Electricity and Magnetism: Physics Narrative 04

Contents

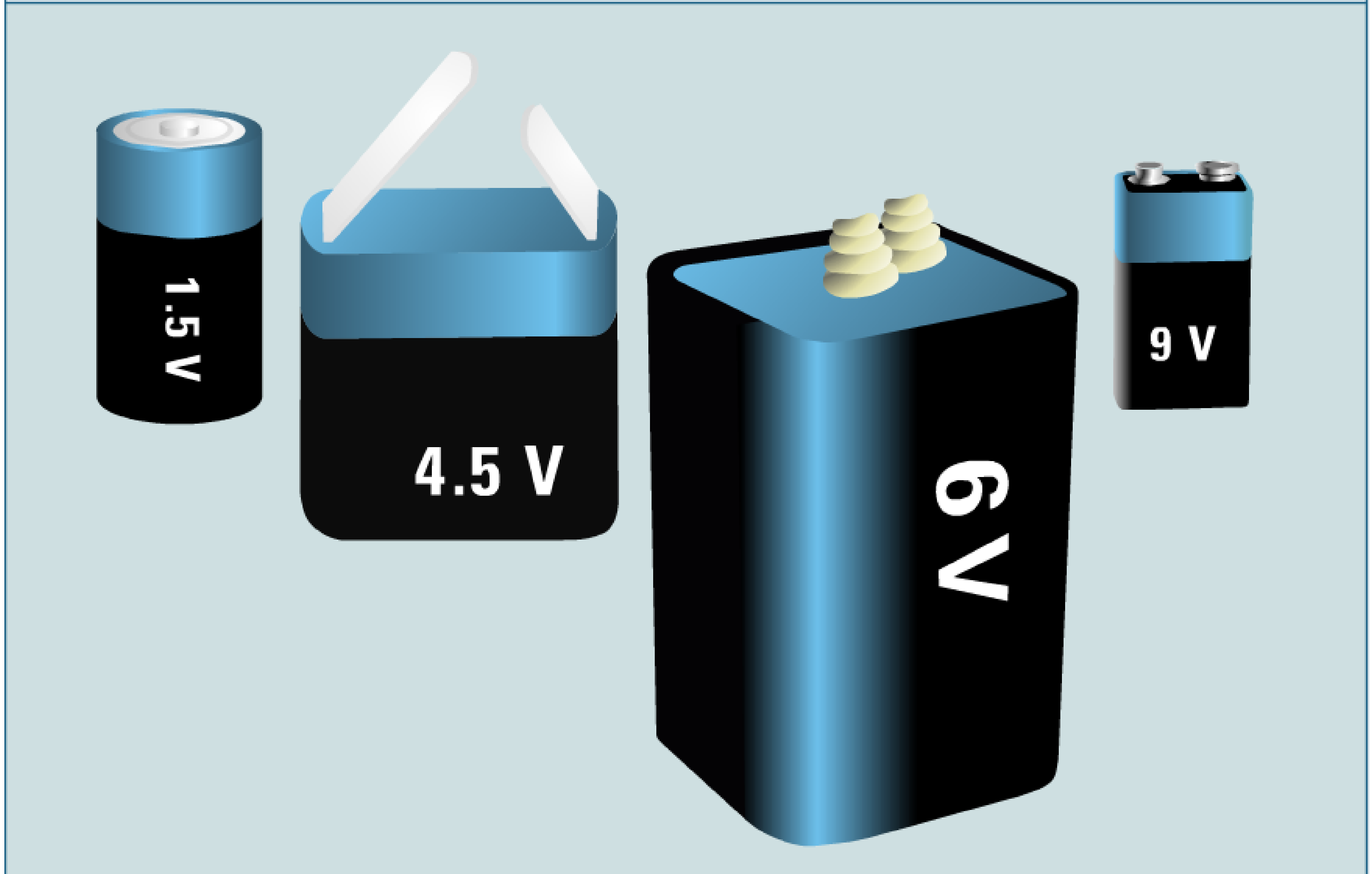
This is the 'Physics Narrative' for this episode, that explains the physics for teachers. To develop your expertise in the episode, work with the 'Teaching and Learning Issues' and the 'Teaching Approaches'. Navigate to any part of the topic using the Topic Menu, or use the tabs below to stay within this episode..

What does voltage tell us?

Batteries come in all shapes and sizes. The batteries commonly used in school science practical work are torch batteries rated at 1.5 volt. If two of these batteries are connected into a circuit one after the other (in series), the total rating is 3.0 volt. If three batteries are used we have 4.5 volt and so on. A single 9 volt battery might be used to supply a radio, whilst a 12 volt battery is used in cars.

A key specification for any battery is its voltage, and this is what we need to know when buying a battery in a shop. But what exactly does the voltage tell us?

Batteries come in many sizes and shapes



STEP 1 of 4

What does voltage tell us?

There are two ways of thinking about voltage. These are, in fact, two ways of telling the same story and relate directly to ideas introduced in earlier episodes.

TWO WAYS OF THINKING

VOLTAGE

as an electrical 'push'

VOLTAGE

to find energy shifted

What does voltage tell us?

Voltage as an electrical "push"

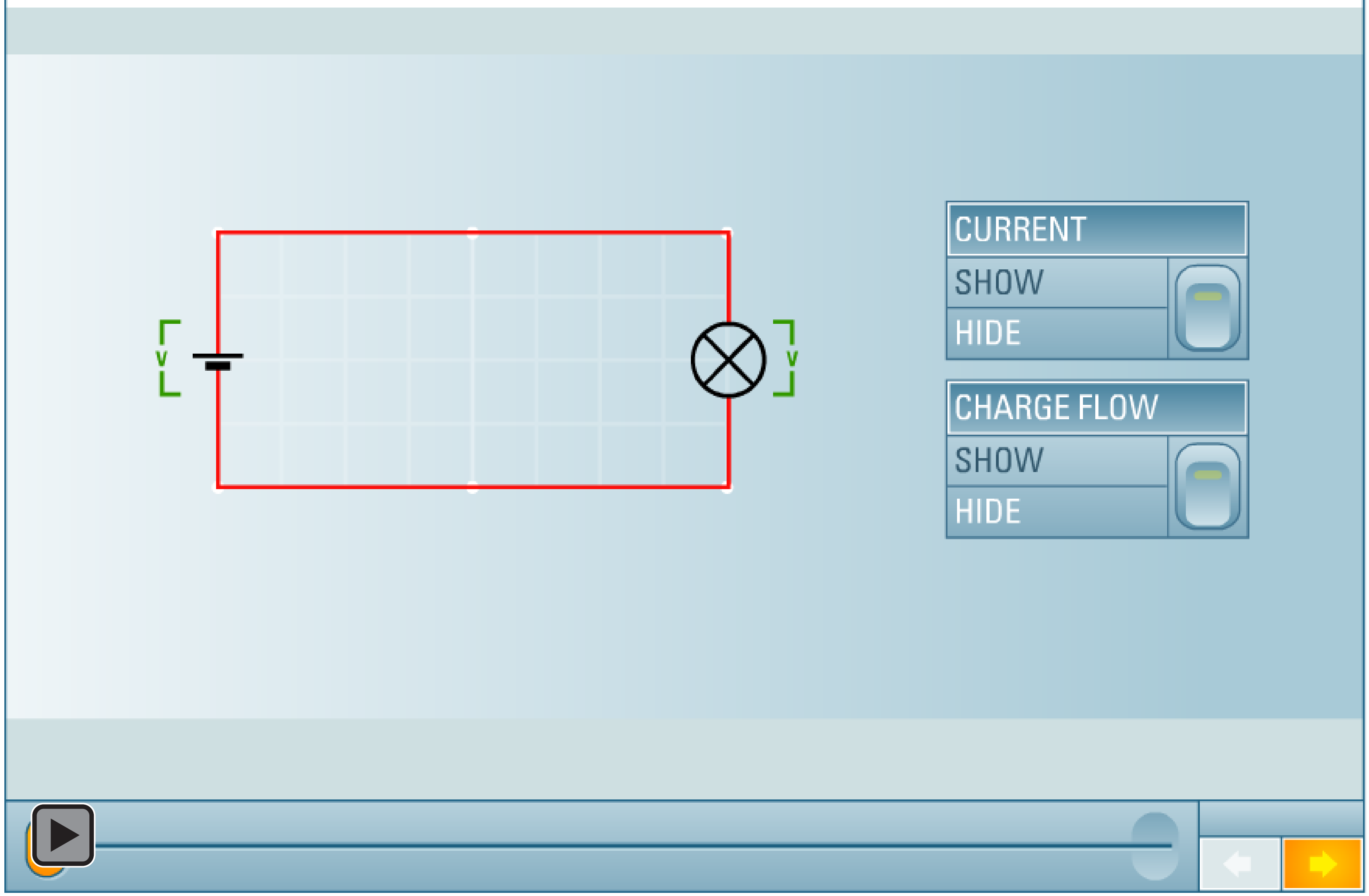
Firstly we may think of voltage as being a measure of the size of the force or "push" provided by a battery on the charges in a circuit. The idea of a battery providing a push to set charges in motion was first introduced in episode 1. Furthermore, we saw in episode 3 that adding an extra battery to a circuit (or using a battery with a higher voltage) provides a bigger push, moving charges around more quickly and increasing the electric current.

Sometimes the battery voltage is referred to as the battery e.m.f., which stands for electromotive force. This term captures the idea of the battery providing a force or push on all of the charges in the circuit.

Thinking about voltage as a push links up closely with the rope loop analogy, in which increasing the number of batteries is seen in terms of pulling the rope around with a greater force.

Voltage sets current

Use the switches to show the current and charge flow.



What does voltage tell us?

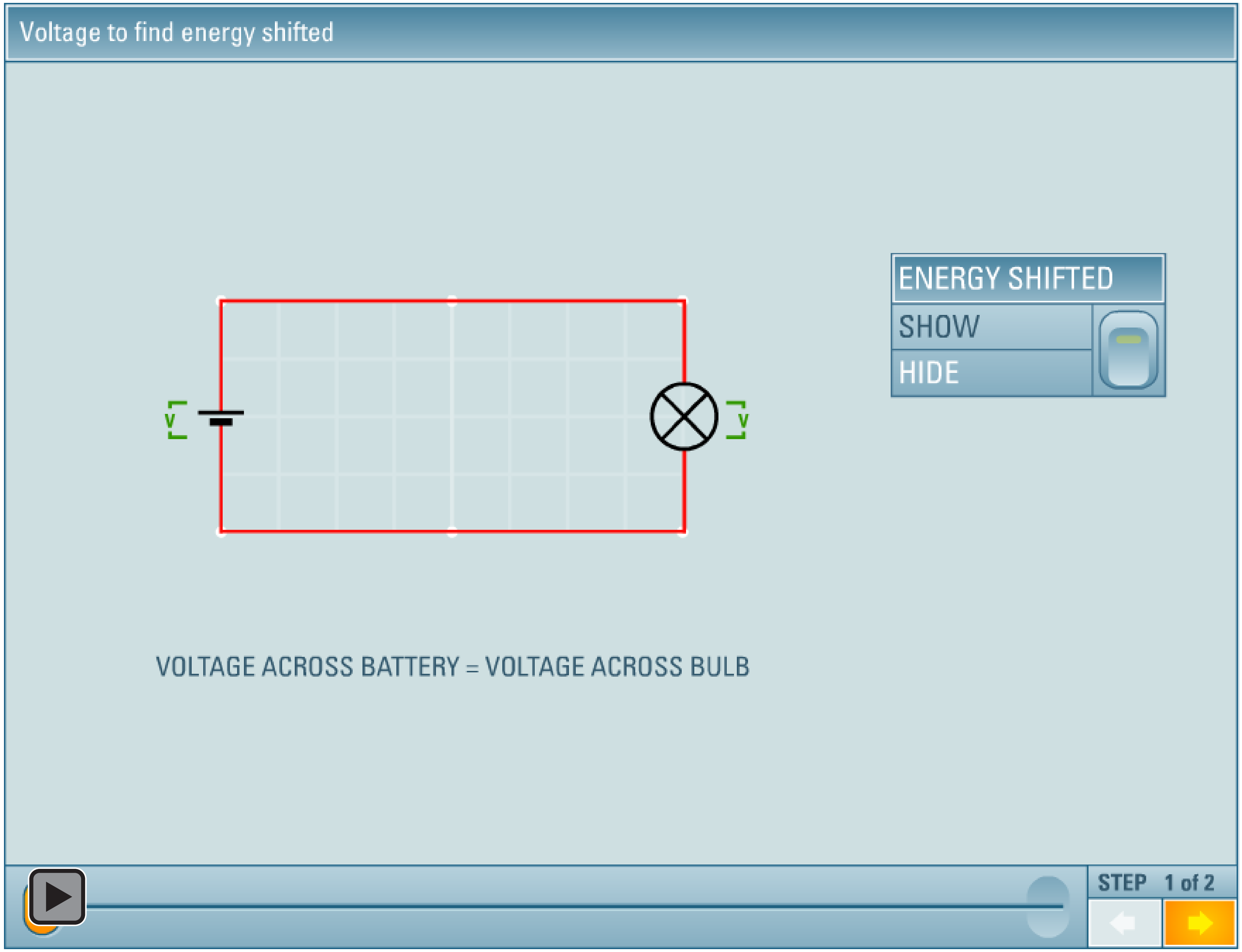
Voltage in terms of energy shifted

Whilst it makes sense to refer to voltage as being a measure of the push of a battery, it makes little sense at all to talk about voltage as being a measure of the push of a bulb.

