1. This is an inverting amplifier, therefore, $V_{out} = -\frac{R_f}{R_1} V_{in}$

So:

a) $V_{out} = -\frac{100}{10} \times 3 = \boxed{-30V}$

b) $V_{out} = -\frac{1M}{1M} \times 2.5 = \boxed{-2.5V}$

c) $V_{out} = -\frac{4.7}{3.3} \times -1 = \boxed{1.42V}$

2. This is also an inverting amplifier. The loading resistance R_S only affects the output current drawn from the op-amp. Therefore,

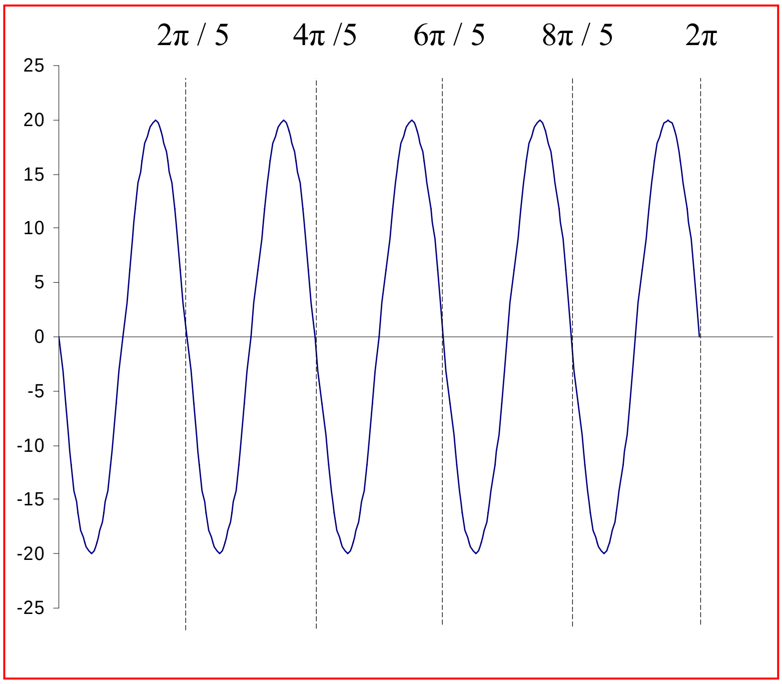
a) $V_{out} = -\frac{47}{10} \times 1.5 = \boxed{-7.05V}$

b) $V_{out} = \boxed{9V}$

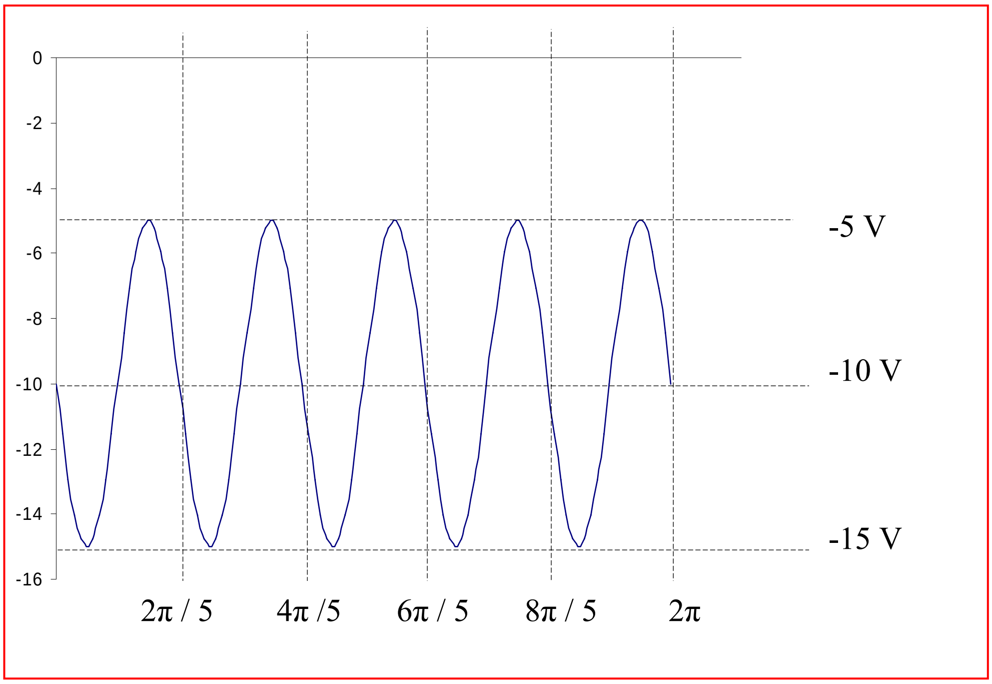
c) $V_{out} = \boxed{-680mV}$

3. For this inverting amplifier, $v_{out} = -\frac{10k}{1k} \times v_{in} = -10v_{in}$. Therefore,

a) $v_{out} = -10v_{in} = -20\sin 5t$

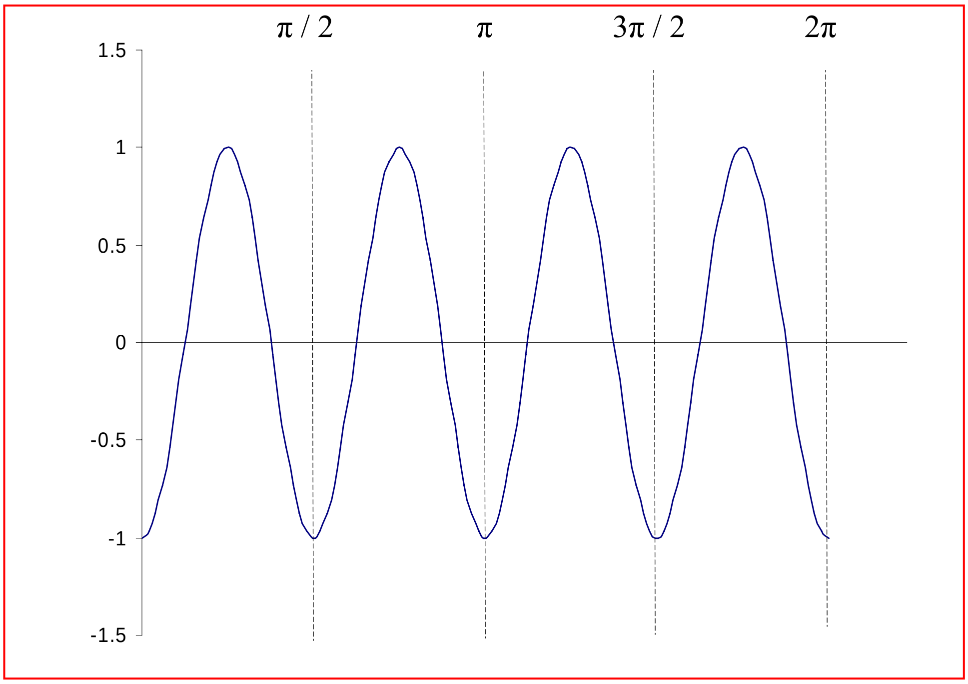


b) $v_{out} = -10v_{in} = -10 - 5\sin 5t$

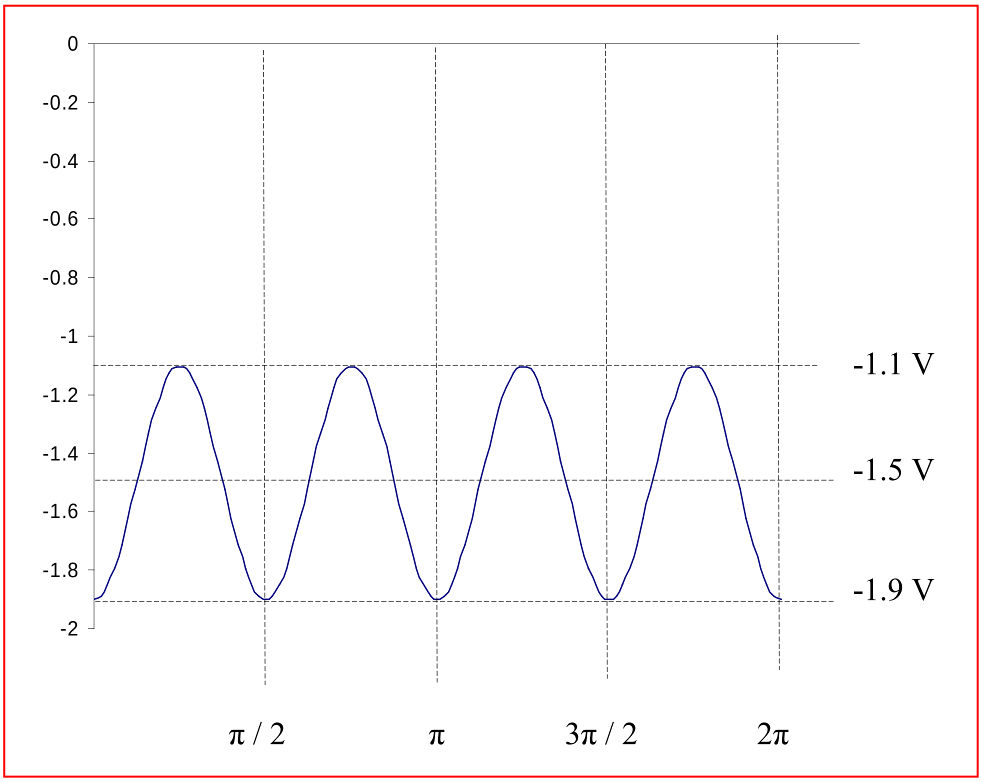


4. For this inverting amplifier, $v_{out} = -\frac{R_f}{R_1} v_{in} = -0.1 v_{in}$, hence,

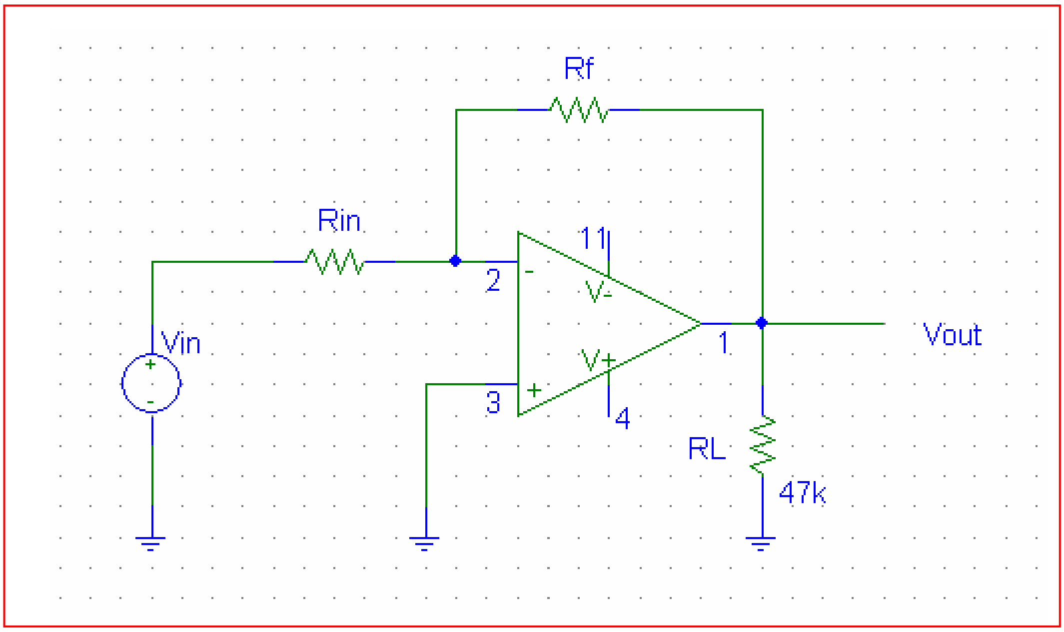
a) $v_{out} = -0.1 v_{in} = -\cos 4t$



b) $v_{out} = -0.1 v_{in} = -1.5 - 0.4\cos 4t$



5. One possible solution is by using an inverting amplifier design, we have

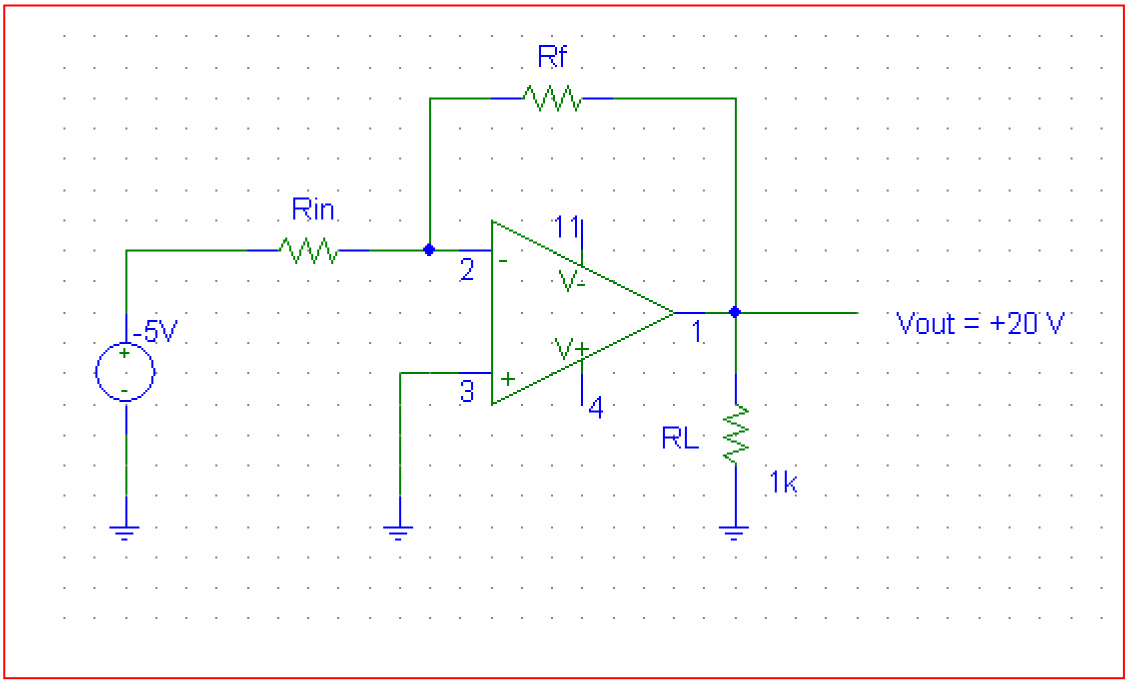


$$V_{out} = -\frac{R_f}{R_{in}} V_{in}$$

$$\Leftrightarrow \frac{R_f}{R_{in}} = -\frac{V_{out}}{V_{in}} = \frac{9}{5}$$

Using standard resistor values, we can have R_f=9.1kΩ and R_{in}=5.1kΩ

6. One possible solution is by using an inverting amplifier design, and a -5V input to give a positive output voltage:

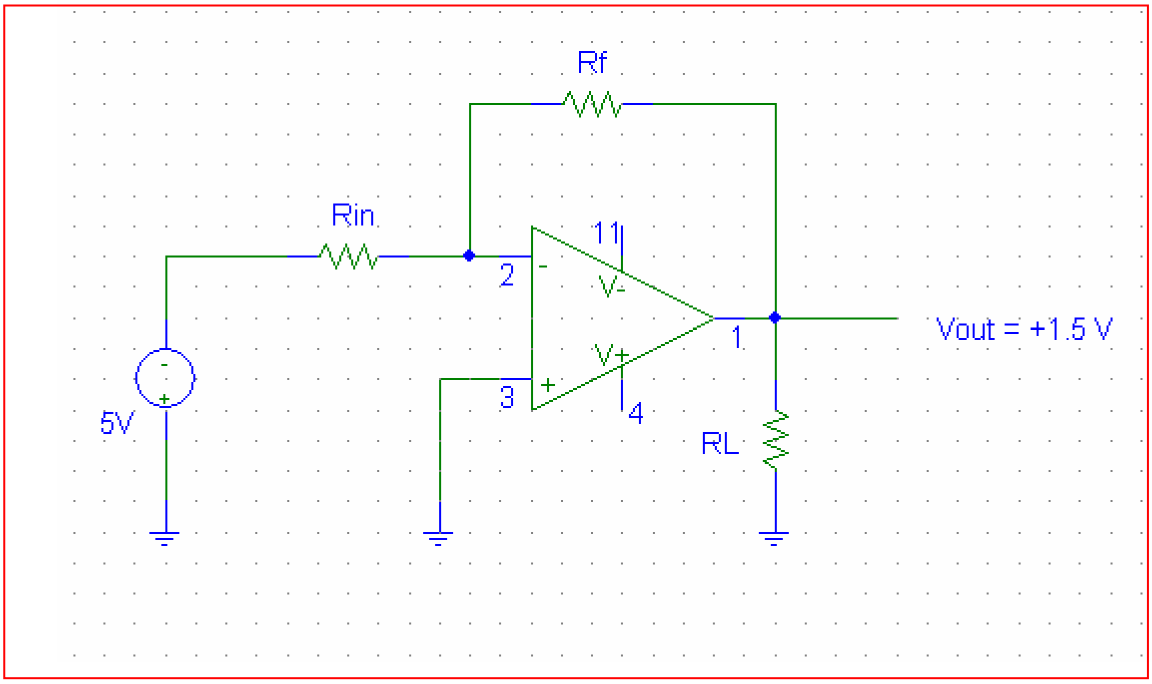


The resistance values are given by:

$$\frac{R_f}{R_{in}} = \frac{20}{5}$$

Giving possible resistor values $R_f = 20\ \text{k}\Omega$ and $R_{in} = 5.1\ \text{k}\Omega$

7. To get a positive output that is smaller than the input, the easiest way is to use inverting amplifier with an inverted voltage supply to give a negative voltage:

