2.4 Using Voltaic Cells

Figure A2.20: Gold is ideal for jewellery because it will never tarnish.

In this chapter you have seen many examples of the role metals play in the lives of humankind. You have also seen how the different rates of chemical reactivity make some metals more susceptible to the effects of corrosion than others. For example, silver jewellery can tarnish, whereas gold jewellery does not. While corrosion is usually seen as an unwanted effect, it is sometimes helpful. Copper artifacts that were made thousands of years ago by the ancient ancestors of the First Nations people in Canada, for example, were preserved by a protective surface layer of green corrosion—basic copper carbonate.

In each of these cases, oxidation and reduction play a key role in describing the reaction. In this lesson, the focus shifts from corrosion on a metal surface to applications that make use of the flow of electrons between different metals.

You know from your own experiences that many modern devices operate using **voltaic cells**. Most people call one of these devices a **battery**. However, a battery actually refers to a group of cells that are connected together.

A battery of voltaic cells in a graphing calculator provides a continuous flow or current of electrons when the calculator is operating. The different components within the calculator convert the energy from the current into other work. This transfer of energy allows each component to accomplish its designed task. As one set of electrons leaves the battery of voltaic cells, another group enters to keep the device working. A graphing calculator operates because the components can access the energy within the current of electrons that continuously loops through the circuits.

What causes this river of electrons to flow in the first place? Why do electrons leave one end of a voltaic cell and return to the other end? Answers to these questions involve reduction and oxidation reactions—combining metals that have a tendency to lose electrons with metal ions that have a tendency to gain electrons.

- **voltaic cell:** a device that spontaneously produces electricity by redox reactions
- **battery:** a set of voltaic cells joined to produce an electric current

Figure A1.21: This calculator is powered by a battery of four voltaic cells.

Practice

33. Use the terms *voltaic cell* and *battery* to describe the process shown in Figure A2.22.
34. Construct a simple flowchart showing the energy transformations necessary for a flashlight to produce light energy.
35. Hundreds of years ago, before the invention of electrical devices, the word *battery* was a military term that referred to a collection of cannons. Suggest a reason why this military term was adapted by people using electricity.

Figure A2.22: It's a good idea to have a fully charged flashlight handy.

Inside a Voltaic Cell

A voltaic cell uses the transfer of electrons between its chemical components to create an electric current that can flow through an external circuit. The connection to the external circuit is made through wires that contact each **electrode** of the voltaic cell.

As one substance in the cell is oxidized—losing electrons—another substance in the cell is reduced—gaining electrons. In the next investigation you will have an opportunity to explore the oxidation and reduction reactions that occur inside a voltaic cell.

electrode: a solid electrical conductor in a cell that connects a cell to an external circuit

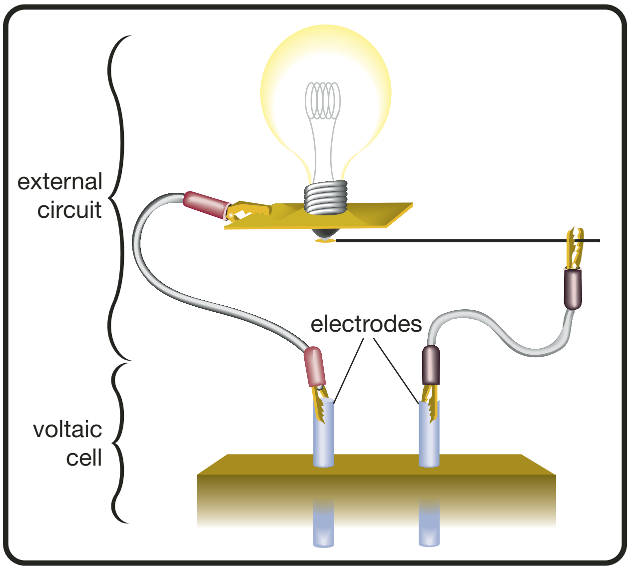


Figure A2.23: The electrodes of a voltaic cell connect to an external circuit.

