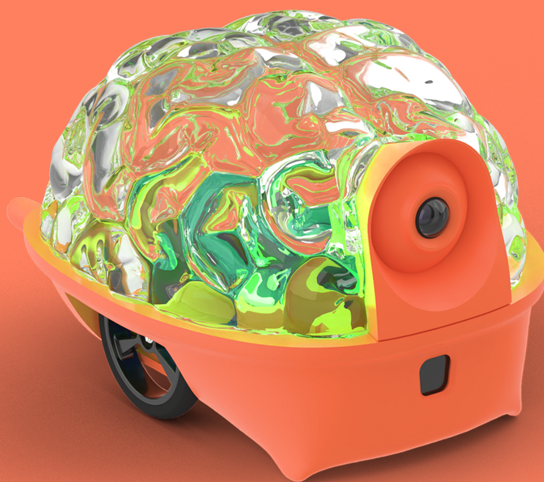
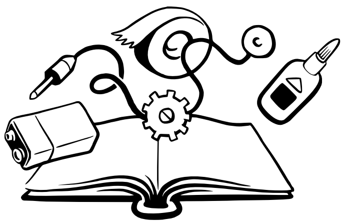
BACKYARD BRAINS



SPIKERBOT EDUCATOR GUIDE

A HANDS-ON CURRICULUM FOR NEUROSCIENCE, ROBOTICS AND AI

Christopher A. Harris, Ph.D



Contents

You can also review our online documentation.

The SpikerBot Learning Experience

Welcome!

This guide will help you transform your classroom into a hands-on neuroscience lab. The SpikerBot platform is built on a simple premise: **the best way to understand the brain is to build one**. SpikerBot is designed to bridge the gap between abstract neuroscience concepts and tangible, observable behaviors.

Students won't just learn about neural circuits - they'll design, build, and test them. Using the visual SpikerBot App, they will become neural engineers. They will drag and drop excitatory and inhibitory neurons, wire them to the robot's sensors and motors, and tune synaptic connections to create behaviors from scratch. When they press "Play," they will see their unique brain design come to life as the physical robot navigates and interacts with its environment.

Neuroscience is driving the future of medicine, technology, and artificial intelligence, but it is often inaccessible in the pre-college classroom. SpikerBot makes it accessible. By designing brains for a simple robot, students will grapple with the same fundamental principles that govern our own minds - from simple reflexes to complex decision-making.

This curriculum uses an inquiry-driven approach that aligns with Next Generation Science Standards (NGSS) to foster critical thinking, problem-solving, and creativity. The lessons are structured as hands-on engineering challenges. Students will explore core ideas like **LS1.A (Structure and Function)** by seeing how a circuit's design determines its behavior , and **LS1.D (Information Processing)** as they build brains that respond to sensory stimuli. This guide provides the lesson plans, student handouts, and solutions to help you lead these explorations with confidence.

The Big Ideas: From Neurons to Behavior

At the heart of any brain - biological or artificial - are a few simple rules. SpikerBot makes these rules tangible. As students build, they will gain an intuitive understanding of the following core concepts.

The Building Blocks

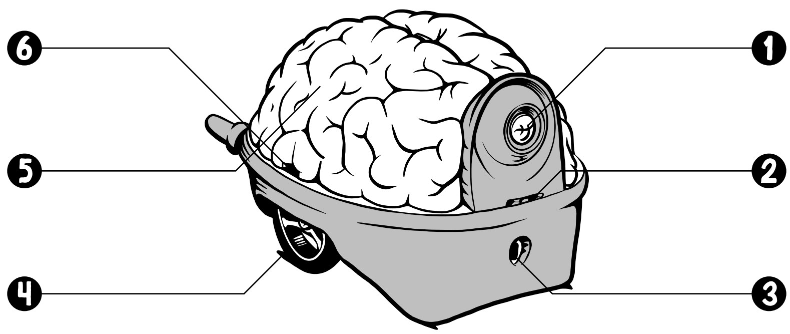
- **Neurons:** The fundamental processing units of the brain. In SpikerBot, students can use Excitatory (black) neurons that activate other cells or Inhibitory (white) neurons that silence them. Neurons can be "quiet" (firing only when stimulated) or "spontaneously active" (firing in bursts or at random intervals).
- **Synapses:** The connections between neurons. Students create these by wiring neurons together. The synaptic weight (1-100) acts like a volume knob, controlling how strongly one neuron influences another. A weight above ~25 is needed for reliable activation