Here we need to turn to the alternative view of voltage as a measure of the energy shifted by each charge in different parts of the circuit.

More precisely, it is a measure of:

- the amount of energy shifted per unit charge by the battery (energy shifted from the chemical store in a battery as charge flows through the battery).
- the amount of energy shifted per unit charge to the surroundings in any circuit resistance (energy shifted to thermal store in surroundings as charge flows through resistance).



What does voltage tell us?

If there is to be an energy balance for the circuit as a whole (which there must be!), then the voltage across the battery and across the bulb must be equal. This way of thinking about voltage links up closely with the supermarket analogy, in which increasing the voltage is seen in terms of more bread being loaded onto each van in the bakery (more energy per unit charge), with the vans moving around the circuit more quickly (due to the bigger push). These changes result in a greater amount of bread being "dissipated" in the supermarket per unit time.

Relationship between voltage, current and resistance

The relationship between the push of the battery and the size of electric current is summarised by:

$$I = \frac{V}{R}$$

Where:

V: voltage, measured in volt

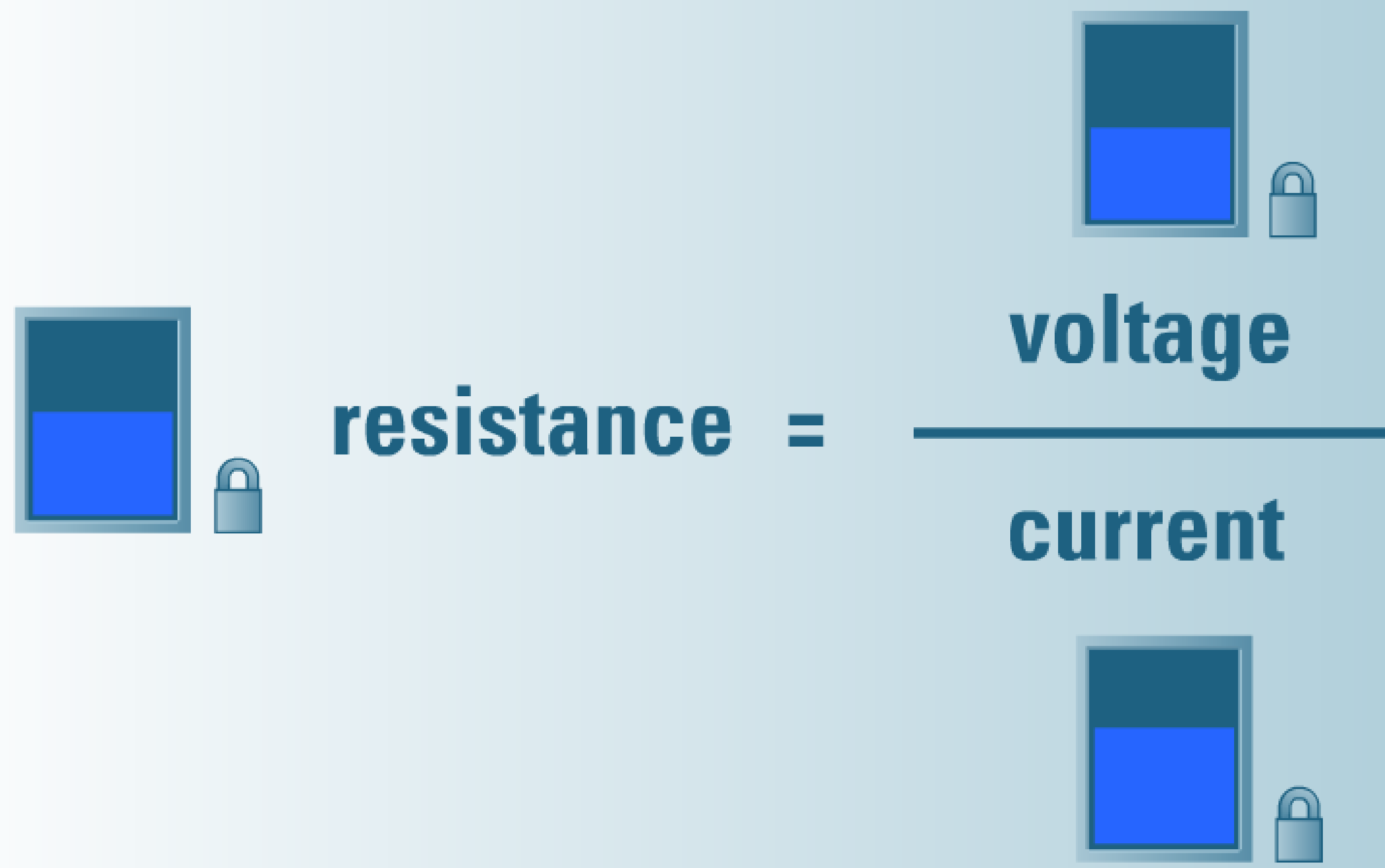
I: current, measured in ampere

R: resistance, measured in ohm

According to this relationship, if the resistance does not change, then increasing the voltage results in an increase in current.

Relationship between voltage current and resistance

Click on a term to make it the subject of the relationship.
Unlock a pair of variables, then drag one to see how the other varies.



Relationship between voltage, current and resistance

An example:

Suppose a 3 volt battery drives a current of 0.3 ampere through a 10 ohm resistor.

If the battery voltage is doubled to 6 volt, the new current is given by:

$$I = \frac{V}{R}$$

$$I = \frac{6 \text{ volt}}{10 \text{ ohm}} = 0.6 \text{ ampere}$$

Double the battery voltage gives double the current.

The same story

Read more about the action of the battery on the charges.

Why do we say that these ideas about voltage are two ways of telling the same story? The answer to this question takes us back to the detailed explanation, introduced in episode 1, of how electric circuits work.

When a second battery is added to a circuit, increasing the voltage, the effect is to strengthen the electric field around the circuit, between the positive and negative terminals of the battery. There is a greater force (or push) on each and every charge in the circuit due to the stronger field (as the positive terminal becomes more positively charged with respect to the negative terminal). This greater force produces a greater acceleration of charges between collisions with the ions in the filament of the bulb, and so more energy is shifted from charge to ion during each collision. So, at one and the same time, increasing the voltage results in a bigger push on each charge and more energy being transferred by each charge.

The volt

The volt is actually defined in terms of energy shifted from store to store by charges as they move around a circuit.

What does this mean? Let's consider the two cases of energy shifted in a resistor and in a battery.

The volt

Energy shifted by a resistor

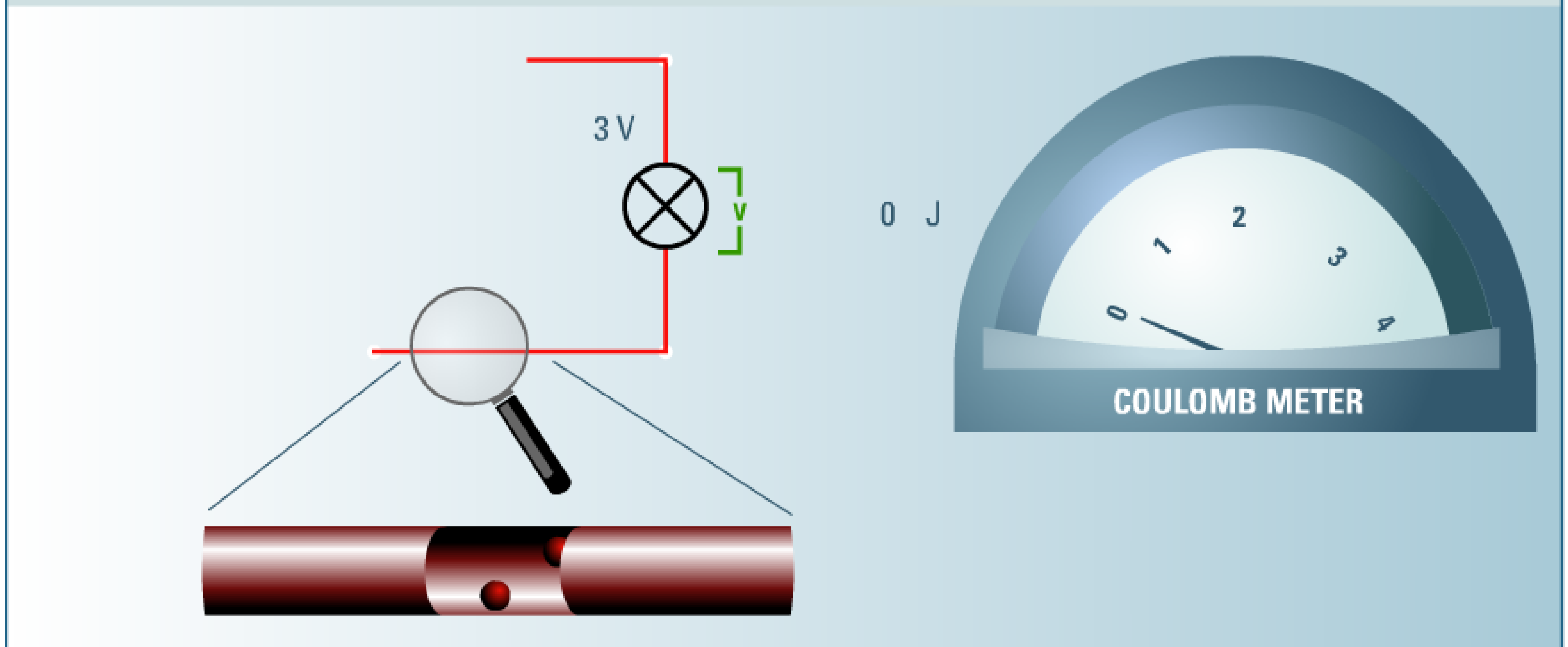
If one coulomb of charge passes through a resistance (such as a bulb) and one joule of energy is transferred by the charge to the bulb (by electrical working; see energy topic), then the voltage across the bulb is one volt.

If the voltage across the bulb is 3 volt, then the energy shifted to the surroundings as each coulomb of charge passes will be 3 joule.

The voltage across the bulb (or any other resistor) tells us how much energy is shifted to the surroundings as each coulomb of charge passes through. The voltage is the energy shifted per unit charge.

Voltage sets the energy shifted by one coloumb in a bulb

Run the animation, to see one coulomb flow and shift energy.



