Laboratory #4
Feedback Circuits

I. Objectives

1. Review the basic properties of the feedback circuits.
2. Learn how to evaluate the stability of the feedback systems.

II. Components and Instruments

1. Components
   (1) OPAMP IC : LM324 ×1.
   (2) Resistor : 1kΩ ×2, 10kΩ ×1, 100kΩ ×2, 1MΩ ×1
   (3) Capacitor : 0.1μF ×1, 1nF ×1
2. Instruments
   (1) DC power supply (Keysight E36311A)
   (2) Digital multimeter (Keysight 34450A)
   (3) Oscilloscope (Agilent MSOX 2014A)

III. Reading

1. Chapter 9 of the Textbook "Microelectronic circuits, 6th edition, Sedra /Smith".
2. Datasheet of "LM324", National Semiconductor.

IV. Preparation

1. Feedback circuits

(a) Feedback

The definition of feedback is a system which has portion of the output returned to its input and form as a part of the system excitation. The block diagram of a general feedback circuit is shown in Fig. 4.1. As Fig. 4.1 shows, the output signal is sampled and it is then sent to the feedback loop. After some operations, such as scaling, delay, or phase shift, the sampled and processed signal is finally summed with the input source.

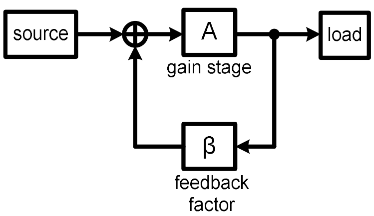
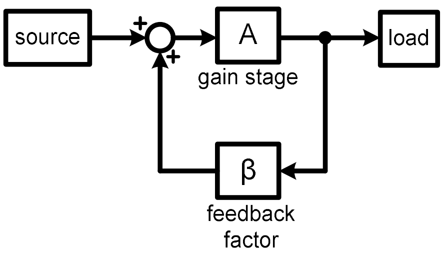


Fig. 4.1 The block diagram of a general feedback system.

Depending on the sign (addition or subtraction) of the feedback path, feedback system can be categorized into two types: positive and negative feedbacks. The differences of these two feedback circuit is explained below.

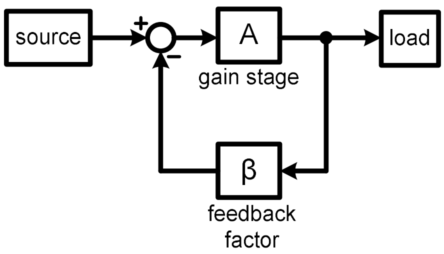
Fig. 4.2 (i) depicts a positive feedback circuit, the transfer function below it tells us about the characteristics of positive feedback. Since the denominator (1-βA) is always smaller than 1, with the feedback process, the circuit will oscillate even a small excitation. In general, positive feedback circuit is used as oscillator.

On the other hand, as shown in Fig. 4.2 (ii), negative feedback can be used to improve the frequency response of amplifier. Negative feedback compares the feedback signal and source, and then the output signal will be modified according to this error signal. Therefore, with negative feedback applied, the output can be maintained under specific conditions. In the following sections, all discussions are based on the negative feedback circuits.



$$A_f = \frac{y}{u} = \frac{A}{1-\beta A}$$

(i)



$$A_f = \frac{y}{u} = \frac{A}{1+\beta A}$$

(ii)

Fig. 4.2 (i) Positive feedback (ii) Negative feedback

(b) Properties of negative feedback circuits

In the application of amplifiers, negative feedback is used to make the operating point insensitive to both manufacturing variations and environmental changes (e.g. temperature, humidity, and brightness).

- Gain desensitivity

  One of the advantages that feedback circuits can offer is gain desensitivity. Usually, the OPAMP characteristics vary from chip to chip because of the process variation. On the other hand, different operating environments also affect the performance of OPAMP. By using negative feedback, the operating points of the transistors can be insensitive to both manufacturing variation and operating environmental change. We can explain this phenomenon more clearly with the following example.

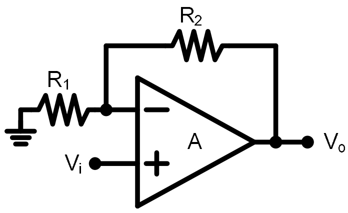


Fig. 4.3 Amplifier with negative feedback loop.