Putting It Together: Neural Circuits

- **Synaptic Integration:** A single neuron can receive many weak inputs. It will only fire if multiple inputs arrive at the same time - a key principle for detecting complex patterns. In the app, this can be achieved with multiple weak synapses (weight ≤15) converging on one neuron.
- **Recurrent Excitation (Feedback Loops):** When neurons excite each other in a loop, they can sustain their activity long after an initial stimulus is gone. This is a fundamental mechanism for working memory and generating rhythmic patterns. To create a stable loop, synapses need high weights (≥90).
- **Lateral Inhibition (Winner-Take-All):** When two circuits actively inhibit each other, only one can be active at a time. This is how the brain makes clear decisions, sharpens sensory perception, and prevents conflicting behaviors.

Your Toolkit: The Robot and The App

SpikerBot is a complete system: a physical robot with senses and motors (the "body") and a powerful application for designing its neural controller (the "brain"). The two communicate in real-time over a direct Wi-Fi connection.



The Robot (The Body)

SpikerBot is packed with sensors and outputs that students can wire their neurons to.

Senses (Inputs):

❶ **RGB Camera:** The robot's "eye" for detecting colors and objects.
❷ **Microphone:** An "ear" to detect sounds.
❸ **Distance Sensor:** "Feelers" to detect objects up to 1 meter away.

Actions (Outputs):

❹ **Motors:** Two independent wheels for movement and turning.
❺ **RGB LEDs:** Four programmable lights for communication.
❻ **Speaker:** For producing tones and sounds.

The App (The Brain)

The SpikerBot App is a visual canvas where students bring their neural circuits to life. It is available for all major platforms (Windows, macOS, iOS, Android, and ChromeOS) at robot.backyardbrains.com. The workflow is simple:

1. **Design:** Drag and drop excitatory or inhibitory neurons onto the brain canvas.
2. **Connect:** Wire neurons to each other and to the robot's sensors and motors.
3. **Tune:** Click on any neuron or synapse to adjust its properties, like firing patterns or connection strength.
4. **Test:** Press Play to run the simulation and see your custom brain control the physical robot in real time. Brain designs can be saved and shared as .brain files.

Getting Started: First Connection

1. **Power On** the robot using the switch on the underside. The LEDs will turn blue.
2. **Connect Device** to the robot's Wi-Fi network (e.g., "SpikerBot_123").
3. **Wait for Green** LEDs, which signal the robot is ready.
4. **Launch the App** and press the Play icon to begin!

Setting Up for Success in the Classroom

Here are some practical tips and alignments to help you integrate SpikerBot smoothly into your lessons.

Classroom Setup

- **Groups:** We recommend students work in small groups of **2-4** per SpikerBot.
- **Materials:** Each group will need one SpikerBot, a compatible device (laptop or tablet) with the app installed, and student handouts.
- **Environment:** A smooth, open floor space is best for movement-based exercises. Use brightly colored objects (like construction paper) for vision-based tasks.
- **Teacher's Tip:** Start by having students load the pre-made example brains from the Brain Library. Letting them see a working brain first is a great way to build confidence before they start designing their own.

Quick Troubleshooting

- **Wi-Fi Issues?** Make sure you're connected to the correct SpikerBot network. The robot's LEDs must be green for the app to connect.
- **No Movement?** Check that the robot is powered on and the wheels are unobstructed.
- **Poor Color Detection?** Ensure good lighting in the room and check the app's live camera view to see what the robot "sees".

Curriculum Alignment (NGSS Core Ideas)

SpikerBot activities are inquiry-based engineering challenges that naturally align with NGSS standards:

- **LS1.A: Structure and Function:** Students design neural structures and directly observe how their organization determines the robot's function and behavior.
- **LS1.D: Information Processing:** Students see directly how sensory receptors (the robot's camera and sensors) respond to stimuli by sending messages that result in immediate behaviors or stored "memories" in recurrent circuits.
- **ETS1.B: Developing Possible Solutions:** The entire curriculum is an engineering design challenge. Students must design, test, and iteratively refine their neural circuits to solve specific problems and achieve desired behaviors.

