Introduction to Sensors

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1 Concept Review

- Last class, we passed around mechanical switches, reed (magnetic) switches, linear varistors, photoresistors, and thermistors.
- Some sensors act primarily as switches, and some act as variable resistors (note that extremely low or high resistance behaves essentially as an open or closed switch).
- We built simple circuits with these components and appropriate resistors, using incandescent bulbs as indicators and transistors to amplify low currents.

2 Today's Concepts

- We are adding one new sensor component today, pressure-sensing resistors. We also introduce operational amplifiers (op-amps).
- Transistors have three pins, a base (B), collector (C), and emitter (E). The control signal comes into B, and causes current to flow from C to E. The datasheet for the TO-92 shows how these labels correspond to the circuit symbol and the actual transistor package. The TO-220 has a different assignment of pins, also listed in its datasheet.
- The LM358 contains two op-amps in one package. First connect them to power (pin 8) and ground (pin 4), and then you have one op-amp on each side. Check the datasheet for details on the pinouts.
- To build circuits with more sensitivity to sensor signals, you need to determine the range of outputs and limit or amplify them as necessary. Voltage and current dividers are effective, but dissipate power quickly.
- When designing these multi-stage circuits, check the input and output requirements on I and V at every stage; if you expect your thermistor to vary from 36 $k\Omega$ to 6 $k\Omega$ under normal operating conditions, a 12V power supply will produce $< .5mA$. That's a good range to feed into a transistor, but not adequate to directly run a lightbulb. (See further discussion below.)
- Using op-amps with feedback resistors allows us to multiply a voltage by a precise amount.

3 Tips for Success

1. Diodes (including LEDs), transistors, and op-amps are directional - check their pin diagrams to be sure about where power, ground, and signals should go. Running too much power through these components can burn them out!

2. Resistors, physical switches, and incandescent bulbs are **not** directional.
3. Breadboards have power rails on both edges, running the length of the board. Each horizontal row is also connected, but not across the center gap; put your op-amp across the gap so each pin is isolated properly.
4. To troubleshoot a circuit that's not working, first start by double-checking that everything is connected according to the diagram (it's easy to be one row off), with correctly-valued resistors and nothing flipped around. Next, use a multimeter to check that voltages are what you expect, and look for any unexpectedly large drops or short circuits.
5. If everything seems to be working properly but the current is too low to produce much light, consider changing the lightbulb for an LED+resistor combo.

Circuit	**Resistor Value**	**Color Code**
3a (thermistor)	$120 \times 10^2\Omega$	brown red black red (brown)
3a (photoresistor)	$499 \times 10^2\Omega$	yellow white white red (brown)
3b (current-source)	$22 \times 10^1\Omega$	red red brown (gold)

Table 1: Resistors have printed stripes denoting their value. The first two or three stripes are the digits, followed by one stripe for the exponent value, and the last stripe giving the tolerance or variation.

4 Bonus Topics

4.1 Why Circuits 2e, 2f Fail

Why do the naïve circuits 2e and 2f not work? The thermistor has a resistance of about 12 $k\Omega$ (12,000 Ω) at room temperature. The lamp has a resistance of about 20 Ω. The circuit follows the rule $V = IR$, where V is the voltage drop over a component, R is the resistance of the component, and I is the current through the component.

The current through the thermistor is the same as the sum of the currents through the 12k resistor and the lamp. But since 12k is much larger than 20, nearly all the current goes through the lamp, and none through the resistor. And since the thermistor also has a much higher R than the lamp, almost all of the voltage drop is across the thermistor, and almost none across the lamp. Another way to describe the problem is that the current through the lamp is $I = \frac{V}{R} = \frac{12V}{12{,}000\Omega+20\Omega} = 1mA$, which is very small. Compare that to circuit 2(a), with $I = \frac{12V}{20\Omega} = 0.6A$.

The circuit in 2f fails to work for the same reason, except the photoresistor has an even higher resistance than the thermistor, so even less current flows.

4.2 Why Circuits 3a, 3b, and 3c Work

The circuit 3a works because the transistor amplifies the current flowing into the lamp. If 1 mA flows from base (vertical line) to emitter (arrow), roughly 100 mA flow from collector to emitter. That's still not as much current as in 2a, but it's plenty to make the bulb light up. The calculation above assumed the thermistor is at $75°F$. Table 2 shows the resistance of this particular thermistor for other temperatures.

Temperature ($°F$)	**Resistance (Ω)**
32	35902
68	14687
78	11662
90	8926
105	6478

Table 2: Thermistor Resistance at Selected Temperatures

Circuit 3b uses an LED instead of a lamp. LEDs always have a constant voltage drop when they are lit—they cannot be dimmed by changing the voltage (at least, not very well). So the circuit uses the voltage to set the current going through the LED. The power (in Watts) used by the LED is $P = IV$, so halving the current halves the power, the same way halving the voltage did for the lamp. Power here corresponds roughly to brightness.

The voltage at the emitter of the transistor is about 0.6 V less than the voltage at the base. This voltage, and the resistance of the resistor on the right hand side of 2b, determine the current through that resistor. The current through the resistor is nearly the same as the current through the LED. We've chosen a fairly low resistance, so we can get a high current (bright LED) and not heat up the resistor too much.

The top input to the op-amp in 3c is determined by the photoresistor and its matched resistor. The op-amp is stable when its two input voltages are equal. The bottom input is determined by the output. The bottom input voltage is always half the output voltage. So the output is twice the top input, giving a gain of 2.

4.3 How do op-amps work?

Operational amplifiers (op-amps) take the difference between two inputs, V_+ and V_-, and produce an output equal to that difference multiplied by some gain A, typically 100,000 or more. Usually (and in this class) op-amps have the output running back to V_+ or V_-, with two effects: $V_+ = V_-$, and the gain is now determined by the value of the surrounding resistors. Note that current doesn't really "flow" through an op-amp, so the nodes V_+ and V_- should be treated as having essentially infinite resistance.