Lesson Summary: Neurons, or nerve cells, are the basic functional units of the nervous system. Students use the **Virtual Neurons** software to construct neural circuits and visualize how messages travel through the circuits. As an extension, students can design and implement an experiment manipulating circuit components to alter neural communication.

Grade Level 5-12

**Lesson Length
1-2 class periods**

Standards Alignment

Next Generation Science Standards
- MS-LS1-3. Use argument supported by evidence for how the body is a system of interacting subsystems composed of groups of cells.
- MS-LS1-8. Gather and synthesize information that sensory receptors respond to stimuli by sending messages to the brain for immediate behavior or storage as memories.
- HS-LS1-2. Develop and use a model to illustrate the hierarchical organization of interacting systems that provide specific functions within multicellular organisms, e.g. organism movement in response to neural stimuli.
- HS-LS1-3. Plan and conduct an investigation to provide evidence that feedback mechanisms maintain homeostasis.
- **Framework for K-12 Science Education**: Science & Engineering Practices 1,2,3,4,6,8

Objectives—Students will

- model working neural circuits using three types of neurons (motor, sensory, and interneurons).
- draw and label a neural circuit using a motor neuron, sensory neuron, and interneuron, indicating the direction of neural communication.
- identify and draw a motor neuron, a sensory neuron, and an interneuron.

Extension Objectives—Students will

- calculate, predict, and test muscle twitch rate.
- test and describe how neuronal communication in a circuit is affected by the neuron's threshold, by the presence of excitatory and inhibitory neurons in the circuit, and by the pattern of connections within the circuit.
- design a circuit that behaves according to a predetermined goal or pattern.
- write rules for making circuits that work.

Assessment Options—Ask students to

- design circuits that meet any of the following suggested sets of criteria or those of your own choosing. You may suggest they build a circuit that
  - contracts the muscle at a steady rate.
  - causes the muscle to contract in a syncopated or uneven manner.
  - contracts the muscle fast initially then slows to a steady rate.
  - contracts the muscle to contract without any sensory input.
  - causes the muscle to contract from two separate input sources.
- challenge each other to build circuits that behave in specific ways.
- explain how feedback loops work and why they are important in a homeostatic biological system.

Terms — important vocabulary that strengthens the lesson. Select terms according to the needs and abilities of your students.

- **action potential** – an electrical signal that travels along the axon, away from the cell body, to the axon terminal where it triggers the release of neurotransmitters

- **excitatory neuron** – a neuron whose neurotransmitter excites, stimulates, or depolarizes (cell membrane becomes less negative) another neuron, increasing the probability that the target neuron will fire an action potential

- **inhibitory neuron** – a neuron whose neurotransmitter inhibits or hyperpolarizes (cell membrane becomes more negative) another neuron, decreasing the probability that the target neuron will fire an action potential

- **interneuron** – any neuron that is not a sensory or motor neuron, interneurons carry information between neurons, for example, between sensory and motor neurons

- **motor neuron** – a neuron that carries information away from the central nervous system to muscles or glands

- **neuromuscular junction** – a specialized synapse onto a muscle

- **neuron** – the principal cell of the nervous system, also called a *nerve cell*, specialized for the transmission of information and characterized by long fibrous projections called *axons* and short, branch-like projections called *dendrites*

- **pacemaker neuron** – interneurons that fire spontaneously

- **sensory neuron** – a neuron that carries information from the body's sensory receptors in the skin, tongue, ear, nose, and eyes towards the central nervous system

- **threshold** – the minimum amount of depolarization (becoming more positive) of the cell membrane potential needed to cause firing of a neuronal action potential

Materials

- computer
- Virtual Neurons software
- Virtual Neurons Student Guide

Procedures

This activity can be applied in various ways in the classroom depending on the time assigned for the completion of the Nervous System unit. If a week has been assigned then this activity is recommended as a mid-week exercise when the students have some familiarity with basic terms such as *neurons*, *synapse*, *electrical signal*, *chemical signal*, and *action potential*.

Engage students with a review of previously learned vocabulary in the form of a clicker quiz or pop quiz before proceeding to the activity itself.

If the students have not previously learned about basic nervous system vocabulary then their engagement should begin with neuron communication focused on a discussion about how a message is sent from one part of the body to another via neurons and how the brain interprets it. Next, have students explore neuron communication by drawing two connected neurons, labeling the parts, and reviewing their functions. Reviewing the functioning of a simple circuit and the flow of electrical signal is highly recommended before moving on to the software activity.

Questioning — Introducing New Concepts

1. Write the following terms on the board or overhead: **Motor Neuron**, **Sensory Neuron**, and **Interneuron**. Use cues in the words (motor, sense, inter) to help students guess the functions of the different neurons.

