Laboratory 7
Comparators, Photoresistors, Thermistors, and Hysteresis

Introduction

In this lab, you will learn about a stripped-down, souped up, type of operational amplifier (op amp) called a *comparator*, used to accurately compare two voltages. You will provide these two voltages using a Wheatstone bridge, in which one voltage divider is a reference and the other is varied by a sensor, either a photoresistor or a thermistor. The comparator will thus be able to control an output based on a measurement of light or temperature. You will be introduced to the concept of hysteresis and learn how it can be used in an oscillator.

Parts List

- 2N3904 Transistor
- LM339 comparator
- Cadmium-sulfide photoresistor (PVD-P9007)
- 10 K Ω Thermistor (BC2298-ND)
- Red LED
- 100 K Ω potentiometer
- 39 Ω ½ Watt resistor
- various ¼ resistors

The symbol for a comparator is shown in Fig. 1, with two inputs (+) and (-), an output, a positive power supply and a ground. These last two connections provide power to the comparator. As with any op amp, the comparator has 3 basic qualities:

(1) high input impedance: practically no current enters the inputs

(2) low output impedance: the output can handle appreciable current

(3) very high gain: $V_{OUT} \cong \infty (V_{IN+} - V_{IN-})$

The comparator is generally used to determine which of the two inputs has a higher voltage.

If $V_{IN+} > V_{IN-}$ then V_{OUT} goes as high as it can (near the positive power supply, +V).

If $V_{IN+} < V_{IN-}$ then V_{OUT} goes as low as it can (near ground).

If $V_{IN+} = V_{IN-}$ or more realistically if the two inputs are within some small difference of each other (called the “maximum offset voltage”), the output is indeterminate.

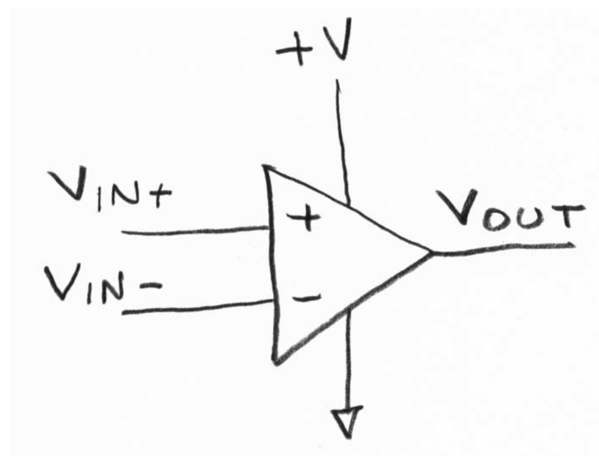

Fig. 1

The Comparator

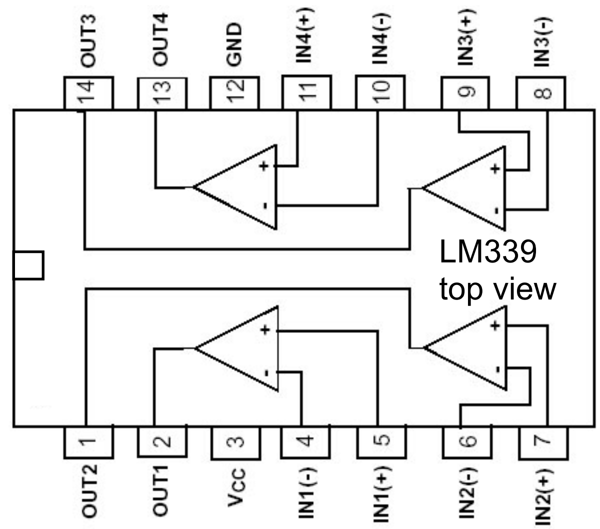

Fig. 2

In most respects, the comparator is less sophisticated internally than a full-fledged operational amplifier (which you will use in Lab 8), and its specifications are inferior, except for speed. We will use the LM339 quad comparator, a very useful 14-pin integrated circuit containing 4 comparators (see pin-out diagram in Fig. 2 and specifications in Fig. 3). Note the fast response time of 1 μs.

Unlike a full-fledged op amp, which typically uses + and – power supplies, comparators such as the LM339 expect only a single + power supply (V_{CC} = pin 3) and ground (pin 12). The chip can work over a wide range of power supply voltages, from 2-36 V (see Fig 3). The comparator's output is designed only to *sink*, but not *source*, positive current. This type of output is known as *open collector*, since within the chip, the output is connected to the isolated collector lead of a bipolar NPN transistor. Thus, a path (usually a resistor) must be supplied to provide current from the positive power supply to the output, as will be seen in each of the circuits in this lab. Full-fledged op amps usually have two transistors at their output, arranged in a "push-pull" configuration that can both source and sink current.