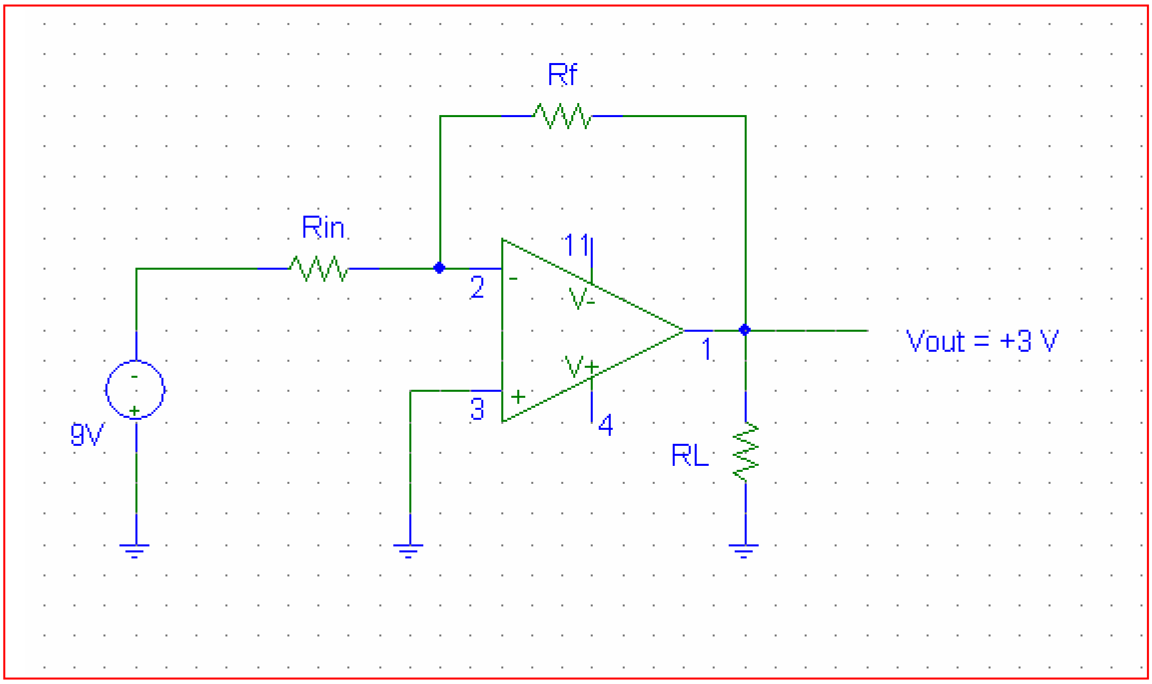


The resistances are given by:

$$\frac{R_f}{R_{in}} = \frac{1.5}{5}$$

Giving possible resistor values R_f = 1.5 kΩ and R_{in} = 5.1 kΩ

8. Similar to question 7, the following is proposed:



The resistances are given by:

$$\frac{R_f}{R_{in}} = \frac{3}{9}$$

Giving possible resistor values $R_f = 3.0\text{k}\Omega$ and $R_{in} = 9.1\ \text{k}\Omega$

9. This circuit is a non-inverting amplifier, therefore, $V_{out} = (1 + \frac{R_f}{R_1})V_{in}$

So:

a) $V_{out} = (1 + \frac{47}{10}) \times 300m = 1.71\text{ V}$

b) $V_{out} = (1 + \frac{1M}{1M}) \times 1.5 = 3\text{ V}$

c) $V_{out} = (1 + \frac{4.7}{3.3}) \times -1 = -2.42\text{ V}$

10. This is again a non-inverting amplifier. Similar to question 9, we have:

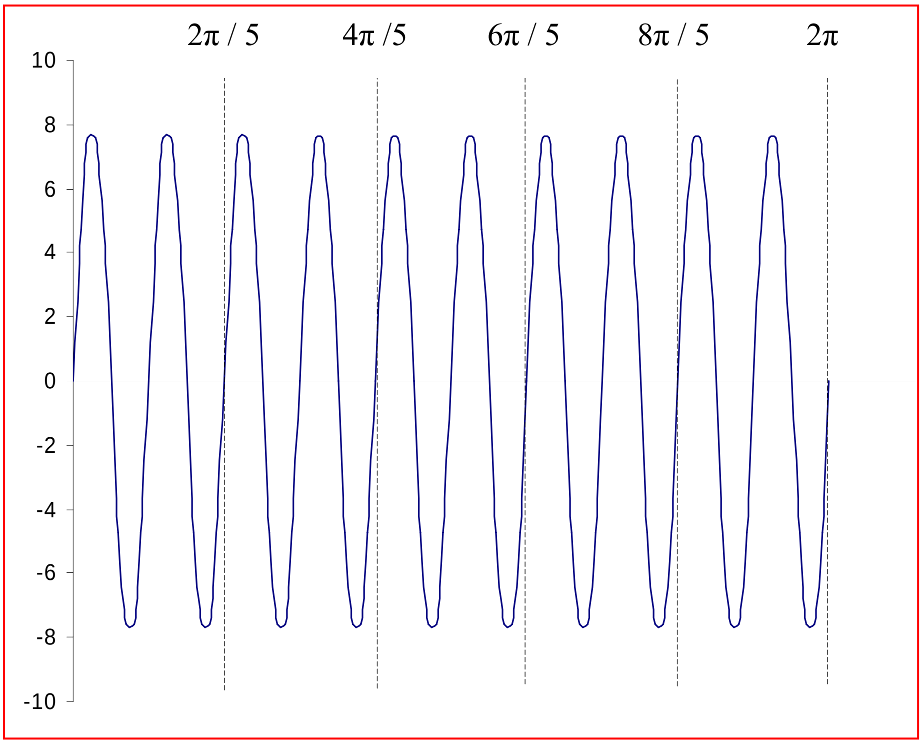
a) $V_{out} = 200m \times (1 + 4.7) = 1.14$ V

b) $V_{out} = (1 + 1) \times 9 = -18$ V

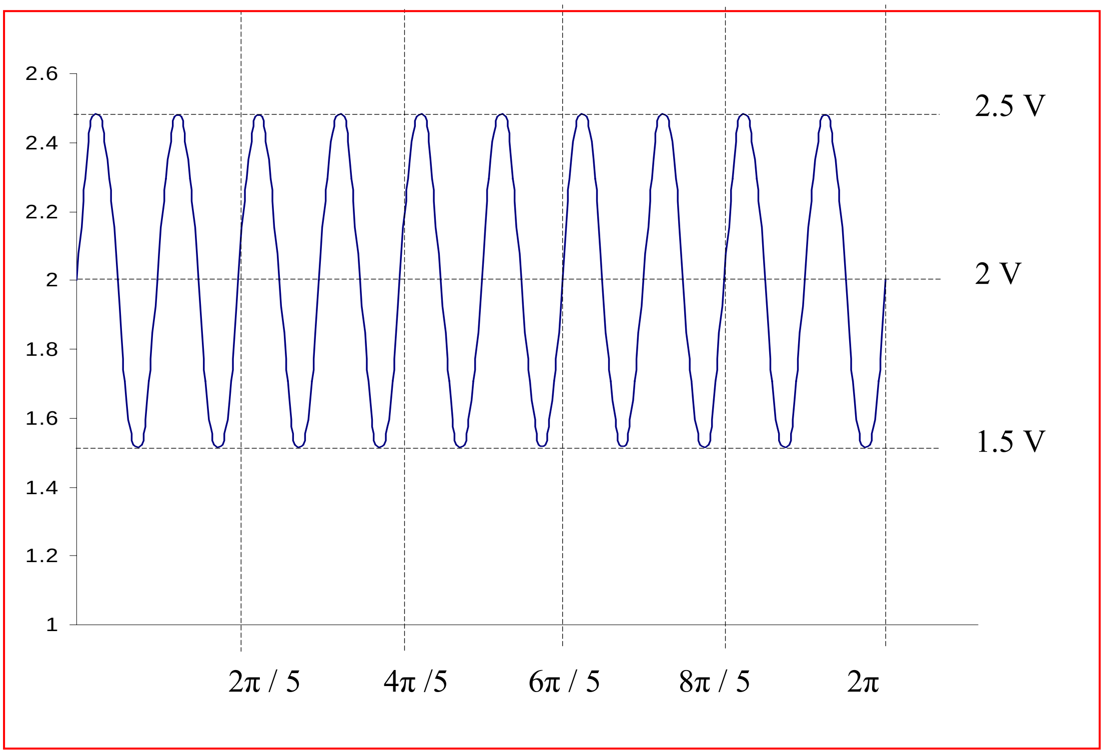
c) $V_{out} = 7.8 \times 100m = 0.78$ V

11. $v_{out} = (1+\frac{1}{1})v_{in} = 2v_{in}$ for this non inverting amplifier circuit, therefore:

a) $v_{out} = 2v_{in} = 8\sin 10t$

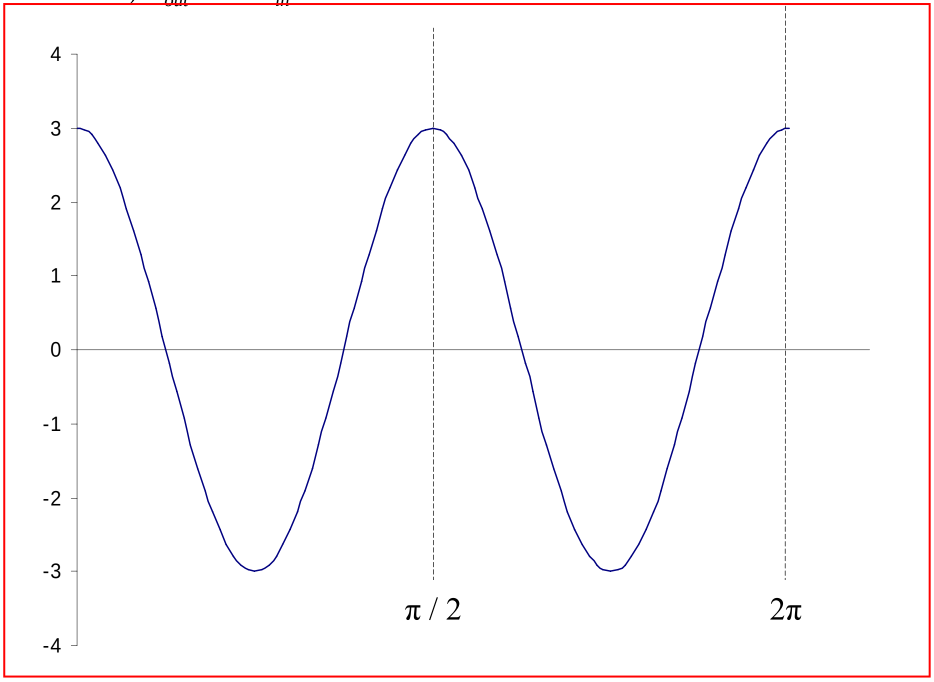


b) $v_{out} = 2v_{in} = 2 + 0.5\sin 10t$

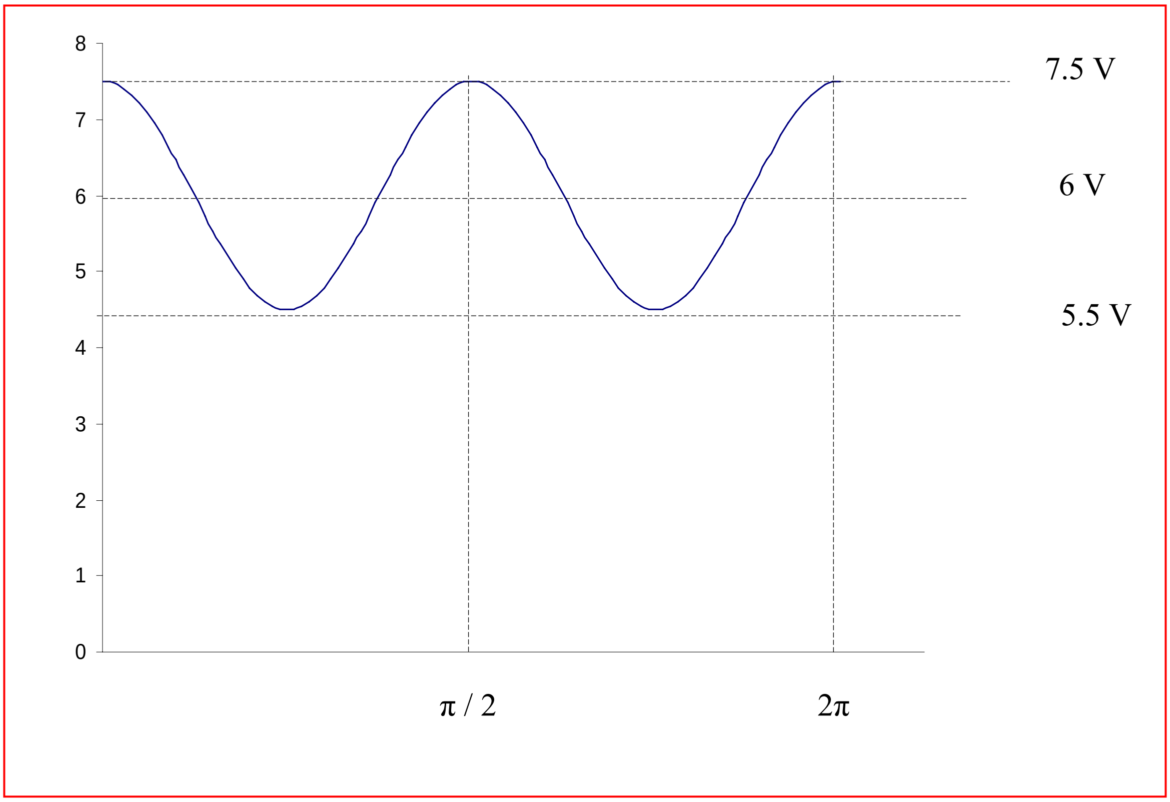


12. $v_{out} = (1+\frac{R_f}{R_{in}})v_{in} = 1.5v_{in}$ for this non inverting op-amp circuit. Hence,

a) $v_{out} = 1.5v_{in} = 3\cos 2t$



b) $v_{out} = 1.5v_{in} = 6 + 1.5\cos 2t$



13. The first step is to perform a simple source transformation, so that a 0.15-V source in series with a 150-Ω resistor is connected to the inverting pin of the ideal op amp.

Then, $v_{\text{out}} = -\dfrac{2200}{150}(0.15) = \boxed{-2.2\ \text{V}}$

14. In order to deliver 150 mW to the 10-kΩ resistor, we need v_{out} = $\sqrt{(0.15)(10\times10^3)}$ = 38.73 V. Writing a nodal equation at the inverting input, we find

$$0 = \frac{5}{R} + \frac{5 - v_{out}}{1000}$$

Using v_{out} = 38.73, we find that **R = 148.2 Ω.**

15. Since the 670-Ω switch requires 100 mA to activate, the voltage delivered to it by our op amp circuit must be (670)(0.1) = 67 V. The microphone acts as the input to the circuit, and provides 0.5 V. Thus, an amplifier circuit having a gain = 67/0.5 = 134 is required.

One possible solution of many: a non-inverting op amp circuit with the microphone connected to the non-inverting input terminal, the switch connected between the op amp output pin and ground, a feedback resistor R_f = 133 Ω, and a resistor R_1 = 1 Ω.

16. We begin by labeling the nodal voltages v_- and v_+ at the inverting and non-inverting input terminals, respectively. Since no current can flow into the non-inverting input, no current flows through the 40-kΩ resistor; hence, $v_+ = 0$. Therefore, we know that $v_- = 0$ as well.

Writing a single nodal equation at the non-inverting input then leads to

$$0 = \frac{(v_- - v_S)}{100} + \frac{(v_- - v_{out})}{22000}$$

or

$$0 = \frac{-v_S}{100} + \frac{-v_{out}}{22000}$$

Solving,

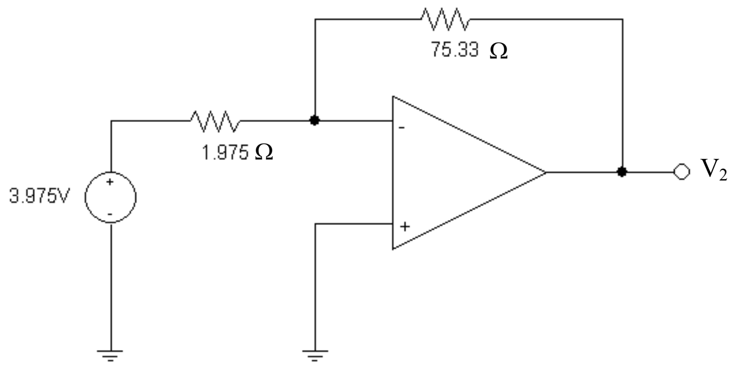
$$\boxed{v_{out} = -220\, v_S}$$

17. We first label the nodal voltage at the output pin V_o. Then, writing a single nodal equation at the inverting input terminal of the op amp,

$$0 = \frac{4 - 3}{1000} + \frac{4 - V_o}{17000}$$

Solving, we find that $V_o = 21$ V. Since no current can flow through the 300-kΩ resistor, $\boxed{V_1 = 21}$ as well.

18. A source transformation and some series combinations are well worthwhile prior to launching into the analysis. With 5 kΩ || 3 kΩ = 1.875 kΩ and (1 mA)(1.875 kΩ) = 1.875 V, we may redraw the circuit as



This is now a simple inverting amplifier with gain – R_f/ R_1 = -75.33/ 1.975 = -38.14.

Thus, V_2 = -38.14(3.975) = -151.6 V.

19. This is a simple inverting amplifier, so we may write

$$v_{out} = \frac{-2000}{1000}(2 + 2\sin 3t) = -4(1 + \sin 3t)\text{ V}$$

$v_{out}(t = 3\text{ s}) = -5.648$ V.

20. We first combine the 2 MΩ and 700 kΩ resistors into a 518.5 kΩ resistor.

We are left with a simple non-inverting amplifier having a gain of
1 + 518.5/ 250 = 3.074. Thus,

$v_{out} = (3.074)\, v_{in} = 18$ so $\boxed{v_{in} = 5.856 \text{ V.}}$

21. This is a simple non-inverting amplifier circuit, and so it has a gain of $1 + R_f / R_1$.
We want v_{out} = 23.7 cos 500*t* V when the input is 0.1 cos 500*t* V, so a gain of 23.7/0.1 = 237 is required.
One possible solution of many: R_f = 236 kΩ and R_1 = 1 kΩ.

22. Define a nodal voltage V_- at the inverting input, and a nodal voltage V_+ at the non-inverting input. Then,

At the non-inverting input: $$-3\times10^{-6} = \frac{V_+}{1.5\times10^{6}} \quad [1]$$

Thus, $V_+ = -4.5$ V, and we therefore also know that $V_- = -4.5$ V.

