frac{R_2}{R_1 + R_2}\right]\left[\frac{R_3 + R_4}{R_4}\right]$$

We can also solve it in stages, as shown below. First, simulate the left half.

```
s\dc("e,1,0,vs:r1,1,2,r1:r2,2,0,r2"):v2/vs
```

$$\frac{r2}{(r1 + r2)}$$

Which is correct for this part. Then, simulate the right half.

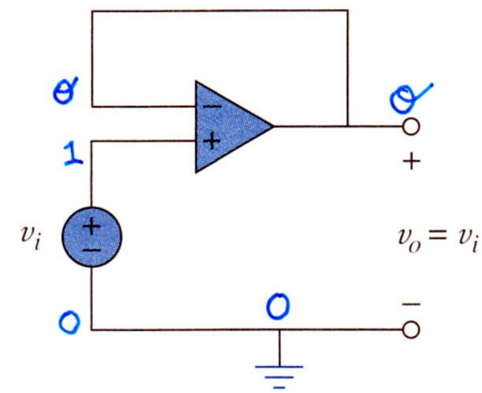
```
s\dc("e,2,0,1:o,2,3,o:r3,o,3,r3:r4,3,0,r4"):vo/v2
```

$$\frac{(r3 + r4)}{r4}$$

Which is correct for this part. The product of these two partial answers produces the same expression shown above after the big simulation, and is the right answer.

AS2's Figure 5.17 (Voltage Follower)

Find v_o.



s\dc("e,1,0,vi:o,1,o,o"):vo

The answer, **vi**, is correct.

TR5's Figure 4-32 (Voltage Follower)

The circuits in Figure 4–32 have $v_S = 1.5$ V, $R_S = 2$ kΩ, and $R_L = 1$ kΩ. Compute the maximum power available from the source. Compute the power absorbed by the load resistor in the direct connection in Figure 4–32(b) and in the voltage follower circuit in Figure 4–32(a). Discuss any differences.

Answers: 281 μW; 250 μW; 2250 μW

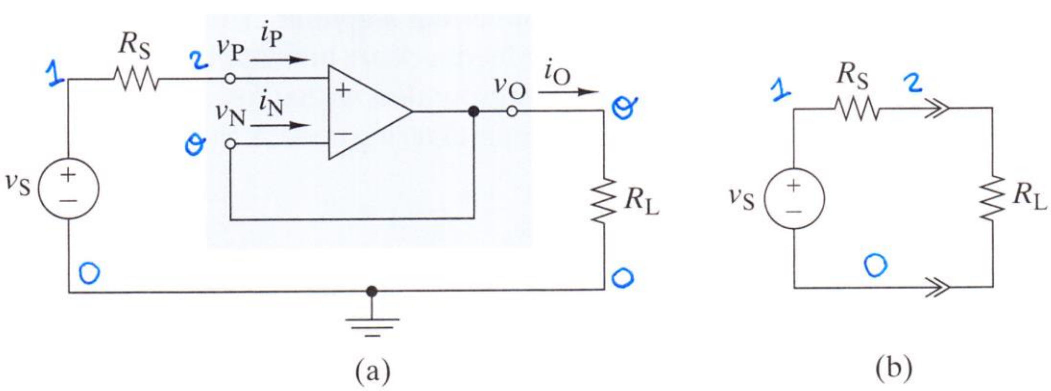


FIGURE 4–32 *(a) Source-load interface with a voltage follower. (b) Interface without the voltage follower.*

Alright, so first we simulate the (b) circuit, to find its maximum power and load power:

s\th("e,1,0,1.5:rs,1,2,2’k",2,0):{pmax,prL|L=1000}

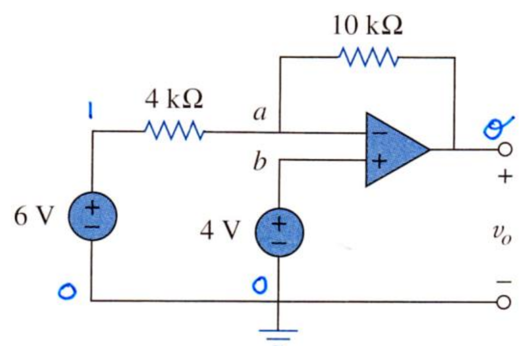
The answers we get, **{2.8125E-4,2.5E-4}**, are correct. Now we simulate the (a) circuit.

s\dc("e,1,0,1.5:rs,1,2,2’k:o,2,o,o:rl,o,0,1’k"):prL

The answer,**.00225**, is correct. The explanation to the apparent paradox that the load in (a) is drawing more power than the source in (b) seems able to provide evaporates once we remember that the ideal op amp shown in the schematic is only part of the truth: the real op amp has its own source of power, which provides the difference.