2. Ask students to think about a time when they were excited and to describe what the word *excitatory* means.

3. Discuss how some neurons are **excitatory**, meaning that they excite or stimulate other neurons.

4. Ask students to think about a time when they were inhibited and ask them to describe what the word *inhibitory* means.

5. Discuss how some neurons are **inhibitory**, meaning that they inhibit or inactivate another neuron.

Be sure to read the Virtual Neurons Features document available on the website at
www.brainu.org/virtual-neurons

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If you like to explore and want to figure out how this program works on your own, play with it now, before you read the detailed explanation that follows. You are encouraged to run the lesson so your students may benefit from your experience with the program. If you want specific instructions and/or explanations, read on. These instructions may make more sense after you have tried playing on your own.

Have Fun!!! Make your own circuits and analyze them.

Additional circuits suggested as extensions to the sequence below are available in the Additional Circuits document, available at the link shown above. The number of circuits that can be made is limited by your time, imagination, and the speed and size of the program. Many more circuits can be created beyond these suggestions.

**Explore — Virtual Neurons software**

1. Working in pairs, ask students to open the Virtual Neurons software.
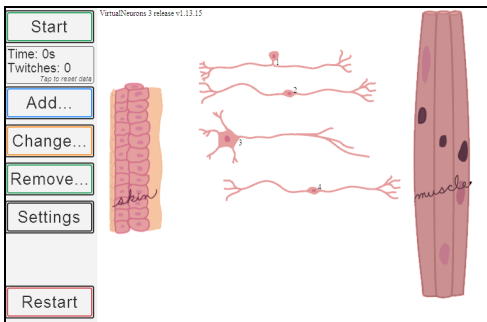
   **Virtual Neurons
   opening screen**

2. Give students time to explore moving neurons, starting and stopping operation of the circuit. The muscle *twitches* or contracts when it receives a signal from the motor neuron. Discuss what might cause changes in how fast the muscle twitches.

   Skin: outer cells are less sensitive than the cells in the center.
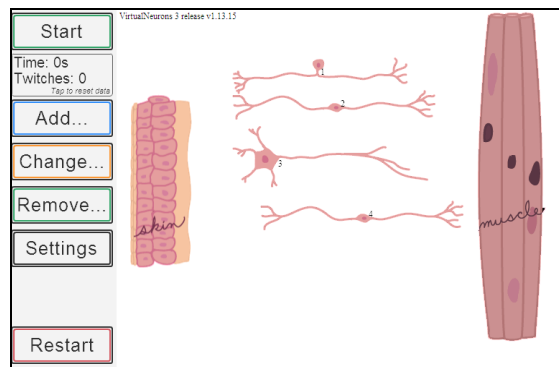
   Muscle with neuromuscular functions.

3. Direct students to construct a simple circuit that makes the muscle twitch.

   • Try doing this with only two neurons.

   • Try it again with three neurons and note how the number of twitches changes over time.

4. Ask students to try the simple circuit (one sensory, one inter, and one motor neuron) with different interneurons. Students will discover that some neurons are excitatory and some inhibitory. How does the rate of muscle twitching change with different interneurons in the circuit? [An inhibitory interneuron will not excite the next neuron in the circuit and the muscle will not twitch.]
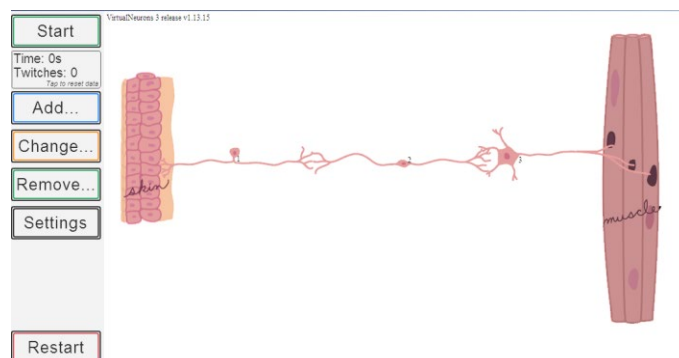
Allowing students to explore the software with the guidance of the teacher and in the absence of a handout will highlight any misconceptions and points where the students may be struggling. At this stage, the teacher can take time to address these issues. This makes Part 3 (Causing the neurons to activate or fire in the Student Guide) easier for students to understand and to do.

5. Provides students with a copy of the Virtual Neurons Student Guide. Allow them to complete Parts 1 and 2. This should take 15-20 minutes if most of the students' questions were addressed earlier.

Explain and Review

1. Invite three students to come to the board and draw a motor neuron, an interneuron, and a sensory neuron.

2. Ask the class to share how they figured out which neurons were the sensory neuron, interneuron, and motor neuron.

3. Ask students to describe how they knew which neurons were excitatory and inhibitory.

4. Ask students to write a reflection paragraph that describes how working with the Virtual Neurons software helped them learn about neurons and neuronal communication.