LM339 Quad Comparator	
Positive supply voltage (V_{CC})	2-36 V
Quiescent supply current	0.8 mA
Input current	25 nA
Max output current	16 mA
Max output saturation voltage (low)	1 V
Response time	1 μs
Max offset voltage (input + to -)	3 mV
Output type	Open Collector

Fig. 3

The maximum current that each of the comparators in the LM339 can sink is 16 mA, and the furthest from ground that the collector will ever be, when that transistor is completely on (saturated), is 1 V. The biggest error between the + and – inputs (the biggest difference when the comparator considers them equal) is 3 mV. Looking at the specifications in Fig. 3, what would the effective input impedance be for the LM339 assuming 5 V is present at one of the inputs, and how does that compare to the theoretical input impedance for a perfect op amp? **(A)**

The Photoresistor

The cadmium-sulfide photoresistor is a robust (hard to destroy) and simple (obeys Ohm's law) component, whose resistance decreases when photons create carriers in its substrate. The photoresistor is less sensitive than its cousins, the photodiode and phototransistor, but simpler to use. At a given level of illumination, it works just like a resistor, linear and thus behaving the same for current in either direction. The specifications for our photoresistor are shown in Fig. 4. Use your ohmmeter to measure and record the resistance of your photoresistor in the dark and under a bright light. **(A)**

PVD-P9007 Cadmium Sulfide Photoresistor	
light resistance @10 lux	10-100 K Ω
dark resistance	~1 M Ω
response time	10-60 msec

Fig. 4

Build the photoresistor circuit in Fig. 5, being sure to insert the integrated circuit with the little notch to the right and observing the proper pin numbering. Note the specification of clockwise ("cw") rotation for the pot, recalling from Lab 2 that clockwise moves the wiper (pin 2) towards pin 3 (the pin numbers are on the pot).

The circuit employs a Wheatstone bridge, consisting of 4 resistors arranged as 2 voltage dividers. These include the photoresistor, and the pot representing 2 resistors in a divider above and below the wiper. Basically, the comparator asks the question, which of the two dividers is yielding a higher voltage? Under normal ambient lighting, adjust the pot so that the LED just turns off (when the comparator output is high). If you have wired the potentiometer properly, this set point will be found for brighter ambient lighting conditions by turning the potentiometer further clockwise.

Now cast a shadow on the sensor. You should see the LED turn on. Explain the circuit's behavior in terms of the voltages on pins 4, 5, and 2, with and without the shadow. **(B)**

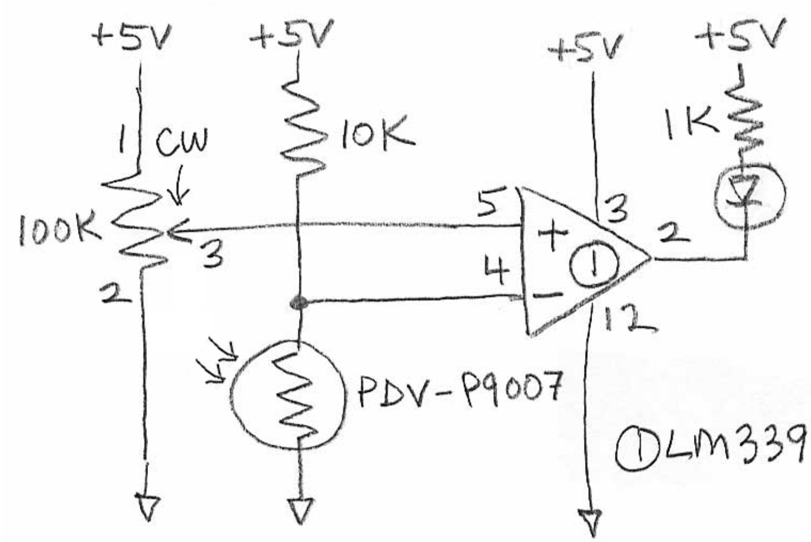

Fig. 5

Thermistors

Thermistors are resistors with intentionally "bad" immunity to temperature effects. Thermistors come with both positive and negative temperature coefficients ($\Delta\Omega/\Delta°C$). Ours is negative (see specifications in Fig. 6). Measure and record the resistance of the thermistor at room temperature. With the ohmmeter still attached, warm the thermistor with your fingertip (not touching the electrical leads) and record the resulting resistance. **(C)** Note the symbol for the thermistor in Fig. 7 is a resistor with a circle around it, very much like the symbol for the photoresistor in Fig. 5, but without the arrows symbolizing incoming light for the photoresistor.