PLAY PAUSE RESET

STEP 1 of 2

The volt

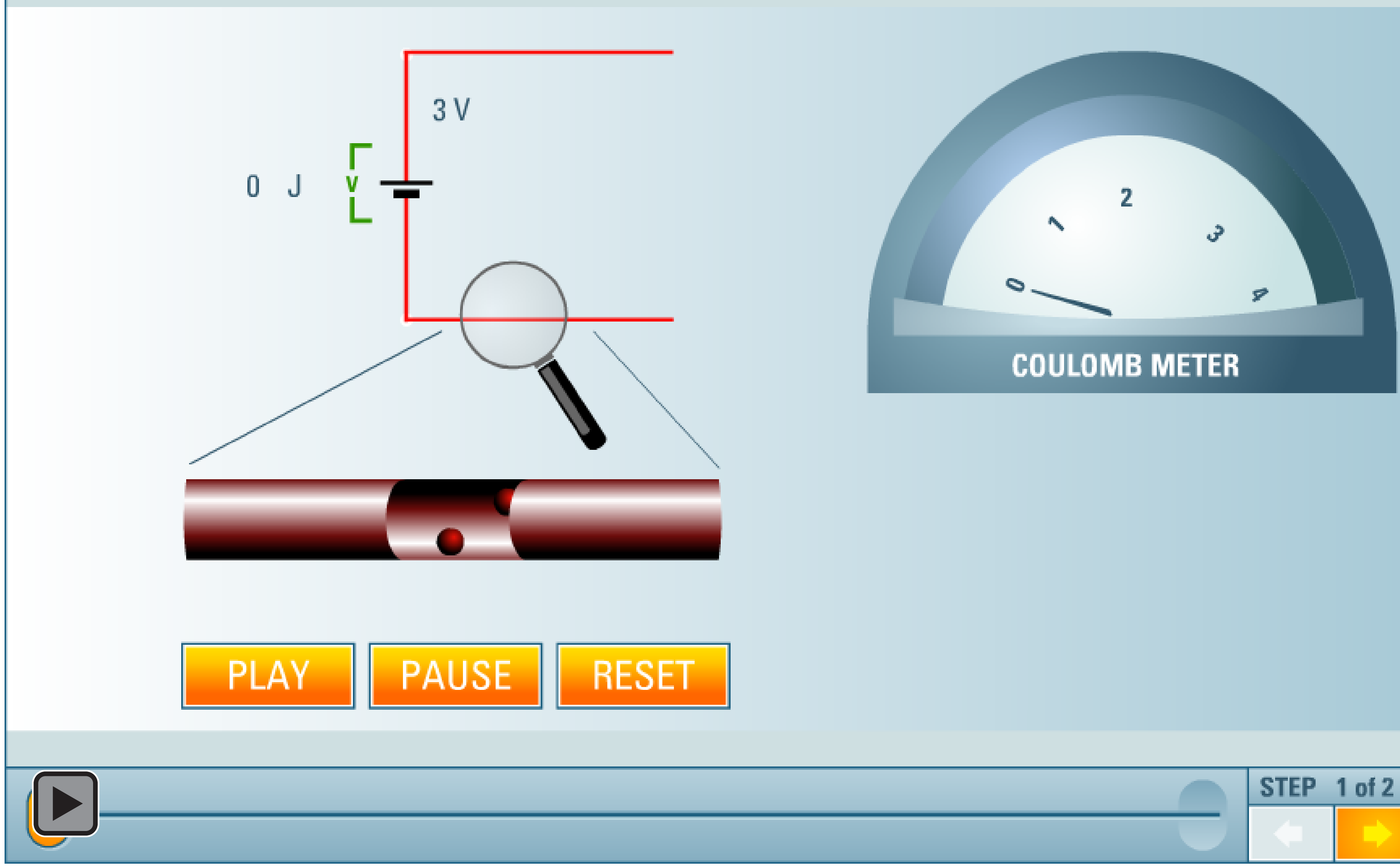
Energy transfer by a battery

What does it mean if a voltmeter is connected across a battery and it reads 3 volt? Simple! In this case, 3 joule of energy are shifted from the battery by a coulomb of charge passing through the bulb.

The voltage across the battery tells us the amount of energy which is shifted from the battery per coulomb of charge passing thorugh that battery.

Voltage sets the energy shifted by one coloumb in a battery

Run the animation, to see one coulomb flow and shift energy.



Shifting energy from a battery

Find out more about describing the energy shifted from the chemical store.

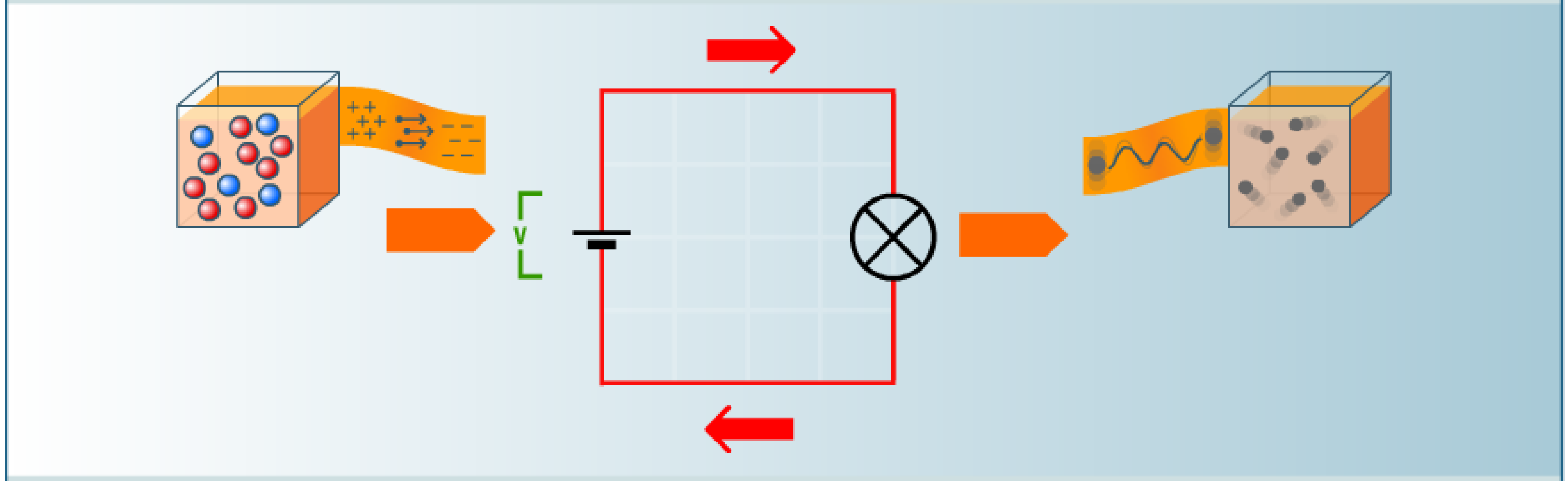
The point has been made that energy is shifted to the charges as they pass through the battery. What does this mean? To answer the question it is helpful to return to the detailed explanation of how electric circuits work introduced in episode 1.

All of the charges (imagine positive charges) in the circuit experience a push/pull to move them round from the positive to the negative terminal of the battery. When each charge arrives at the negative terminal, energy must be shifted as it moves across the battery from the negative plate to the positive plate (against the repelling force of the positive plate). The energy required comes from the chemical store of the battery, using the electrical working pathway.

So, for example, if the battery is rated at 3 volt, 3 joule of energy is shifted from the chemical store. What is in the rest of the circuit determines the stores of energy that are filled as a result of the chemical store being emptied. This ability to shift energy is why electric circuits are so useful.

Electrical circuits link energy stores

Use the stepper to alter the circuit.



CHOOSE YOUR COMPONENT
LAMP
MOTOR ACCELERATING MODEL
MOTOR LIFTING LOAD
RESISTOR WARMING ROOM

Measuring voltages

The instrument used to measure voltages is the voltmeter.

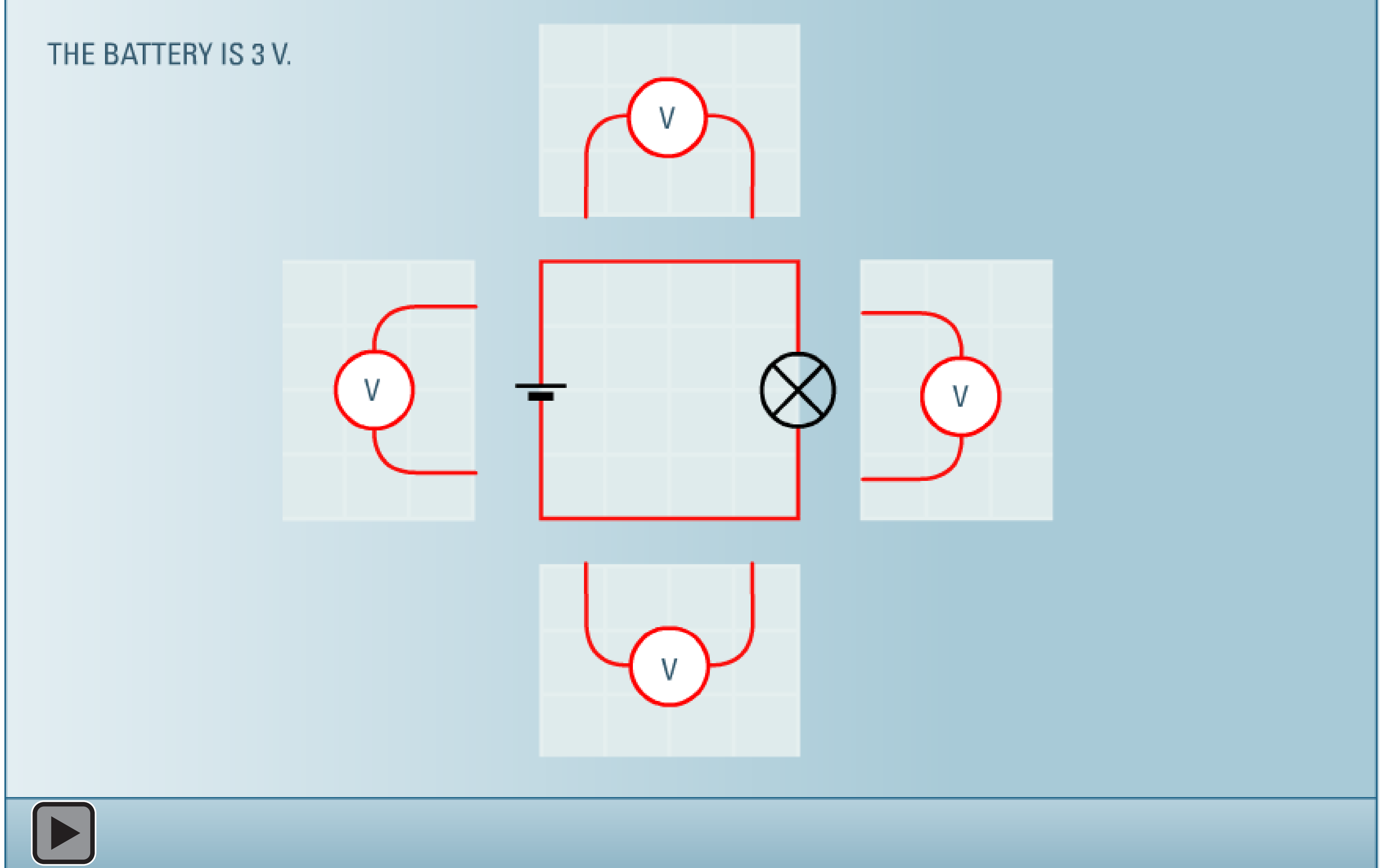
Voltmeters are always connected across circuit components, whether a battery, bulb or some other device.

Voltmeters are connected differently to ammeters (see episode 2). With the ammeter, the instrument is connected into the circuit so that the flow of charge in the circuit can be measured.

Why are voltmeters connected across components? To be able to provide an answer to this question, we need to be clear about what it is that the voltmeter is measuring.

Measuring voltages in a simple circuit

Drag the voltmeters to measure the voltages.



Measuring voltages

Energy shifted by a battery

In the circuit here, the battery is rated at 3 volt and therefore shifts 3 joule of energy to each coulomb of charge.