At first, when feedback has not yet been included, the open-loop gain "A" will be affected by manufacturing variation and operating environment. After applying negative feedback to the OPAMP, as Fig.4.3 shows, the closed-loop gain A_f becomes,

$$A_f = \frac{V_o}{V_i} = \frac{A}{1+\beta A} \quad \ldots\ldots (4.1)$$

Where the feedback factor β can be derived as below,

$$\beta = \frac{R_1}{R_1 + R_2} \quad \ldots\ldots (4.2)$$

Furthermore, if $A >> 1$, closed-loop gain becomes,

$$A_f \approx \frac{1}{\beta} = \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1} \quad \ldots\ldots (4.3)$$

From equation (4.3), it can be noted that the closed-loop gain depends on only feedback resistors' value. As a result, negative feedback makes OPAMP less sensitive to component variations.

- Bandwidth extension

Another advantage that negative feedback brings is the extension of bandwidth. To explain this, we assume that the OPAMP to be a single-pole system,

$$A(s) = \frac{A_0}{1 + \frac{s}{\omega_H}} \quad \ldots\ldots (4.4)$$

Then, with negative feedback applied, the transfer function becomes:

$$A_f(s) = \frac{A(s)}{1+\beta\cdot A(s)} = \frac{\frac{A_0}{1+\beta\cdot A_0}}{1+\frac{s}{\omega_H\cdot(1+\beta\cdot A_0)}} = \frac{A_{0f}}{1+\frac{s}{\omega_{HF}}} \quad \ldots\ldots (4.5)$$

From (4.5), we can observe that the negative feedback increases the 3dB frequency by $1+\beta A_0$ times. Meanwhile, because of the unity-gain bandwidth product is a constant for specified OPAMP, the DC gain will reduce $1+\beta A_0$ times. Fig. 4.4 demonstrates the bandwidth extension result.

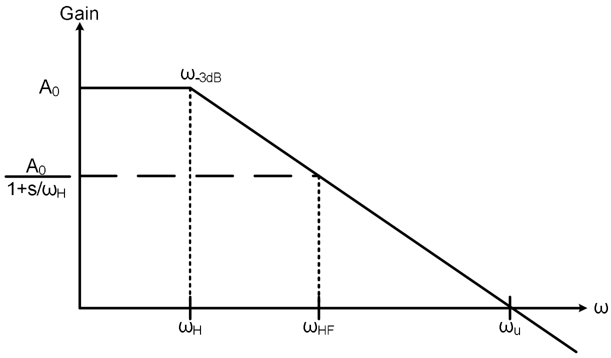


Fig. 4.4 Bandwidth extension results from negative feedback.

- Noise reduction

In practice, there will are disturbance sources which might be injected into the system. To maintain the system operation, the noise should be removed or minimized as far as possible. By applying the negative feedback loop, the non-ideal effect caused by the injected noise can be significantly reduced.

With the noise path shown in Fig.4.5, the transfer function with noise source V_d included can be derived as follows.

$$\begin{cases} V_i = V_s - \beta \cdot V_o \\ V_o = V_d + A \cdot V_i \end{cases} \quad \ldots\ldots (4.6)\ (4.7)$$

$$(1+\beta \cdot A)V_o = A \cdot V_s + V_d \quad \ldots\ldots (4.8)$$

$$\therefore V_o = \frac{A}{1+\beta A} \cdot V_s + \frac{1}{1+\beta A} \cdot V_d \quad \ldots\ldots (4.9)$$

Obviously, according to (4.9), the noise item can be ignored if A>>1.

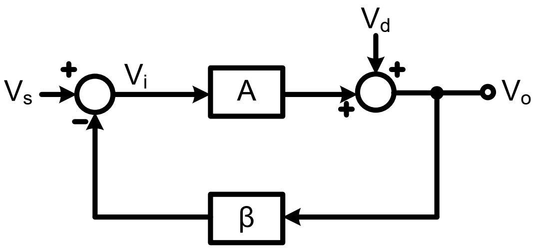


Fig. 4.5 Negative feedback system with noise source injected.

- Smaller nonlinear distortion

  If an OPAMP is used without negative feedback, its open-loop gain "A" will vary since that the different amplitudes of input signal change the operating point. With negative feedback applied, the factor decides gain transfer function is dominated by β, which is less sensitive to the amplitude of the input signal. Fig. 4.6 depicts the transfer curves with/without negative feedback applied.