Lesson 1: Actions and Reactions

Big Question: How do simple circuits of neurons create purposeful behavior?

In this foundational lesson, students will build their first neural networks from scratch. They will discover how wiring sensory neurons to motor neurons can produce both simple reflexes and more complex, internally-driven behaviors.

Learning Objectives

By the end of this lesson, students will be able to:

- **Build a neural network** that responds to a visual stimulus.
- **Design a circuit** that allows the robot to follow a moving target.
- **Create a network** that enables the robot to explore a space autonomously.
- **Explain the roles** of sensory neurons, motor neurons, and synapses in creating behavior.

Materials Needed

- One SpikerBot per group
- One connected device (laptop or tablet) with the SpikerBot app
- Colored objects (e.g., blue construction paper)
- Lesson 1 Student Handout

Teacher Prep & Demo (10 min)

In this foundational lesson, students will build their first neural networks from scratch. They will discover how wiring sensory neurons to motor neurons can produce both simple reflexes and more complex, internally-driven behaviors.

Recommended Demo Flow:

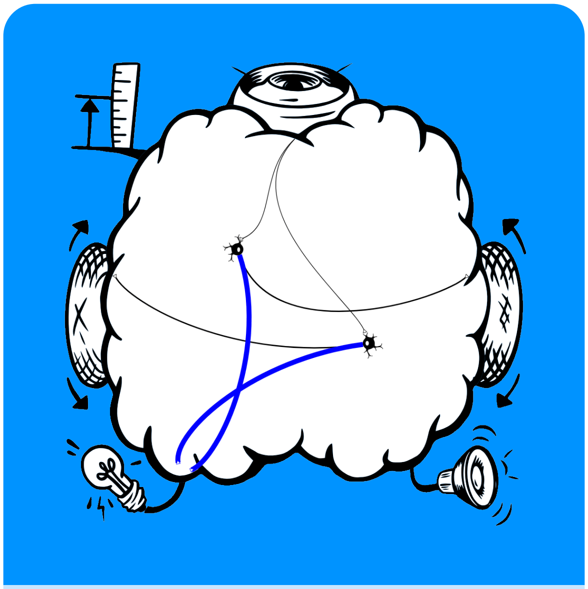
1. **Connect to Robot:** Follow the "First Connection" steps in this guide to connect your device to a SpikerBot.
2. **Add & Move Neurons:** Drag a few neurons from the side panel onto the canvas. Show how to move them around.
3. **Create a Synapse:** Click a neuron and drag its axon handle to another neuron to create a synapse.
4. **Connect to Motors:** Drag an axon handle from a neuron to one of the wheel icons to create a motor synapse.
5. **Adjust Properties:** Click on a neuron and show the pop-up menu. Point out the firing patterns (Quiet, Bursting). Then click on a synapse to show how to adjust its weight.
6. **Run & Test:** Press Play to run the simple circuit and show the robot's wheel moving. Press Pause to stop and make adjustments.
7. **Save & Load:** Briefly show how to save and load brain files.

After the demo, distribute the Lesson 1 Student Handout and encourage students to begin Exercise 1. Remind them that there is no single "correct" design.

Exercises, Solutions & Explanations

Exercise 1.1: Approach A Target

Behavior: Approaches a colored object (e.g., blue)
Neurons: 2 (Excitatory)
Circuits: Crossed Circuit / Braitenberg Vehicle
How it Works: This brain uses two quiet, excitatory neurons. Each neuron is tuned to detect the color blue in one half of the visual field (left or right). The circuit is crossed: the left sensor neuron activates the right motor, and the right sensor neuron activates the left motor. This simple but powerful design, known as a Braitenberg Vehicle, causes the robot to automatically turn **toward and approach the blue stimulus.**



