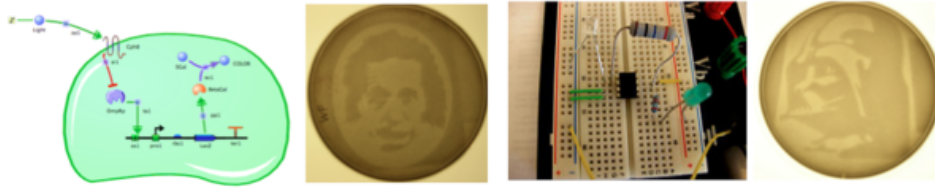


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Lab 3: Picture this



Electronics Modeling

During this activity the students will create an electronic analogy for the bacterial photography system.

The bacterial photography system is constructed from two devices:

1. A **Sensor**: an input detection device which, in response to darkness, produces a signal.
2. An **Actuator**: an output generating device which takes an input signal from the first device and produces a detectable output.

The devices are connected through the two-component signaling pathway. We can construct an analogous system from electrical components:

1. A **photodiode**: a sensor device that allows current to pass through it in response to incoming light
2. An **LED**: an actuator that responds to a current input by emitting colored light. We also include a resistor in this box so we don't burn out the LED.

The devices are connected through an operational amplifier and a resistor to build a circuit that will operate identically to the bacterial photography system. The photodiode will sense light and generate an electrical signal that will be detected by the LED, which produces a color output in response (on in the dark, off when the flashlight is shining on the photodiode). If you'd like to explore the issue of "gain" in the signaling system, then the resistor associated with the OpAmp can be swapped out for smaller ones (or open circuit or wire), and the system can be observed to behave less digitally (because the system gain is proportional to the resistance). Depending on your goals, it may be sufficient to simply build the circuit with a large resistor in place and omit the gain exercise. We recommend that the students spend one class period on the electronic model. Building the model takes only a short time and the students can then experiment with the system.

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Needed Materials

Kit Provides Electronics Build

Part	Source	Catalog #	~Cost
Breadboard	Global (UDoIt)	PB83E	\$17.00
Alligator clips	Mueller Electric Co (DigiKey)	314-1010-ND	\$0.50
9V battery snap cover	Philmore (UDoIt)	BC120	\$1.50
9V battery	Energizer (UDoIt)	EN22, industrial	\$1.60
Flashlight	LED keychain lights (Walgreen's)	Anything cheap and bright will do	\$2.00
LED	AllElectronics	LED-2, 5mm, green T1 3/4	\$0.50
Resistor, 820 Ω	NTE (UDoIt)	QW182, 820 Ω , 2%	\$0.50
OpAmp	Analog Devices Inc. (DigiKey)	AD8031ANZ	\$3.00
Resistor, 10M Ω	NTE (UDoIt)	2W610	\$1.00
Photodiode	LediTech (AllElectronics)	LT959X91-0125	\$0.50
Jumper Wires	Global (UDoIt)	WK-3	\$3.00
Extras:			
Resistor color code card	Elenco (UDoIt)	CC-100	\$1.00
Clear case to hold parts	Flambeau (UDoIt)	DB221	\$2.00

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Annotated Procedure

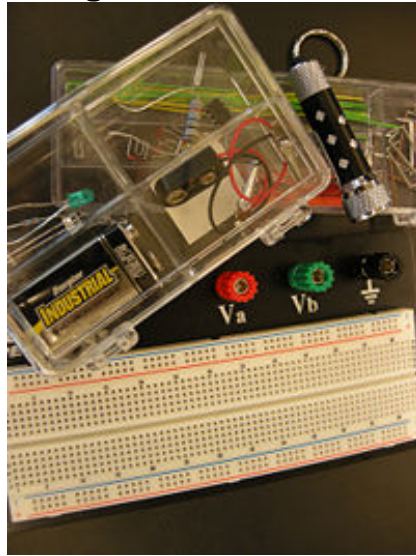
Introduction

If you have not had a lesson on how the bacterial photography system works, go read the first half of the [design assignment page](#).



TEACHERS: We recommend you give a lecture describing two-component signaling and the bacterial photography system in more detail.

Part II. Electronic vs Biological Circuits



Circuit kit

In this activity, we'll explore signaling in the context of an electrical circuit. As you work through this exercise, consider how the lessons learned from experimenting with an electronic circuit would map to the engineering of biological systems. You will be given a kit to construct this circuit.