5. Ask for volunteers to share their reflections on using the Virtual Neurons software.

   Review (using clicker quiz, pop quiz) and assess student knowledge about neurons, types of neurons, functions of neurons, circuit, flow of signal, threshold, and action potential. Explain *threshhold*.

6. Ask students to explore Part 3 of the student guide. In this activity, students will work with the Settings screen where they may enable additional features in the program.

   Action Potential Meters After activating this feature, action potential meters for each neuron will appear at the left of the screen. In addition, the neuron number will appear by the neuron's cell body. The action potential meter records the number of times a neuron receives a synaptic signal that moves it closer to threshold, indicated by the large number in the meter. When the green color fills the meter, the

neuron fires an action potential. When the action potential travels to the next nerve terminal, it releases neurotransmitter onto the dendrites of the next neuron or onto the muscle at the neuro-muscular junction.
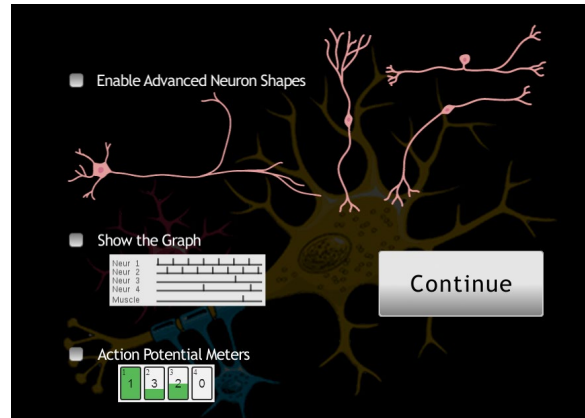
   The filling green color represents neuronal membrane potential *depolarizing,* or going up, a little (+1) with each received excitatory synaptic signal and depolarizing fully with an action potential once membrane potential reached threshold. What happens to neuronal membrane potential when an inhibitory synaptic signal is reached? [Membrane potential *hyperpolarizes*, or goes down, a little   (-1) with each inhibitory synaptic signal received.]

   When the threshold is set to the minimum (0), the neuron fires spontaneously at a fixed rate. This models pacemaker activity in the central nervous system. In the central nervous system,

the rate of spontaneous firing of a pacemaker neuron can be modulated up and down by synaptic input. This program is not sophisticated enough to do that.

You may change the threshold for a neuron by clicking in its action potential meter. The number will increment +1 for each click on the meter. Possible values are 0-5. If you click in a meter set at maximum, the value will change to 0.

7. Ask students to select Action Potential Meters in the Settings screen and click Continue. At the program's main screen, they should create a simple circuit, observe the changes in the action potential meters, and answer the questions in step 6 of Part 3.

8. Click on the Settings button and select Show the Graph. Click Continue to return to the main screen where the graph is shown below the circuit. Students may need help here to understand the graph and correlate the information with the action potential meters.
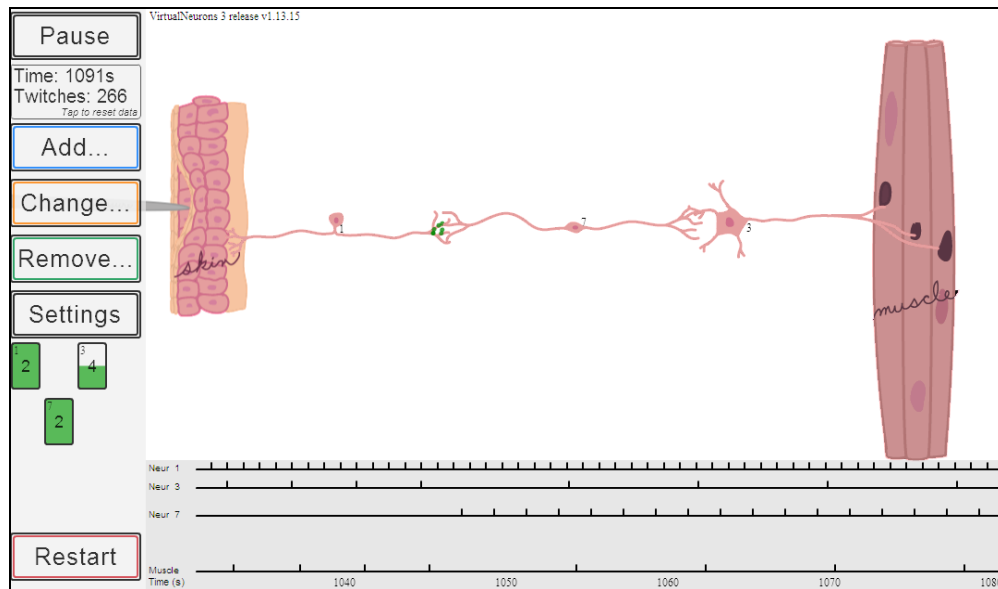
Address these questions:

- What does each vertical line on the graph represent?