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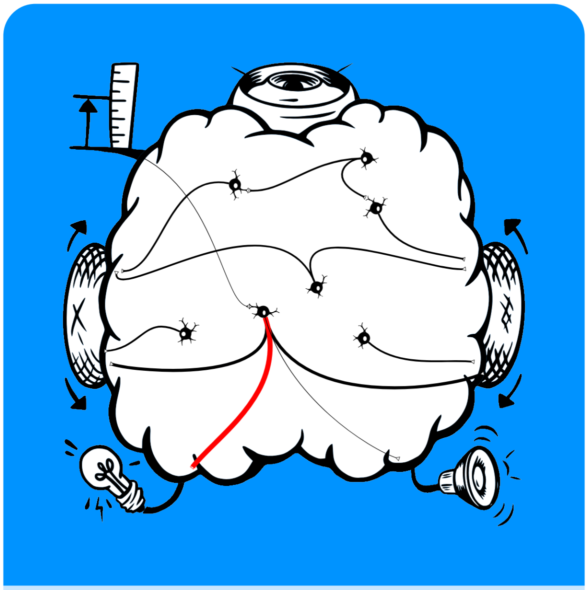
Exercise 1.2: Explore Autonomously

Behavior: Explores autonomously and wanders without getting stuck
Neurons: 7 (Excitatory)
Circuits: Central Pattern Generator
How it Works: This brain uses six spontaneously active ("bursting") neurons that fire at random intervals to activate the motors, creating a **wandering movement.** A separate, seventh quiet neuron is configured as a distance detector. When the robot gets too close to an object, this neuron strongly activates backward movement, allowing the robot to **avoid getting stuck.**



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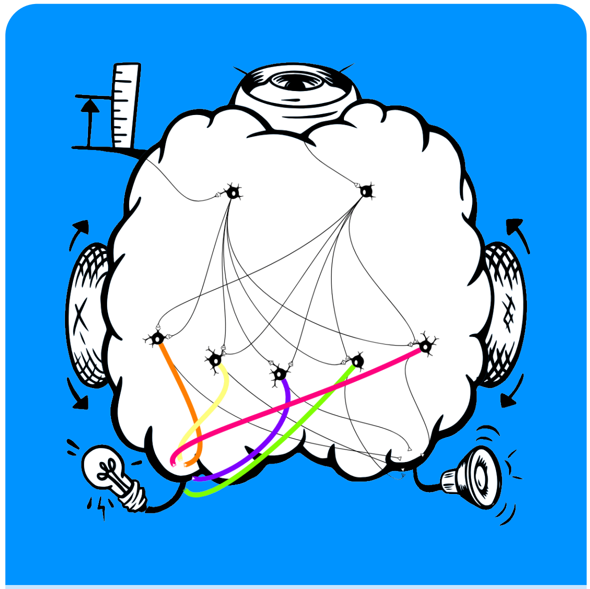
Exercise 1.3: Greet Nearby People

Behavior: Blinks lights and beeps, but only when it detects a person at a medium distance.
Neurons: 7 (Excitatory)
Circuits: Synaptic Integration
How it Works: Two quiet sensory neurons are present: one that fires when an object is at a "medium distance" and one that fires when it detects a "person". Both of these neurons connect to five output neurons that control the LEDs and speaker.
The key is that the synaptic weights from the sensory neurons are set to be weak (e.g., a **weight of 15**). Because a single weak input isn't enough to make a neuron fire, the output neurons will only activate when they receive signals from both sensory neurons at the same time. This makes the robot **respond only when it observes a person at medium distance**.



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Lesson 1: Actions and Reactions

Student Handout

Today, you are a neuroscientist. Your mission is to design three different "brains" for your SpikerBot. You'll start with a simple reflex and build up to a brain that can explore on its own and react to specific conditions in its environment.

Your Mission

1. Build a brain that can follow a moving target.
2. Design a brain that explores its surroundings on its own.
3. Create a brain that blinks and beeps only when a person is nearby.

Key Concepts

- **Sensory Neurons:** Neurons that respond to inputs from the environment, like color or distance.
- **Motor Neurons:** Neurons that control outputs, like the wheels, lights, or speaker.
- **Synapse Strength:** The "volume" of the connection between two neurons. A weak connection may not be enough to activate the next neuron on its own.

Exercise 1.1: Following a Moving Target

- **Goal:** Make your robot follow a colored object (like a piece of blue paper).
- **Hint for Your Brain Design:** Think about this: If the robot sees the blue object on its left side, which wheel should it turn on to move towards the object?

Exercise 1.2: Autonomous Exploration

- **Goal:** Make the robot wander around the room on its own without getting stuck.
- **Hint for Your Brain Design:** You don't need a color sensor for this. Try using neurons with a "bursting" activity pattern to create random movements. How can you use the distance sensor to make the robot back away from walls?