BC2298-ND Thermistor

Resistance at 25 degrees C ~10K Ω
Temperature coefficient: Negative

Fig. 6

Thermoregulated Heater with Hysteresis

Construct the circuit in Fig. 7, without the 2.4 M feedback resistor (labeled *hysteresis*), and ignoring for now the illustration on the right of taping the thermistor to the resistor. Be sure to use the special ½ Watt 39 Ω resistor (you received one in a baggie with your PittKit, and there are more in Cabinet 2). Adjust the pot so that the LED just turns on. Touch the thermistor to warm it until the LED turns off. Explain the behavior in terms of the expected voltages on pins 4, 5 and 2. **(D)** Notice the addition of the transistor in a common-emitter configuration to boost current and stiffen the voltage source (the LM339 is only rated at 16 mA, but the 2N3904 can handle a lot more current, ~200 mA). Given that the 39 Ω heater resistor is a ½ Watt resistor (it's maximum specified power), measure the voltage at the collector of the 2N3904 transistor and calculate the power dissipated by

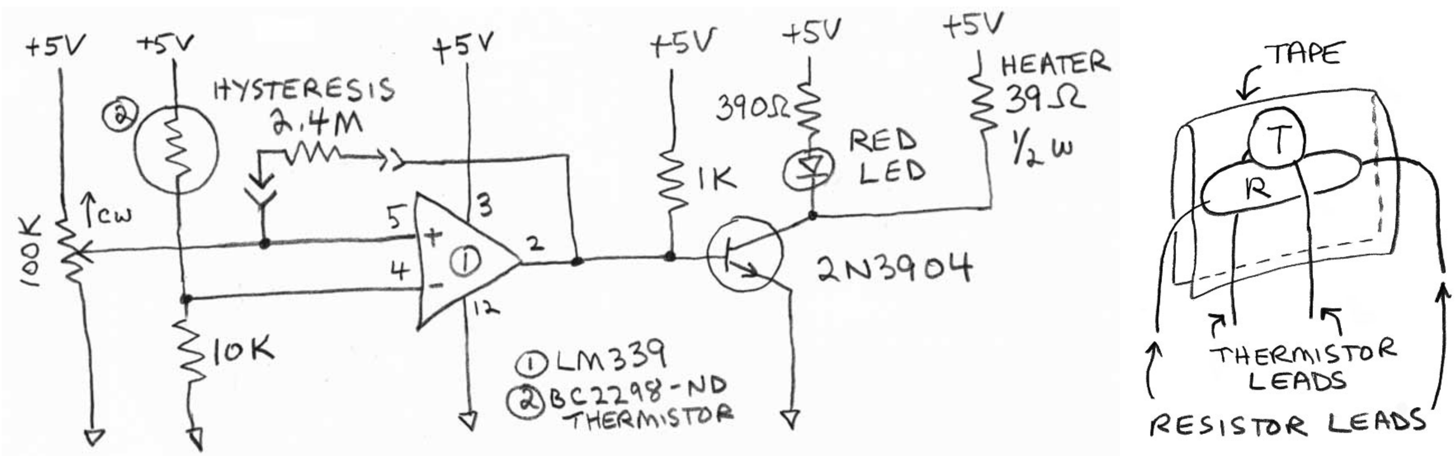

Fig. 7

the 39 Ω resistor. **(E)** The transistor is being saturated, i.e., it is "on" as far as it can go and is not in its active (biased) region. Thus, I_C is not βI_B, but rather is limited by other components, mainly the 39 Ω heater resistor. Note the clockwise notation of the potentiometer on this schematic is upwards whereas on the previous (photocell) circuit it was downwards. In both cases, the intended result is that turning the pot clockwise should turn the LED *on*. Explain why the direction needs to be reversed in the second circuit (hint consider the transistor). **(F)**

Now physically arrange the 39 Ω heater resistor and the thermistor as shown in Fig. 7 (right), so that heat given off from the resistor will maximally affect the thermistor. The two elements should touch physically, but the leads should not touch. Scotch tape may be used to hold them in the proper configuration and to thermally insulate them from the room.

Adjust the pot counterclockwise so that the LED turns off and let the 100 Ω resistor cool to room temperature. Then turn the pot clockwise so that the LED just turns on. The resistor should heat the thermistor and turn the LED (and the heater) off again. Observe the behavior of the LED as it indicates continued thermoregulation by the circuit by (hopefully) turning on and off. Now add the 2.4 MΩ feedback resistor and, again, observe the LED. Describe the change in behavior with the addition of hysteresis. **(G)**

The circuit demonstrates how hysteresis can make the comparator behave in a more predictable manner. Without hysteresis, the thermoregulation may exhibit "chatter" (rapid and sporadic oscillation). Or it may come to rest in a half-on, half-off state, which is not what comparators (or most heaters) are supposed to do. Hysteresis provides positive feedback for more predictable behavior, driving the output to a stable *on* or *off* state. The 2.4 MΩ resistor either raises or lowers the "set point" established by the potentiometer, by being in parallel with either the top or bottom half of the potentiometer, depending on the state of the comparator (Fig. 8).