At the inverting input: $$0 = \frac{V_-}{R_6} + \frac{V_- - V_{out}}{R_7} \quad [2]$$

Solving and making use of the fact that $V_- = -4.5$ V,

$$v_{out} = -\frac{R_7}{R_6}(4.5) - 4.5 = -4.5\left(\frac{R_7}{R_6}+1\right) \text{ V}$$

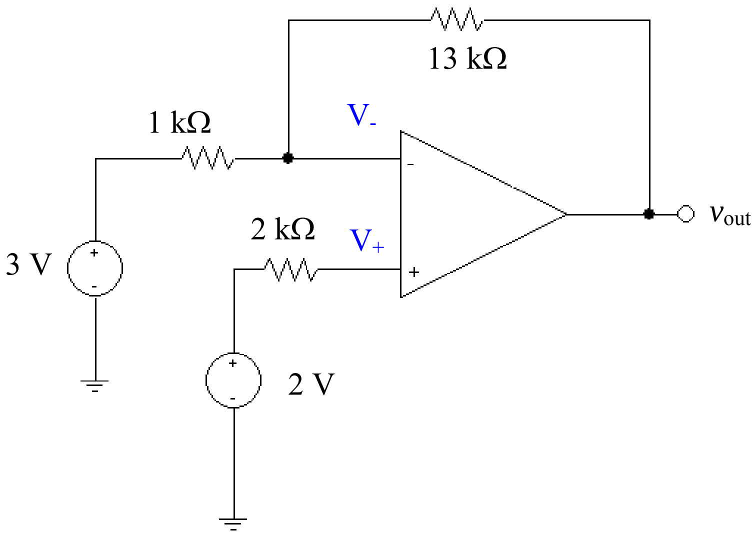
23. (a) **B** must be the non-inverting input: that yields a gain of 1 + 70/10 = 8 and an output of 8 V for a 1-V input.

(b) $R_1 = \infty$, $R_A = 0$. We need a gain of 20/10 = 2, so choose $R_2 = R_B = 1\ \Omega$.

(c) **A** is the inverting input since it has the feedback connection to the output pin.

24. It is probably best to first perform a simple source transformation:

(1 mA)(2 kΩ) = 2 V.



Since no current can flow into the non-inverting input pin, we know that $V_+ = 2$ V, and therefore also that $V_- = 2$ V. A single nodal equation at the inverting input yields:

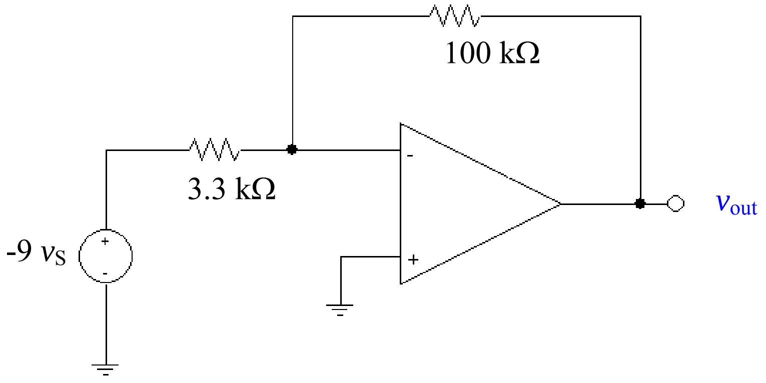
$$0 = \frac{2 - 3}{1000} + \frac{2 - v_{out}}{13000}$$

which yields $v_{out} = -11$ V.

25. We begin by find the Thévenin equivalent to the left of the op amp:

$$V_{th} = -3.3(3)\, v_\pi = -9.9\, v_\pi = -9.9\frac{1000\, v_S}{1100} = -9\, v_S$$

R_{th} = 3.3 kΩ, so we can redraw the circuit as:

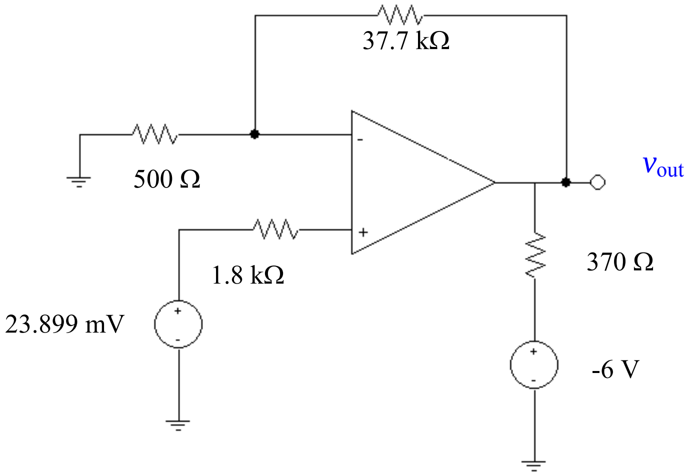


which is simply a classic inverting op amp circuit with gain of -100/3.3 = -30.3.

Thus, $v_{out} = (-30.3)(-9\, v_S) = 272.7\, v_S$

For $v_S = 5 \sin 3t$ mV, $v_{out} = 1.364 \sin 3t$ V, and $v_{out}(0.25\text{ s}) = 0.9298$ V.

26. We first combine the 4.7 MΩ and 1.3 kΩ resistors: 4.7 MΩ || 1.3 kΩ = 1.30 kΩ. Next, a source transformation yields $(3\times10^{-6})(1300)$ = 3.899 mV which appears in series with the 20 mV source and the 500-Ω resistor. Thus, we may redraw the circuit as



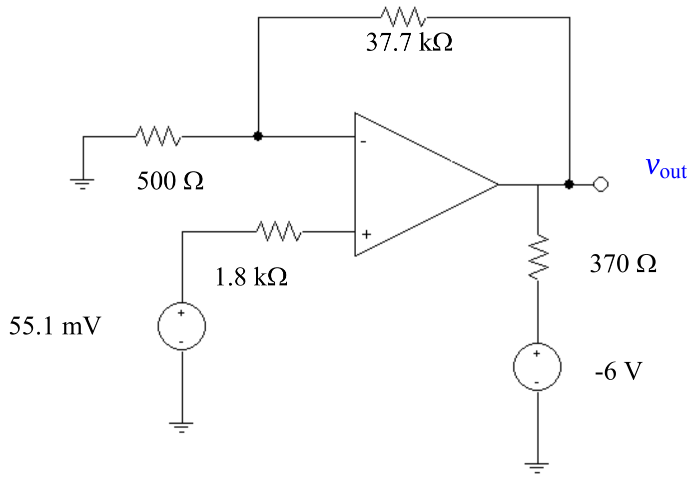
Since no current flows through the 1.8 kΩ resistor, V_+ = 23.899 mV and hence V_- = 23.899 mV as well. A single nodal equation at the inverting input terminal yields

$$0 = \frac{23.899\times10^{-3}}{500} + \frac{23.899\times10^{-3} - v_{out}}{37.7\times10^{3}}$$

Solving,

$$v_{out} = 1.826 \text{ V}$$

27. We first combine the 4.7 MΩ and 1.3 kΩ resistors: 4.7 MΩ || 1.3 kΩ = 1.30 kΩ. Next, a source transformation yields $(27\times10^{-6})(1300)$ = 35.1 mV which appears in series with the 20 mV source and the 500-Ω resistor. Thus, we may redraw the circuit as



Since no current flows through the 1.8 kΩ resistor, V_+ = 55.1 mV and hence V_- = 55.1 mV as well. A single nodal equation at the inverting input terminal yields

$$0 = \frac{55.1\times10^{-3}}{500} + \frac{55.1\times10^{-3} - v_{out}}{37.7\times10^{3}}$$

Solving,

$$v_{out} = 4.21 \text{ V}$$

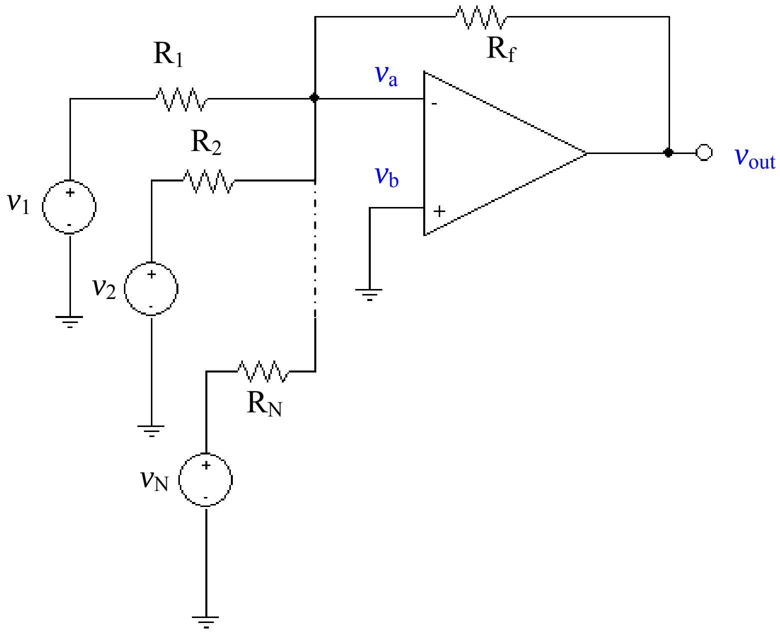
28. The 3 mA source, 1 kΩ resistor and 20 kΩ resistor may be replaced with a –3 V source ("+" reference up) in series with a 21 kΩ resistor. No current flows through either 1 MΩ resistor, so that the voltage at each of the four input terminals is identically zero. Considering each op amp circuit separately,

$$v_{\text{out}}\Big|_{\text{LEFTOPAMP}} = -(-3)\frac{100}{21} = 14.29\text{ V}$$

$$v_{\text{out}}\Big|_{\text{RIGH OPAMP}} = -(5)\frac{100}{10} = -50\text{ V}$$

$$v_{\text{x}} = v_{\text{out}}\Big|_{\text{LEFTOPAMP}} - v_{\text{out}}\Big|_{\text{RIGH OPAMP}} = 14.29 + 50 = \boxed{64.29\text{ V.}}$$

29. A general summing amplifier with N input sources:



1. $v_a = v_b = 0$
2. A single nodal equation at the inverting input leads to:

$$0 = \frac{v_a - v_{out}}{R_f} + \frac{v_a - v_1}{R_1} + \frac{v_a - v_2}{R_2} + \ldots + \frac{v_a - v_N}{R_N}$$

Simplifying and making use of the fact that $v_a = 0$, we may write this as

$$\left[-\frac{1}{R_f}\prod_{i=1}^{N} R_i\right] v_{out} = \frac{v_1}{R_1}\prod_{i=1}^{N} R_i + \frac{v_2}{R_2}\prod_{i=1}^{N} R_i + \ldots + \frac{v_N}{R_N}\prod_{i=1}^{N} R_i$$

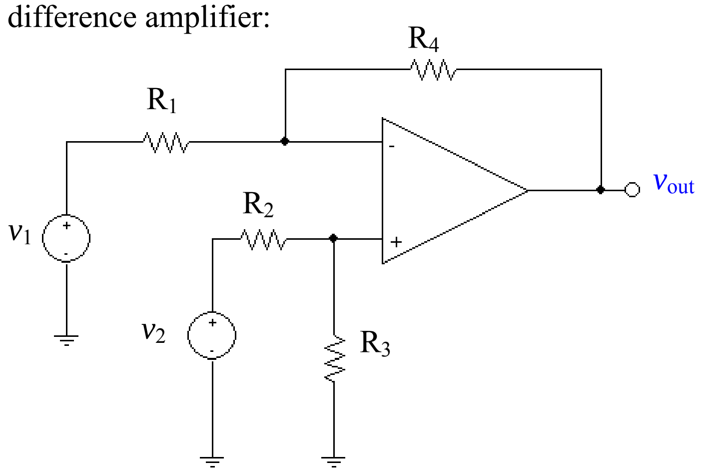
or simply

$$-\frac{v_{out}}{R_f} = \frac{v_1}{R_1} + \frac{v_2}{R_2} + \ldots + \frac{v_N}{R_N}$$

Thus,

$$v_{out} = -R_f \sum_{i=1}^{N} \frac{v_i}{R_i}$$

30. A general difference amplifier:



Writing a nodal equation at the inverting input,

$$0 = \frac{v_a - v_1}{R_1} + \frac{v_a - v_{out}}{R_f}$$

Writing a nodal equation at the non-inverting input,

$$0 = \frac{v_b}{R_3} + \frac{v_b - v_2}{R_2}$$

Simplifying and collecting terms, we may write

$$(R_f + R_1)\, v_a - R_1\, v_{out} = R_f\, v_1 \qquad [1]$$

$$(R_2 + R_3)\, v_b = R_3\, v_2 \qquad [2]$$

From Eqn. [2], we have $v_b = \frac{R_3}{R_2 + R_3} v_2$

Since va = vb, we can now rewrite Eqn. [1] as

$$-R_1\, v_{out} = R_f v_1 - \frac{(R_f + R_1)R_3}{R_2 + R_3} v_2$$

and hence

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

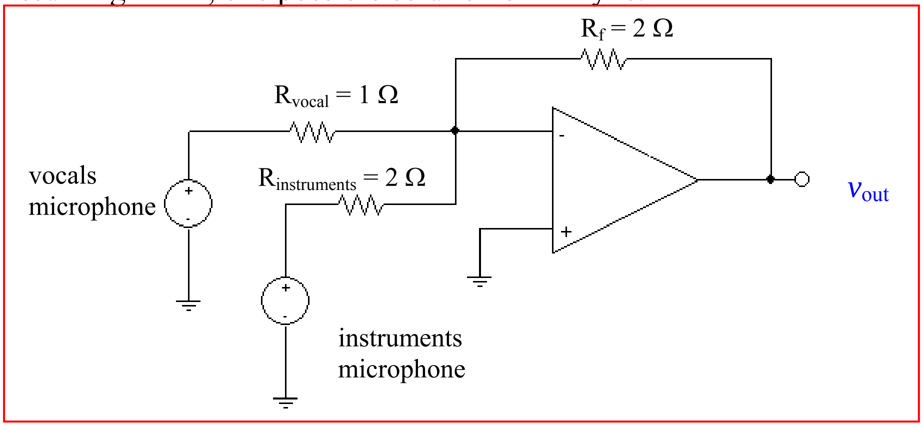
31. In total darkness, the CdS cell has a resistance of 100 kΩ, and at a light intensity L of 6 candela it has a resistance of 6 kΩ. Thus, we may compute the light-dependent resistance (assuming a linear response in the range between 0 and 6 candela) as $R_{CdS} = -15L + 100\ \Omega$.

Our design requirement (using the standard inverting op amp circuit shown) is that the voltage across the load is 1.5 V at 2 candela, and less than 1.5 V for intensities greater than 2 candela.

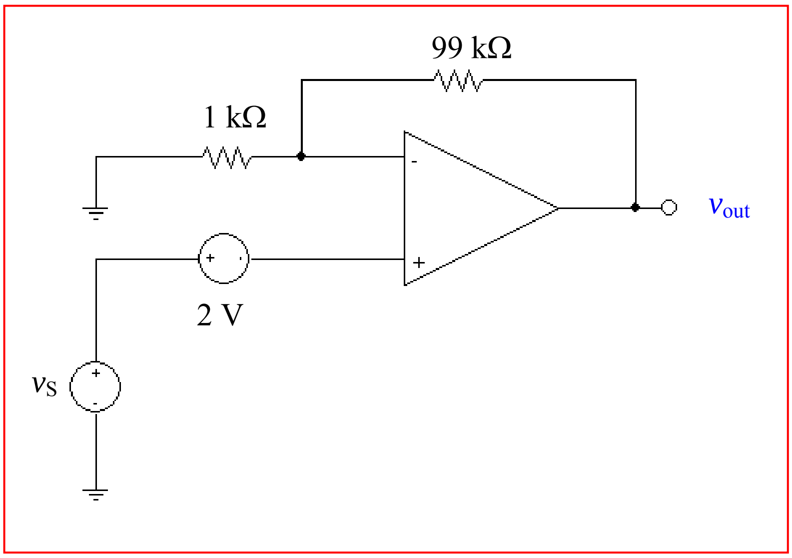
Thus, $v_{out}(2 \text{ candela}) = -R_{CdS}\, v_S / R_1 = -70\ V_S / R_1 = 1.5$ (R_1 in kΩ).

Pick $R_1 = 10$ kΩ. Then $v_S = -0.2143$ V.

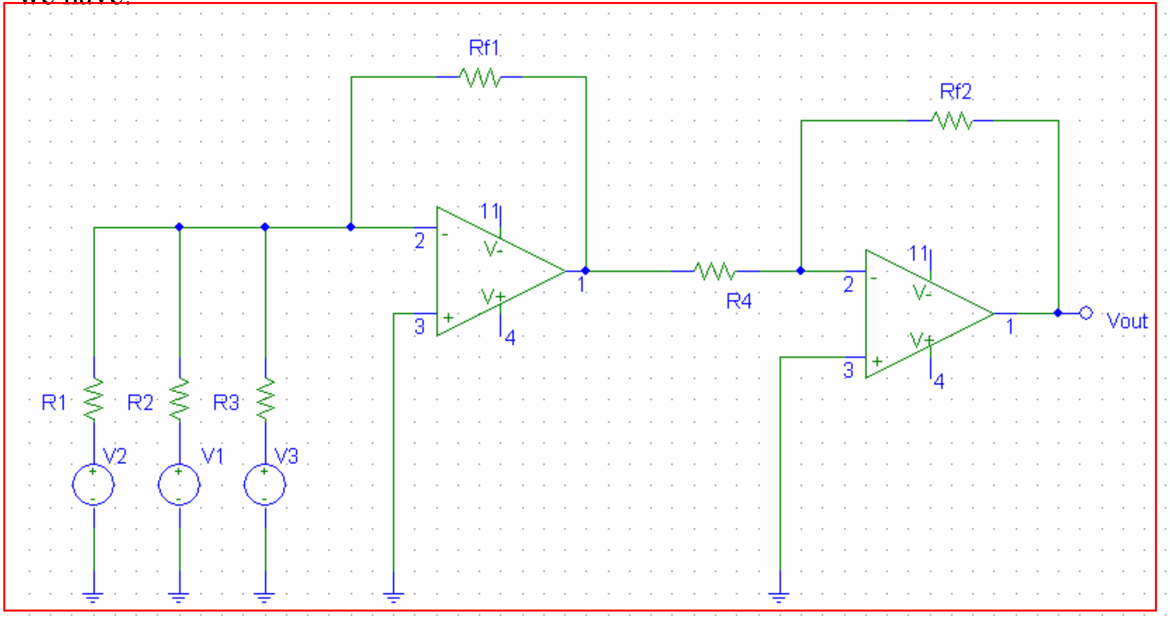
32. We want $R_f / R_{instrument} = 2K$, and $R_f / R_{vocal} = 1K$, where K is a constant not specified. Assuming K = 1, one possible solution of many is:



33. One possible solution of many:



34. To get the average voltage value, we want $v_{out} = \frac{v_1 + v_2 + v_3}{3}$. This voltage stays positive and therefore a one stage summing circuit (which inverts the voltage) is not sufficient. Using the cascade setup as shown figure 6.15 and modified for three inputs we have:



The nodal equation at the inverting input of the first op-amp gives

$$\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3} = \frac{-v_o}{R_{f_1}}$$