Exercise 1.3: Blink and Beep at Nearby People

- **Goal:** Make the robot flash its lights and play a sound, but only when it detects a nearby person.
- **Hint for Your Brain Design:** This requires two conditions to be true at the same time. You'll need one sensory neuron that detects people and another that detects distance. How can you connect them to your output neurons so that both sensory neurons have to be active at the same time? Try using very weak synapses (e.g., a weight of **15**).

Lesson 2: Creating Memory with Feedback Loops

Big Question: How can a brain "remember" to keep doing something after the trigger is gone?

This lesson introduces **recurrent excitation** - a fundamental circuit for creating persistent activity. Students will design a brain that starts a behavior in response to one signal (green) and sustains that behavior until it is stopped by a different signal (red). This introduces the concept of a neural "state" or working memory.

Learning Objectives

By the end of this lesson, students will be able to:

- Explain how a recurrent excitatory circuit (a positive feedback loop) can sustain neural activity.
- Design a circuit that maintains its state after an initial trigger.
- Use an inhibitory signal to turn off a recurrent circuit.
- Build a robot brain that starts moving with a "go" signal and stops with a "stop" signal.

Materials Needed

- One SpikerBot per group
- One connected device with the SpikerBot app
- One green object and one red object
- Lesson 2 Student Handout

Teacher Prep & Demo (10 min)

Introduce this lesson's concept using a simple analogy: a light switch. You press it once (the "go" signal), and the light stays on without you having to hold the switch. It remains "on" until you press it again (the "stop" signal). A recurrent circuit is a neural version of this switch.

Recommended Demo Flow:

1. **Build the Loop:** Create two quiet neurons on the canvas. Connect them to each other with very strong excitatory synapses (weight ≥ 90) to form a recurrent loop.
2. **Add the "Go" Trigger:** Create a third neuron and configure it as a sensory neuron that responds to the color green. Connect its axon to one of the neurons in the loop.
3. **Connect to Motors:** Wire the neurons in the loop to the robot's forward motors.
4. **Add the "Stop" Trigger:** Create a fourth sensory neuron that responds to the color red and is inhibitory. Connect its axon to one of the neurons in the loop.
5. **Run the Test:** Press Play. Show students that when you briefly show the robot a green object, the loop activates and the robot continues to drive forward even after the green object is removed. Then, show it the red object to make it stop.

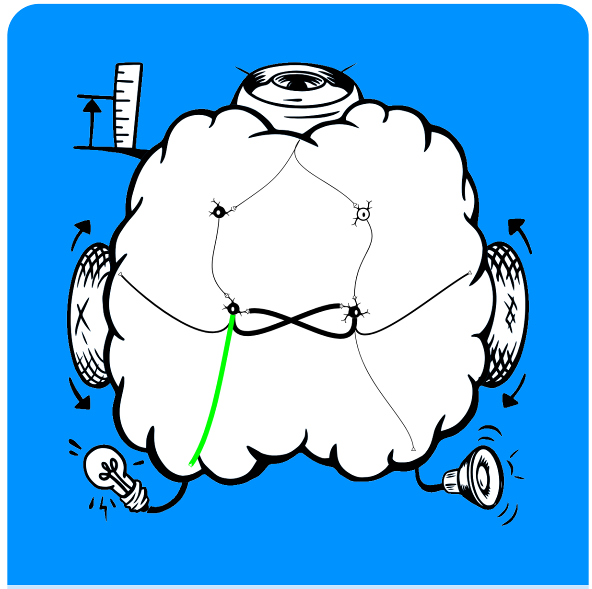
After the demo, distribute the Lesson 2 Student Handout.

Exercises, Solutions & Explanations

Exercise 2.1: Sustained Movement

Behavior: The robot starts moving forward when it sees a "go" signal (green) and continues to move even after the signal is gone. It stops moving when it sees a "stop" signal (red).
Neurons: 4 (3 Excitatory, 1 Inhibitory)
Circuits/Motifs: Recurrent Excitation (Feedback Loop)
How it Works: This brain is built in three parts:

1. **The Memory Loop:** Two excitatory neurons are connected in a strong positive feedback loop, strongly activating each other. To sustain this activity, their synaptic weights must be very high (≥90). These neurons are connected to the forward motors.
2. **The 'Go' Trigger:** A third excitatory sensory neuron detects green. It sends an activation signal to the memory loop, "flipping the switch" on.
3. **The 'Stop' Trigger:** A fourth, inhibitory sensory neuron detects red. When activated, it silences the neurons in the memory loop, breaking the feedback cycle and stopping the robot.