  [The line represents the firing of an action potential in that neuron.]

- What would happen if I change the threshold of neuron X? Why does the muscle twitch less frequently?

  [A higher threshold will result in less frequent firing.]

9. Explain a simple circuit and the accompanying graph. This is easiest when the circuit is running.

Construct a different simple circuit and follow the neuronal activity with the graph. Be able to explain why each neuron fires when it does. Calculate the rates of firing for each neuron in the circuit. Predict quantitatively what will happen when you change the thresholds.

Change one threshold, run the circuit again and follow the graph. What are the rates now? Was your prediction correct? Why or why not? Repeat the process until you are confident of your predictions.

Expand

1. Direct students to design a circuit (Student Guide Part 4) to test how manipulating a factor in a neuronal circuit affects neuronal communication.

2. Before conducting these manipulations, ask each student or group to describe their circuit to the class and receive feedback about their experimental plan.

3. Give students time to write a lab report on the operation of their circuit(s) and how and under what circumstances it changed or did not change. Have students explain why circuit behavior changed.

4. Allow students to discuss and share their results with the rest of the class.

5. Ask students to write rules for making and testing circuits.

6. Compare making, testing, and debugging circuits to doing an experiment. How are theses processes alike? How are they different?

The following circuits are examples of some scenarios that can be demonstrated using the Virtual Neurons software. Short descriptions are provided.

Circuit Illustrating Summation of Excitation and Inhibition

In this circuit all neurons are excitatory except neuron 2 which is inhibitory. Since the skin is depressed **less** farther away from the pin, neuron 1 fires at a slower rate than neuron 5 where the pin depresses the skin maximally. This illustrates the big concept that the rate of firing in the sensory neuron is proportional to the strength of the sensory signal.
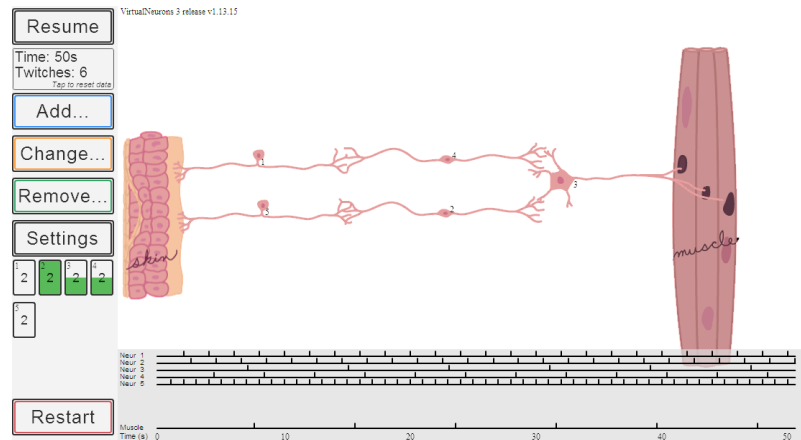
Neuron 2 fires following neuron 5. Neuron 4 fires more slowly following neuron 1. Neuron 3 adds up the excitatory (+1) and inhibitory (-1) inputs as they come along, keeping a running sum since the last time the motor neuron fired triggering a muscle contraction. Since the threshold for neuron 9 is 2, the green must fill the meter for neuron 3 for the motor neuron to fire and cause the muscle to twitch. If an inhibitory (-1) input arrives too quickly from neuron 2, neuron 3's action potential won't be triggered and the muscle will not contract. Threshold is a teeter-totter point where a neuron is making the decision to fire an action potential after getting the right amount of input.

What happens in this circuit if you substitute an excitatory interneuron for neuron 2?

What happens in this circuit if you move neuron 1 just a little bit farther away from the pin?

What happens in this circuit if you move neuron 1 closer to the pin?

What happens in this circuit if you remove neuron 2 completely?

Does the muscle have a threshold? Why or why not?

[The muscle contracts reliably every time it receives a signal from the motor neuron. Muscles need to work every time the body signals them to do so. All variations in how strongly a muscle contracts come from changing the number of muscle fibers that act simultaneously. The nervous system makes those calculations and activates many motor neurons together or in a sequence as a limb is moved.]

When an incoming synaptic event occurs simultaneously with firing of an action potential in the receiving neuron, does the synaptic signal influence the action potential?

[No, because the action potential is already underway. So the running sum tallied by the neuronal cell body does not add in that event. But in your brains, those simultaneous events can result in strengthening that particular synaptic connection. This program is not sophisticated enough to model those changes in synaptic strength we call learning.]