If we assume R_1=R_2=R_3=R, then

$$v_0 = -R_{f_1} \frac{v_1 + v_2 + v_3}{R}$$

Using the nodal equation at the inverting input of the second op-amp, we have:

$$\frac{-v_{out}}{R_{f_2}} = \frac{v_o}{R_4} = \frac{-R_{f_1}}{R_4} \frac{v_1 + v_2 + v_3}{R}$$

Or,

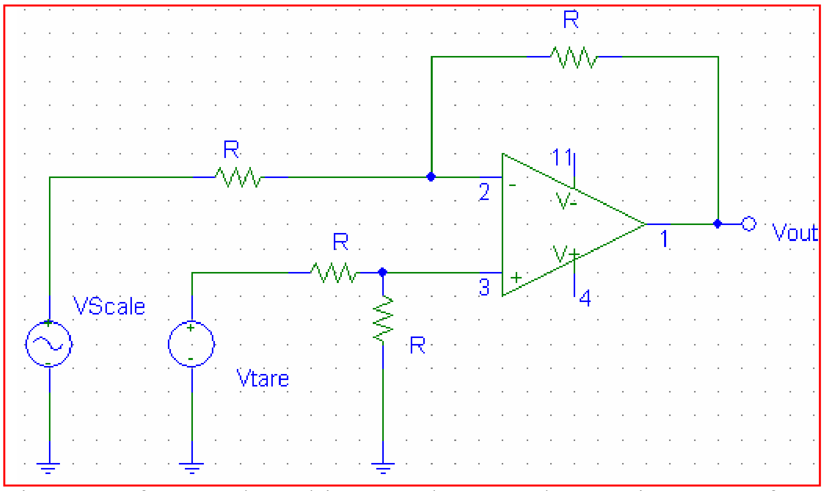
$$v_{out} = \frac{R_{f2} R_{f_1}}{R_4} \frac{v_1 + v_2 + v_3}{R}$$

For simplicity, we can take $R_{f2} = R_{f1} = R_4 = R_x$, then, to give a voltage average,

$$v_{out} = R_x \frac{v_1 + v_2 + v_3}{R} = \frac{v_1 + v_2 + v_3}{3}$$

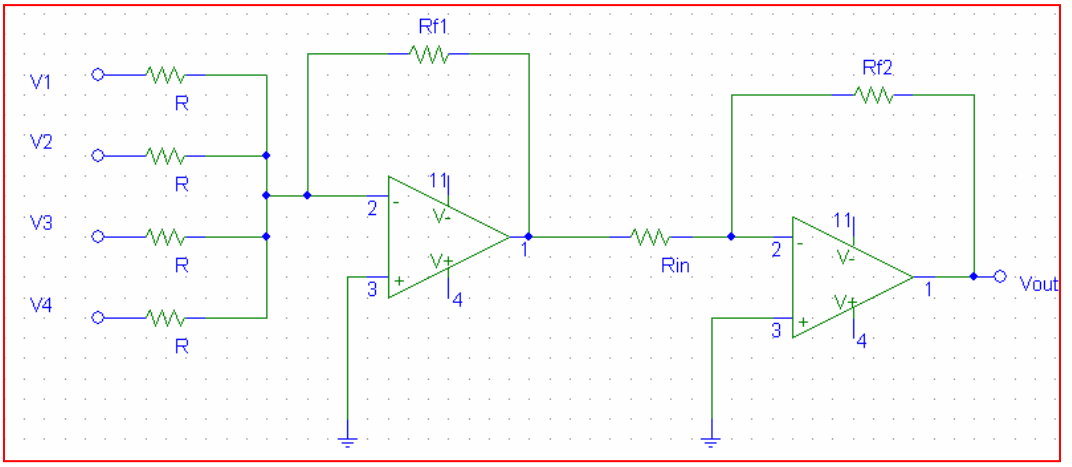
I.e. $R_x/R = 3$. Therefore, the circuit can be completed with $R_1 = R_2 = R_3 = 30$ kΩ and $R_{f2} = R_{f1} = R_4 = 10$ kΩ

35. The first stage is to subtract each voltage signal from the scale by the voltage corresponding to the weight of the pallet (V_{tare}). This can be done by using a differential amplifier:



The resistance of R can be arbitary as long as they resistances of each resistor is the same and the current rating is not exceeded. A good choice would be R = 10 kΩ.

The output voltage of the differential amps from each of the scale, $V_1 – V_4$ (now gives the weight of the items only), is then added by using a two stage summing amplifier:

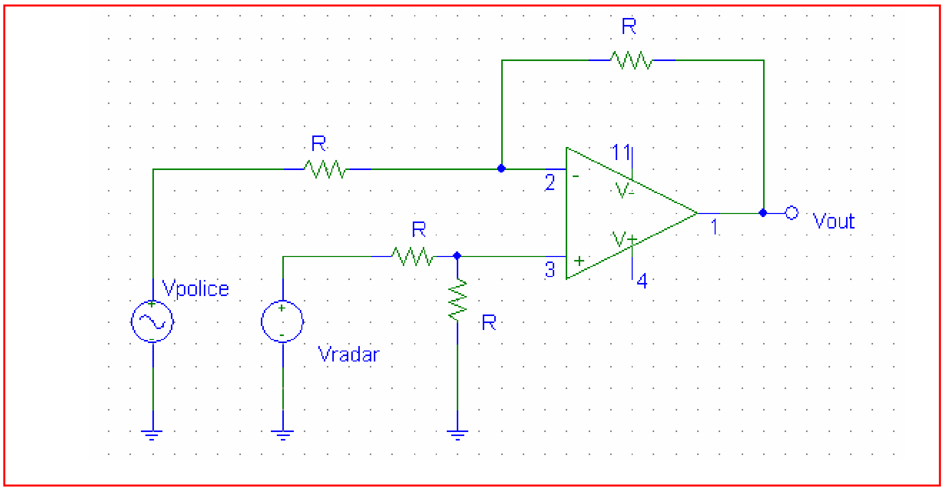


The output is given by:

$$v_{out} = \frac{R_{f2} R_{f1}}{R_{in}} \frac{v_1 + v_2 + v_3 + v_4}{R}$$

Therefore, to get the sum of the voltages v_1 to v_4, we only need to set all resistances to be equal, so setting $R_{f2} = R_{f1} = R_{in} = R = 10$ kΩ would give an output that is proportional to the total weight of the items

36. a) Using a difference amplifier, we can provide a voltage that is the difference between the radar gun output and police speedometer output, which is proportional to the speed difference between the targeted car and the police car. Note that since a positive voltage is required which the police car is slower, the police speedometer voltage would be feed into the inverting input:

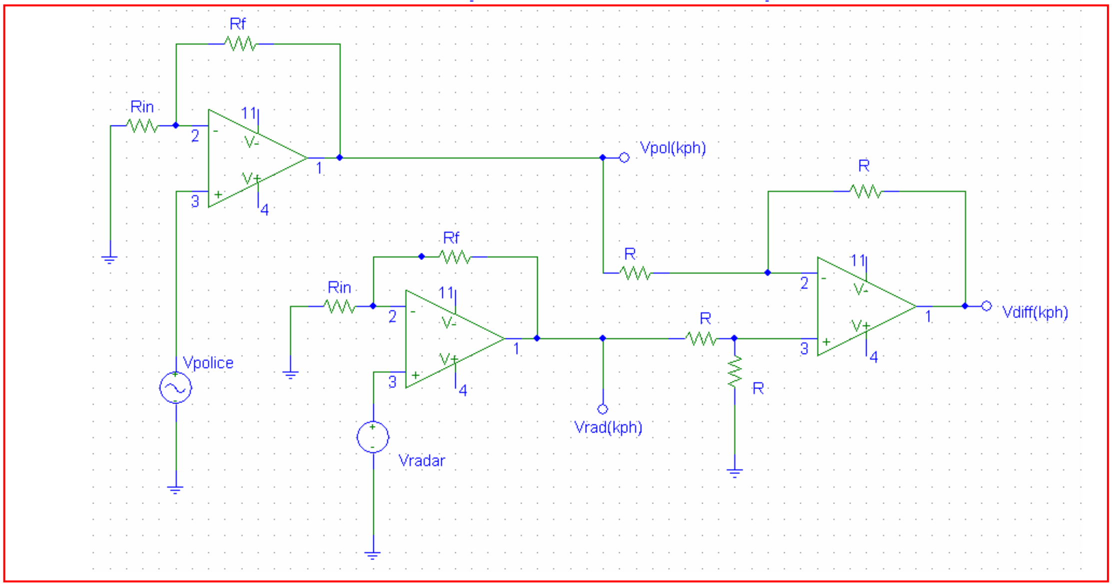


Again, R can be arbitary as long as they are equal and doesn't give an excessive current. 10 kΩ is a good choice here.

b) To convert to kph (km per hour) from mph (miles per hour), it is noted that 1 mph = 1.609 kph. Therefore, the voltage output from each device must be multiplied by 1.609. This can be done by using a non-inverting amplifier, which has an output given by:

$$v_{out} = (1 + \frac{R_f}{R_{in}})v_{in} = 1.609 v_{in}$$

This gives Rf/Rin =0.609 ≈ 61/100, i.e. $R_f = 6.2$ kΩ and $R_{in} = 10$ kΩ



37. v_{out} of stage 1 is (1)(-20/ 2) = -10 V.

v_{out} of stage 2 is (-10)(-1000/ 10) = 1000 V

Note: in reality, the output voltage will be limited to a value less than that used to power the op amps.

38. We have a difference amplifier as the first amplifier stage, and a simple voltage follower as the second stage. We therefore need only to find the output voltage of the first stage: v_{out} will track this voltage. Using voltage division, then, we find that the voltage at the non-inverting input pin of the first op amp is:

$$V_2\left(\frac{R_3}{R_2 + R_3}\right)$$

and this is the voltage at the inverting input terminal also. Thus, we may write a single nodal equation at the inverting input of the first op amp:

$$0 = \frac{1}{R_1}\left[V_2\left(\frac{R_3}{R_2 + R_3}\right) - V_1\right] + \frac{1}{R_f}\left[V_2\left(\frac{R_3}{R_2 + R_3}\right) - V_{out}\Big|_{Stage\,1}\right]$$

which may be solved to obtain:

$$V_{out} = V_{out}\Big|_{Stage\,1} = \left(\frac{R_f}{R_1} + 1\right)\frac{R_3}{R_2 + R_3}V_2 - \frac{R_f}{R_1}V_1$$

39. The output of the first op amp stage may be found by realising that the voltage at the non-inverting input (and hence the voltage at the *inverting* input) is 0, and writing a ingle nodal equation at the inverting input:

$$0 = \frac{0 - V_{out}\big|_{stage\,1}}{47} + \frac{0-2}{1} + \frac{0-3}{7} \quad \text{which leads to } V_{out}\big|_{steage\,1} = -114.1 \text{ V}$$

This voltage appears at the input of the second op amp stage, which has a gain of –3/ 0.3 = 10. Thus, the output of the second op amp stage is –10(-114.1) = 1141 V. This voltage appears at the input of the final op amp stage, which has a gain of –47/ 0.3 = -156.7.

Thus, the output of the circuit is –156.7(1141) = -178.8 kV, which is completely and utterly ridiculous.

40. The output of the top left stage is –1(10/ 2) = -5 V.
The output of the middle left stage is –2(10/ 2) = -10 V.
The output of the bottom right stage is –3(10/ 2) = -15 V.

These three voltages are the input to a summing amplifier such that

$$V_{out} = -\frac{R}{100}(-5 - 10 - 15) = 10$$

Solving, we find that R = 33.33 Ω.

41. Stage 1 is configured as a voltage follower: the output voltage will be equal to the input voltage. Using voltage division, the voltage at the non-inverting input (and hence at the inverting input, as well), is

$$5\frac{50}{100+50} \;=\; 1.667\text{ V}$$

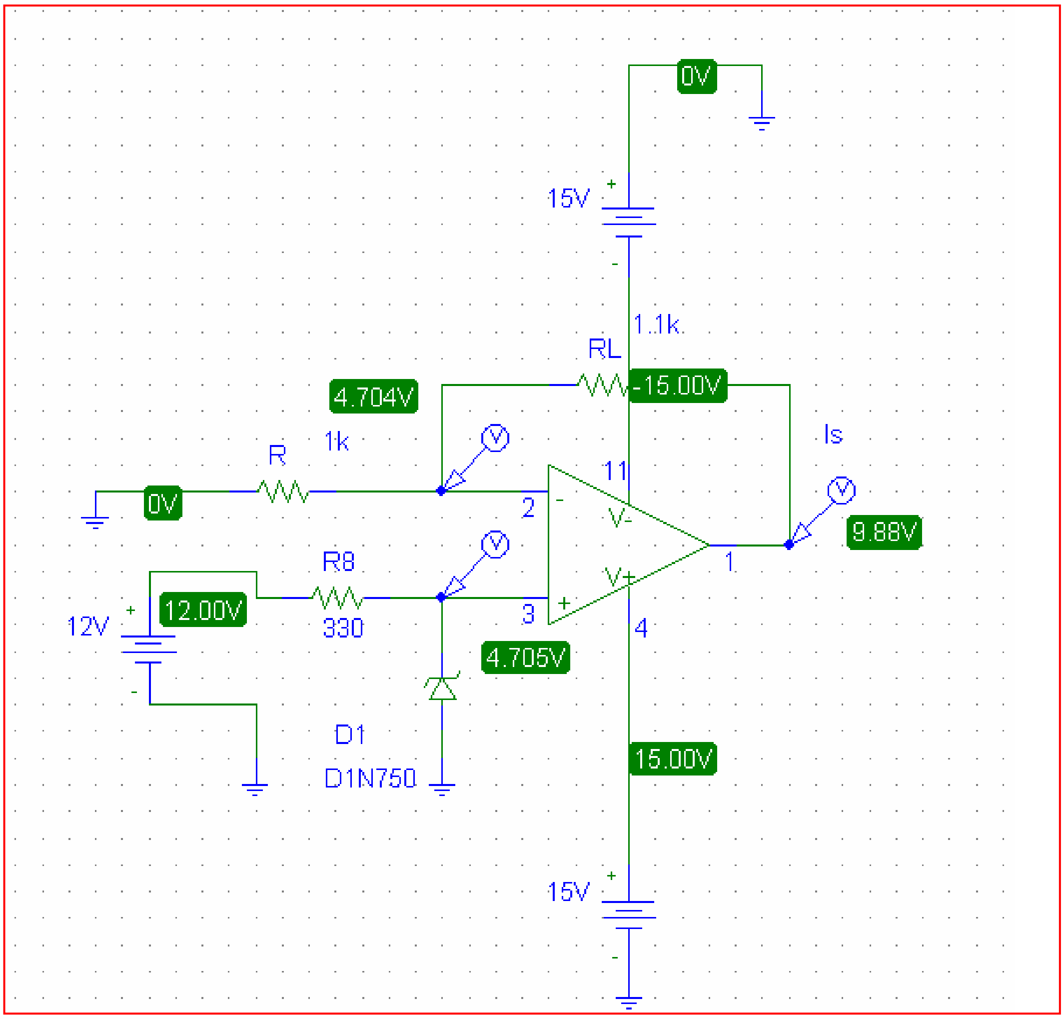
The second stage is wired as a voltage follower also, so v_{out} = 1.667 V.

42. a) Since the voltage supply is higher than the Zener voltage of the diode, the diode is operating in the breakdown region. This means $V_2 = 4.7$ V, and assuming ideal op-amp, $V_1 = V_2 = 4.7$ V. This gives a nodal equation at the inverting input:

$$\frac{4.7}{1k} = \frac{V_3 - 4.7}{1.1k}$$

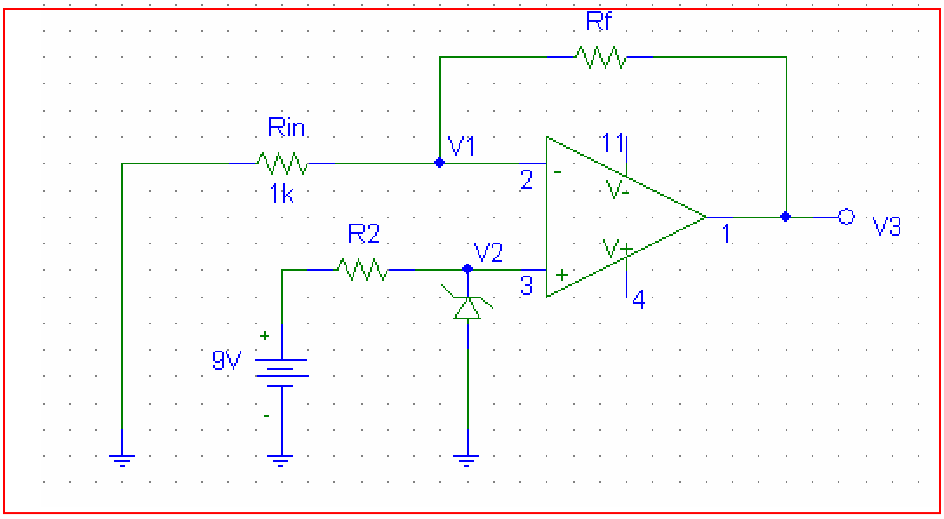
Solving this gives $V_3 = 9.87$ V

b) PSpice simulation gives:



It can be seen that all voltage values are very close to what was calculated. The voltage output V_3 is 9.88Vinstead of 9.87 V. This can be explained by the fact that the operating voltage is slightly higher than the breakdown voltage, and also the non-ideal characteristics of the op-amp.