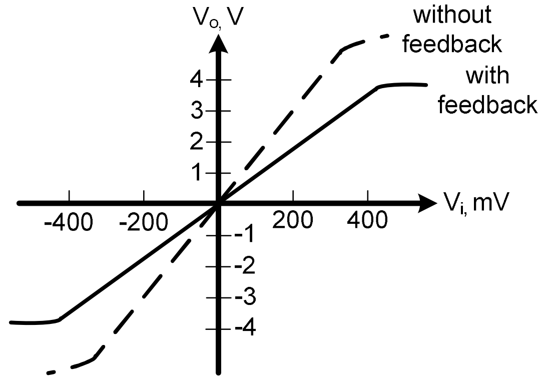


Fig. 4.6 Transfer curves with/without negative feedback.

- Reduced gain and more phase shift

  Although negative feedback features many advantages, there is still something to be sacrificed, such as $1+\beta A$ times reduction of the gain (4.1). Moreover, negative feedback may introduce extra poles and zeros and appends phase shift to the overall system. Because of the additional phase shift, system stability must be carefully evaluated. The stability issue will be discussed in the next section.

2. Multiple poles system and loop stability

   Negative feedback will introduce extra poles and zeros into system, and the resulted phase shift may lead the system instability. In this section, the methods how to evaluate the stability of a system by using Bode plot is briefly reviewed. (For further details and other evaluating methods, please refer to the section 8.8~8.10 in the text book and the related books in the field of control engineering)

   (1) One-pole system

   In a one-pole system, maximum phase shift is 90 degrees, and the phase margin is at least 90 degrees. So, there is no stability problem in one-pole system.

(2) Multiple pole system and stability analysis

In multiple poles system, the relative positions of poles & zeros will change the shape of Bode plot. By moving the positions of poles and zeros, system may have broader bandwidth. In frequency domain, one pole will lead gain decay with -20dB/decade slope and phase reduction by 90^o. Instead, one zero will lead gain increase with +20dB/decade slope and $+90^o$ phase shift.

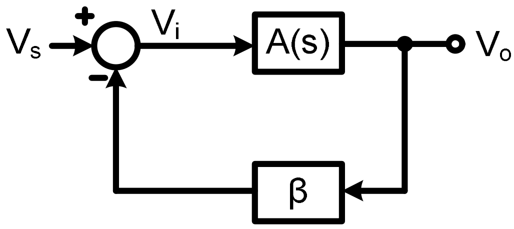


Fig. 4.7 A negative feedback system.

To evaluate the stability of system as shown in Fig. 4.7, there are two parameters that called gain margin (GM) and phase margin (PM) could be used. Gain margin is defined as the magnitude of gain at -180-degrees phase shift. Eq. (4.10) describes the gain margin mathematically.

$$GM = -20\log_{10}(\left|\beta A(s)\right|_{s=j\omega_{-180^\circ}}) \quad \text{...... (4.10)}$$

In additional to the gain margin, another index is the phase margin. Phase margin is defined as the difference between -180 degrees and the phase shift at crossover frequency. The mathematical description is as below.

$$PM = \angle\beta A(s)\Big|_{s=j\omega_c} - (-180^\circ) \quad \text{...... (4.11)}$$

Fig 4.8 is a diagram which indicates the definitions of the gain margin and the phase margin on the Bode plot. Theoretically, to keep a system stable, the negative feedback system should have positive gain margin and phase margin, or else the system stability cannot be guaranteed.

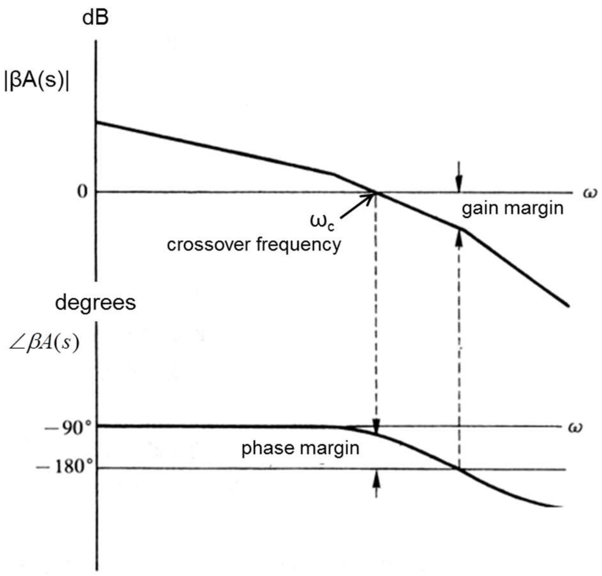


Fig. 4.8 Gain margin and phase margin.