When examining any of these circuits, do not forget to calculate individual neuron firing rates and the muscle contraction rate. Quantitative comparisons may yield subtle differences.

Creating Feedback Loops

Using the setup menu, click Enable Advanced Neuron Shapes and click Continue. Back on the main screen, click the Change button and then click on the neuron whose shape you want to change. Choose the desired shape. Use the curved and branched shapes to create feedback loops. All feedback involves sending information backwards in a circuit creating loops in the flow of information.

Positive Feedback tries to increase the event that has caused it. For example, as you pick up a box that is heavier than expected, positive feedback from your muscle receptors increases the rate of motor neuron firing and muscle contraction since more effort is needed to lift it.
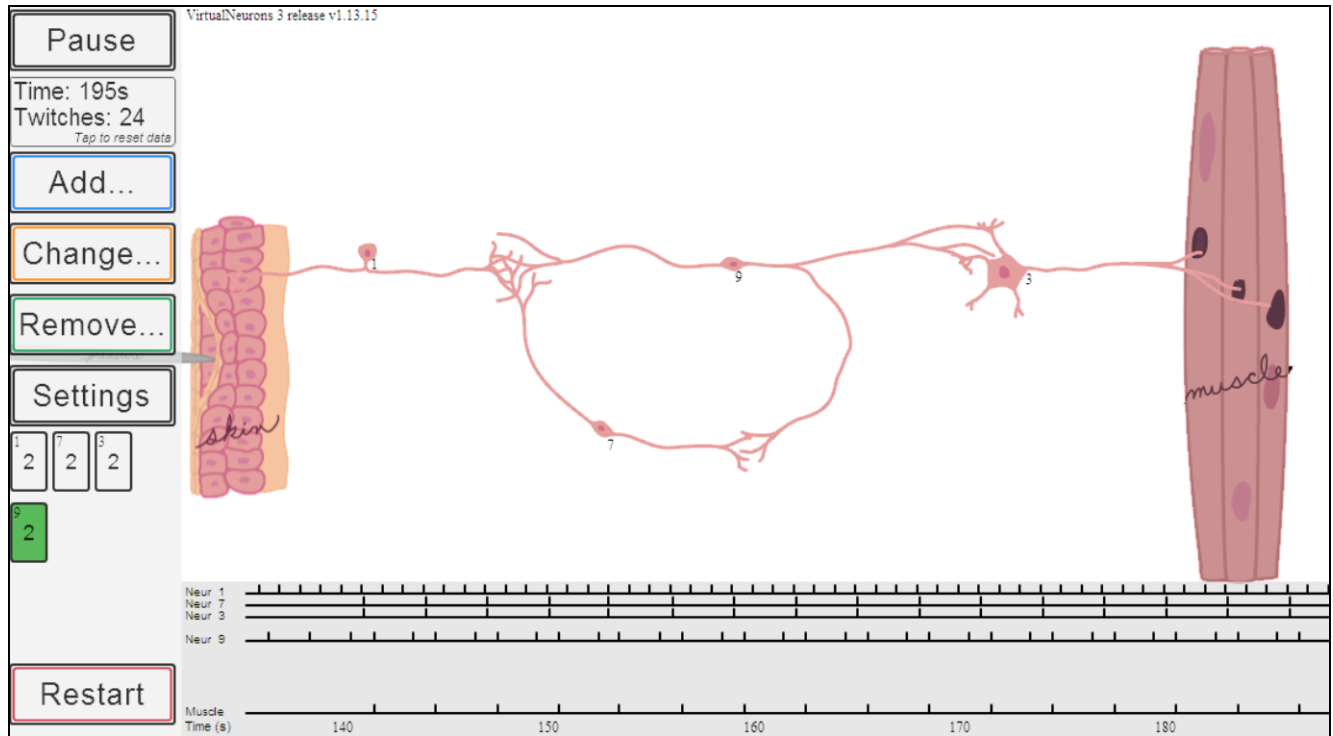
In this circuit, neurons 9 and 7 form a positive feedback loop. All neurons in this circuit are excitatory. Initially neuron 1 fired two times (+1+1) to activate neuron 3. Neuron 7 fires following every time neuron 9 fires. Since neuron 7's threshold is 2, neuron 3 adds the incoming signal from neuron 7 (+1) to the incoming signal from neuron 1 (+1), bringing neuron 9 to the above threshold (+3) and firing its own action potential. Neuron 3 fires following every time neuron 9 fires. The muscle contracts every time neuron 3 fires.