43. The following circuit can be used:



The circuit is governed by the equations:

$$V_3 = (1 + \frac{R_f}{R_{in}})V_1$$

And

$$V_1 = V_2 = V_{diode}$$

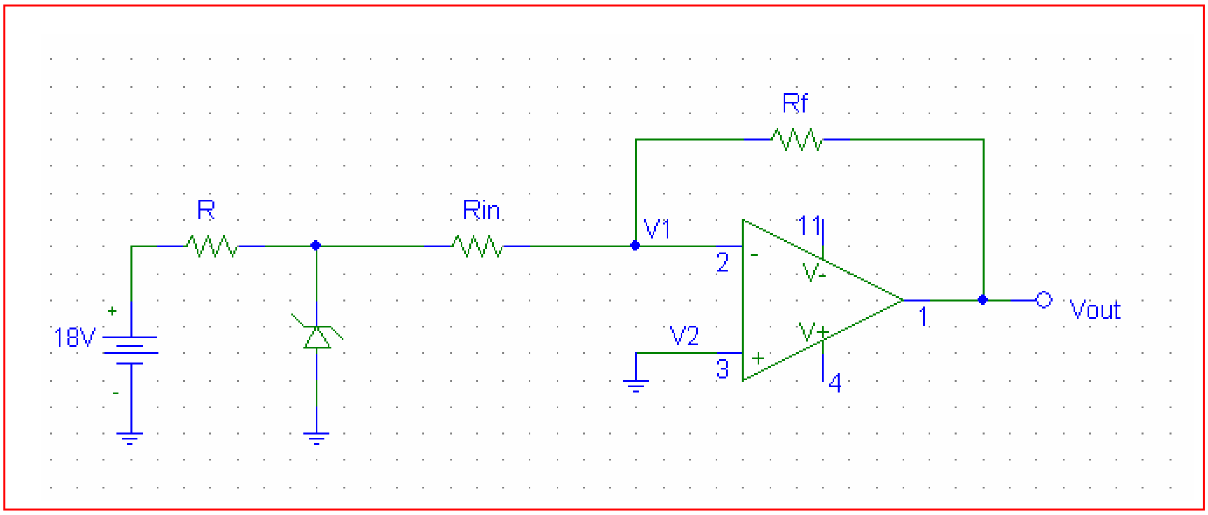
Since the diode voltage is 5.1 V, and the desired output voltage is 5.1 V, we have Rf/Rin = 0. In other words, a voltage follower is needed with $R_f = 0\Omega$, and R_{in} can be arbitary – $R_{in} = 100\ k\Omega$ would be sufficient.

The resistor value of R2 is determined by:

$$R_2 = \frac{V_s - V_{diode}}{I_{ref}}$$

At a voltage of 5.1 V, the current is 76 mA, as described in the problem. This gives $R_2 \approx 51\ \Omega$ using standard resistor values.

44. For the Zener diode to operate in the breakdown region, a voltage supply greater than the breakdown voltage, in this case 10 V is needed. With only 9 V batteries, the easiest way is the stack two battery to give a 18 V power supply. Also, as the input is inverted, an inverting amplifier would be needed. Hence we have the following circuit:

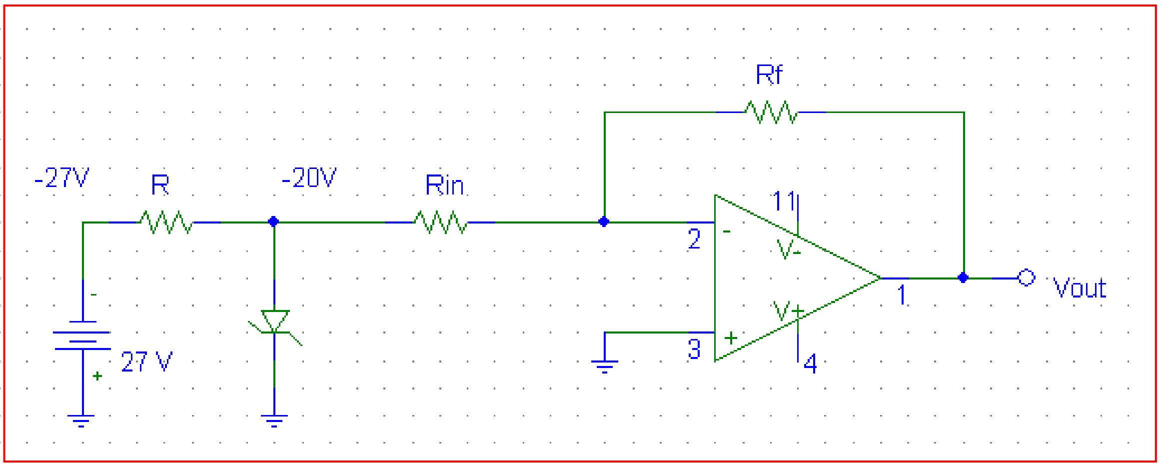


$$V_{out} = -\frac{R_f}{R_{in}} V_{in}$$

Here, the input voltage is the diode voltage = 10 V, and the desired output voltage is -2.5 V. This gives R_f/R_{in} = 25 / 100 = 50 / 200, or R_f = 51 kΩ and R_{in} = 200 kΩ using standard values. Note that large values are chosen so that most current flow through the Zener diode to provide sufficient current for breakdown condition.

The resistance R is given by R = (18-10) V /25 mA = 320 Ω = 330 Ω using standard values.

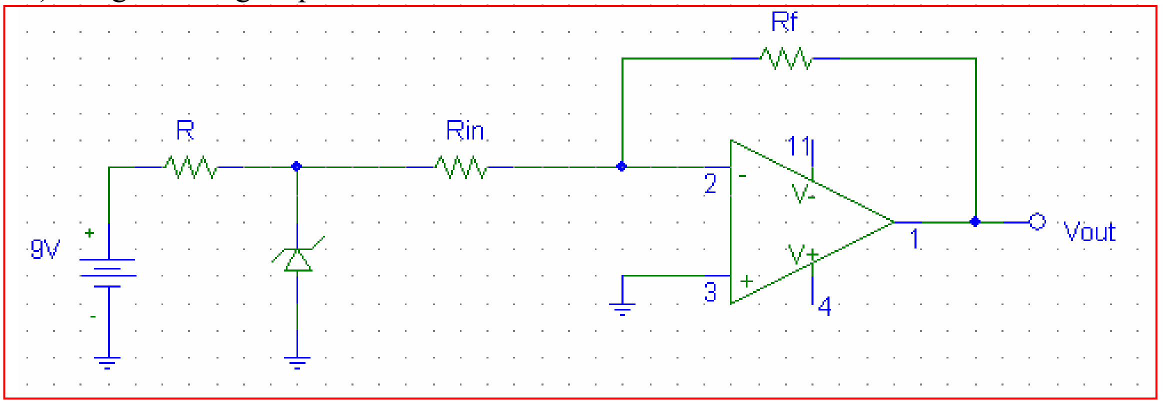
45. For a 20 V Zener diode, three 9 V batteries giving a voltage of 27 V would be needed. However, because the required voltage is smaller than the Zener voltage, a non-inverting amplifier can not be used. To use a inverting amplifier to give a positive voltage, we first need to invert the input to give a negative input:



In this circuit, the diode is flipped but so is the power supply, therefore keeping the diode in the breakdown region, giving V_{in} = -20 V. Then, using the inverting amp equation, we have R_f / R_{in} = 12/20 giving R_f = 120 kΩ and R_{in} = 200 kΩ using standard resistor values.

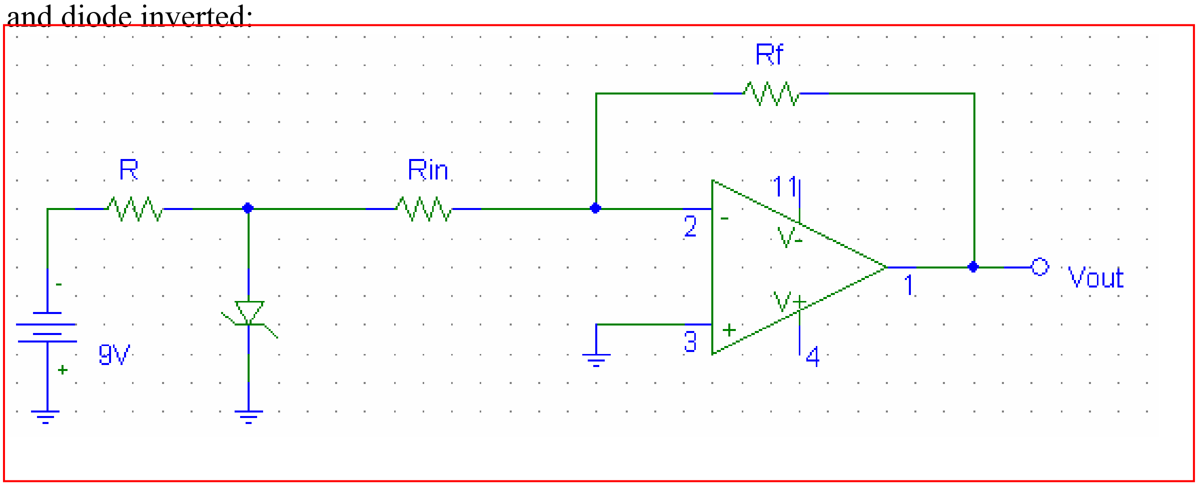
The resistance R is then given by R = (-20 - -27) V / 12.5 mA = 560 Ω using standard resistor values.

46. a) using inverting amplifier:



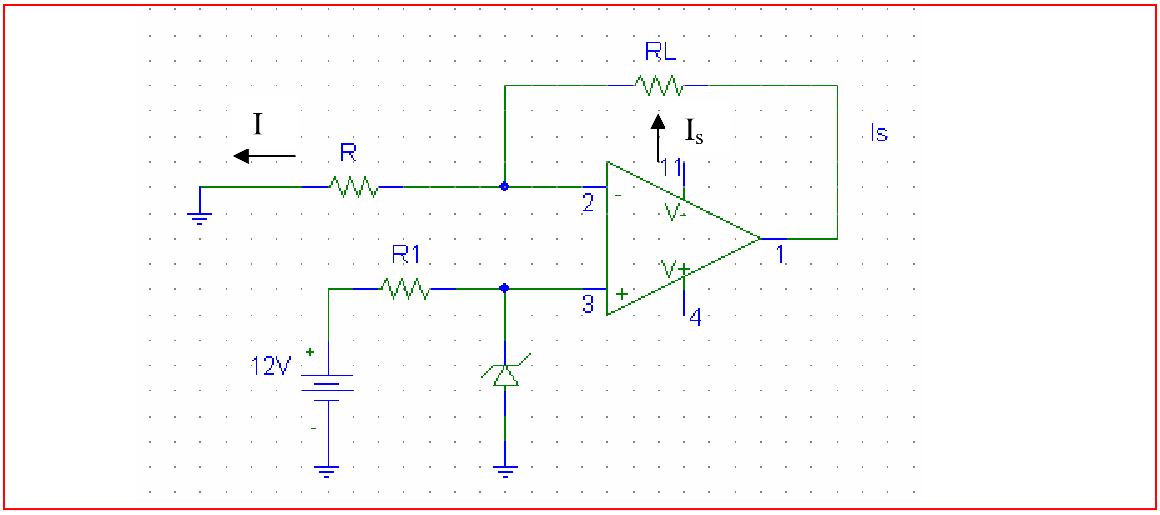
R_f/R_{in} = 5/3.3 giving R_f = 51 kΩ and R_{in} = 33 kΩ. R = (9-3.3) V / 76 mA = 75 Ω using standard resistor values.

b) To give a voltage output of +2.2 V instead, the same setup can be used, with supply and diode inverted:



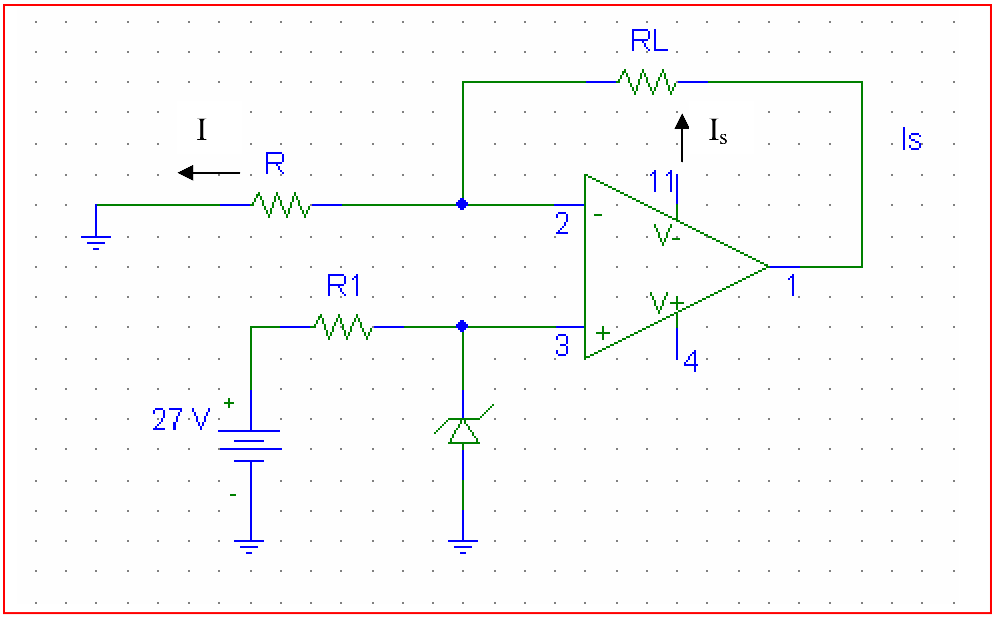
Correspondingly, the resistor values needs to be changed:
Rf / Rin = 3.3/2.2 giving R_f = 33 kΩ and R_{in} = 22 kΩ. R would be the same as before as the voltage difference between supply and diode stays the same i.e. R = 75 Ω.

47. The following setup can be used:



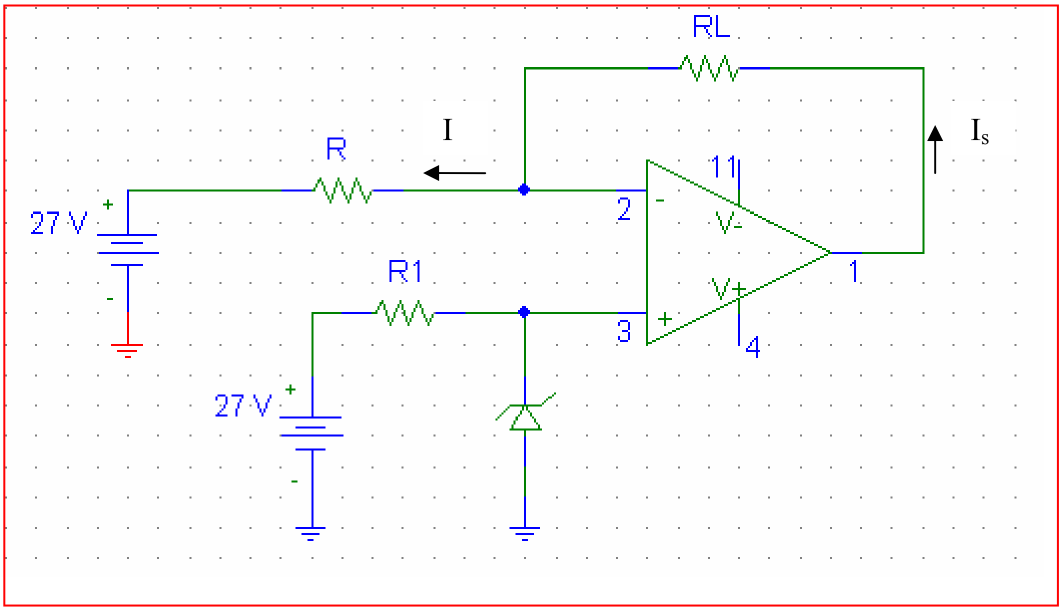
$I_s = I = 10 \text{ V} / R = 25$ mA assuming ideal op-amp. This gives $R = 400\ \Omega$. Again, taking half of max current rating as the operating current, we get $R_1 = (12 - 10) \text{ V} / 25 \text{ mA} = 80\ \Omega = 82\ \Omega$ using standard values.

48. Using the following current source circuit, we have:



$I_s = I = 12.5$ mA = 20 V / R, assuming ideal op-amp. This gives R = 1.6 kΩ and R_1 = (27 – 20) / 12.5 mA = 560 Ω.

49. In this situation, we know that there is a supply limit at ±15 V, which is lower than the zener diode voltage. Therefore, previous designs need to be modified to suit this application. One possible solution is shown here:

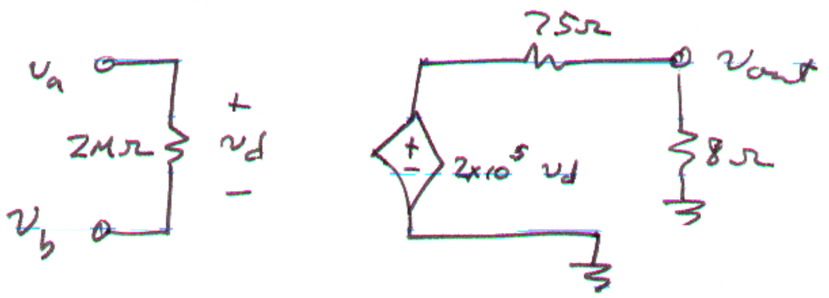


Here, we have Is = I = (27-20)/ R = 75 mA, assuming infinite op-amp input resistance. This gives R = 93.3 ≈ 91 Ω using standard values. We also have R1 = (27-20)/ 12.5 mA = 560 Ω.

Now look at the range of possible loads. The maximum output voltage is approximately equal to the supply voltage, i.e. 15 V. Therefore, the minimum load is given by R_L = (20 – 15) V / 75 mA = 66.67 Ω. Similarly, the maximum load is given by RL = (20 - -15) V/ 75 mA = 466.67 Ω. i.e. this design is suitable for

466.67 Ω > R_L > 66.67 Ω.

50.



(a) $v_a = v_b = 1$ nV $\therefore$ $v_d = 0$ and $v_{out} = 0$. Thus, $P_{8\Omega} = 0$ W.

(b) $v_a = 0$, $v_b = 1$ nV $\therefore$ $v_d = -1$ nV

$$v_{out} = (2\times10^5)(-1\times10^{-9})\frac{8}{75+8} = -19.28\ \mu\text{V. Thus, } P_{8\Omega} = \frac{v_{out}^2}{8} = 46.46\ \text{pW.}$$

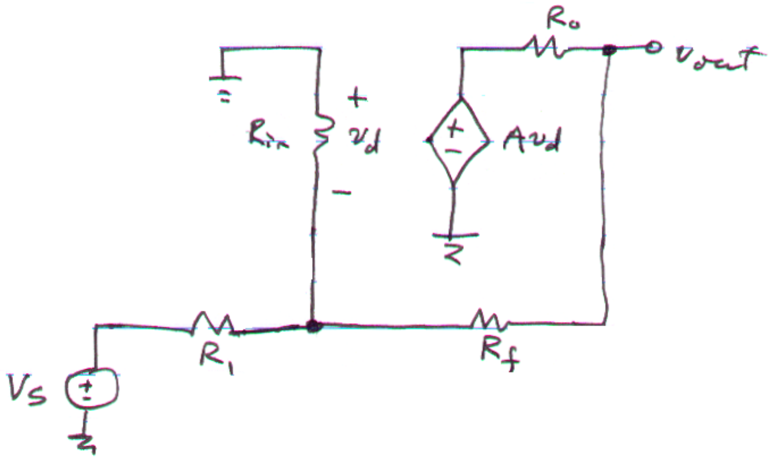
(c) $v_a = 2$ pV, $v_b = 1$ fV $\therefore$ $v_d = 1.999$ pV

$$v_{out} = (2\times10^5)(1.999\times10^{-12})\frac{8}{75+8} = 38.53\ \text{nV. Thus, } P_{8\Omega} = \frac{v_{out}^2}{8} = 185.6\ \text{aW.}$$

(c) $v_a = 50\ \mu$V, $v_b = -4\ \mu$V $\therefore$ $v_d = 54\ \mu$V

$$v_{out} = (2\times10^5)(54\times10^{-6})\frac{8}{75+8} = 1.041\ \text{V. Thus, } P_{8\Omega} = \frac{v_{out}^2}{8} = 135.5\ \text{mW.}$$

51.