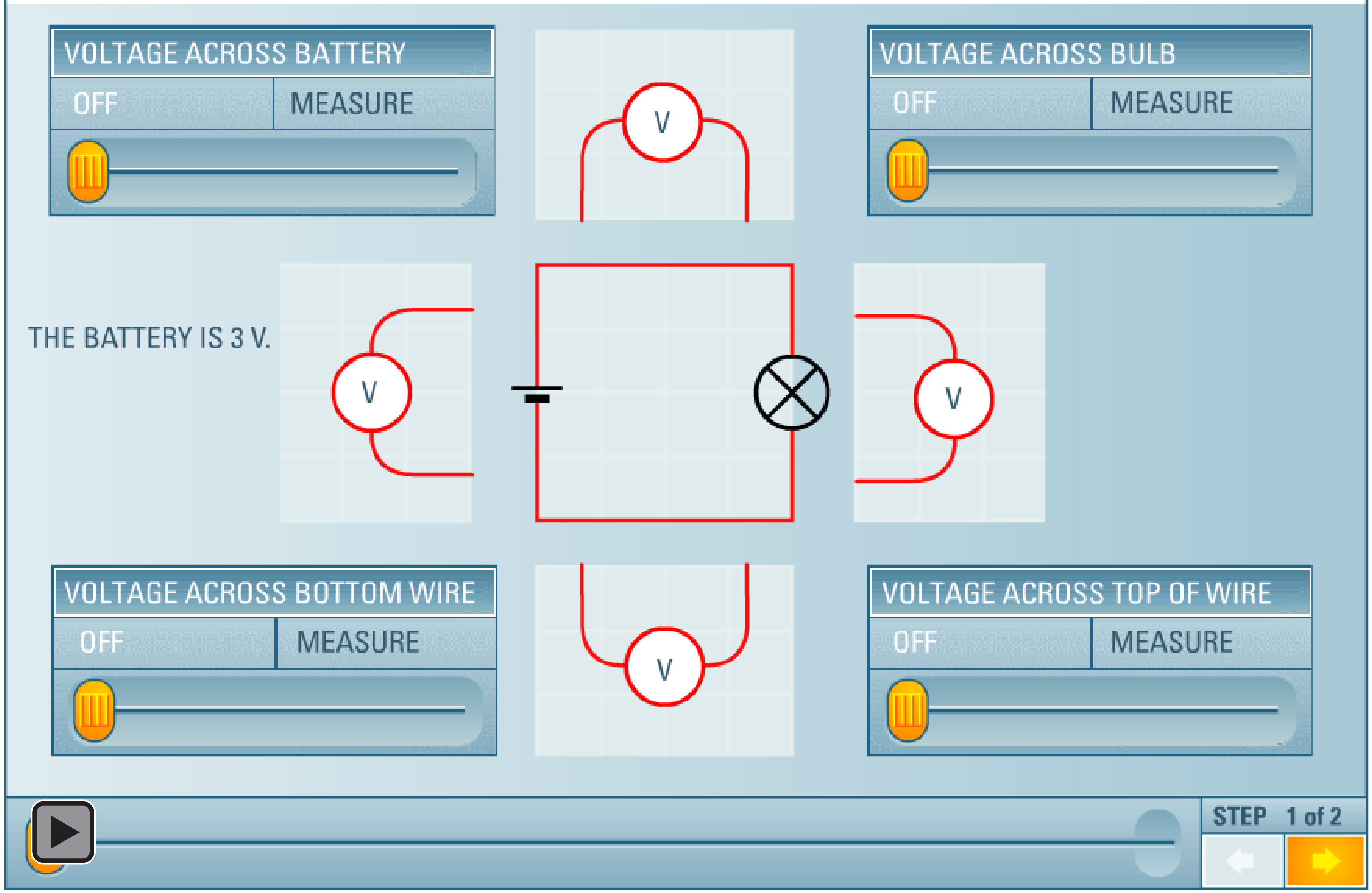
What do these mean?

In this circuit, all of the energy which is shifted from the chemical store of the battery is shifted to the thermal stores of the surroundings by the bulb. In other words we are assuming that no energy is shifted to the surroundings through the connecting wires as the charges move around the circuit and collide with the fixed ions in the wires. We are assuming that the connecting wires do not heat up at all as the current passes (in fact, the connecting wires must heat up a little, but the energy involved is negligible compared with that in the bulb).

If this is the case, then we can picture what is happening in two ways. One uses a gravitational analogy: "Energy hill" diagrams appear alongside the circuit. You need to be careful with this one. The other uses the rope loop analogy, which emphasises electrical working, tying in well with the energy topic.

Measuring voltages in a simple circuit

Use the sliders to measure the voltages.



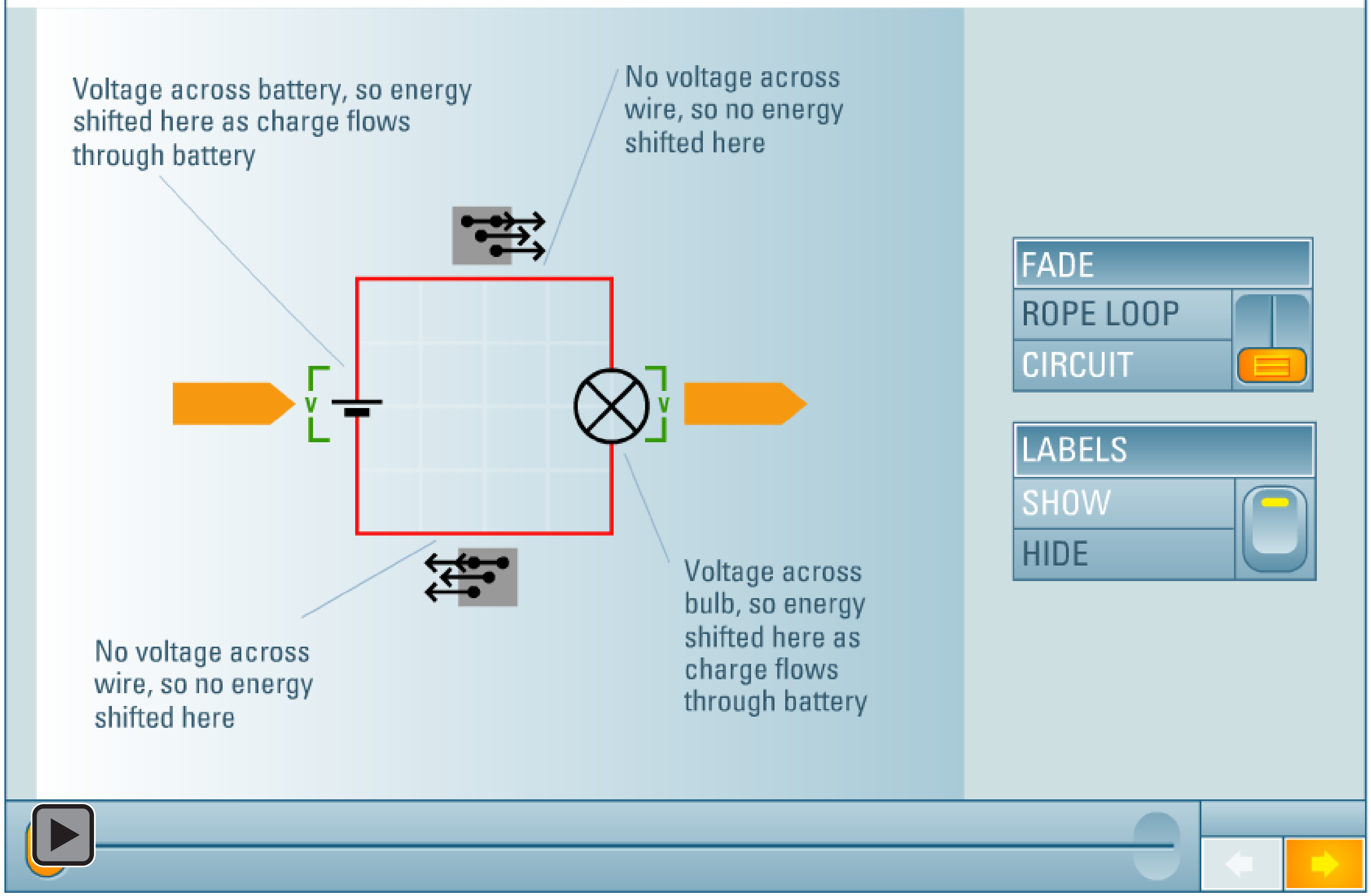
Measuring voltages

Making sense of voltmeter readings using a rope loop

In the electrical circuit, the voltage sets the energy shifted per coulomb. In the rope loop, the force sets the energy shifted per metre of rope. Both larger voltages and larger forces (grip or pull harder) lead to more energy shifted as the charge or rope flows past.

Energy and voltage in a simple circuit: Rope loop

Use the fader to alter the picture and switch to explore the diagrams.



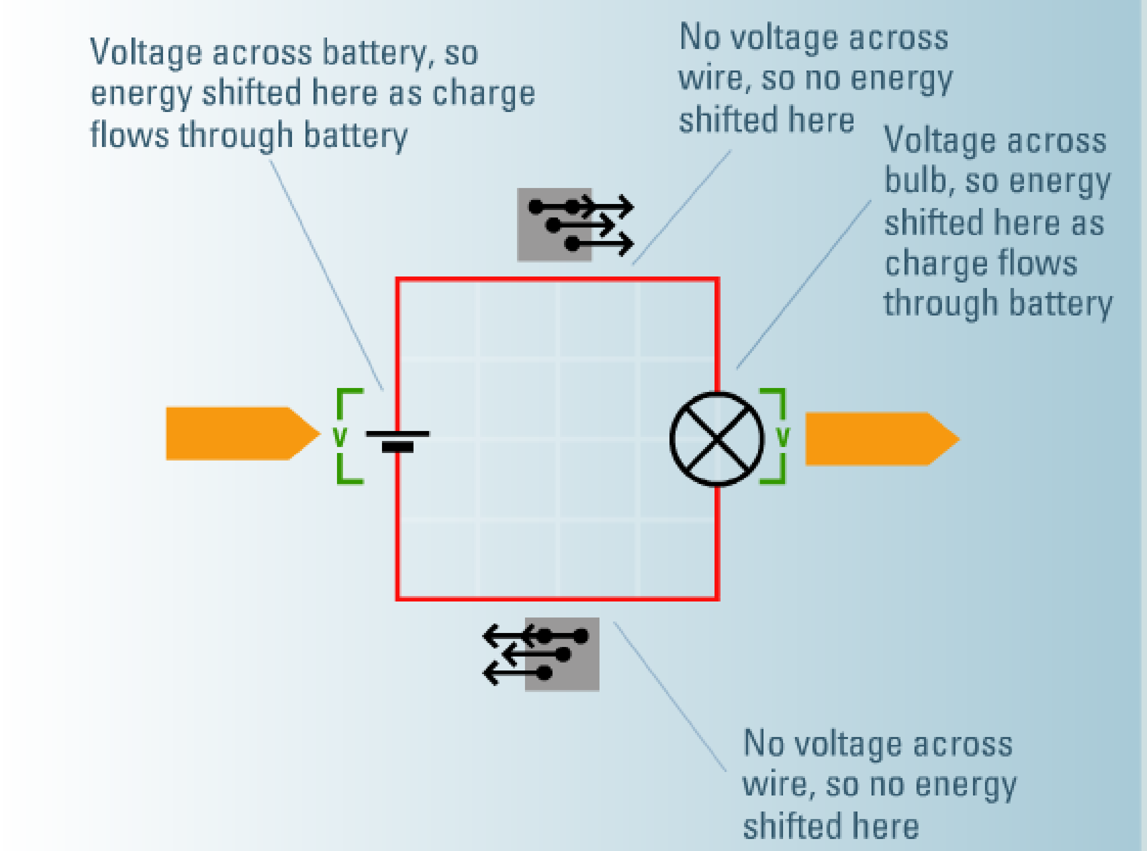
Measuring voltages

Making sense of voltmeter readings using energy hills

So, the voltmeter is connected across the circuit component (battery or bulb) in order to measure the energy shifted for each coulomb of charge passing through the component. It measures the energy transferred per unit charge, passing through the component.

Energy and voltage in a simple circuit: Hill analogy

Use the fader to move to the analogy and the switch to explore the diagrams.