V. Explorations

The layout and connections of LM324 OPAMPs is shown in Fig. 4.9. As what it shows, LM324 consists of four independent, high gain, internal frequency compensated OPAMPs in a DIP package. LM324 uses single supply instead of dual supplies.

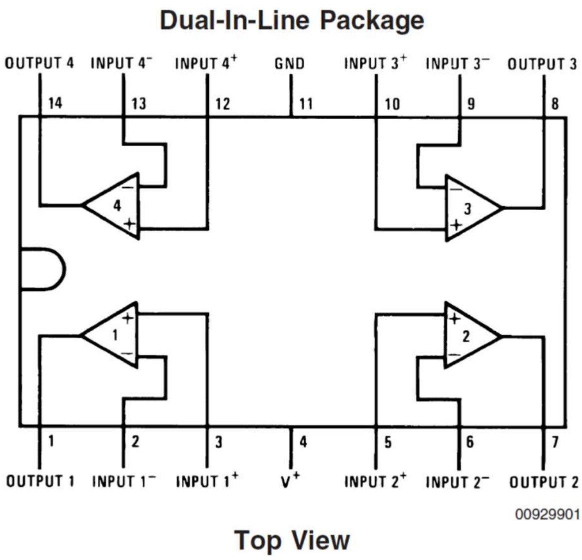


Fig. 4.9 Pin diagram of LM324 OPAMP

Table 4.1 Absolute maximum ratings of LM324 OPAMP

Supply voltage	32	V
Differential input voltage	32	V
Input voltage	-0.3 to +32	V
Operating Temperature Range	0 to +70	^{o}C

NOTE: Pin 4 must be connected to the most positive voltage (**+15V** in this Lab), and pin 11 to the **ground**. For the sake of safety, maintain the voltage between pin 4 and pin 11 at or below 15V to avoid internal voltage breakdown. **Make sure you turn off the power supply before changing any circuit connection**.

1. Open-loop Frequency Response

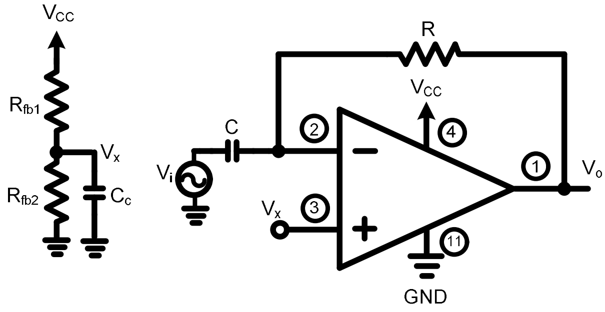


Fig. 4.10 Open-loop gain measurement setup.

(1) Assemble the circuit as shown in Fig. 4.10 and select R= 1MΩ, R_{fb1}=R_{fb2}=100 kΩ, C_c=0.1 μF and C=1 nF. Make sure that the pin4 and pin11 are connected to power supply correctly.

(2) Set V_{CC}=5V, and bias pin3 at 0.5V_{CC} (ignore the offset voltage).

(3) Inject a 0.02 V_{pp}, 10 kHz sine wave signal with 2.5 V_{offset} at V_i. Use the oscilloscope to measure V_i and V_o and find the voltage gain of $\frac{V_o}{V_i}$ in dB.

(4) Repeat the steps at different bias conditions and record the current values listed in Table 4.2.