Writing a nodal equation at the "-v_d" node,

$$0 = \frac{-v_d}{R_{in}} + \frac{-v_d - V_S}{R_1} + \frac{-v_d - v_{out}}{R_f} \qquad [1]$$

or $\quad (R_1R_f + R_{in}R_f + R_{in}R_1)\, v_d + R_{in}R_1 v_{out} = -R_{in}R_fV_S \qquad [1]$

Writing a nodal equation at the "v_{out}" node,

$$0 = \frac{-v_{out} - Av_d}{R_o} + \frac{v_{out} - (-v_d)}{R_f} \qquad [2]$$

Eqn. [2] can be rewritten as:

$$v_d = \frac{-(R_f + R_o)}{R_o - AR_f}\, v_{out} \qquad [2]$$

so that Eqn. [1] becomes:

$$v_{out} = -\frac{R_{in}(AR_f - R_o)V_S}{AR_{in}R_1 + R_fR_1 + R_{in}R_f + R_{in}R_1 + R_oR_1 + R_oR_{in}}$$

where for this circuit, $A = 10^6$, R_{in} = 10 TΩ, R_o = 15 Ω, R_f = 1000 kΩ, R_1 = 270 kΩ.

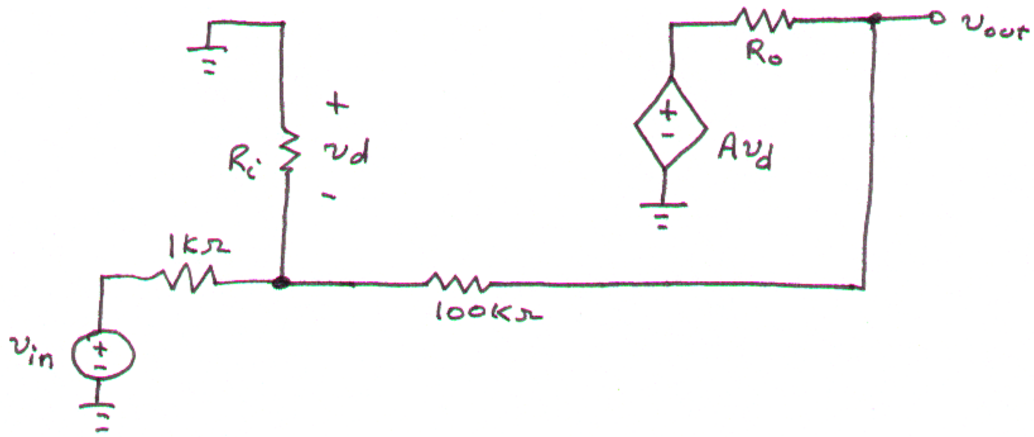
(a) –3.704 mV; (b) 27.78 mV; (c) –3.704 V.

52. $v_{out} = Av_d = A\dfrac{R_i}{16+R_i}\left(80\times10^{15}\right)\sin 2t\ \text{V}$

(a) $A = 10^5$, $R_i = 100\ \text{M}\Omega$, R_o value irrelevant. $\boxed{v_{out} = 8\sin 2t\ \text{nV}}$

(b) $A = 10^6$, $R_i = 1\ \text{T}\Omega$, R_o value irrelevant. $\boxed{v_{out} = 80\sin 2t\ \text{nV}}$

53.



(a) Find v_{out}/ v_{in} if $R_i = \infty$, $R_o = 0$, and A is finite.

The nodal equation at the inverting input is

$$0 = \frac{-v_d - v_{in}}{1} + \frac{-v_d - v_{out}}{100} \qquad [1]$$

At the output, with $R_o = 0$ we may write $v_{out} = Av_d$ so $v_d = v_{out}/ A$. Thus, Eqn. [1] becomes

$$0 = \frac{v_{out}}{A} + v_{in} + \frac{v_{out}}{100A} + \frac{v_{out}}{100}$$

from which we find

$$\boxed{\frac{v_{out}}{v_{in}} = \frac{-100A}{101 + A}} \qquad [2]$$

(b) We want the value of A such that $v_{out}/ v_{in} = -99$ (the "ideal" value would be –100 if A were infinite). Substituting into Eqn. [2], we find

$$\boxed{A = 9999}$$

54. (a) $\delta = 0$ V $\therefore$ $v_d = 0$, and $P_{8\Omega} = 0$ W.

(b) $\delta = 1$ nV, so $v_d = 5 - (5 + 10^{-9}) = -10^{-9}$ V
Thus,

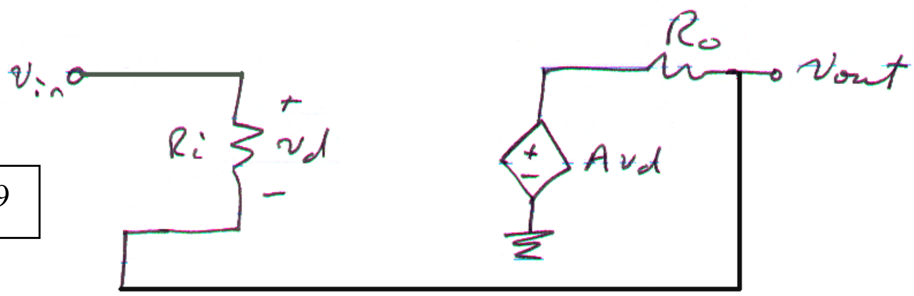
$$v_{out} = (2\times10^5)v_d \frac{8}{8+75} = -19.28\ \mu\text{V and } P_{8\Omega} = (v_{out})^2/\ 8 = 46.46\ \text{pW.}$$

(c) $\delta = 2.5$ μV, so $v_d = 5 - (5 + 2.5\times10^{-6}) = -2.5\times10^{-6}$V
Thus,

$$v_{out} = (2\times10^5)v_d \frac{8}{8+75} = -48.19\ \text{mV and } P_{8\Omega} = (v_{out})^2/\ 8 = 290.3\ \mu\text{W.}$$

55.

AD549



Writing a single nodal equation at the output, we find that

$$0 = \frac{v_{out} - v_{in}}{R_i} + \frac{v_{out} - Av_d}{R_o} \qquad [1]$$

Also, $v_{in} - v_{out} = v_d$, so Eqn. [1] becomes

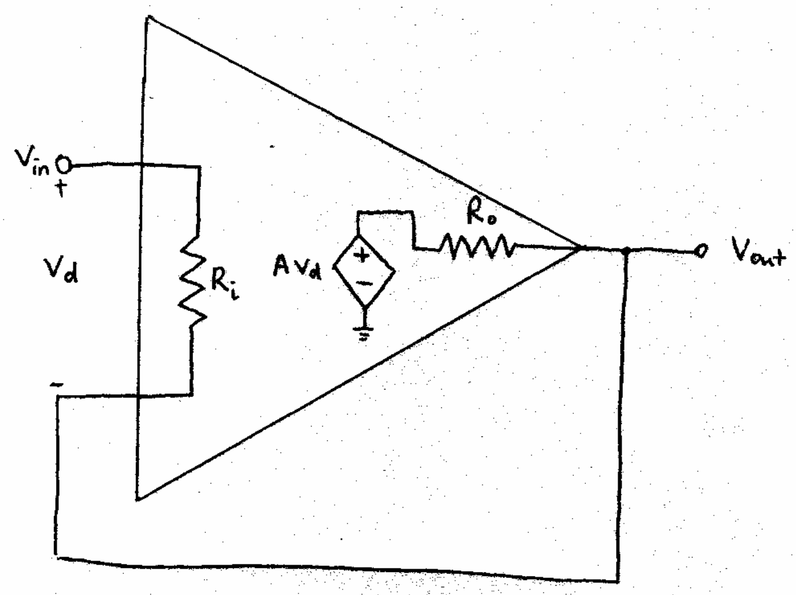
$$0 = (v_{out} - v_{in})\, R_o + (v_{out} - Av_{in} + Av_{out})\, R_i$$

and

$$v_{out} = \frac{(R_o + AR_i)}{R_o + (A+1)\, R_i} v_{in}$$

To within 4 significant figures (and more, actually), when v_{in} = -16 mV, v_{out} = -16 mV (this is, after all, a voltage follower circuit).

56. The Voltage follower with a finite op-amp model is shown below:



Nodal equation at the op-amp output gives:

$$\frac{V_{out} - V_{in}}{R_i} = \frac{AV_d - V_{out}}{R_o}$$

But in this circuit, $V_d = V_{in} - V_{out}$. Substitution gives:

$$\frac{V_{out} - V_{in}}{R_i} = \frac{A(V_{in} - V_{out}) - V_{out}}{R_o} = \frac{AV_{in} - (A+1)V_{out}}{R_o}$$

Further rearranging gives:

$$R_o V_{out} + R_i(A+1)V_{out} = R_o V_{in} + R_i A V_{in}$$

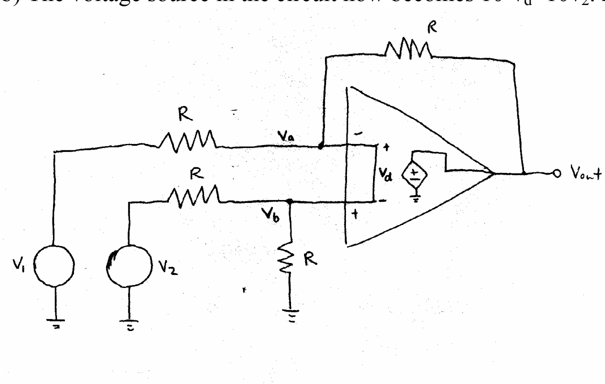
$$\Leftrightarrow \qquad V_{out} = \frac{R_o + R_i A}{R_o + R_i(A+1)} V_{in}$$

This is the expression for the voltage follower in non-ideal situation. In the case of ideal op-amp, A $\rightarrow \infty$, and so A+1 $\rightarrow$ A. This means the denominator and the numerator would cancel out to give $V_{out} = V_{in}$, which is exactly what we expected.

57. a) By definition, when the op-amp is at common mode, $v_{out} = A_{CM}v_{in}$. Therefore, a model that can represent this is:

This model relies on that fact that A_{CM} is much smaller than the differential gain A, and therefore when the inputs are different, the contribution of A_{CM} is negligible. When the inputs are the same, however, the differential term Av_d vanishes, and so $v_{out} = A_{CM}v_2$, which is correct.

b) The voltage source in the circuit now becomes $10^5v_d+10v_2$. Assuming $R_o = 0$, the circuit in figure 6.25 becomes:



The circuit is governed by the following equations:

$$v_d = v_b - v_a \quad \text{so} \quad \frac{10^5 v_d + 10v_b - v_a}{R} = \frac{v_a - v_1}{R}$$

$$v_b = v_2/2 \ \text{(from voltage divider)}$$

Rearranging gives:

$$10^5(v_2/2 - v_a) + 10(v_2/2) - v_a = v_a - v_1$$

$$50000v_2 - 10^5 v_a + 5v_2 - v_a = v_a - v_1$$

$$v_a = \frac{50005v_2 + v_1}{(10^5 + 2)}$$

Then, the output is given by:

$$v_{out} = 10^5 v_d + 10v_b = 10^5 \times (v_2/2 - v_a) + 5v_2$$

in this case, $v_1 = 5 + 2 \sin t$, $v_2 = 5$. This gives $v_a=0.50004v_2+9.99980\times10^{-6}v_1$. Thus

$v_{out} = 10^5(-0.00004v_2 - 9.99980\times10^{-6}v_1)+5v_2 = 1.00008v_2 - 0.99998v_1 = 0.0005 - 1.99996 \sin t$

c) If the common mode gain is 0, than the equation for v_a becomes

$$v_a = \frac{50000v_2 + v_1}{(10^5 + 2)}$$

Giving $v_a=0.49999v_2+9.99980\times10^{-6}v_1$. The output equation becomes

$v_{out} = 10^5 v_d = 10^5 \times (v_2/2 - v_a) = 0.99998v_2 - 0.99998v_1 = 1.99996 \sin t$

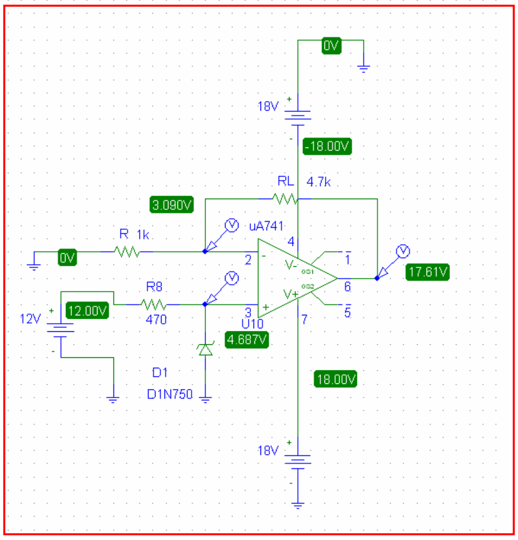
58. Slew rate is the rate at which output voltage can respond to changes in the input. The higher the slew rate, the faster the op-amp responds to changes. Limitation in slew rate – i.e. when the change in input is faster than the slew rate, causes degradation in performance of the op-amp as the change is delayed and output distorted.

59. a) V_2 = 4.7 V from the Zener diode, $V_1 = V_2$ = 4.7 V assuming ideal op-amp, and V_3 is given by the nodal equation at the inverting input:

$$\frac{V_3 - V_1}{4.7k} = \frac{V_1}{1k}$$

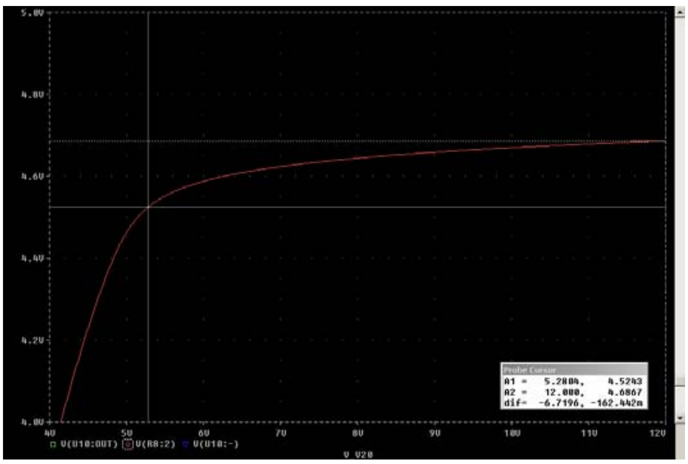
Solving gives V_3 = 26.79 V

b) The simulation result is shown below



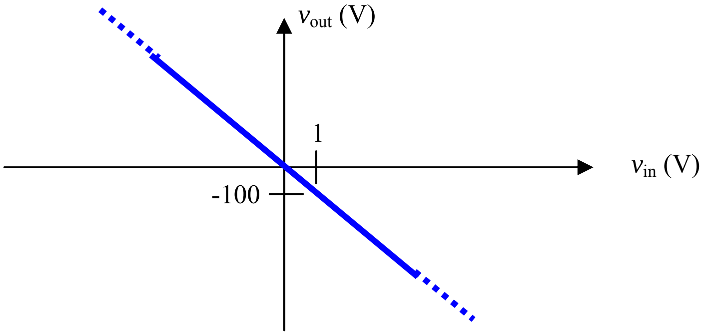
There are considerable discrepancies between calculated and simulated voltages. In particular, V_1 = 3.090 V is considerably lower than the expected 4.7 V. This is due to the non-ideal characteristics of uA741 which has a finite input resistance, inducing a voltage drop between the two input pins. A more severe limitation, however, is the supply voltage. Since the supply voltage is 18V, the output cannot exceed 18 V. This is consistent with the simulation result which gives V_3 = 17.61 V but is quite different to the calculated value as the mathematical model does not account for supply limitations.

c) By using a DC sweep, the voltage from the diode (i.e. V_2) was monitored as the battery voltage changes from 12 V to 4V.

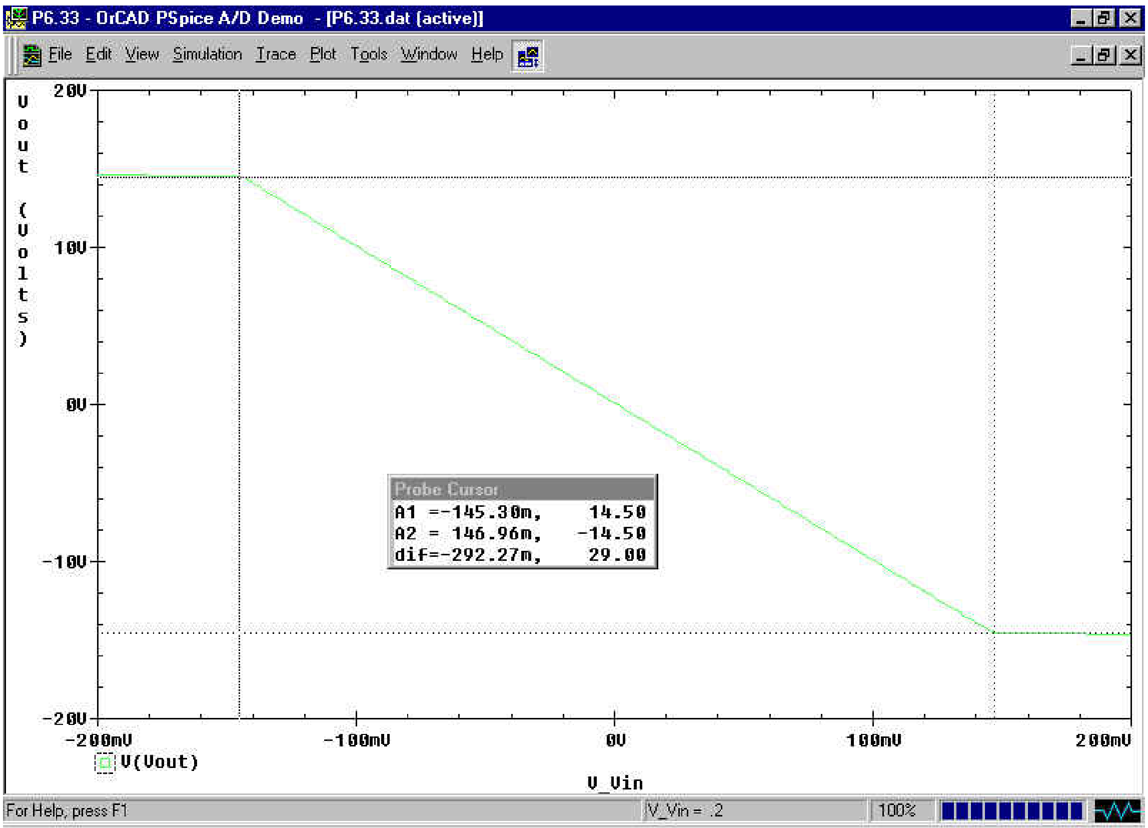


It can be seen that the diode voltage started dropping when batteries drop below 10 V. However, the diode can still be considered as operating in the breakdown region, until it hit the knee of the curve. This occurs at V_{supply} = 5.28 V

60. The ideal op amp model predicts a gain v_{out}/ v_{in} = -1000/ 10 = -100, regardless of the value of v_{in}. In other words, it predicts an input-output characteristic such as:



From the PSpice simulation result shown below, we see that the ideal op amp model is reasonably accurate for $|v_{in}| \times 100 < 15$ V (the supply voltage, assuming both have the same magnitude), but the onset of saturation is at ±14.5 V, or $|v_{in}| \sim 145$ mV. Increasing $|v_{in}|$ past this value does not lead to an increase in $|v_{out}|$.