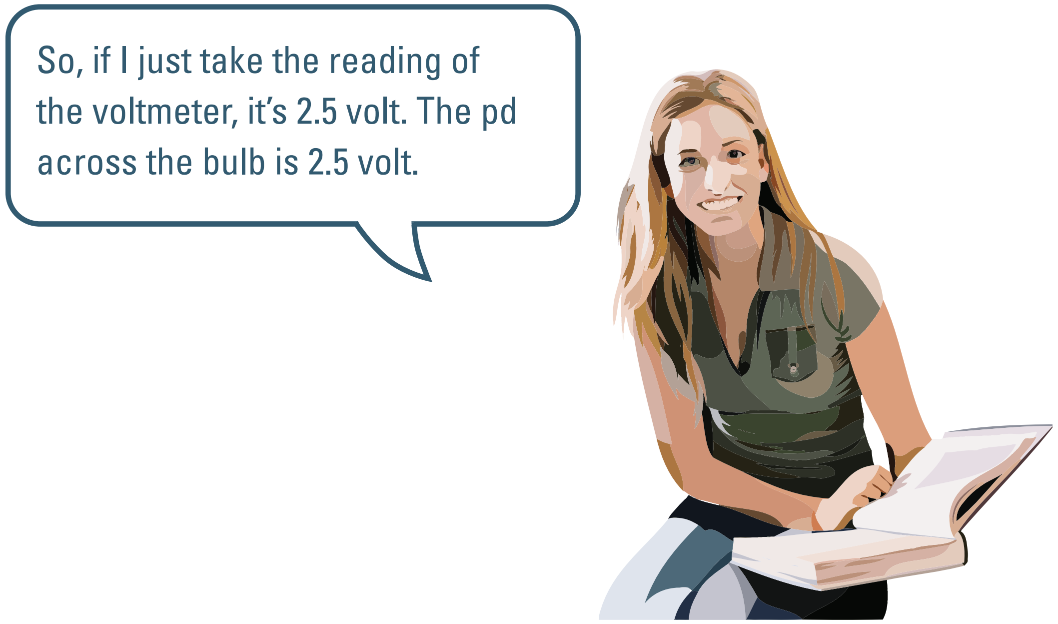
FADE
HILLS
CIRCUIT
LABELS
SHOW
HIDE

Different terms for the same thing

Read this if you are confused about the use of many different terms:

“Voltage” and “potential difference” and “potential drop” and “pd”

Very often, the voltage across a circuit component, such as a bulb, is referred to as a potential difference or a pd.



Sometimes you might hear people talk about the “voltage across the bulb”, at other times about the “potential difference across the bulb” and sometimes about the “potential drop” or “pd”. On first hearing this, it can be confusing! However, the diagrams we use show that the voltage is a measure of the difference in “potential energy per coulomb” as charge passes through a circuit component. Hence the use of the terms potential difference or potential drop. At this stage is probably simpler for pupils just to use “voltage”.

Test your understanding of voltage

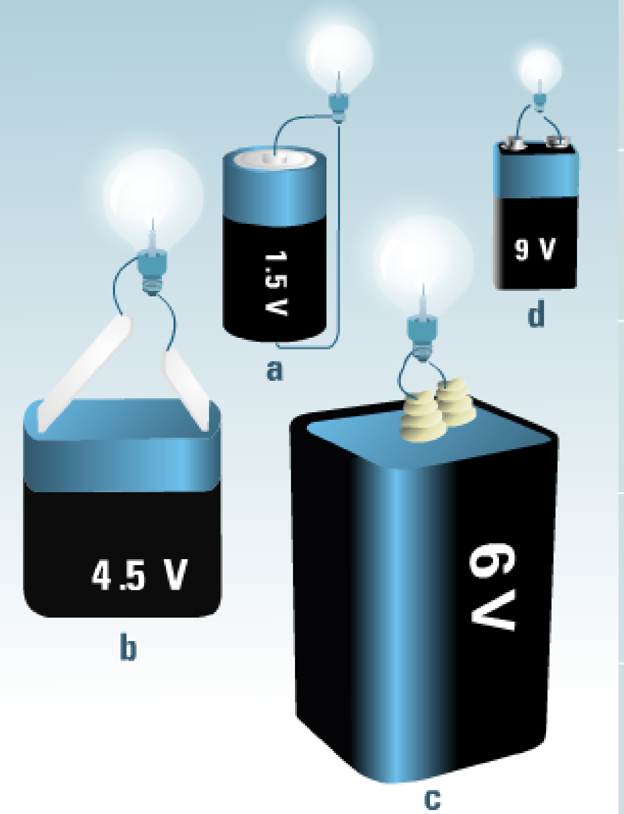
You can use the following questions to check your own understanding of this episode and your pupils' understanding.

Questions to check your understanding - Four batteries

Question 1 of 5

1. Which battery lights the bulb brightest?

Four different batteries are used to light a bulb. All the bulbs are identical.



	CORRECT	INCORRECT	DON'T KNOW
a) Battery a			
b) Battery b			
c) Battery c			
d) Battery d			
e) All the bulbs will be the same brightness.			

Once you are happy with your answer click "check it" to continue

CHECK IT

Sharing voltage in series circuits

A simple series circuit

How do the ideas about voltage work with a circuit where there is more than one bulb? In this circuit, two identical bulbs are connected in series to a 3 volt battery and a voltmeter is connected across each bulb.

What happens in the circuit?

We have already seen that adding a bulb in series results in the current being reduced (due to the increased resistance) and both bulbs becoming dim.

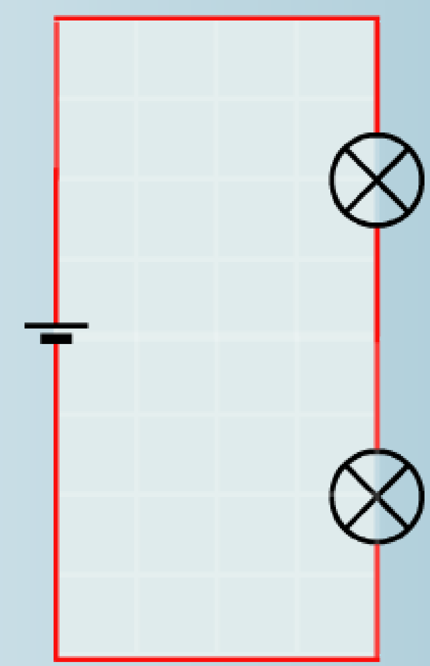
What happens to the voltage across each bulb?

When the second bulb is added, the voltage is shared between the two bulbs.

Each voltmeter reads 1.5 volt.

A simple series circuit

The bulbs are of equal brightness, but dimmer than if just one lamp was in the circuit.



STEP 1 of 2

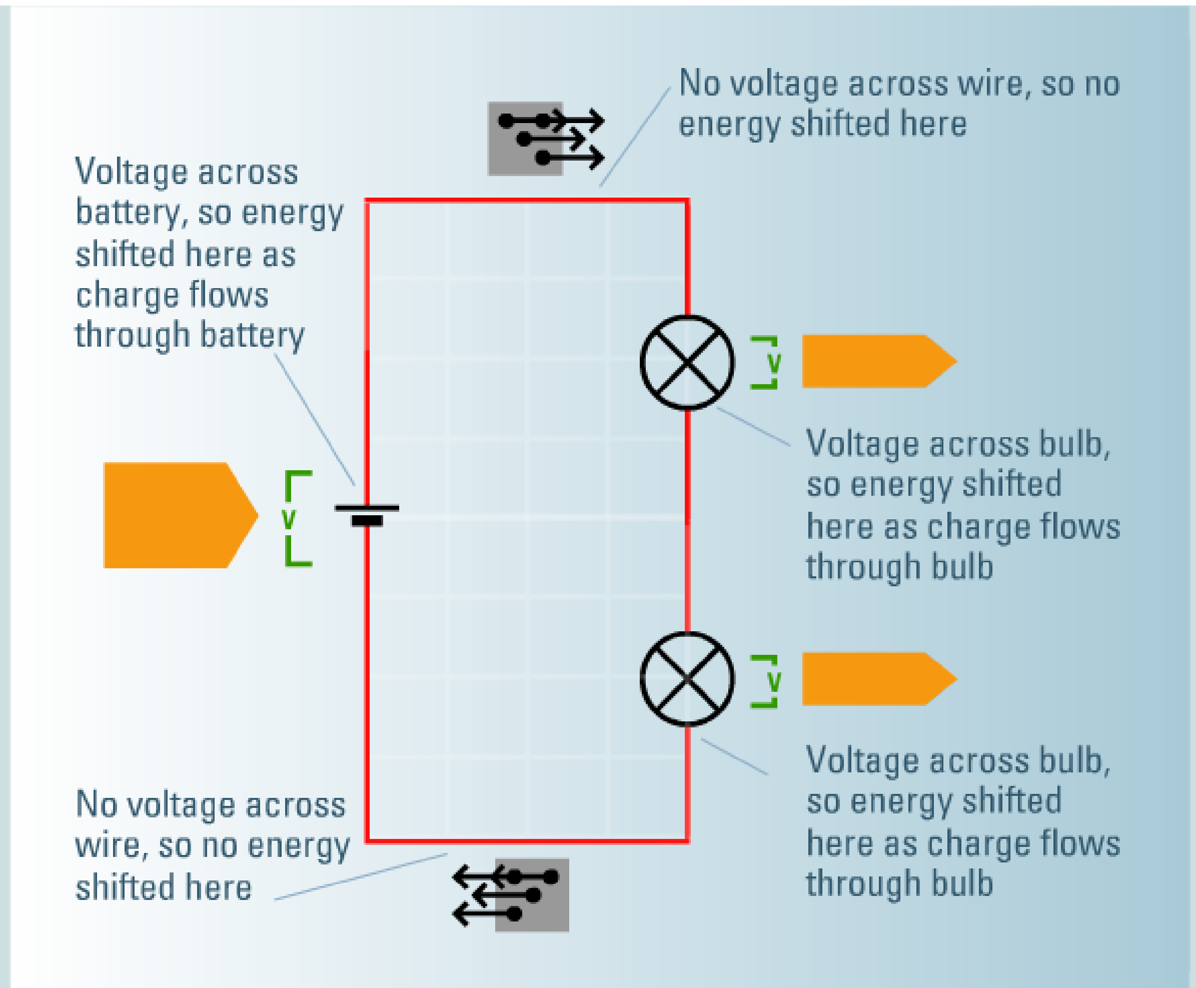
Sharing voltage in series circuits

Making sense of voltmeter readings using a rope loop

This provides a good model to reason with.

Energy and voltage in a series circuit: Rope loop model

Use the fader and the switch to explore the diagrams.



FADE
ROPE LOOP
CIRCUIT

LABELS
SHOW
HIDE

Sharing voltage in series circuits

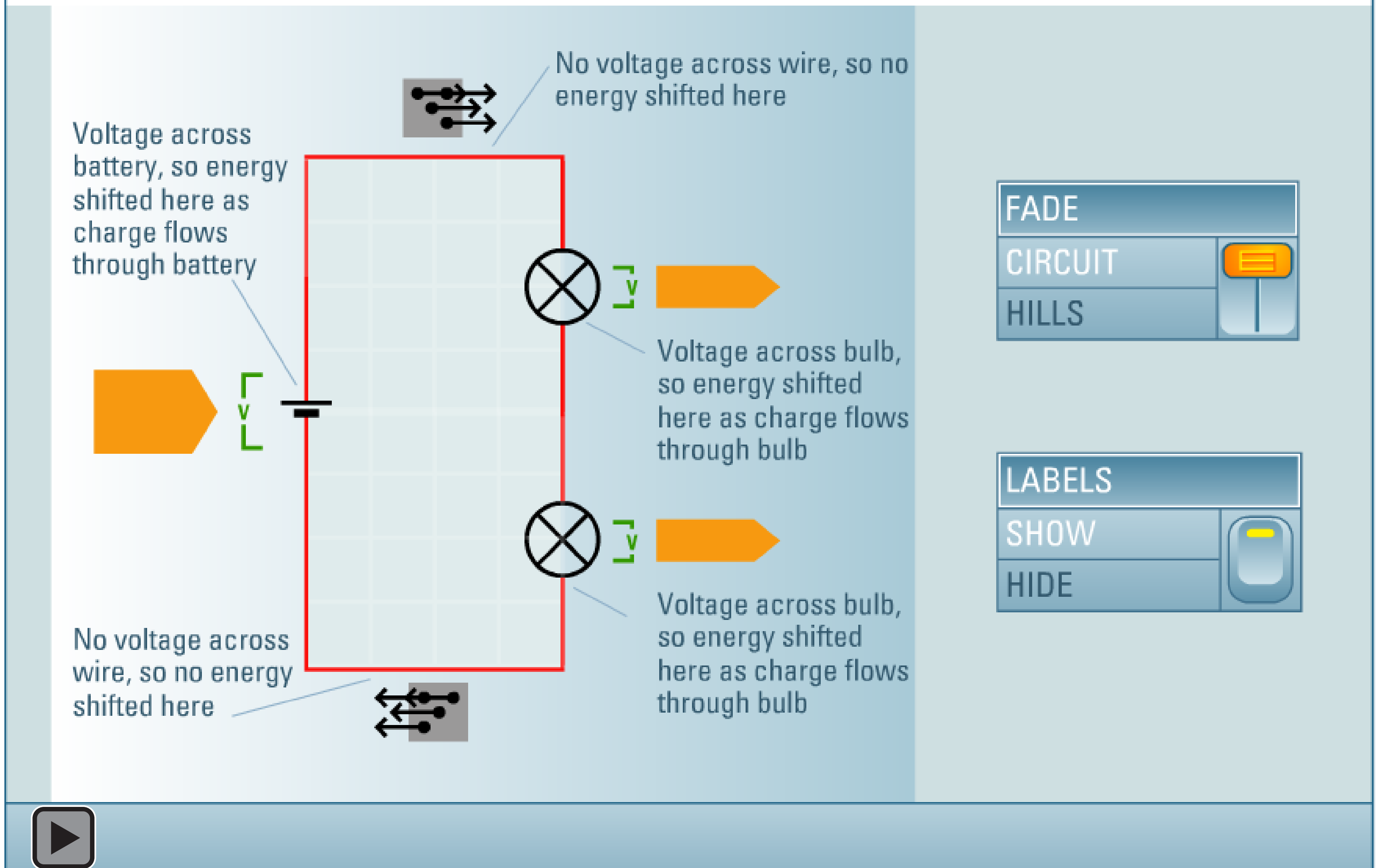
Making sense of voltmeter readings using energy hills

As before, we assume that no energy is transferred to the surroundings through the connecting wires.