Safety

Safety for you:

In this exercise, you'll be working with circuits connected to a battery. Although you are unlikely to seriously injure yourself, you should make a habit of unplugging / powering-off the circuit before you touch it.

Safety for the circuit components:

- Never directly connect the two battery terminals (+/power and -/ground) with only wire. This is called a "short circuit" and can damage or drain your battery.
- Take note of which components require power to be applied in one direction

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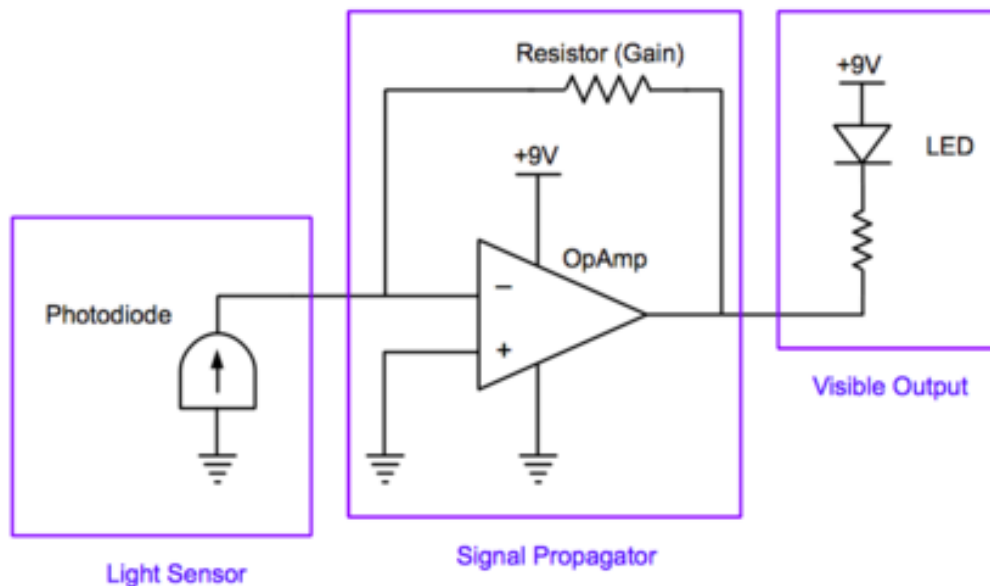
and not the other. Applying power backwards can fry your components. Specifically:

- The OpAmp has one pin for + power and one pin for ground.
- The diodes (photodiode and LED) must have their positive legs toward power and their negative legs toward ground. Notice that the diodes are round except for one flat side, which indicates the negative leg (flat line looks like a minus sign).
- Make sure not to connect your battery backwards. Use red for power and black/blue for ground.
- Wires and resistors don't care which direction they are plugged in.



TEACHERS: The components in this kit are fairly robust. The only component that is easy to damage is the OpAmp, which can be fried by having power applied to it in the wrong direction. A damaged OpAmp looks just like a regular one.

System design



A diagram of the electrical circuit that is analogous to the bacterial photography system. Circuit designed by Steve Wasserman, MIT

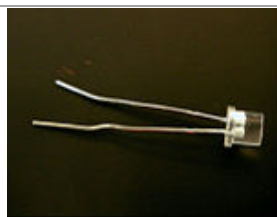
This system is a fairly simple one, consisting of only a few components. In contrast to the bacterial photography system in which the signal is propagated through protein activities, here signals are propagated as either voltage or current. When light hits the photodiode, it generates a current signal. The OpAmp takes in this current signal and produces a voltage, which signals the LED to produce light. As you can see in the schematic, the circuit contains the following parts:

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- **Photodiode:** a light sensor. When light shines on the photodiode, its resistance decreases, and current flows through it. The photodiode is analogous to the Cph8-OmpR signaling system in the living bacterial photography system.
- **OpAmp:** a signal propagator. More generally, an OpAmp is a logic device that detects and amplifies a difference between the currents into its plus and minus inputs. With the addition of the feedback resistor connecting the output to the minus input, the OpAmp translates an incoming current signal into an outgoing voltage signal. The OpAmp is analogous to the transcription/translation machinery that translates an OmpR signal into synthesis of LacZ in the living bacterial photography system.
- **Resistor:** component which resists current flow by producing a voltage drop across it. The voltage equals the current times the resistance of the resistor; thus, the resistance sets the "gain" or amplifier strength of the system. By varying the resistance, we can vary the circuit's sensitivity to light. The resistor is analogous to the strength of the promoters and ribosome binding sites in the biological system, which raise or lower the efficiency of LacZ production in the living bacterial photography system.
- **LED:** a device with a detectable output (*analogous to LacZ*). A voltage drop across its terminals turns the green-colored light on. The small 820Ω resistor is placed in line with the LED to ensure that the current through the LED isn't too high, which can fry the LED. This small resistor has no direct analogue in the bacterial photography system. The LED is analogous to LacZ in the living bacterial photography system.



TEACHERS: You may wonder why the circuit design does not use an inverter chip to simulate the NOT-logic of the bacterial photography circuit (light = no output, no light = output). The circuit was designed to use an OpAmp instead of an inverter because inverters tend to have much more strictly switch-like behavior than OpAmps, which prevented students from exploring the issues of gain and switch-like vs. dial-like behavior. With the OpAmp, the NOT-logic is provided by the fact that the LED is connected between power and the OpAmp's output, rather than between the OpAmp's output and ground. You can invert the NOT-logic by moving the LED and its resistor to the ground side of the OpAmp's output.



Photodiode (sensor)



OpAmp (logic)



Resistor (gain)



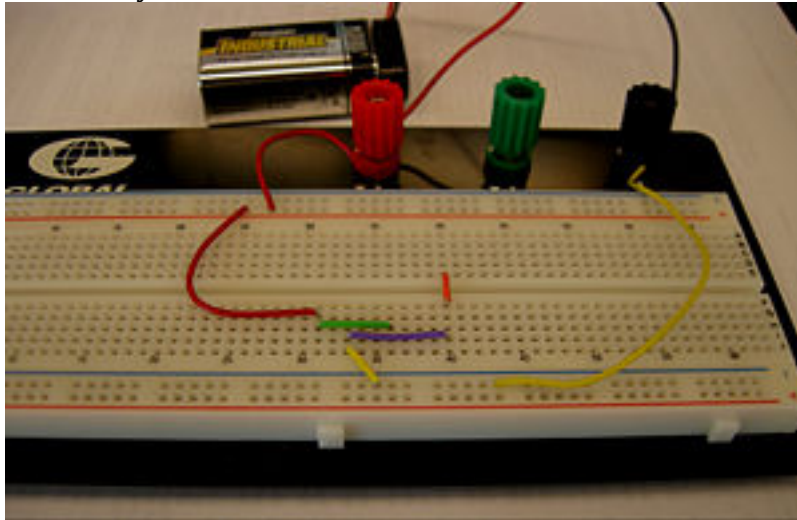
LED (actuator)

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Introduction to Breadboards

You will be building this circuit on a breadboard, which is a much cleaner way to construct circuits than just wiring everything together. Start by building a very simple, "Hello World" circuit to understand intuitively how breadboarding works. (If you have used a breadboard before, feel free to skip this section.)

Take a look at the rows of holes on your breadboard. In the middle, the holes are arranged in short rows of five. The five holes in each row are all connected to each other (via thin strips of metal inside the breadboard). On the sides are the **rails**, or long rows of holes marked with red or blue lines and a plus or minus sign. All the holes in a rail are connected to each other. Rails allow you to conveniently serve power/ground to many locations at once.

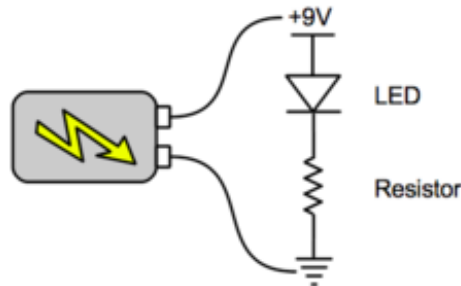


Example showing breadboard connections

For example:

- The purple wire and the orange wire are connected. The orange wire bridges the two separate halves of the breadboard.
- The purple wire and the green wire are **not** connected.
- Power is delivered to the red rail at the top of the breadboard via the red binding post, which connects to the battery holder. The short yellow wire, the purple wire, and the orange wire are all connected to power.
- Ground is delivered to the blue rail at the bottom of the breadboard via the black binding post, which connects to the battery holder. The green wire is connected to ground.