AS2's Example 5.5 (Inverting)

Find v_o.

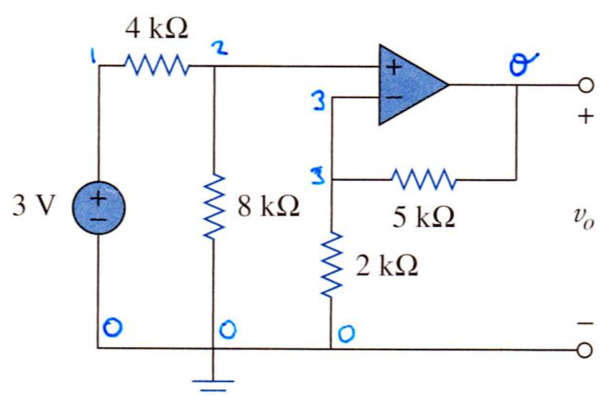


s\dc("e,1,0,6:r4,1,a,4’k:r10,a,o,10’k:e4,b,0,4:o,b,a,o"):vo

The answer, **-1**, is correct.

AS2's Practice Problem 5.5 (Non-Inverting)

Calculate v_o.

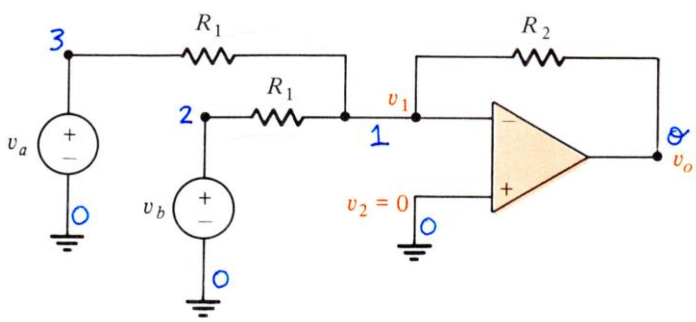


s\dc("e,1,0,3:r4,1,2,4’k:r8,2,0,8’k:r2,3,0,2’k:r5,3,o,5’k:o,2,3,o")

The answer for vo, **7**, is correct.

Bo2's Example 3.2 (Adder or Summing)

Find v_o.



s\dc("ea,3,0,va:eb,2,0,vb:r31,3,1,r1:r21,2,1,r1:r1o,1,o,r2:o,0,1,o"):vo

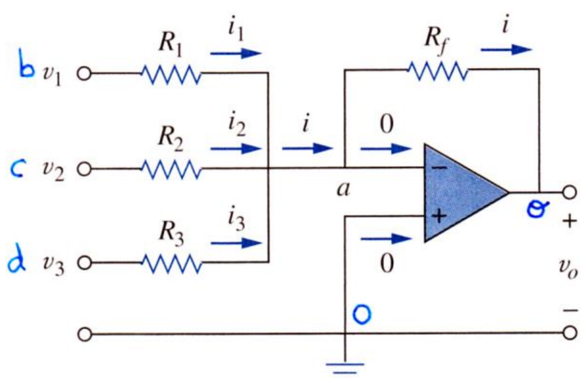
$$-\frac{\mathrm{r2}}{\mathrm{r1}}(\mathrm{va}+\mathrm{vb})$$

which is correct, as can be seen by comparing it to the book's answer, shown below:

$$v_o = -\frac{R_2}{R_1}(v_a + v_b)$$

AS2's Figure 5.21 (Adder or Summing)

Find v_o.



s\dc("e1,b,0,v1:e2,c,0,v2:e3,d,0,v3:r1,b,a,r1:
r2,c,a,r2:r3,d,a,r3:rf,a,o,rf:o,0,a,o"):expand(vo)

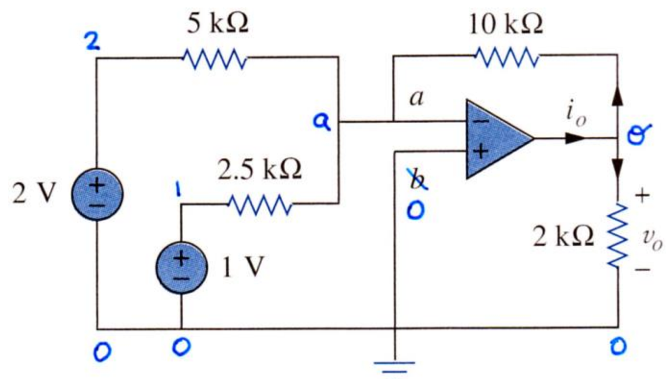
$$-\mathrm{rf}\,\frac{\mathrm{v1}}{\mathrm{r1}} - \mathrm{rf}\,\frac{\mathrm{v2}}{\mathrm{r2}} - \mathrm{rf}\,\frac{\mathrm{v3}}{\mathrm{r3}}$$

which is correct, as can be seen by comparing it to the book's answer, shown below:

$$v_o = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3\right)$$

AS2's Example 5.6 (Adder or Summing)

Find v_o and i_o.