Why are the firing rates from neurons 9, 7, and 3 and the muscle contraction rate *syncopated,* or not evenly spaced in time?
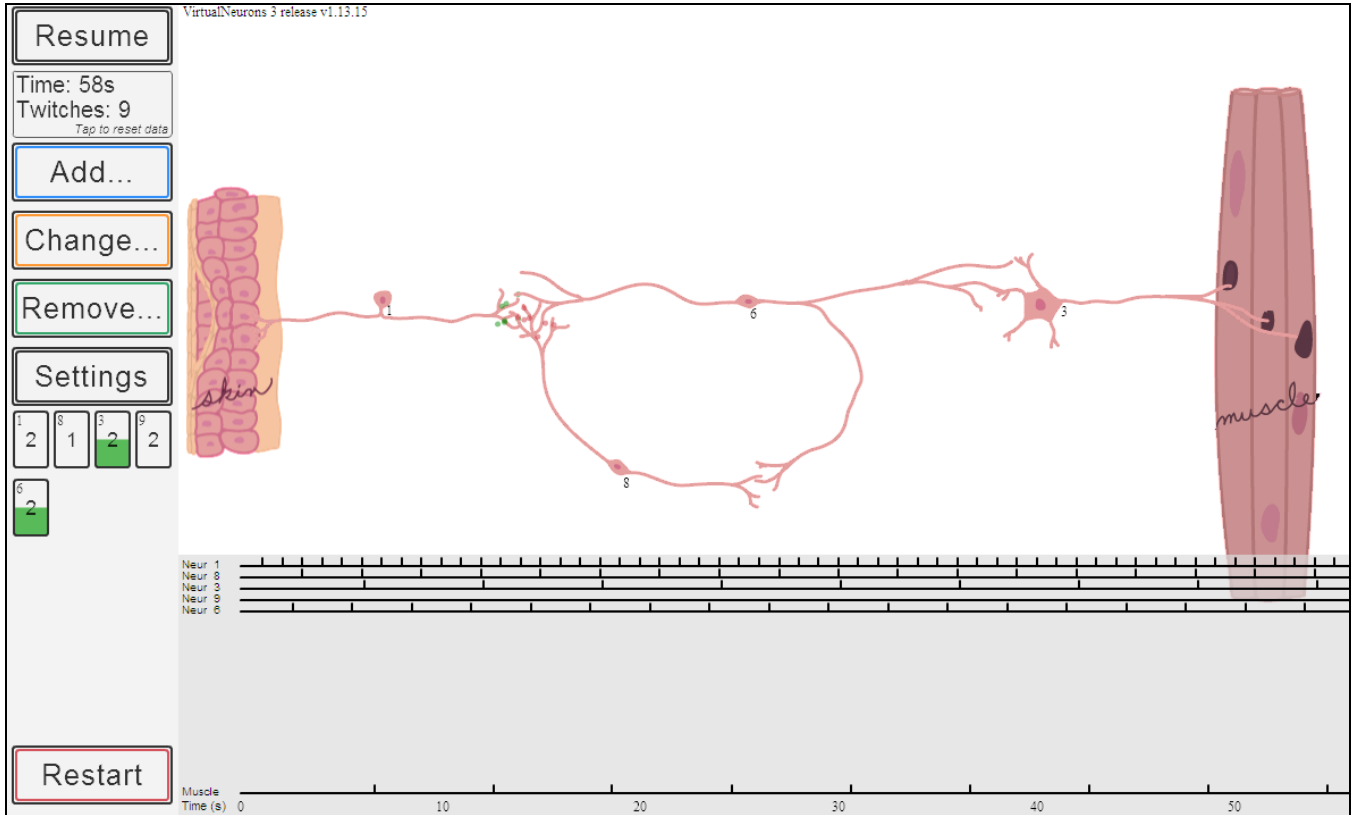
What happens to the muscle contraction rate when neuron 7 is removed from the circuit?

What does neuron 7 do to muscle contraction rate?

What happens if you raise the threshold of neuron 3 with and without neuron 7 in the circuit?

What happens to the circuit if the threshold for neuron 9 is lowered? Raised?

Negative Feedback works to decrease the event that caused it. This is the more common type of feedback. For example, as you pick up a box that is lighter than expected, negative feedback from your muscle receptors decreases the rate of motor neuron firing and muscle contraction since less effort is needed to lift a light box.

In this circuit, neurons 6 and 8 form a negative feedback loop. Initially neuron 1 fired two times (+1+1) to activate neuron 6. Neuron 8 fires following every time neuron 6 fires since neuron 8's threshold is 1. Neuron 6 adds the incoming signal from neuron 8 (-1) to the incoming signal from neuron 1 (+1 several times), bringing neuron 6 to threshold (+2) and firing its own action potential. Neuron 3 fires following every time neuron 6 fires. The muscle contracts every time neuron 3 fires.