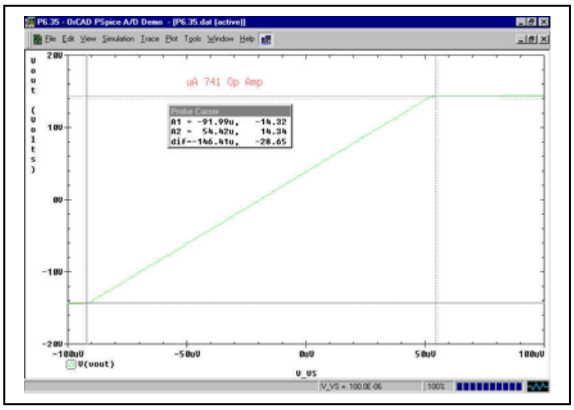


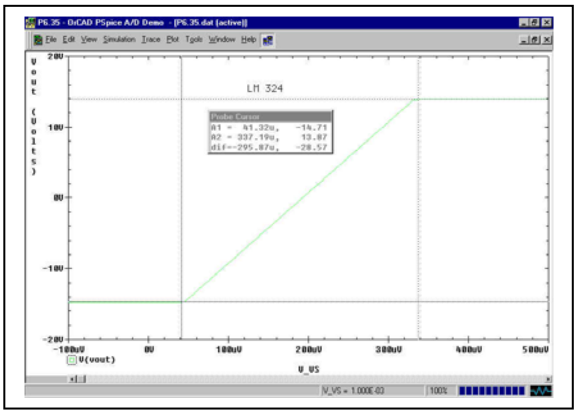
61. Positive voltage supply, negative voltage supply, inverting input, ground, output pin.

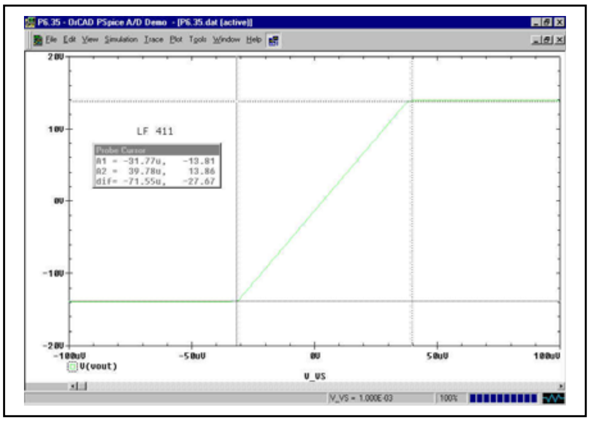
62. This op amp circuit is an open-loop circuit; there is no external feedback path from the output terminal to either input. Thus, the output should be the open-loop gain times the differential input voltage, minus any resistive losses.

From the simulation results below, we see that all three op amps saturate at a voltage magnitude of approximately 14 V, corresponding to a differential input voltage of 50 to 100 μV, except in the interest case of the LM 324, which may be showing some unexpected input offset behavior.

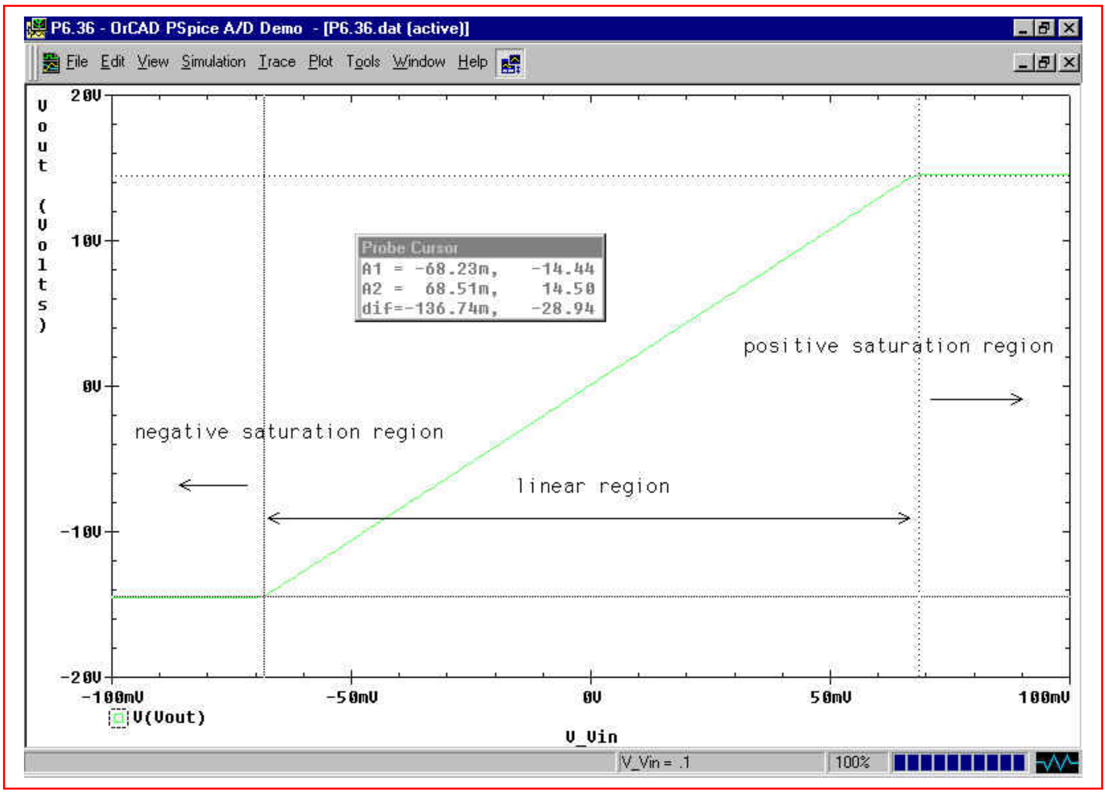
op amp	onset of negative saturation	negative saturation voltage	onset of positive saturation	positive saturation voltage
μA 741	-92 μV	-14.32 V	54.4 mV	14.34 V
LM 324	41.3 μV	-14.71 V	337.2 mV	13.87 V
LF 411	-31.77 μV	-13.81 V	39.78 mV	13.86 V





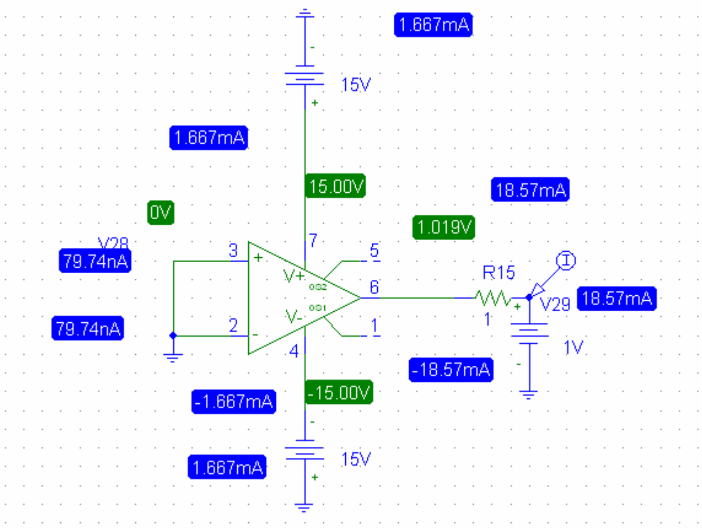


63. This is a non-inverting op amp circuit, so we expect a gain of 1 + 1000/4.7 = 213.8. With ±15 V DC supplies, we need to sweep the input just above and just below this value divided by the gain to ensure that we see the saturation regions. Performing the indicated simulation and a DC sweep from –0.1 V to +0.1 V with 0.001 V steps, we obtain the following input-output characteristic:



Using the cursor tool, we see that the linear region is in the range of
–68.2 mV < V_{in} < 68.5 mV.
The simulation predicts a gain of 7.103 V/ 32.87 mV = 216.1, which is reasonably close to the value predicted using the ideal op amp model.

64. To give a proper simulation, the inputs are grounded to give an input of 0. This gives:



As can be seen, a current of 18.57 mA is drawn from the uA741. Assuming the output voltage from the op-amp before R_o is 0, we have Ro = (1-18.57m)/18.57m = 52.9 Ω. This is close to the value given in table 6.3. There is difference between the two as here we are still using the assumption that the voltage output is independent to the loading circuit. This is illustrated by the fact that as the supplied voltage to the 1 ohm resistor changes, the voltage at the output pin actually increases, and is always higher than the voltage provided by the battery, as long as the supplied to the op-amp is greater than the battery voltage. When the supply voltage drops to 1V, the output current increased greatly and gave an output resistance of only 8 Ω. This suggests that the inner workings of the op-amp depend on both the supply and the loading.

For LF411, a current of 25.34 mA is drawn from the op-amp. This gives a output resistance of 38.4 Ω. This value is quite different to the 1 Ω figure given in the table.

65. Based on the detailed model of **the LF 411 op amp**, we can write the following nodal equation at the inverting input:

$$0 = \frac{-v_d}{R_{in}} + \frac{v_x - v_d}{10^4} + \frac{Av_d - v_d}{10^6 + R_o}$$

Substituting values for the LF 411 and simplifying, we make appropriate approximations and then solve for v_d in terms of v_x, finding that

$$v_d = \frac{-10^6}{199.9 \times 10^6} v_x = -\frac{v_x}{199.9}$$

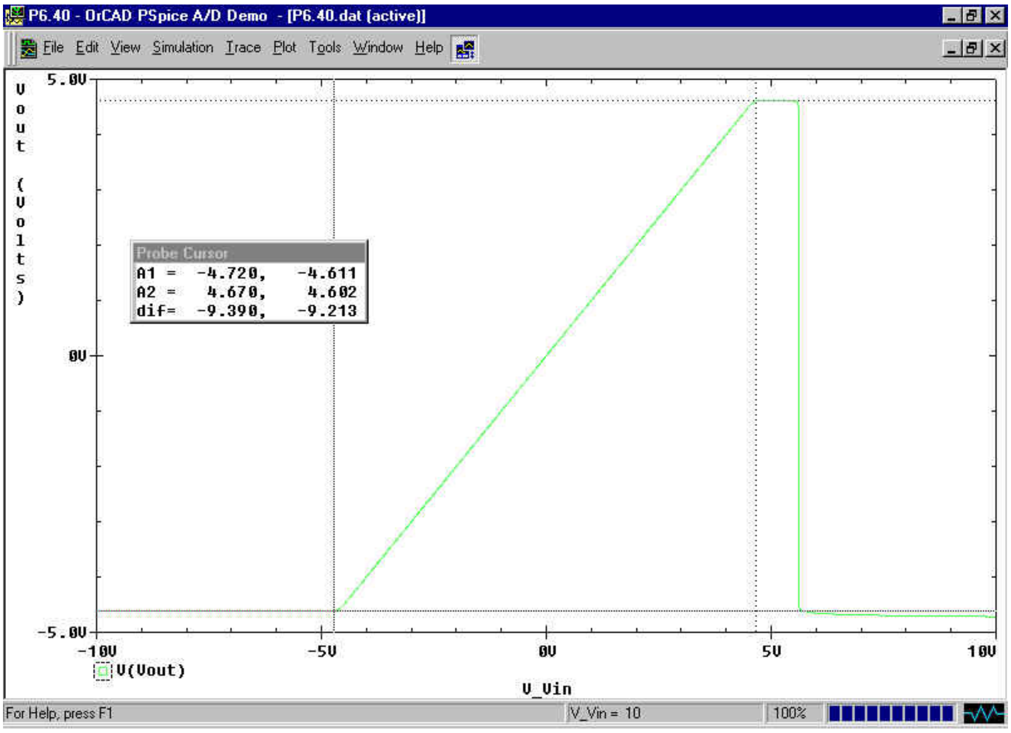
With a gain of –1000/10 = -100 and supply voltage magnitudes of 15 V, we are effectively limited to values of $|v_x| < 150$ mV.

For v_x = -10 mV, PSpice predicts v_d = 6 μV, where the hand calculations based on the detailed model predict 50 μV, which is about one order of magnitude larger. For the same input voltage, PSpice predicts an input current of -1 μA, whereas the hand calculations predict 99.5v_x mA = -995 nA (which is reasonably close).

66. (a) The gain of the inverting amplifier is –1000. At a sensor voltage of –30 mV, the predicted output voltage (assuming an ideal op amp) is +30 V. At a sensor voltage of +75 mV, the predicted output voltage (again assuming an ideal op amp) is –75 V. Since the op amp is being powered by dc sources with voltage magnitude equal to 15 V, the output voltage range will realistically be limited to the range
$-15 < V_{out} < 15$ V.

(b) The peak input voltage is 75 mV. Therefore, $15/\ 75\times10^{-3} = 200$, and we should set the resistance ratio $R_f/\ R_1 < 199$ to ensure the op amp does not saturate.

67. (a)

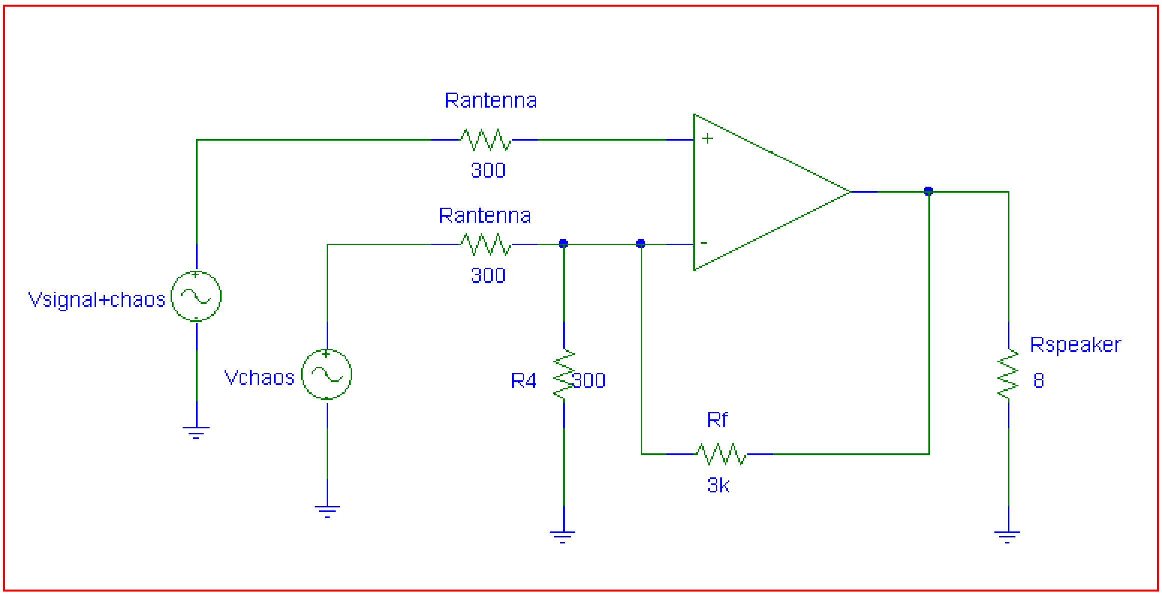


We see from the simulation result that negative saturation begins at V_{in} = –4.72 V, and positive saturation begins at V_{in} = +4.67 V.

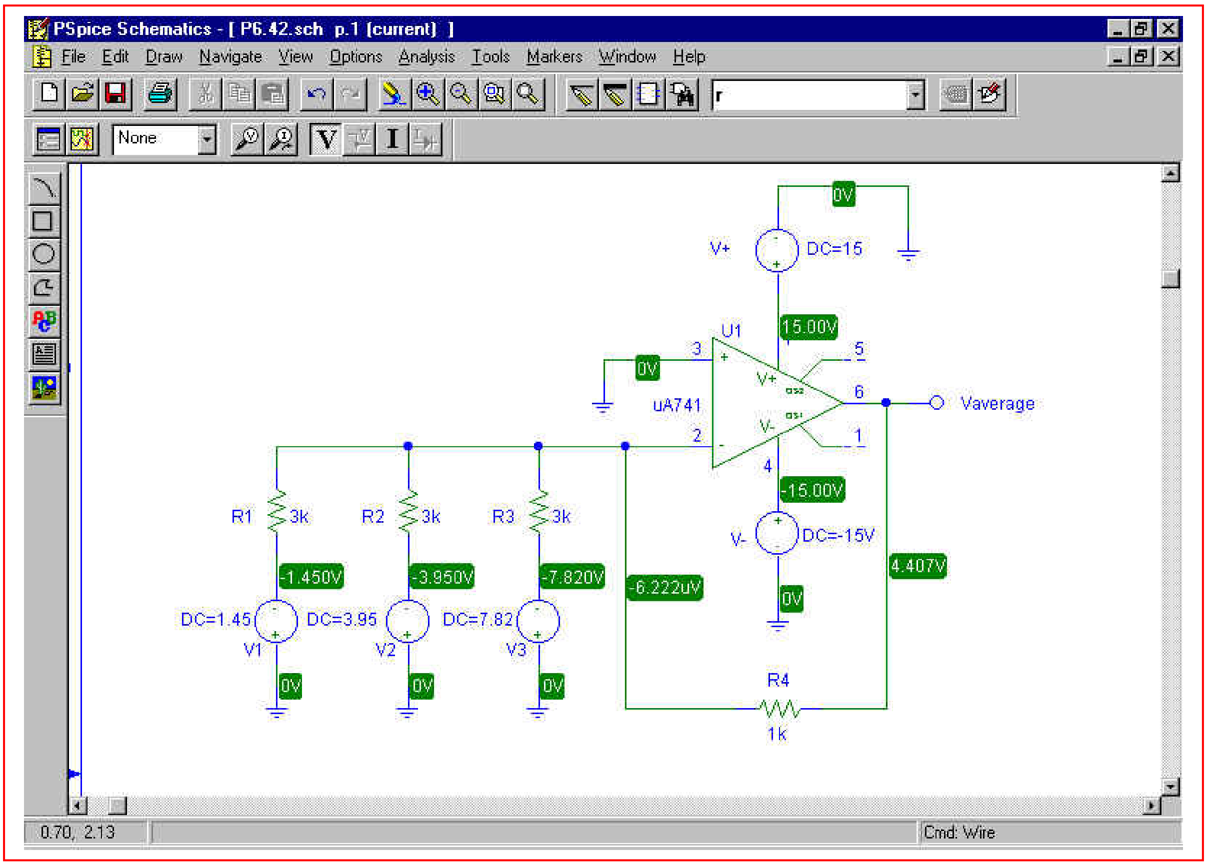
(b) Using a 1 pΩ resistor between the output pin and ground, we obtain an output current of 40.61 mA, slightly larger than the expected 35 mA, but not too far off.