So, the energy from the battery is shared between the two bulbs, with 1.5 volt being dropped across each.

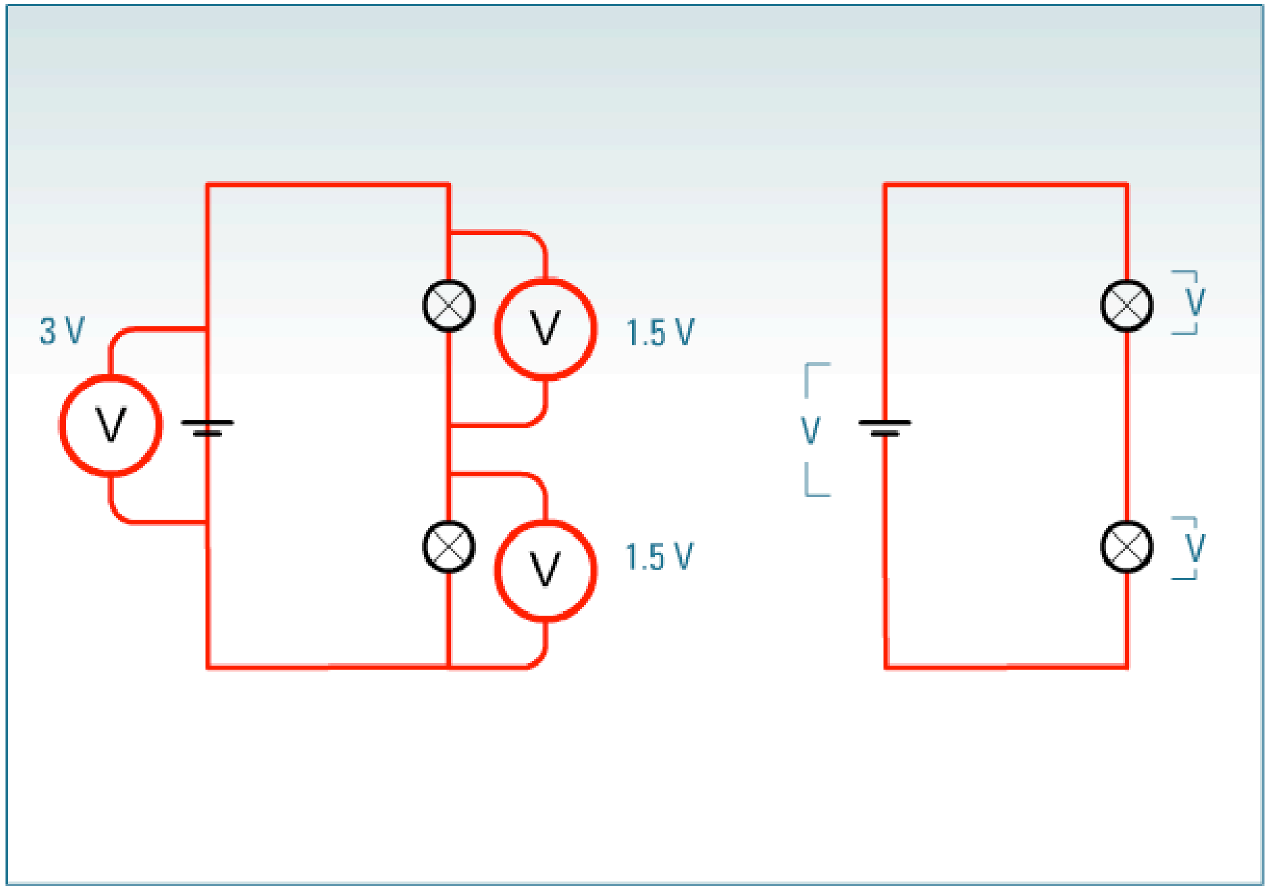
Energy and voltage in a series circuit: The hill analogy

Use the fader to move to the analogy and the switch to explore the diagrams.



General rule: Bulbs/resistors in series

The battery voltage is shared between two bulbs/resistors that are connected in series. If the bulbs/resistors are identical, the voltage is shared equally.



The sum of the voltages across the bulbs/resistors must equal the battery voltage. In terms of energy we can say that the energy shifted from the chemical store to the charges in the battery must equal the energy shifted from the charges as they pass through the bulbs/resistors.

Non-equal bulbs/resistors connected in series

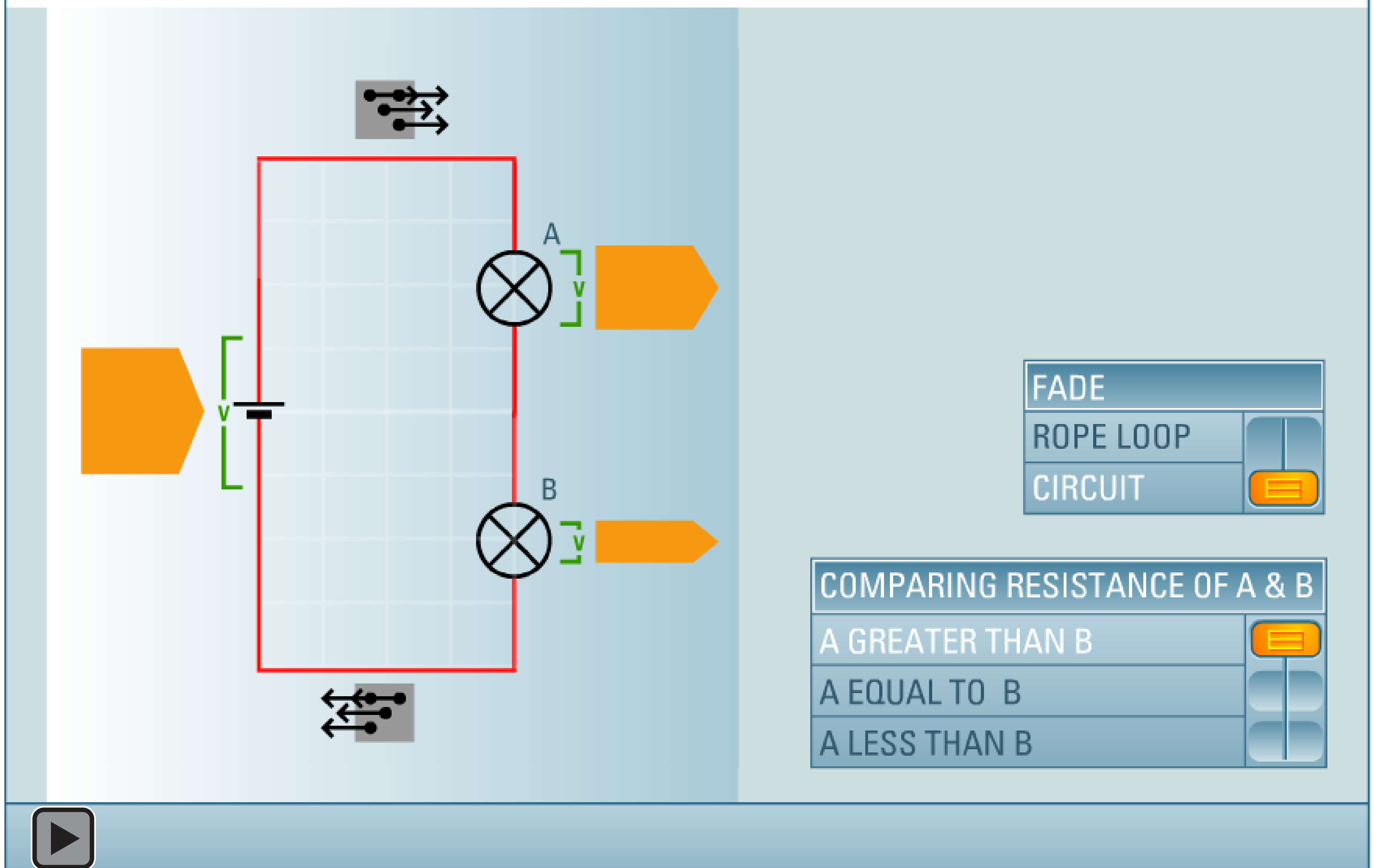
Find out what happens when the resistance of the two objects in series is not equal.

Suppose two bulbs are connected in series and they are not identical. Suppose the resistance of bulb A is greater than the resistance of bulb B. How will the battery voltage be shared between the two bulbs?

The answer to this question is that a higher voltage is dropped across the greater resistance. In other words there is a larger voltage drop across bulb A.

Energy and voltage in a series circuit: Total resistance constant

Use the fader and stepper to explore the diagram.



Non-equal bulbs/resistors connected in series

Why should this be?

The basic idea is that more energy is shifted as charges pass through a bigger resistance. Think of the rope loop teaching analogy. If two pupils act as resistors but one pupil grips the rope more tightly than the other (greater resistance), the hand with the tighter grip heats up more than that with the looser grip.

The same conclusion is reached using the equation $V = I \times R$.
The current (I) is the same through each bulb as the two bulbs are connected in series. Therefore a higher voltage must be dropped across the greater resistor. More on this in the SPT14-16 topic, Energy and Electricity.

Remember that the sum of the voltages across the two bulbs must still be equal to the battery voltage.

Progress check: Sharing voltage in series circuits

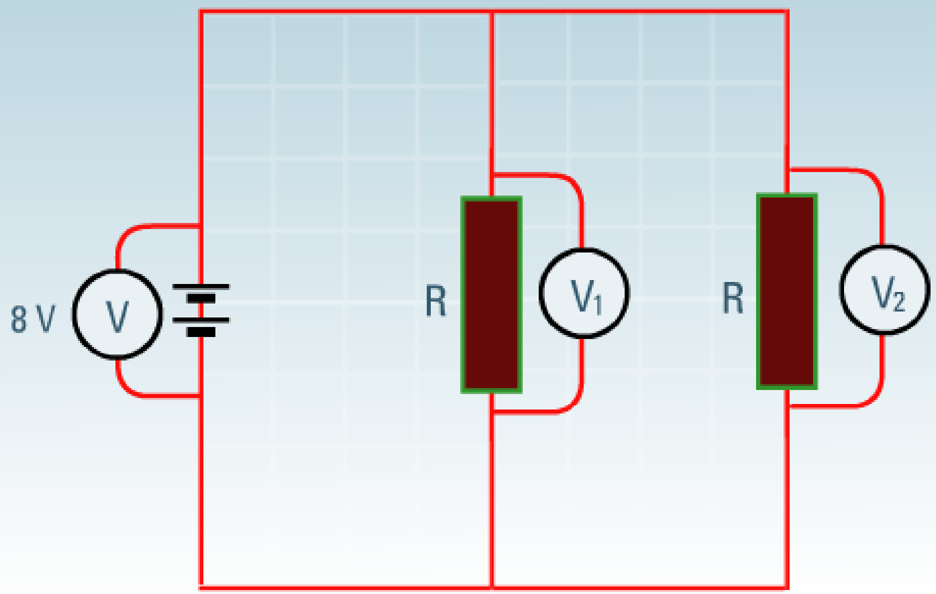
You can use the following questions to check your own understanding of this episode and your pupils' understanding.