How do the firing rates in this circuit compare with those from the positive feedback circuit?

What happens to the muscle contraction rate when neuron 8 is removed from the circuit?

What does neuron 8 do to muscle contraction rate?

What happens if you raise the threshold of neuron 3 with and without neuron 8 in the circuit?

What happens to the circuit if the threshold for neuron 6 is lowered? Raised?

Spontaneously Firing Neurons Do Not Need Sensory Input

If the threshold of the interneurons is lowered to the minimal level, then these interneurons start firing simultaneously even in the absence of a sensory input. This demonstrates the fact that in the central nervous system, all neurons do not need a sensory input for activation. Some have such low thresholds that just by detecting a random change in the ion concentrations in their surrounding environment, they can self-activate and fire spontaneously.

For example, pacemaker neurons set up the oscillating (regular back and forth) rhythms that generate crawling behavior in worms, swimming behavior in fish, or the action of walking.
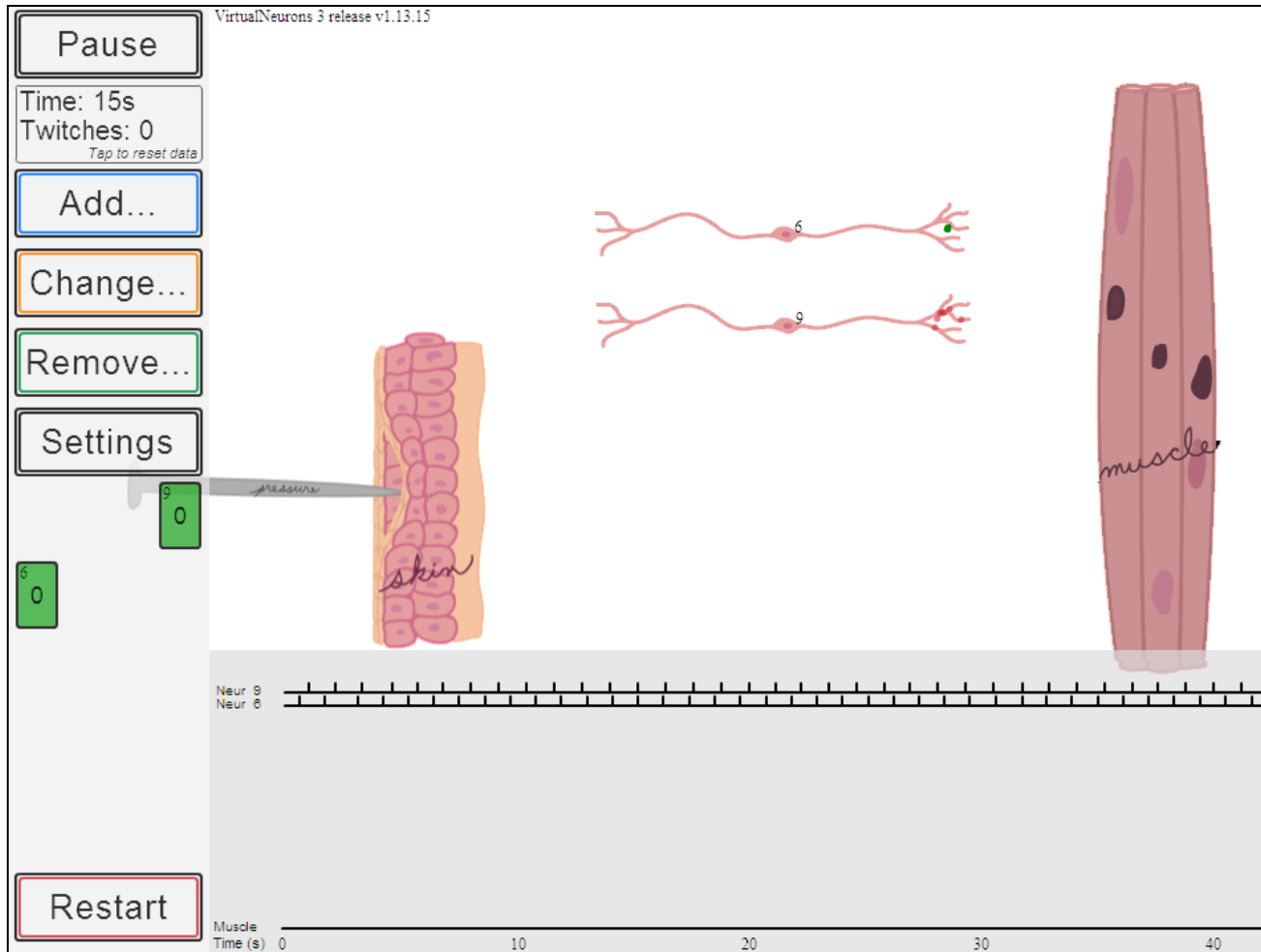
Neurons 6 and 9 are firing spontaneously as shown in the image above. The graph shows they are firing maximally without any inputs.