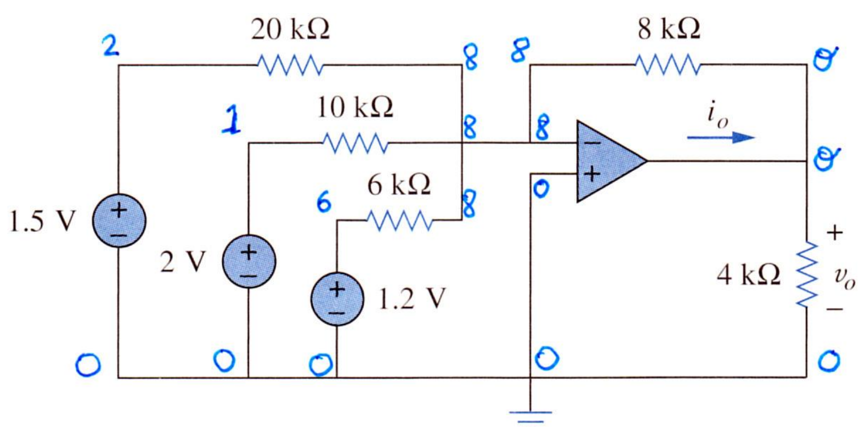


s\dc("e1,1,0,1:e2,2,0,2:r1,2,a,5’k:
r2,1,a,2.5’k:r3,a,o,10’k:r4,o,0,2’k:o,0,a,o"):{vo,io}

The answer, **{-8.,-.0048}**, is correct. Notice a current of 4.8mA is going into the op amp.

AS2's Practice Problem 5.6 (Adder or Summing)

Find v_o and i_o.



s\dc("e2,2,0,1.5:e1,1,0,2:e6,6,0,1.2:r2,2,8,20’k:
r1,1,8,10’k:r6,6,8,6’k:r8,8,o,8’k:r4,o,0,4’k:o,0,8,o"):{vo,io}

The answer, **{-3.8,-.001425}**, is correct. Again, the current is going into the op amp.

Bo2's Drill Exercise 3.3 (Difference or Differential)

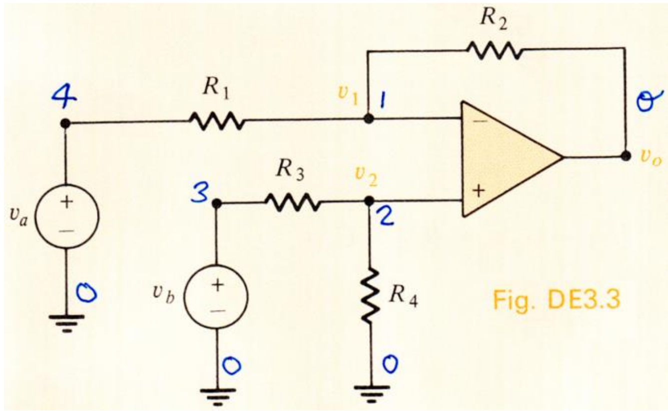


Fig. DE3.3

Find v_o for the **difference-amplifier** circuit shown in Fig. DE3.3 when $R_3 = R_1$ and $R_4 = R_2$.

Answer: $\frac{R_2}{R_1}(v_b - v_a)$

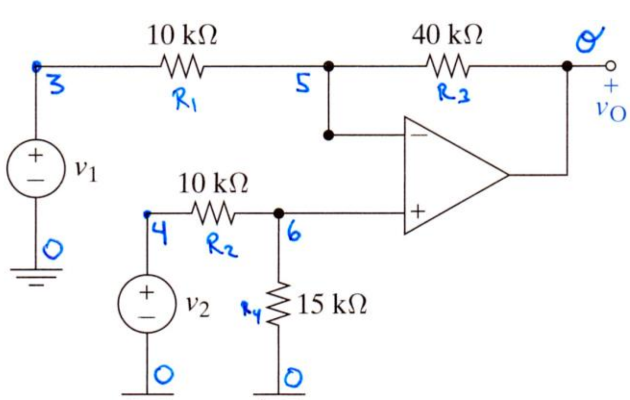
s\dc("ea,4,0,va:eb,3,0,vb:r1,4,1,r1:r2,1,o,r2:
r3,3,2,r1:r4,2,0,r2:o,2,1,o")

Evaluating vo we get the correct answer, equivalent to the book's answer above.

$$\frac{(\mathrm{vb} - \mathrm{va})\ \mathrm{r2}}{\mathrm{r1}}$$

TR5's Exercise 4-13 (Difference or Differential)

Find v_o.