Questions to check your understanding - identical resistors

Question 1 of 3

1. What are the readings on voltmeters V_1 and V_2?

The two resistors in this circuit are identical.
The voltmeter connected across the battery reads 8V.



	CORRECT	INCORRECT	DON'T KNOW
a) V_1 = 8 volt			
b) V_1 = 4 volt			
c) V_1 = 2 volt			
d) V_2 = 2 volt			
e) V_2 = 8 volt			
f) V_2 = 4 volt			

Once you are happy with your answer click "check it" to continue

CHECK IT

Voltage and parallel circuits

A simple parallel circuit

How do the ideas about voltage apply to parallel circuits? In this circuit, two identical bulbs are connected in parallel to a 3 volt battery and a voltmeter is connected across each bulb.

What happens in the circuit?

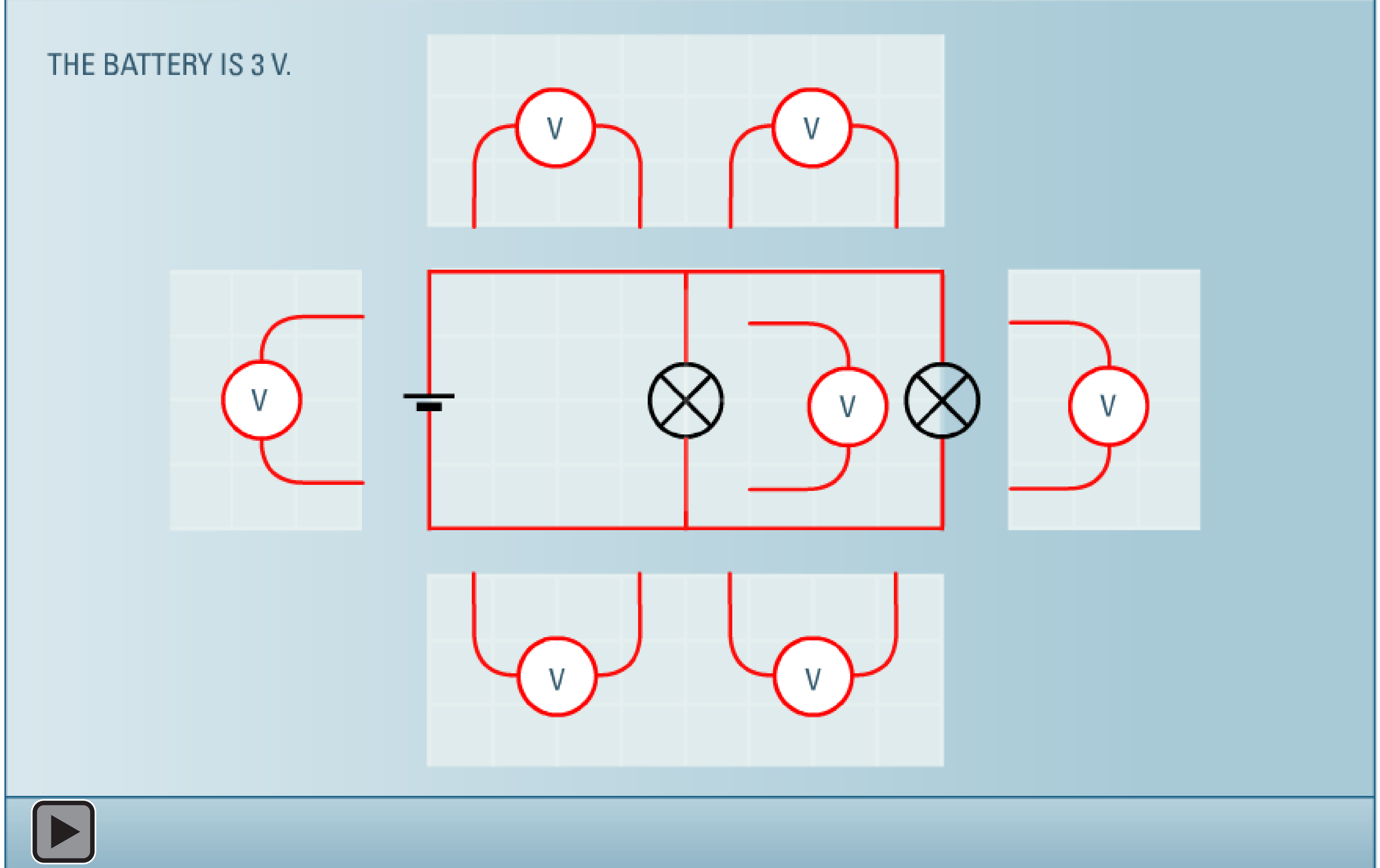
We have already seen that adding a bulb in parallel results in both bulbs being of equal, normal brightness. What happens to the voltage reading across each bulb?

When the second bulb is added in parallel, each bulb gets the full battery voltage. Each voltmeter reads 3 volt.

As the second bulb is added, there is a flow of charge around this additional loop. Whether the charges pass through bulb 1 or bulb 2, each coulomb drops through the full 3 V and so shifts 3 joule of energy.

Measuring voltages in a parallel circuit

Drag the voltmeters to measure the voltages.



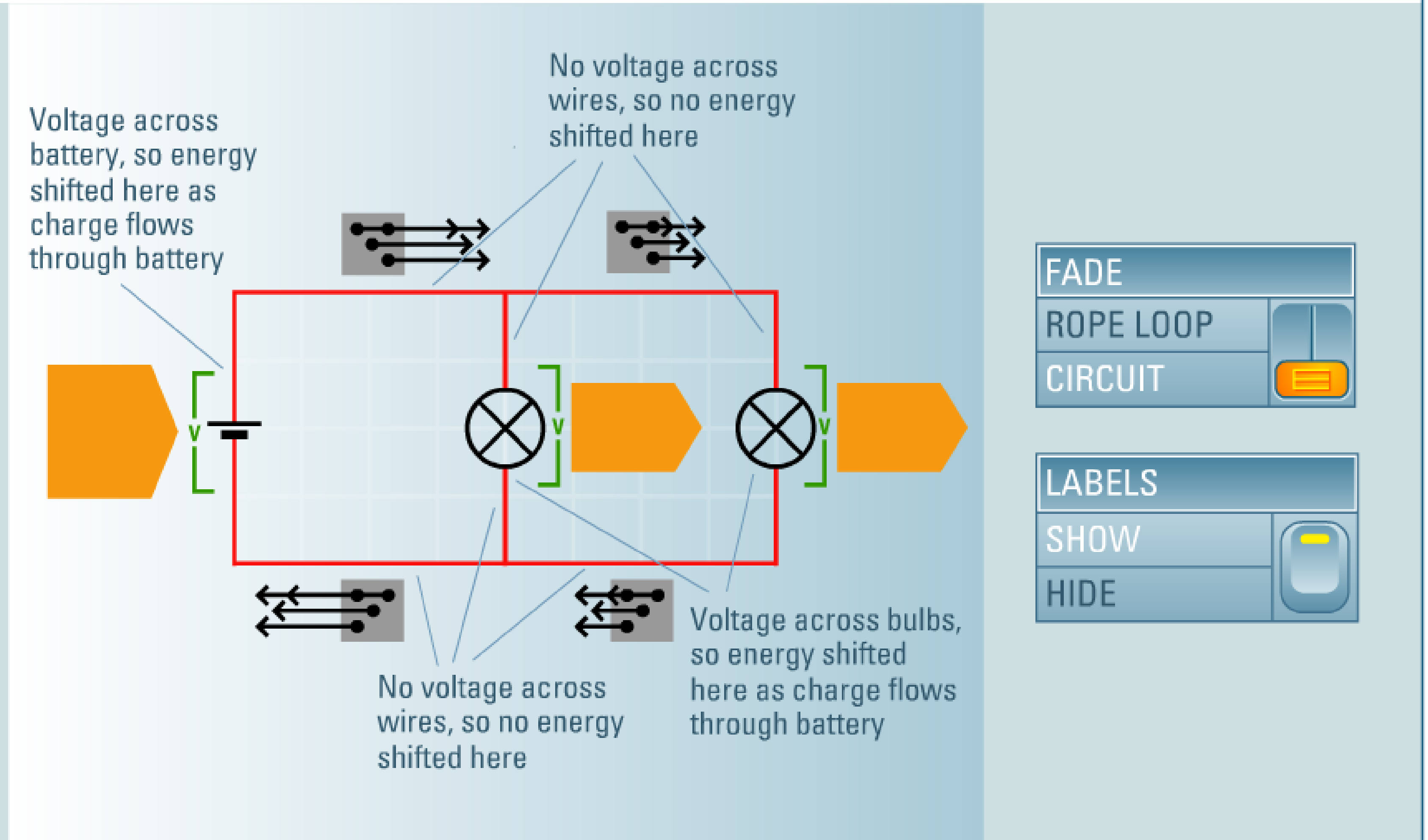
Voltage and parallel circuits

Making sense of voltmeter readings using a rope loop.

Each loop travels at constant speed, so the driving and counter forces must be equal in size (see the forces topic).

Energy and voltage in a parallel circuit: the rope loop model

Use the switch and fader to explore the diagram.



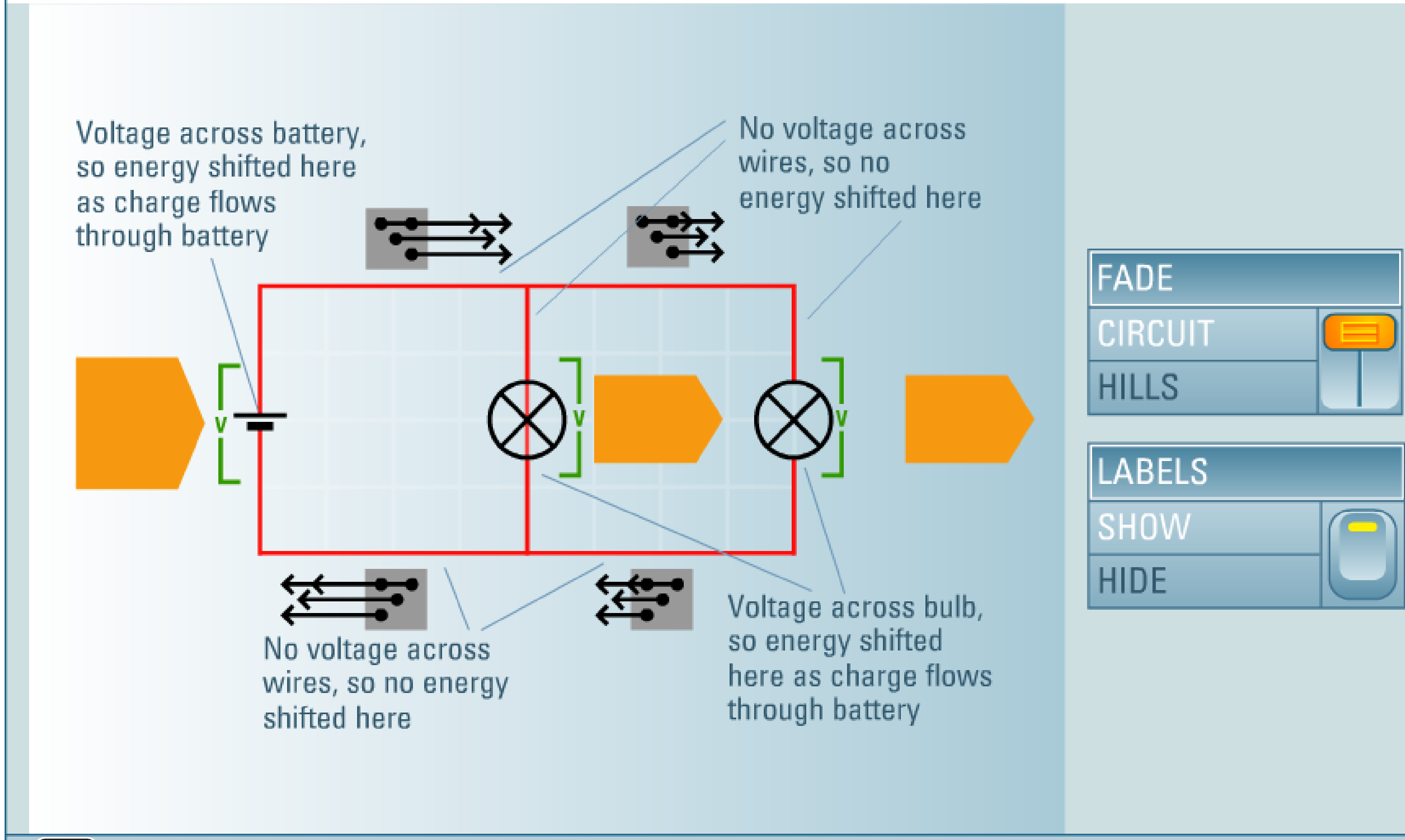
Voltage and parallel circuits

Making sense of voltmeter readings using energy hills

So, the full battery voltage of 3 volt is dropped across each bulb. Once again, we shall assume that no energy is transferred to the surroundings through the connecting wires.