2. Closed-loop Frequency Response

2.1 Feedback ratio $\beta = \frac{1}{2}$

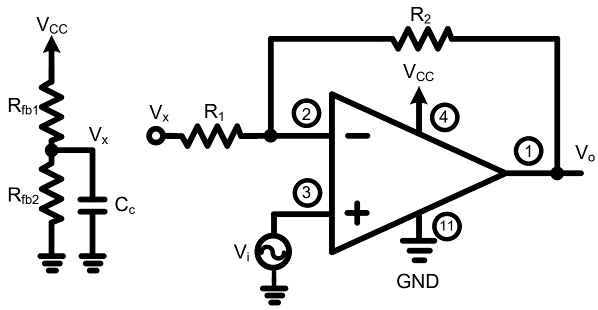


Fig. 4.11 Negative feedback OPAMP with $\beta = \frac{1}{2}$

(1) Assemble the circuit as shown in Fig. 4.11 and select R_1=1 kΩ , R_2=1kΩ, R_{fb1}=R_{fb2}=100 kΩ, and C_c=0.1 μF. Make sure that the pin4 and pin11 are connected to power supply correctly.

(2) Set V_{CC}=5V, then record V_2, V_3 and V_o.

(3) Inject a 0.2 V_{pp}, 1 kHz sine wave signal with 2.5 V_{offset} at V_i. Use the oscilloscope

to measure V_i and V_o and find the voltage gain of $\frac{V_o}{V_i}$ in dB.

(4) Repeat (3) with other input frequencies listed in Table 4.3.

2.2 With feedback ratio $\beta = \frac{1}{11}$

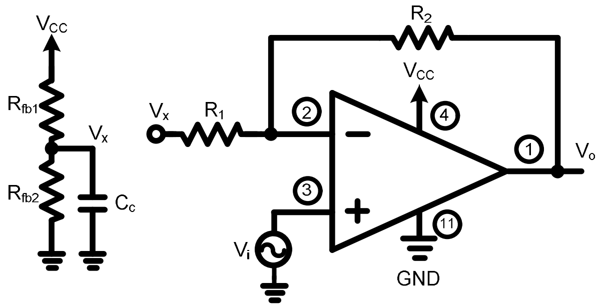


Fig. 4.12 Negative feedback OPAMP with $\beta = \frac{1}{11}$

(1) Assemble the circuit as shown in Fig. 4.12 and select R_1=1 kΩ , R_2=10 kΩ, R_{fb1}=R_{fb2}=100 kΩ, and C_c=0.1 μF. Make sure that the pin4 and pin11 are connected to power supply correctly.

(2) Set V_{CC}=5V, then record V_2, V_3 and V_o.

(3) Inject a 0.2 V_{pp}, 1 kHz sine wave signal with 2.5 V_{offset} at V_i. Use the oscilloscope to measure V_i and V_o and find the voltage gain of $\frac{V_o}{V_i}$ in dB.

(4) Repeat (3) with other input frequencies listed in Table 4.4.

VI. Reference

1. “Laboratory manual for microelectronic circuits”, third edition.
2. “Microelectronic circuit”, fifth edition.
3. “LM324” datasheet, National Semiconductor.

Laboratory #4 Pre-lab

Class:

Name: Student ID:

1. Problem 1 (PSPICE simulation)

   Referring to Fig. 4.13, use PSPICE to find:

   (1) Time-domain waveform of V_i and V_{OUT} (depict both waveforms in the same plot.)

   (2) Frequency-domain Bode plot (from 10k~10M Hz).

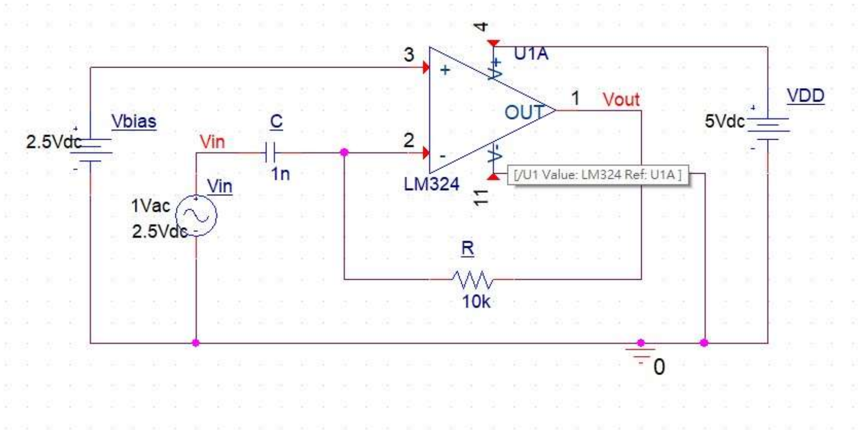


Fig. 4.13 Open-loop gain simulation

2. Problem 2 (PSPICE simulation)

   Referring to Fig. 4.14, use PSPICE to find:

   (1) Time-domain waveform of V_i and V_{OUT} (depict both waveforms in the same plot.)