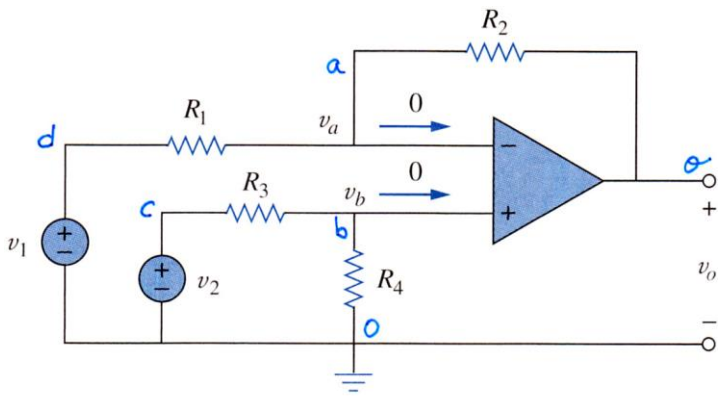


s\dc("e1,3,0,v1:e2,4,0,v2:r1,3,5,10'k:r2,4,6,10'k:
r3,5,o,40'k:r4,6,0,15'k:o,6,5,o")

Evaluating vo we get **3 v2 – 4 v1**, which is the correct answer.

AS2's Figure 5.24 (Difference or Differential)

Find v_o. (And keep it in the memory, for you will use it in the next three problems.)




```
s\dc("e1,d,0,v1:e2,c,0,v2:r1,d,a,r1:r3,c,b,r3:
r2,a,o,r2:r4,b,0,r4:o,b,a,o"):vo
```

$$\frac{\text{r1 r4 v2} - \text{r2}\left(\text{r3 v1} + \text{r4 (v1} - \text{v2)}\right)}{\text{r1} * (\text{r3} + \text{r4})}$$

This expression is equivalent to the book's answer, better formatted, shown below:

$$v_o = \frac{R_2}{R_1}\frac{(1 + R_1/R_2)}{(1 + R_3/R_4)}v_2 - \frac{R_2}{R_1}v_1$$

AS2's Figure 5.24 (Subtractor)

For the same circuit of the previous problem, find v_o when R_1=R_2 and R_3=R_4.

Since we already have the expression for vo stored in the memory, we only do this:

```
expand(vo)|r2=r1 and r3=r4
```

The answer we get, **v2-v1**, is correct.

AS2's Example 5.7 (Difference or Differential)

Design an op amp circuit with inputs v_1 and v_2 such that $v_o = -5v_1 + 3v_2$.

My solution follows. The problem statement is a fancy way to say: for the same circuit of the previous problem, find what values of resistors you need to use if you want to get an output $v_o = -5v_1 + 3v_2$. Although this is not strictly a Symbulator problem, I present it here because it illustrates how Symbulator fits in such design problems.

First we take that part of v_o that is a factor of v_1, and make it equal to -5. Thus:

```
Define v1=1:Define v2=0:expand(vo)=-5
```

We get **-r2/r1=-5**. Now make that part of v_o that is a factor of v_2 equal to 3. Thus:

```
Define v1=0:Define v2=1:expand(vo)=3
```

We get **r2*r4/(r1*(r3+r4))+r4/(r3+r4)=3** Now, since you have two equations, you can solve for two unknowns. Out of the four resistors whose values you can decide upon, two can be whatever you want. The book recommends you use R_1 = 10'k and R_3=20'k. Now let's find the values for the other two resistors, R_2 and R_4.

```
solve(ans(1) and ans(2),{r2,r4})|r1=10000 and r3=20000
```

The expression above assumes that ans(1) and ans(2) are pointing to the two equations we found before.[1] We get **r2=50000 and r4=20000**. This is correct.

Now, if this problem was part of a test, I'd like to verify that the answer is correct. To confirm this, simulate the circuit using the four values given above for the resistors.

```
s\dc("e1,d,0,v1:e2,c,0,v2:r1,d,a,10'k:
r3,c,b,20'k:r2,a,o,50'k:r4,b,0,20'k:o,b,a,o")
```

Evaluating `vo` gives us the desired output, **3*v2-5*v1**. The resistor values are correct.

AS2's Practice Problem 5.7 (Difference or Differential)

Design a difference amplifier with gain 4.

My solution follows. The problem statement, again, is just a fancy way to say: for the same circuit of the previous problem, find what values of resistors you need to use if you want to get an output v_o = **4** (v_2-v_1), or in other terms, -4v_1 + 4v_2. Same as before.

```
Define v1=1:Define v2=0:vo=-4
```

```
Define v1=0:Define v2=1:expand(vo)=4
```

This time the book asks that you use R_1 = 10'k and R_3 = 10'k. So we do that.