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Lesson 2: Creating Memory with Feedback Loops

Student Handout

Last time, you built brains that reacted instantly to things they saw. Now, you're going to give your robot a simple form of memory. You'll build a brain that can be turned "on" by one signal and will stay on until it's turned "off" by another.

The Big Idea: Neural Memory

Think of a light switch. You flip it on, and the light stays on. You don't have to keep holding the switch. A recurrent circuit in the brain works the same way. It's a loop of neurons that excite each other, keeping themselves in an "on" state until something comes along to turn them "off." This is a key mechanism for working memory and for sustained actions like walking or breathing.

Your Mission

Design a brain that makes the SpikerBot:

1. Start moving forward when it sees a green object.
2. Keep moving forward even after the green object is gone.
3. Stop moving when it sees a red object.

Exercise: Sustained Movement

- **Goal:** Create a "Go/Stop" brain using green and red visual triggers.
- **Hints for Your Brain Design:** Build your brain in three parts:

  ❶ **The Memory Loop:** First, create the core memory circuit. Connect two neurons so they strongly excite each other. Hint: For a loop to sustain itself, the synapse weights need to be very high (try a weight of 90 or more).

  ❷ **The 'Go' Signal:** Now, add a sensory neuron that responds to green. How can you connect it to your memory loop to "flip the switch" and turn it on?

  ❸ **The 'Stop' Signal:** Finally, add an inhibitory neuron that responds to red. How can you connect it to your memory loop to shut the circuit down and stop the robot?

- **Connect to Motors:** Don't forget to connect the neurons in your memory loop to the robot's forward motors so that the robot moves when the loop is "on".

Troubleshooting Tips

- **Robot doesn't keep moving?** Your memory loop isn't sustaining itself. Make sure the synaptic weights between the two neurons in the loop are high enough (≥90).
- **Robot won't stop for red?** Your inhibitory synapse might be too weak. Make sure its connection is strong enough to silence the active loop.

Lesson 3: Making Decisions with Competing Circuits

Big Question: How does the brain choose one action when faced with conflicting options?

This lesson introduces **lateral inhibition**, a critical principle for decision-making and sensory processing. Students will build two competing circuits that control the robot in opposite ways. They will first observe the conflict that arises when both are activated, and then they will implement inhibitory connections to allow the brain to make a clear, "winner-take-all" choice.

Learning Objectives

By the end of this lesson, students will be able to:

- Explain the principle of lateral inhibition.
- Design a brain with multiple, competing circuits.
- Use inhibitory neurons to ensure only one circuit controls the robot's actions at a time.
- Describe how inhibition helps produce decisive behaviors and sharpens perception.

Materials Needed

- One SpikerBot per group
- One connected device with the SpikerBot app
- One green object and one red object
- Lesson 3 Student Handout

Teacher Prep & Demo (10 min)

Introduce this concept with an analogy: imagine two people trying to steer the same car. One wants to turn left and the other wants to turn right. If they both pull on the wheel at the same time, the car gets confused. For the car to make a clean turn, one driver needs to let go. Lateral inhibition is how one neural circuit tells another to "let go."

Recommended Demo Flow:

1. **Build Two Circuits:** Create two separate recurrent circuits, like the ones from Lesson 2.
2. **Assign Competing Actions:** Configure one circuit to activate when it sees green and turn the robot left. Configure the other to activate when it sees blue and turn the robot right.
3. **Add an "Off Switch":** Add an inhibitory neuron activated by red that silences both circuits.
4. **Show the Conflict:** Press Play and show both the green and blue objects to the robot. It will likely behave erratically, trying to follow both commands at once. Use red to stop all movement.
5. **Add Lateral Inhibition:** Add an inhibitory neuron that is activated by the "green" circuit and connects to/silences the "red" circuit. Add a second inhibitory neuron that does the opposite.
6. **Test the Decision:** Run the simulation again. Now, when the robot sees both colors, one circuit will "win" by suppressing the other, resulting in a clean, decisive turn.