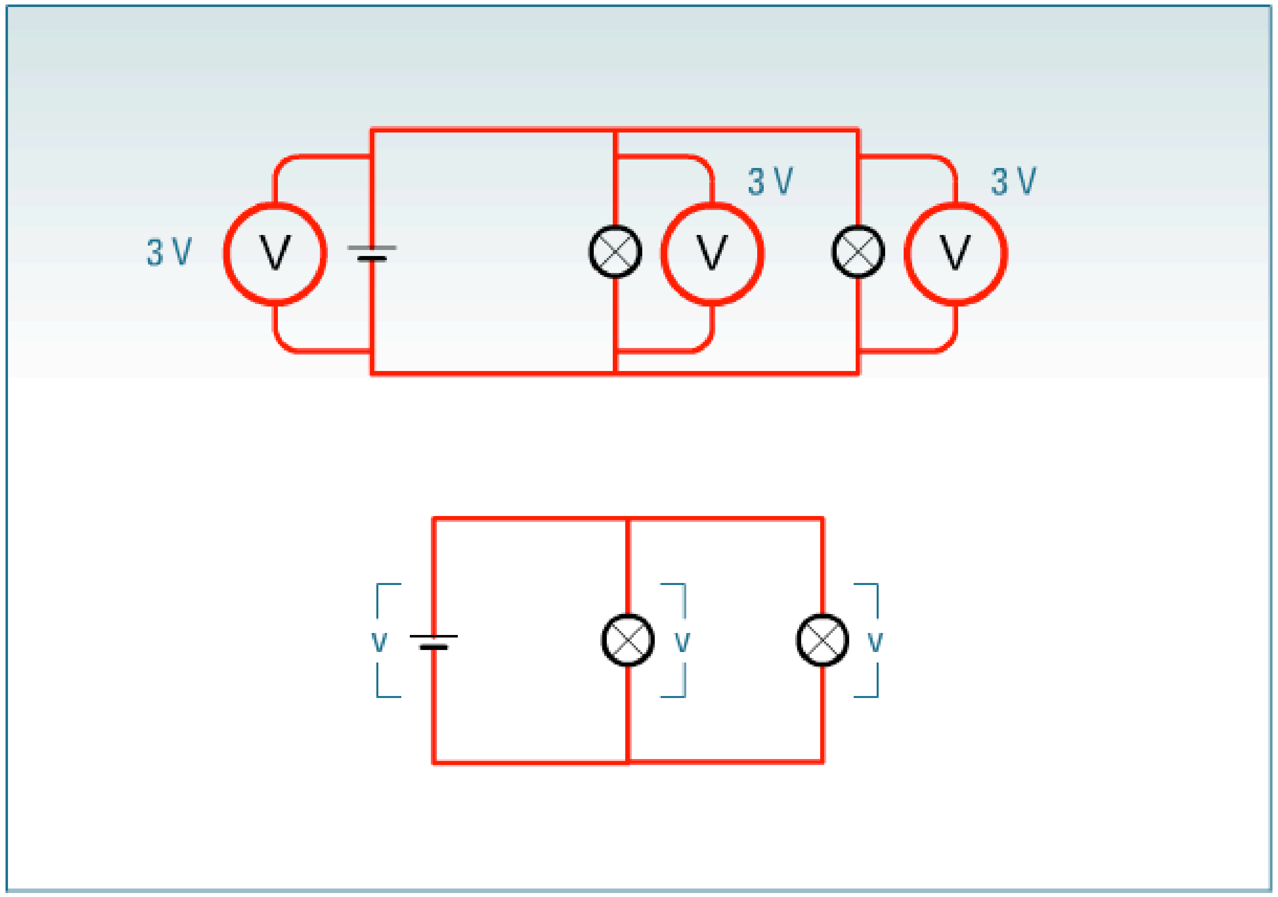
Energy and voltage in a parallel circuit: hill analogy

Use the fader to move to the analogy and the switch to explore the diagrams



General rule: Bulbs/resistors in parallel

When bulbs/resistors are connected in parallel, the full battery voltage is dropped across each.



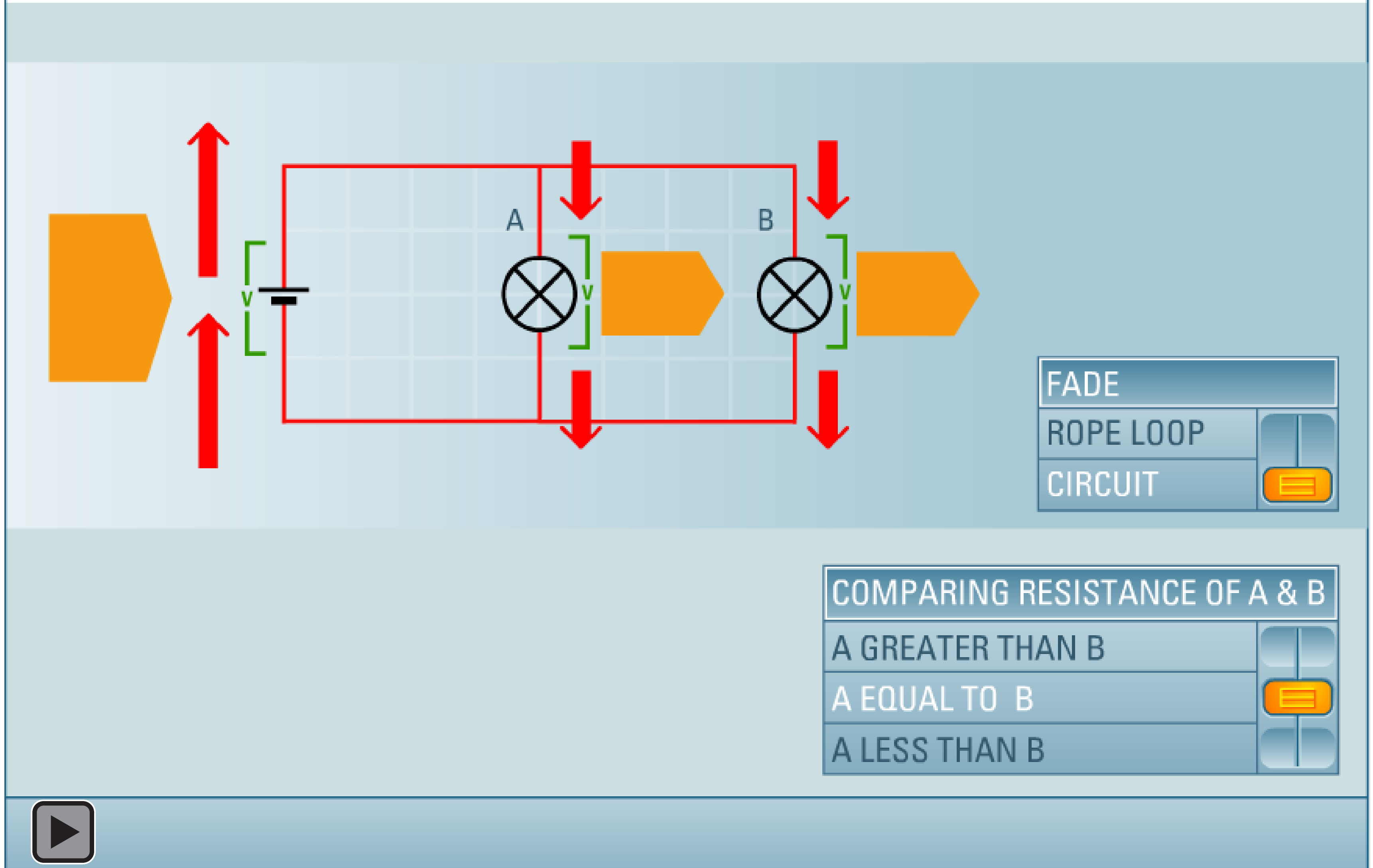
Non-equal bulbs/resistors connected in parallel

Find out what happens when the resistance of the two objects in parallel is not equal.

Suppose two bulbs are connected in parallel to a 3 volt battery and they are not identical. Suppose the resistance of bulb A is greater than the resistance of bulb B. What happens to the current through, and voltage across, each bulb in this case?

Energy and voltage in a parallel circuit: Changing resistance

Use the fader and the stepper to explore the diagram.



Non-equal bulbs/resistors connected in parallel

The first point is that the voltage across both bulbs must be the same. If we think of the two loops separately: the charges passing around loop A move relatively slowly (due to the high resistance) and shift the full 3 joule/coulomb in the bulb and the charges around loop B move relatively more quickly (due to the lower resistance) and yet still shift the full 3 joule/coulomb in the bulb. The rope loop model can help to make sense of this; the energy shifted depends only on the grip and on the quantity of rope passing through the hand, not on the speed.

Voltage across bulb A = 3 volt
Current through bulb A: relatively small

Voltage across bulb B = 3 volt
Current through bulb B: relatively big.

The same conclusion is reached using the equation, $I = V/R$. If the battery voltage (V) is the same across each bulb (which it must be since the two bulbs are connected in parallel to the battery), then a smaller current must pass through the bigger resistor (bulb A).

Progress check: Voltage and parallel circuits

You can use the following questions to check your own understanding of this episode and your pupils' understanding.

Questions to check your understanding - identical resistors

Question 1 of 3

1. What are the readings on voltmeters V_1 and V_2?

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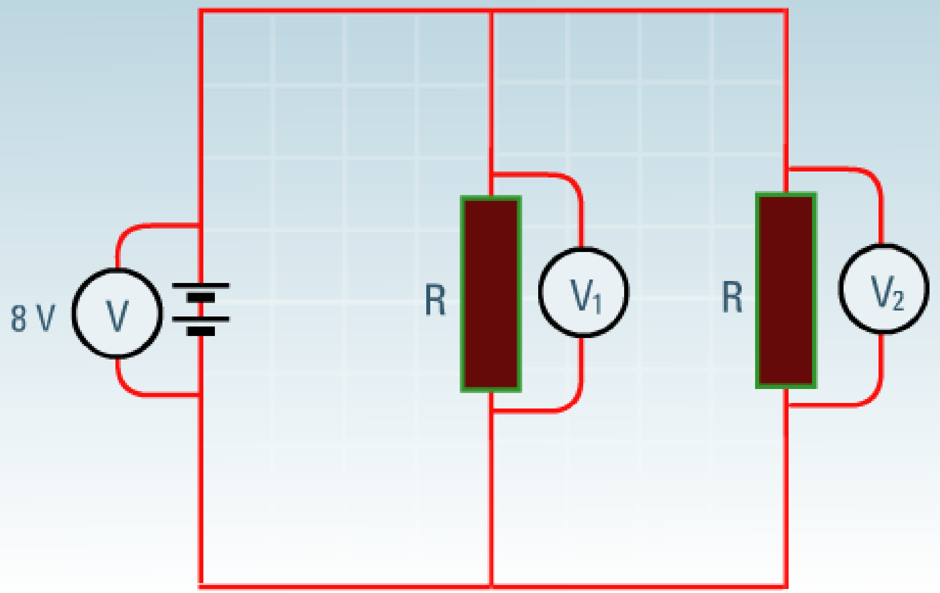
The voltmeter connected across the battery reads 8V.



	CORRECT	INCORRECT	DON'T KNOW
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b) V_1 = 4 volt			
c) V_1 = 2 volt			
d) V_2 = 2 volt			
e) V_2 = 8 volt			
f) V_2 = 4 volt			

Once you are happy with your answer click "check it" to continue

CHECK IT