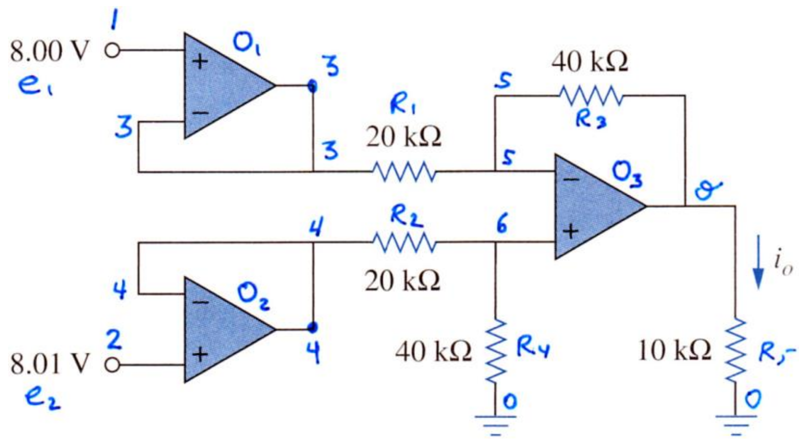
```
solve(ans(1) and ans(2),{r2,r4})|r1=10000 and r3=10000
```

We get **r2=40000 and r4=40000**, the correct values for the remaining resistors.

[1] If you have no idea what I'm talking about, you should learn about ans(#) in the user's manual.

AS2's Practice Problem 5.8 (Instrumentation)

Find i_o.

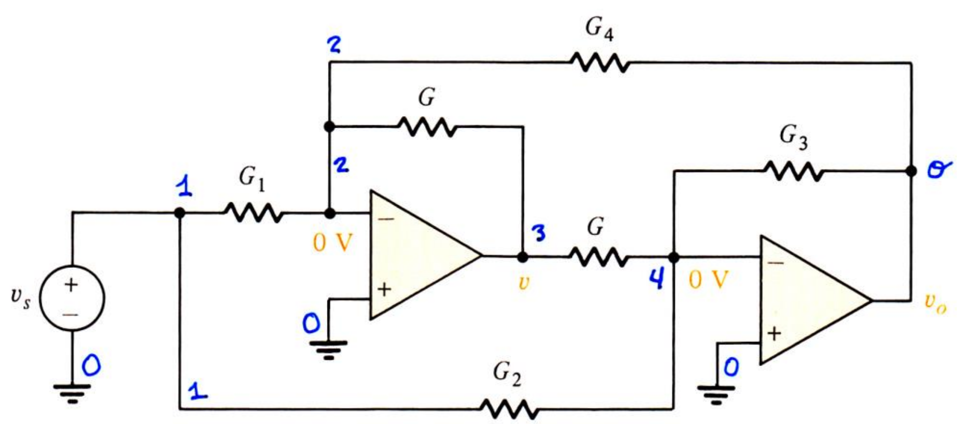



```
s\dc("e1,1,0,8.:e2,2,0,8.01:o1,1,3,3:o2,2,4,4:r1,3,5,20’k:
r2,4,6,20’k:r3,5,o,40’k:r4,6,0,40’k:o3,6,5,o:r5,o,0,10’k"):ir5
```

In the schematic, the current i_o corresponds to `ir5`. The answer, **2.E-6**, is correct.

Bo2's Example 3.3 (Cascade)

Find v_o in terms of the conductances and the applied voltage v_S.




```
s\dc("e,1,0,vs:r12,1,2,1/g1:r14,1,4,1/g2:r4o,4,o,1/g3:
r2o,2,o,1/g4:r23,2,3,1/g:r34,3,4,1/g:o1,0,2,3:o2,0,4,o")
```

Evaluating `vo` we get:

$$\frac{(\mathrm{g1}-\mathrm{g2})\ \mathrm{vs}}{\mathrm{g3}-\mathrm{g4}}$$

which is correct, as can be seen by comparing it to the book's answer, shown below:

$$v_o = \frac{G_1 - G_2}{G_3 - G_4} v_s$$

Bo2's Drill Exercise 3.4 (Cascade)

For the op-amp circuit shown in Fig. DE3.4, suppose that $G_1 = 1$ S, $G_2 = 2$ S, $G_3 = 3$ S, $G_4 = 4$ S, and $G_5 = 5$ S. Find v_o in terms of v_s. Answer: $-0.75v_s$