Make the muscle contract without any sensory input.

Make a circuit where sensory input modifies muscle contraction driven by a pacemaker neuron.

Make a circuit where a spontaneously firing inhibitory neuron silences incoming sensory information.

Have fun!!! Make some of your own circuits and analyze them!

Common Problems in Understanding these Circuits

If the threshold of a neuron receiving multiple inputs is too low, it is difficult to see the result of the summation of the incoming signals. If only one of the inputs is sufficient to trigger firing, additional inputs will not have an effect.
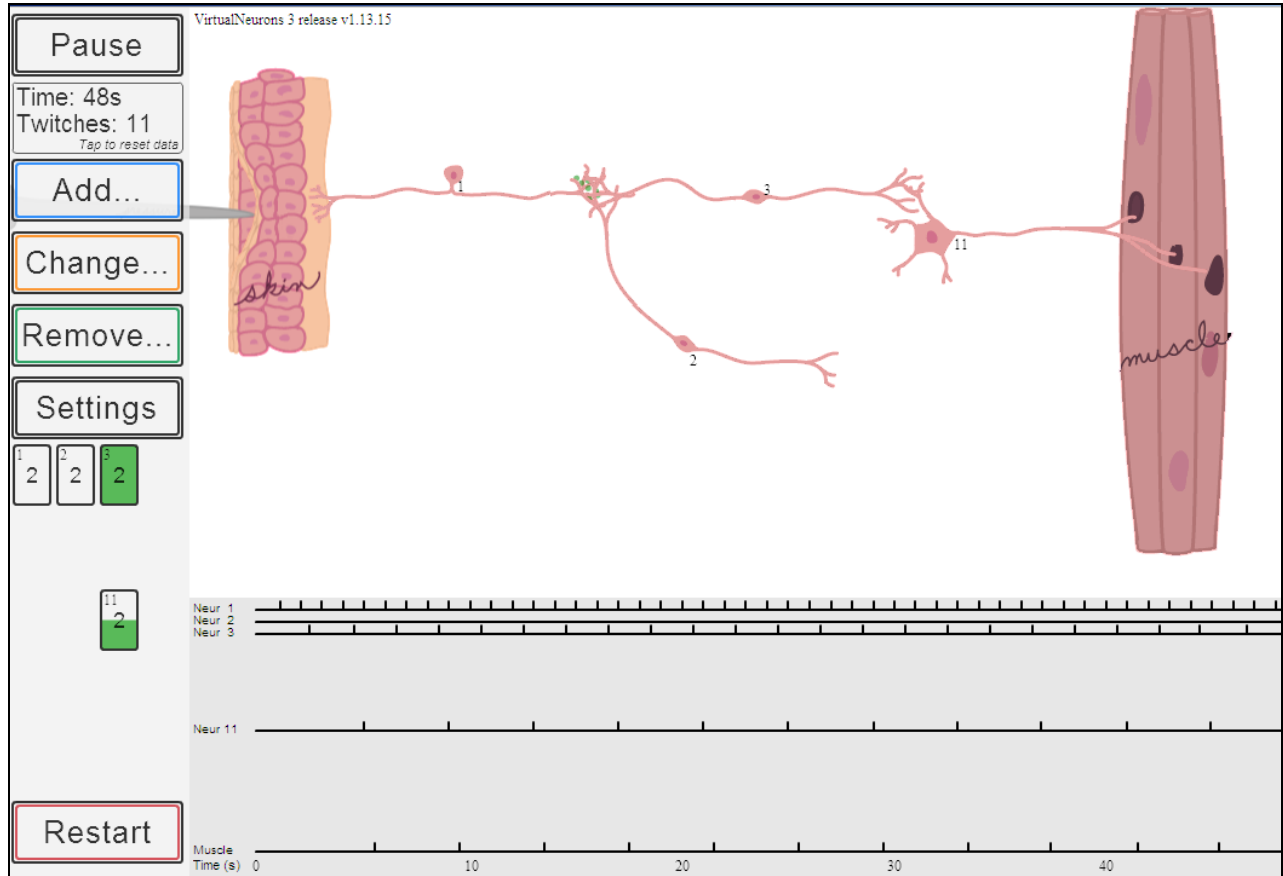
How is this circuit different from the simple three neuron circuit on page 4 or page 6?

What is the function of neuron 2?

What happens if the threshold of neuron 3 is raised? What is the function of neuron 2 in that condition?

Similarly, multiple loops can sometimes be redundant. Carefully follow the flow of information by tracing firing rates in the graph to analyze and debug circuits.