68. We assume that the strength of the separately-broadcast chaotic "noise" signal is received at the appropriate intensity such that it may precisely cancel out the chaotic component of the total received signal; otherwise, a variable-gain stage would need to be added so that this could be adjusted by the user. We also assume that the signal frequency is separate from the "carrier" or broadcast frequency, and has already been separated out by an appropriate circuit (in a similar fashion, a radio station transmitting at 92 MHz is sending an audio signal of between 20 and 20 kHz, which must be separated from the 92 MHz frequency.)

One possible solution of many (all resistances in ohms):



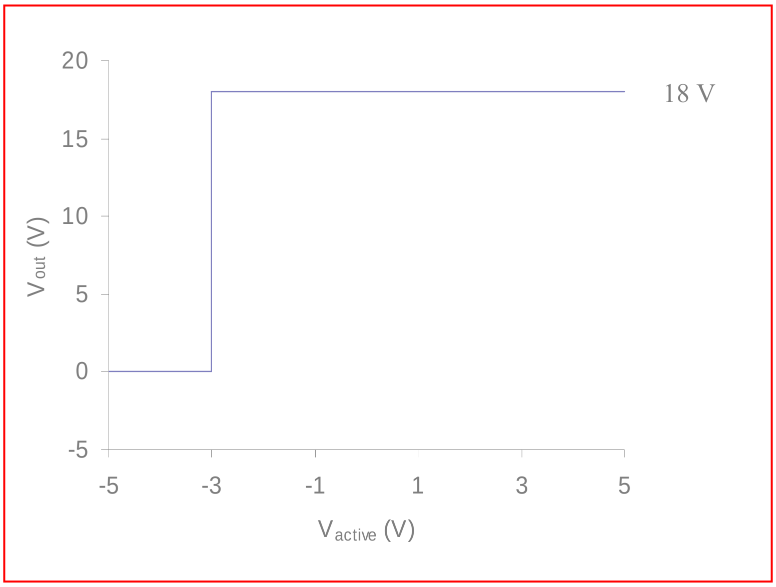
69. One possible solution of many:



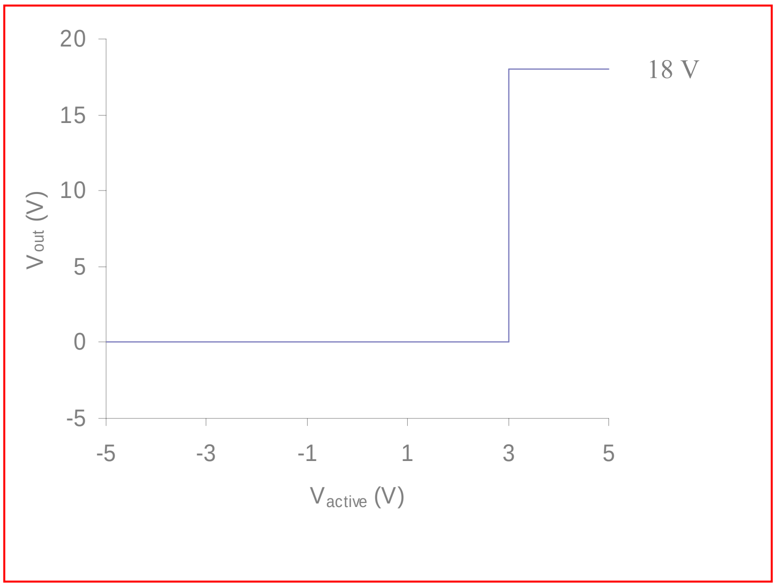
This circuit produces an output equal to the average of V_1, V_2, and V_3, as shown in the simulation result: $V_{average} = (1.45 + 3.95 + 7.82)/3 = 4.407$ V.

70. Assuming ideal situations (ie slew rate = infinite)

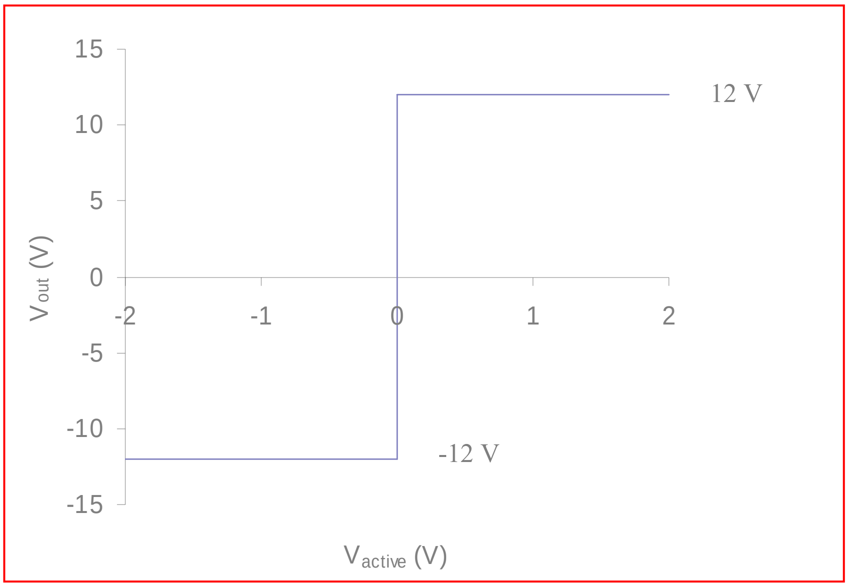
a)



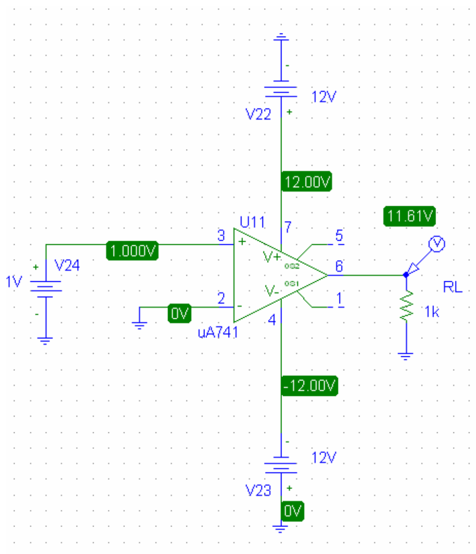
b)

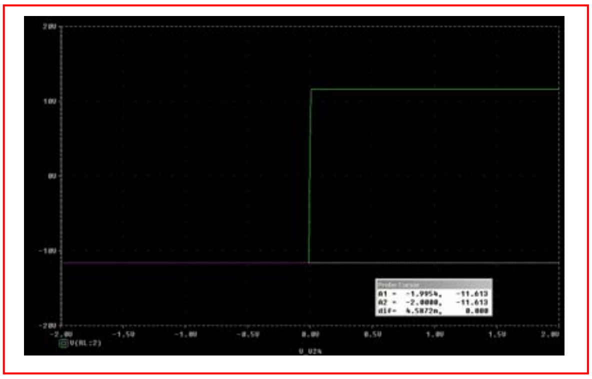


71. a)



b) The simulation is performed using the following circuit:

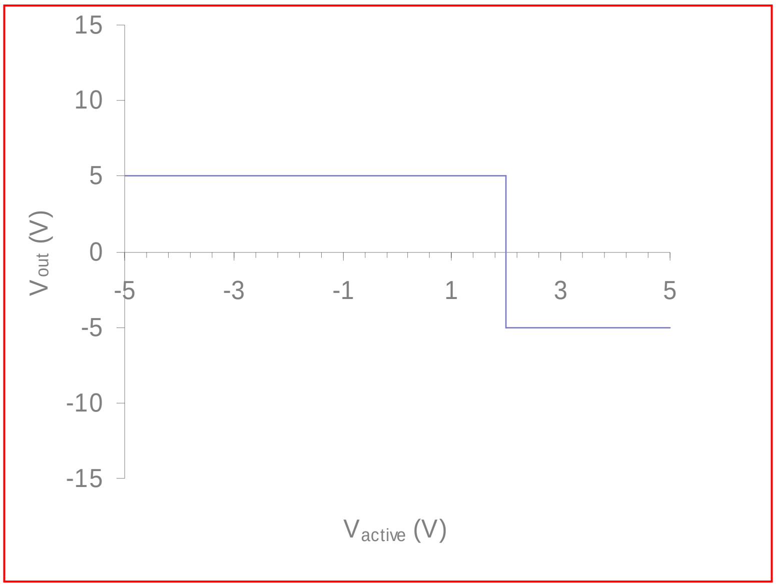




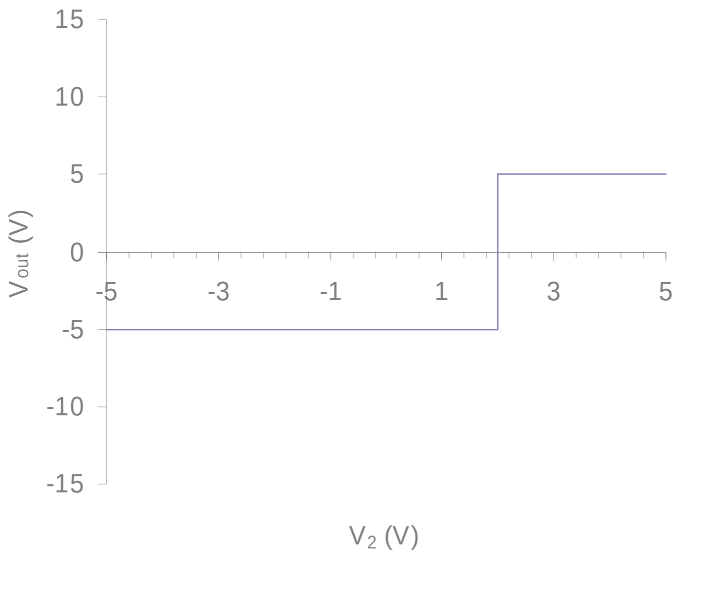
Where R_L = load resistor which is needed for the voltage probe to perform properly. The battery is swept from -2V to +2 V and the voltage sweep is displayed on the next page.

It can be seen that the sweep is very much identical to what was expected, with a discontinuity at 0V. The only difference is the voltage levels which are +11.61V and –11.61 V instead of ±12 V. This is because the output of an op-amp or comparator can never quite reach the supplied voltage.

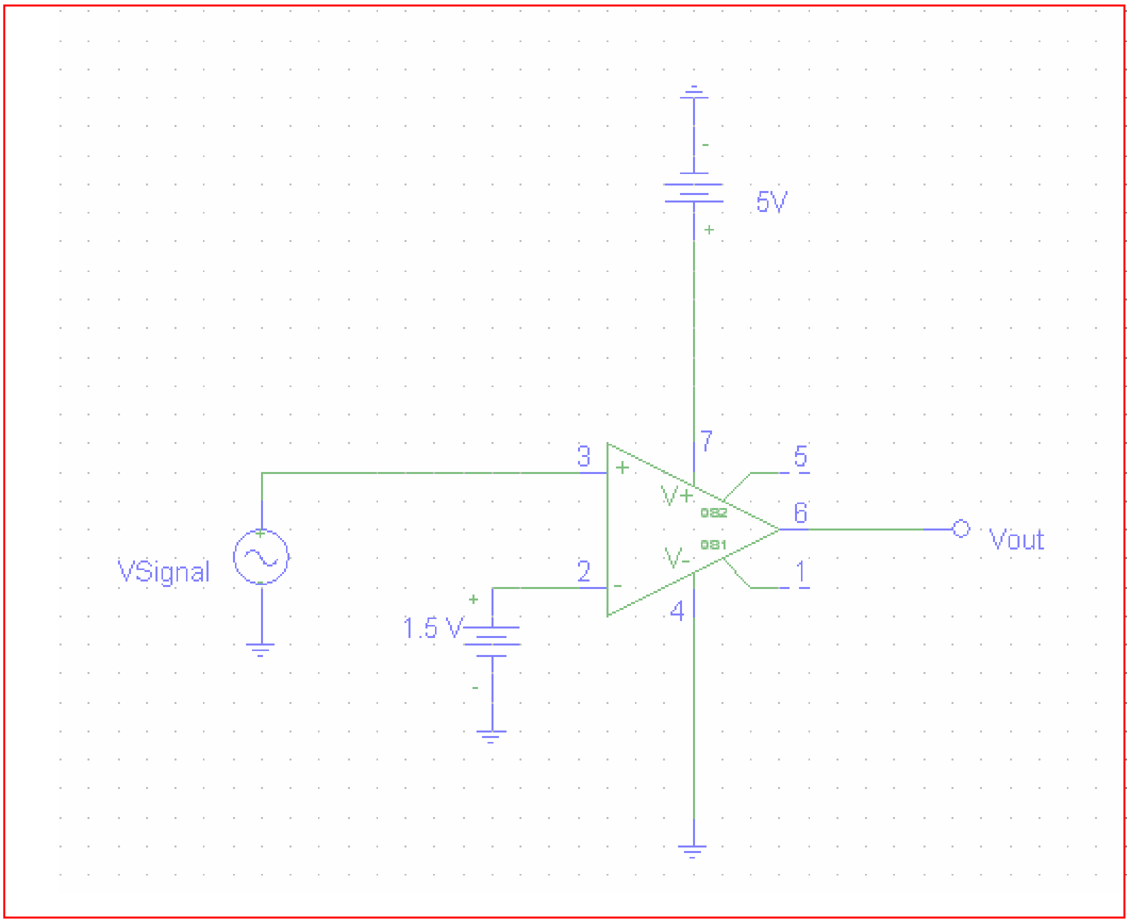
72. a)


15
10
5
0
-5
-10
-15
-5
-3
-1
1
3
5
V out (V)
V active (V)

b)


15
10
5
0
-5
-10
-15
-5
-3
-1
1
3
5
V out (V)
V 2 (V)

73. The following comparator setup would give a logic 0 for voltages below 1.5 V and logic 1 for voltages above 1.5 V



74. The voltage output of the circuit is given by

$$v_{out} = \frac{R_4}{R_3}\left(\frac{1 + R_2 / R_1}{1 + R_4 / R_3}\right)v_+ - \frac{R_2}{R_1}v_-$$

a) When $R_1 = R_3$ and $R_2 = R_4$, the equation reduces to

$$v_{out} = \frac{R_4}{R_3}(v_+ - v_-)$$

When $v_+ = v_-$, $v_{out} = 0$, thus $A_{CM} = 0$. Hence CMRR = ∞

b) If R_1, R_2, R_3 and R_4 are all different, then when $v_+ = v_- = v$,

$$v_{out} = \left(\frac{R_4}{R_3}\left(\frac{1 + R_2 / R_1}{1 + R_4 / R_3}\right) - \frac{R_2}{R_1}\right)v$$

Simplifying the algebra gives

$$v_{out} = \frac{R_1 R_4 - R_3 R_4}{R_1 R_3 + R_1 R_4}v$$

If v_+ and v_- are different, it turns out that it is impossible to separate v_{out} and v_d completely. Therefore, it is not possible to obtain A or CMRR in symbolic form.

75. a) The voltage at node between R_1 and R_2 is

$$V_1 = V_{ref}\left(\frac{R_2}{R_1 + R_2}\right)$$

by treating it as a voltage divider. Similarly, the voltage at node between R_{Gauge} and R_3 is:

$$V_2 = V_{ref}\left(\frac{R_3}{R_3 + R_{Gauge}}\right)$$

Therefore, the output voltage is

$$V_{out} = V_1 - V_2 = V_{ref}\left(\frac{R_2}{R_1 + R_2} - \frac{R_3}{R_3 + R_{Gauge}}\right)$$

b) If $R_1 = R_2 = R_3 = R_{gauge}$ then the two terms in the bracket cancels out, giving V_{out} = 0.

c) The amplifier has a maximum gain of 1000 and minimum gain of 2. Therefore to get a voltage of 1V at maximum loading, the voltage input into the amplifier must fall between 0.001 and 0.5, i.e. $0.5 > V_{out} > 0.001$.

To simplify the situation, let $R_1 = R_2 = R_3 = R$, then at maximum loading,

$$V_{out} = V_{ref}\left(\frac{R}{R+R} - \frac{R}{R + R_{Gauge} + \Delta R}\right) = 12\left(\frac{1}{2} - \frac{R}{R + 5k + 50m}\right)$$

Using this we can set up two inequalities according to the two limits. The first one is:

$$\left(6 - \frac{12R}{R + 5k + 50m}\right) \geq 0.001$$

Solving gives

$$5.999 \geq \frac{12R}{R + 5000.05}$$

$$4998.38 \geq R$$

Similarly, the lower gain limit gives: $5.5 \leq \dfrac{12R}{R + 5000.05}$

$$\Rightarrow 4230 \leq R$$

This gives 4998.38 > R > 4230. Using standard resistor values, the only possible resistor values are R = 4.3 kΩ and R = 4.7 kΩ.

If we take R = 4.7 kΩ, then

$$V_{out} = 12\left(\frac{1}{2} - \frac{4.7k}{4.7k + 5k + 50m}\right) = 0.1855$$

Giving a gain of 5.388. This means a resistor value of R = 50.5/(5.388 – 1) = 11.5 kΩ or 11kΩ using standard value is needed between pin 1 and pin 8 of the amplifier.