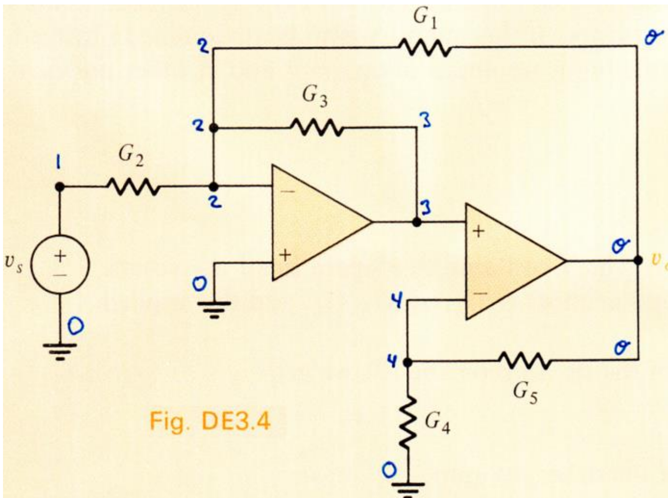


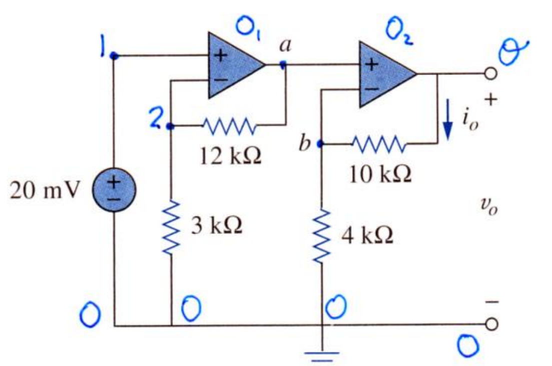
Fig. DE3.4

s\dc("e,1,0,vs:r1,2,o,1/1:r2,1,2,1/2:r3,2,3,1/3:
r4,4,0,1/4:r5,4,o,1/5:o1,0,2,3:o2,3,4,o")

Evaluating vo we get: **-.75 vs**, which is correct.

AS2's Example 5.9 (Cascade)

Find v_o and i_o.

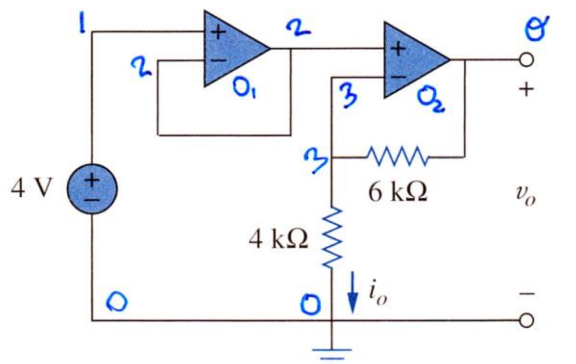


s\dc("e,1,0,20’m:o1,1,2,a:o2,a,b,o:ro,o,b,10’k:
r4,b,0,4’k:r2,a,2,12’k:r3,2,0,3’k")

Evaluating approx({vo,iro}) we get the answer, **{.35,2.5E-5}**. This is correct.

AS2's Practice Problem 5.9 (Cascade)

Determine v_o and i_o.

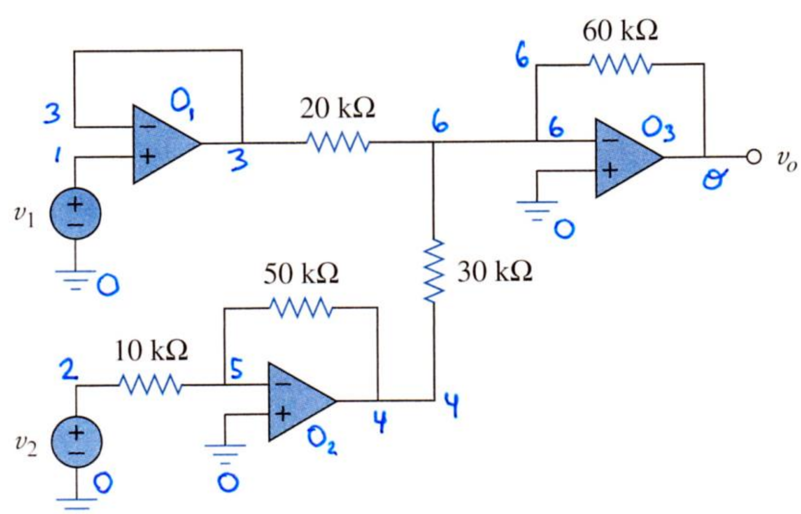



```
s\dc("e,1,0,4:o1,1,2,2:o2,2,3,o:ro,3,0,4’k:r6,3,o,6’k"):{vo,iro}
```

The answer, **{10,1/1000}**, is correct. To say a 1/1000 A current is the same as 1mA.