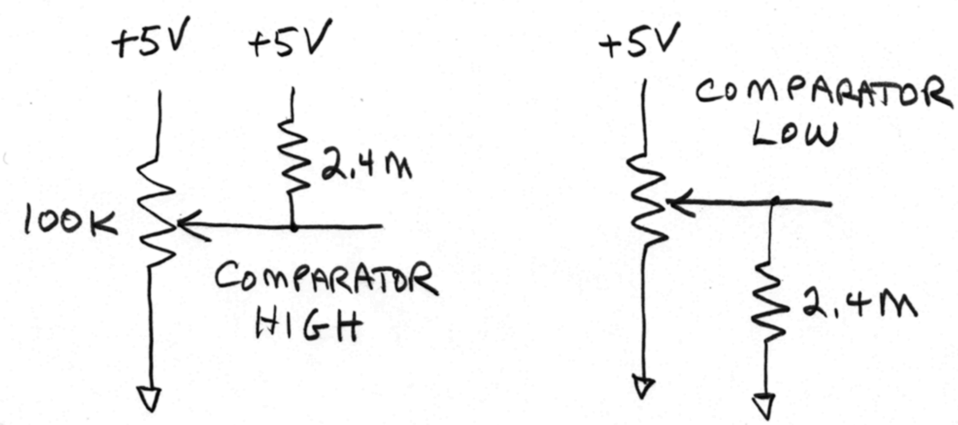

Fig. 8

As we shall see, most digital circuits employ hysteresis internally to each of their inputs to prevent loitering in the gray zone between 0 and

1 when changing state. In digital circuits, this is known as a Schmidt trigger.

Comparator Based Oscillator

Now you will continue to use the LM339 comparator to construct an oscillator using hysteresis. Recall how the thermoregulator circuit heated and cooled between two set points established using hysteresis. It was, in effect, an oscillator, switching back and forth from one state to the other. The circuit in Fig. 9 is similarly unstable, again using hysteresis (the feedback resistor R3) to temporarily stabilize each state. But now, instead of changing the temperature of a mini-environment by powering a heater resistor, the output changes the voltage on a capacitor, charging and discharging it through a resistor.

Build the circuit in Fig. 9, and measure its frequency by counting the blinking LED against a clock. **(H)** Use the oscilloscope in dual trace mode to examine the voltages on pins 4 and 5 of the comparator. Sketch these voltages, and label them as to when the LED is on or off. **(I)** Explain the voltages at pins 4 and 5 in terms of the circuit, describing the functions of resistors R1, R2, R3 and R4, and the capacitor. **(J)** Explain the observed frequency from the RC time constant, using R4 as the resistance. **(L)** Replace R4 with a 1 KΩ resistor. What frequency do you observe from the circuit now, using the scope to measure it? Explain the new observed frequency. **(M)**

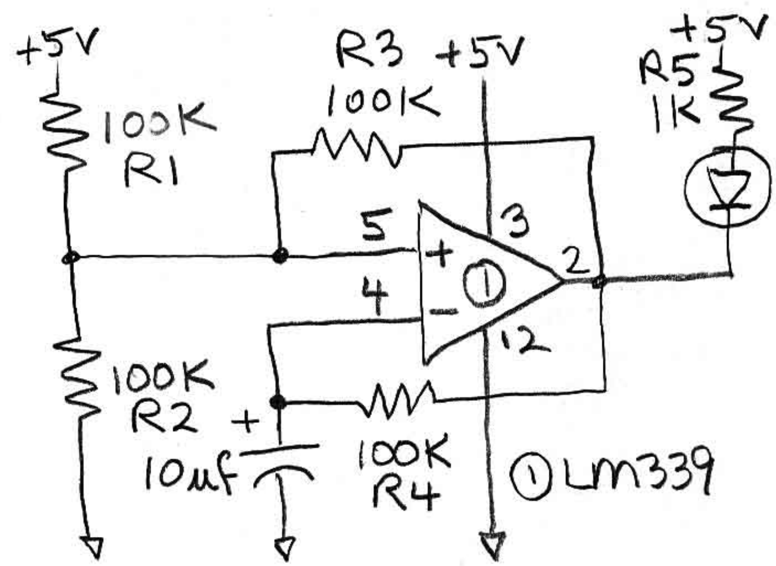

Fig. 9