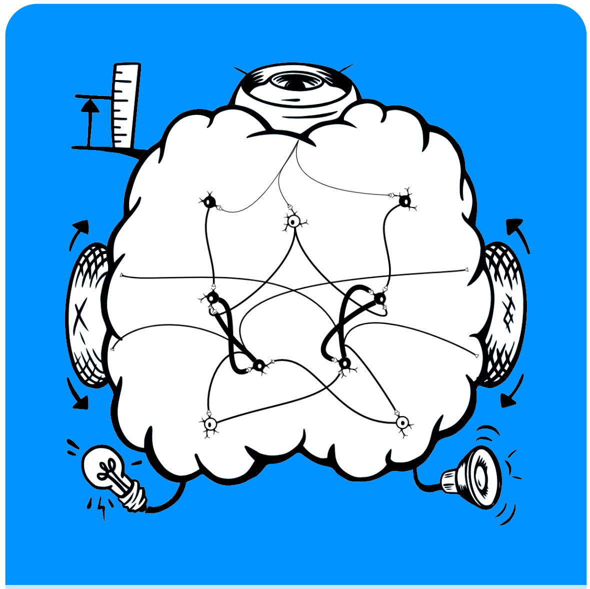
After the demo, distribute the Lesson 3 Student Handout.

Exercises, Solutions & Explanations

Exercise 3.1: Competing Circuits

Behavior: Makes a "winner-take-all" decision between two conflicting commands and stops with a third. Seeing green makes it spin left; seeing blue makes it spin right. Seeing red stops all movement.
Neurons: 9 (6 Excitatory, 3 Inhibitory)
Circuits/Motifs: Recurrent Excitation, Lateral Inhibition.
How it Works: This brain demonstrates how to manage multiple actions using three key motifs:

1. **Recurrent Excitation:** It contains two independent recurrent excitatory circuits (like in Lesson 2) that act as "memory" for an action. Circuit A is activated by a green-detecting sensor to make the robot turn left, while Circuit B is activated by a blue-detecting sensor to turn right.
2. **Lateral Inhibition:** To force a "winner-take-all" decision, the circuits are wired to compete. Circuit A activates an inhibitory neuron that targets and silences Circuit B, and Circuit B does the reverse. This ensures only one of the two "turn" commands can be active at a time.
3. **Inhibitory "Stop" Signal:** A third, inhibitory sensory neuron detects red and is wired to silence both recurrent circuits, stopping all movement.



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Lesson 3: Making Decisions with Competing Circuits

Student Handout

Your robot can now react to things and even "remember" commands. In this final core lesson, you'll teach it how to decide. What should it do when it receives two conflicting commands at the same time? You are going to build a "winner-take-all" brain that can make a choice and stick with it.

The Big Idea: Winner-Take-All

In your brain, countless groups of neurons compete for control. When you decide to turn left instead of right, the "turn left" circuit actively silences the "turn right" circuit. This is called lateral inhibition. It’s a simple but powerful idea: the first thing an active circuit does is tell its competition to be quiet. This is crucial for making clear decisions and preventing your brain from getting "stuck."

Your Mission

Design a brain with two competing circuits that use lateral inhibition so that only one can be active at a time. For example:

- When the robot sees green, it turns left.
- When the robot sees blue, it turns right.
- When it sees both, it cleanly chooses one direction instead of getting confused.

Exercise 3.1: Competing Circuits

Goal: Build a brain that can choose between turning left (for green) and turning right (for blue).
Hints for Your Brain Design:

- **Build Circuit A (Turn Left):** First, create a recurrent loop (like you did in Lesson 2) that activates when it sees a green object. Connect this loop to the motors to make the robot turn left.
- **Build Circuit B (Turn Right):** Next, build a second, separate recurrent loop that activates when it sees a blue object. Connect this loop to make the robot turn right.
- **Add the Inhibition:** Now for the key part. Connect Circuit A to an inhibitory neuron that targets a key neuron in Circuit B. Then, do the reverse: connect Circuit B to an inhibitory neuron that targets Circuit A.

Test and Troubleshoot:

- Present the green and blue targets at the same time. Does the robot make a clear choice?
- If the robot gets stuck, try increasing the strength of your inhibitory synapses.