   (2) Frequency-domain Bode plot (from 0.5k~10M Hz).

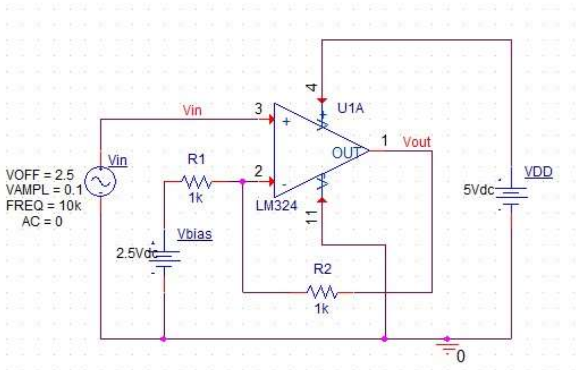


Fig. 4.14 Closed-loop simulation

3. Problem 3 (PSPICE simulation)

Referring to Fig. 4.15, use PSPICE to find:

(1) Time-domain waveform of V_i and V_{OUT} (depict both waveforms in the same plot.)

(2) Frequency-domain Bode plot (from 0.5k~10M Hz).

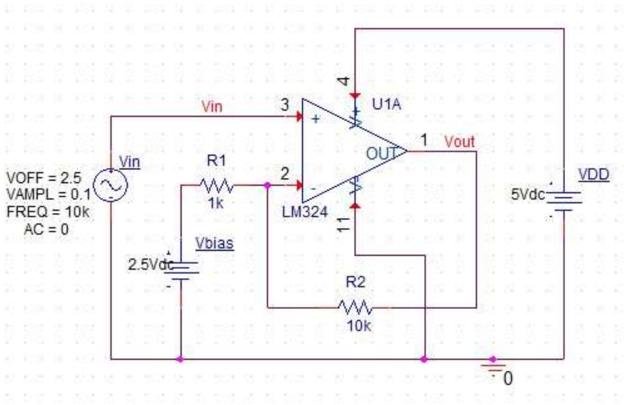


Fig. 4.15 Closed-loop simulation.

Laboratory #4 Report

Class:

Name: Student ID:

1. Open-loop Frequency Response

V_2=________ V, V_3=________ V and V_o=________ V.

Table 4.2

f_{in} (Hz)	$V_{i,pp}$ (V)	$V_{o,pp}$ (V)	$A_o = 20\cdot\log\left(\frac{V_o}{V_i}\right)$ (dB)
20k			
40k			
60k			
80k			
100k			
200k			
500k			

2. Closed-loop Frequency Response ($\beta = \frac{1}{2}$)

V_2=________ V, V_3=________ V and V_o=________ V.

Table 4.3

f_{in} (Hz)	$V_{i,pp}$ (V)	$V_{o,pp}$ (V)	$A_f = 20\cdot\log\left(\frac{V_o}{V_i}\right)$ (dB)
10k			
20k			
100k			
200k			
500k			
1M			
10M			

3. Closed-loop Frequency Response ($\beta = \frac{1}{11}$)

V_2=________ V, V_3=________ V and V_o=________ V.

Table 4.4

f_{in} (Hz)	$V_{i,pp}$ (V)	$V_{o,pp}$ (V)	$A_f = 20 \cdot \log\left(\frac{V_o}{V_i}\right)$ (dB)
1k			
5k			
10k			
20k			
100k			
200k			
500k			
1M			
10M			

4. Problem 1

Use MATLAB or Excel to plot the open-loop Bode plot according to Table 4.2 and the closed-loop Bode plot according to Table 4.3 and Table 4.4.

5. Problem 2

Compare the two Bode plots which have different β values. What are the differences? If a larger feedback ratio (e.g. $\beta = \frac{1}{100}$) is used, try to predict what will happen on OPAMP output node?

6. Bonus

In Exp.1, why can't we measure the open-loop gain directly? Try to explain your opinion. (Hint: you may need your pre-lab work.)

7. Conclusion