Hooking up an LED



Our basic "Hello, World!" circuit

1. Deliver power from the battery to the rails on either side of the breadboard. Use the binding posts to connect the battery leads to wires, and plug the wires into the rails. Unscrew the plastic part of the binding post, insert a lead and a wire into the hole, and tighten the plastic part. To get a good connection, make sure you are clamping down on a metal wire and not on the plastic insulation around each wire.
2. Now plug in the LED and the resistor. Push in the wires firmly to make a good connection.
3. You should see light. If not, check your connections, make sure your battery is not dead, etc.

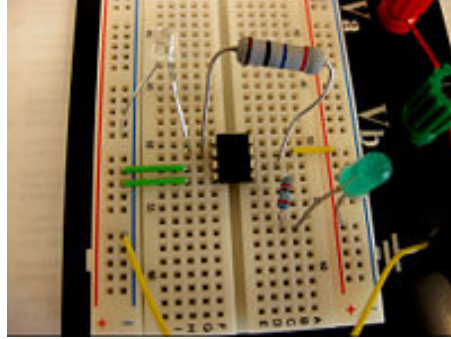
A few hints:

- Remember that the LED allows current to flow through it in only one direction. If you try to put current through it backwards, it won't work. (But it won't damage the LED either, so feel free to try!)
- The resistor is needed to limit the current through the LED. Too much current can damage it. The LEDs in this kit are strong enough that they won't burn out instantly if you connect them straight across the battery, but using a resistor is still recommended.
- You could also put the resistor on the power side and the LED on the ground side; it makes no difference.



TEACHERS: Mysterious failures can sometimes be caused by the undersides of the binding posts forming a short circuit. In principle this should never happen, but if you have metal tables, it's something to check. Try putting paper underneath the breadboard.

Building the bacterial photography circuit



Finished circuit

1. Power the breadboard: Connect the battery leads to wires using the binding posts. Connect the power wire to the red rail at the top of the breadboard, and the ground wire to the blue rail at the bottom. (Power off the breadboard before you continue building, by disconnecting the rails or snapping the battery out of its holder.)
2. Position the OpAmp across the trench in the breadboard.
3. Note the small dot or half-circle marking pin 1 or the "top" of the OpAmp, as shown in the connection diagram. Power the OpAmp by connecting its voltage source inputs to the power rails (pin 7 to +9V, pin 4 to ground).
4. Connect the OpAmp's plus input (pin 3) to ground.

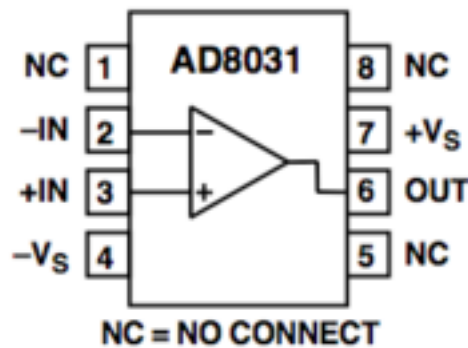


Diagram showing the connection of each pin on the OpAmp. -IN = negative input, +IN = positive input, -Vs = negative voltage supply = ground, +Vs = positive voltage supply = +9V, OUT = output, NC = pin not connected to anything. (Reproduced from [data sheet](#).)

5. Connect the OpAmp's minus input (pin 2) to the photodiode. Remember, the photodiode is polarized. It must be connected so that the leg under the flat side is to ground.
6. You'll make 2 connections to the OpAmp's output (pin 6). First, connect it to the LED and the small, 820 ohm resistor. Remember, the LED is polarized. It must be connected so that the leg under the flat side is to the resistor and the

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- other leg is to power.
7. Next, connect the OpAmp's output (pin 6) to the large, 10 mega-ohm resistor. Connect the other end of the resistor to the OpAmp's minus input (pin 2). You will change the gain of the amplifier by varying the resistance at this point (using the large resistor, a wire for zero resistance, and no wire for infinite resistance).
 8. Double check your connections with the circuit diagram above before you power it up.
 9. Test your circuit by shining a light on the photodiode and seeing if the LED responds.