AS2's Practice Problem 5.10 (Cascade)

If v_1 = 2V and v_2 = 1.5V, find v_o in the circuit below.

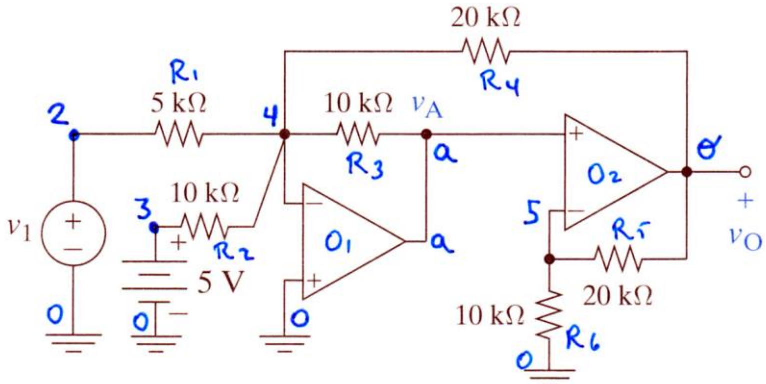



```
s\dc("e1,1,0,2:e2,2,0,1.5:o1,1,3,3:r1,2,5,10’k:r2,3,6,20’k:
r5,5,4,50’k:o2,0,5,4:r3,6,4,30’k:r6,6,o,60’k:o3,0,6,o"):vo
```

The answer, **9.** , is correct.

TR5's Example 4-16 (Cascade)

Derive an expression for v_o in terms of the two inputs.

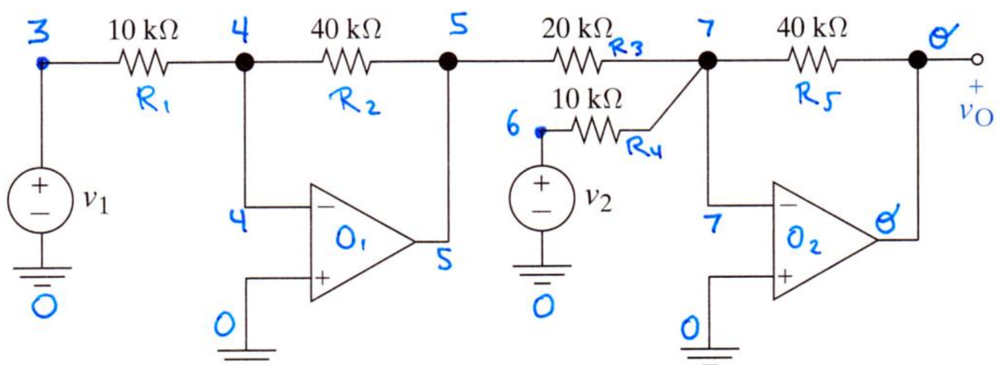



```
s\dc("e1,2,0,v1:e5,3,0,5:r1,2,4,5’k:r2,3,4,10’k:o1,0,4,a:r3,4,a,10’k:
r4,4,o,20’k:o2,a,5,o:r5,5,o,20’k:r6,5,0,10’k"):expand(approx(vo))
```

The answer, **-2.4 v1 – 6**, is correct.

TR5's Exercise 4-14 (Cascade)

Derive an expression for v_o in terms of the inputs v_1 and v_2.

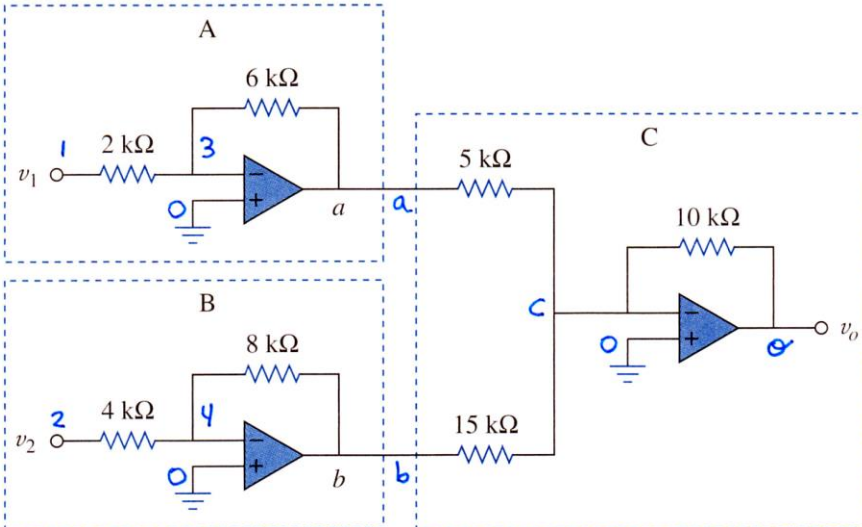



```
s\dc("e1,3,0,v1:r1,3,4,10’k:o1,0,4,5:r2,4,5,40’k:r3,5,7,20’k:
e2,6,0,v2:r4,6,7,10’k:r5,7,o,40’k:o2,0,7,o"):expand(vo)
```

The answer, **8 v1 – 4 v2**, is correct.

AS2's Example 5.10 (Cascade)

If v_1 = 1V and v_2 = 2V, find v_o in the circuit below.

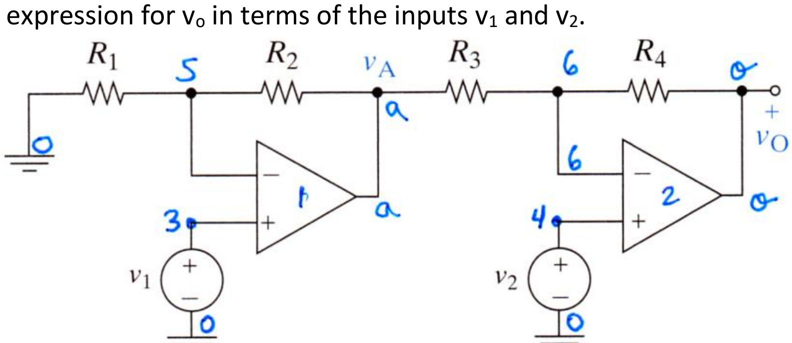


s\dc("e1,1,0,1:e2,2,0,2:r2,1,3,2'k:r4,2,4,4'k:r6,3,a,6'k:r8,4,b,8'k:r5,a,c,5'k:r15,b,c,15'k:r10,c,o,10'k:oa,0,3,a:ob,0,4,b:oc,0,c,o"):approx(vo)

The answer, **8.667**, is correct.

TR5's Example 4-17 (Cascade)

Derive an expression for v_o in terms of the inputs v_1 and v_2.



s\dc("r1,5,0,r1:r2,5,a,r2:r3,a,6,r3:r4,6,o,r4:e1,3,0,v1:e2,4,0,v2:o1,3,5,a:o2,4,6,o"):vo

We get the right answer. Let's compare it with the book's answer, which is below:

$$-\left[\frac{R_4}{R_3}\right]\left[\frac{R_1+R_2}{R_1}\right]v_1+\left[\frac{R_3+R_4}{R_3}\right]v_2$$

Our answer, expanded via `expand(vo)`, is shown below:

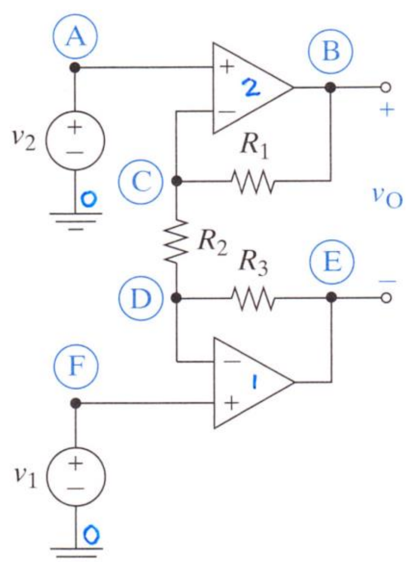
$$\frac{\text{-r2 r4 v1}}{\text{r1 r3}} - \frac{\text{r4 v1}}{\text{r3}} + \frac{\text{r4 v2}}{\text{r3}} + \text{v2}$$

Playing with it by hand we get a form that, in my opinion, is *prettier* ;-) than the book's:

$$\text{v2}\left(\frac{\text{r4}}{\text{r3}} + 1\right) - \text{v1}\left(\frac{\text{r4}}{\text{r3}}\right)\left(\frac{\text{r2}}{\text{r1}} + 1\right)$$

TR5's Example 4-18 (Multiple)

Derive an expression for v_o in terms of the inputs v_1 and v_2.



`s\dc("e2,a,0,v2:e1,f,0,v1:o2,a,c,b:o1,f,d,e:r1,b,c,r1:r2,c,d,r2:r3,d,e,r3")`

To find vo, we ask for `vb-ve`. We get an expression that can easily be rearranged to look like this:

$$-\left(\frac{\text{r1} + \text{r2} + \text{r3}}{\text{r2}}\right)(\text{v1} - \text{v2})$$

This is exactly the answer from the book:

$$v_O = v_B - v_E = \left[\frac{R_1 + R_2 + R_3}{R_2}\right](v_2 - v_1)$$

If you are ever in doubt about whether two expressions are the same, enter them both, separately, into the calculator, and then ask the calculator to compare them using the equality sign. If the answer is '**true**', then they are the same.