Putting it all together

- Explain the role each component plays in the electronic circuit. Which part of the biological circuit does each represent?
- No doubt, building this circuit was quicker and easier than actually assembling a biological circuit -- for example, you didn't have to wait for bacteria to grow, or spend time cutting and pasting wires the way you would cut and paste DNA to make a functional plasmid. What are some traits of these components, of the breadboard, or of electronics in general, that make electrical engineering easy in this way?
- Every analogy has limitations. What are the limitations of the circuit you built as a model of the bacterial photography system? What could you do to make it more realistic?



TEACHERS: Here are some suggestions for answers to the thought questions offered above:

- **Role of each component:** This question is just to make sure students can explain the analogy coherently in their own words.
- **Tools for electrical engineering vs biological engineering:** The breadboard allows you to quickly connect many different parts and easily make changes to the circuit, rather than having to assemble and reassemble plasmids. The different components all connect to each other via standard wires, and they all "speak the same language" of electrical signals. All different parts of the circuit draw energy from the same power source -- in contrast, the bacterial photography system requires both food for the cell and a small molecule in the indicator medium for LacZ to work on. Resistor values are quantitative and there is a wide range of resistors readily available, in contrast to traits like promoter strength, which are less well understood, and there is no readily available wide range of weak to strong promoters. (The BioBricks foundation is working on this, though!)
- **Analogy's limitations:** Light from the LED turns on and off instantly when you change the amount of light you shine on the photodiode -- there is no delay or accumulation of "leftover" light, the way there is with colored pigment.

Examining system behavior at different gain values

If your teacher specifies, continue to this exercise for exploring gain. You may be asked to answer the questions associated with each section.

A circuit with very tight fully-on-or-fully-off behavior is more "digital", or switch-like, while a circuit where the LED can have a wide middle range of brightness is more "analog", or dial-like. The range of flashlight intensities that can hold the LED half-lit is a measure of the *gain* or strength of the amplifier. More precisely, the gain is the slope of the LED-output-vs.-photodiode-input line. Because the *maximum* brightness is the same for every circuit, a high-gain amplifier will cause the LED's brightness to max out even at a low level of input to the photodiode, whereas a low-gain amplifier will cause the LED's brightness to increase slowly before maxing out, as the photodiode input increases. We can *tune* this gain by changing the value of the gain resistor.

Initial Condition: Resistance = 10 M Ω

Right now, the OpAmp's output and minus input are connected with a 10 M Ω resistor.

1. What happens to the LED when you power up the circuit?
2. What happens to the LED when you shine the flashlight on the photodiode?
3. Can you get the LED to hold steady at 1/2 its maximal brightness, by moving the flashlight farther away, shading it, etc?
4. Sketch a graph with flashlight intensity on the x-axis and LED light intensity on the y-axis. At infinite resistance in place, is the circuit's behavior better described as a switch or a dial?

Modification: Resistance = 0 Ω

Replace the 10M Ω resistor with a wire.

1. What happens to the LED when you power up the circuit?
2. What happens to the LED when you shine the flashlight on the photodiode?
3. Can you get the LED to hold steady at 1/2 its maximal brightness?
4. Add a line for this circuit to your graph. Is this circuit's behavior better described as a switch or a dial?

Alternative: Resistance = infinite Ω

Remove the wire connecting the OpAmp's output to its negative input.

1. What happens to the LED when you power up the circuit?
2. What happens to the LED when you shine the flashlight on the photodiode?
3. Can you get the LED to hold steady at 1/2 its maximal brightness?
4. Add one last line to your graph. Is this circuit's behavior better described as a switch or a dial?

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Putting it all together

- How does this relate to the end of the computer simulation exercise, when you tuned the system with sliders?
- When might you want switch-like behavior in a biological system, and when might you want dial-like behavior?
- What are some everyday examples of switch-like and dial-like systems? What element or aspect plays the role of "gain" in each one?

Survey

To help us improve the labs, you can

1. send the students [here](#), where they can upload their data.
2. "join a discussion" from the [BioBuilder homepage](#)
3. email us: "info AT biobuilder DOT org"

Thanks!

Feedback

We're always looking to hear back from you if you've thought about this unit, tried it, or stumbled across it and want to know more. Please email us through [BioBuilder](#), info AT biobuilder DOT org.