Investigation

Building a Voltaic Cell

Science Skills
✓ Performing and Recording
✓ Analyzing and Interpreting

Purpose

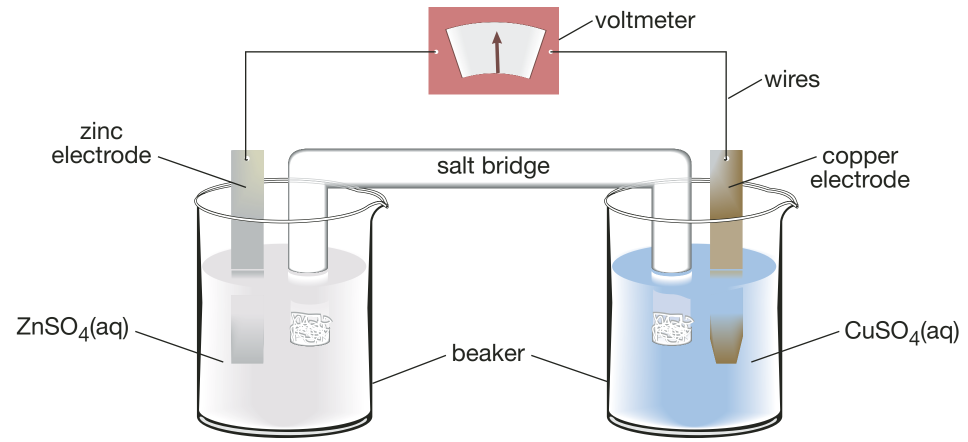
You will build a working voltaic cell.

Materials

- 2 beakers
- voltmeter (or digital multimeter)
- electrical leads with alligator clips
- salt bridge
  - glass U-tube
  - cotton plugs
  - aqueous electrolyte with low reactivity (e.g., 0.500-mol/L sodium sulfate, $NaSO_4(aq)$)
- copper metal strips
- zinc metal strips
- 0.500-mol/L copper(II) sulfate $CuSO_4(aq)$
- 0.500-mol/L zinc sulfate $ZnSO_4(aq)$

CAUTION!
Use gloves, safety glasses, and a lab apron for this investigation.

The Assembled Voltaic Cell



Pre-Lab Analysis

1. List the two metals used in the cell. Use the activity series to determine which is the more reactive metal and which is the more reactive metal ion.
2. Use the activity series to determine the oxidation half-reaction and reduction half-reactions that could occur in the voltaic cell illustrated.
3. Use your knowledge of spontaneous reactions to determine whether the more reactive metal and metal ion will react spontaneously in the cell you have constructed.
4. Use your half-reactions to determine which metal is losing electrons and which metal ion is gaining electrons.
5. Use your spontaneous half-reactions to make a prediction as to what will happen to each metal strip if you were to leave the voltaic cell on for a long time.
6. If the voltaic cell kept operating indefinitely, would any part of the cell labelled in the diagram need to be replaced? Explain your reasoning.
7. Hypothesize which metal strip is the negative electrode of the voltaic cell and which metal strip is the positive electrode of the voltaic cell. Provide a reason for your choice.

Procedure

step 1: Add the copper(II) sulfate solution to one beaker and the zinc sulfate solution to the other beaker. Ensure that there will be enough of each solution to submerge the ends of the salt bridge.

step 2: While working over a sink or basin, assemble the salt bridge by filling the glass U-tube with sodium sulfate. Carefully pack the ends of the U-tube with cotton wool to form plugs. Hold the U-tube upright and carry it to a point above the two beakers. Place gloved fingers over the ends so that the solution does not leak out. Adjust the position of the beakers to prepare for the placement of the U-tube. Turn the U-tube upside down and place it in the beakers so that the ends with the cotton plugs are submerged.

step 3: Refer to the diagram to assemble the rest of the voltaic cell from the materials provided.

step 4: Record the reading of the voltmeter. If the reading is zero, refer to the diagram of the voltaic cell and make adjustments to the apparatus until an output reading appears.

step 5: Carefully lift the salt bridge out of the beakers. Quickly observe the effect this has on the output of the voltmeter. After you have made your observations, return the salt bridge to the solution. Record your results.

step 6: Reverse the leads from the voltmeter so that they are connected to the opposite electrodes. Observe the effect this has on the output of the voltmeter. Record your results.

step 7: Let the voltaic cell continue to operate while you answer the rest of the analysis questions. Periodically check the apparatus for any evidence of change on the electrodes or in the solutions. Record any changes you see.

Analysis

8. Describe the effect on the output of the voltmeter when you lifted the salt bridge out of the cell.

9. Hypothesize why the salt bridge is necessary for the voltaic cell to work.

10. Explain what happened to the output of the voltmeter when you connected the leads from the voltmeter to the opposite electrodes in the voltaic cell.

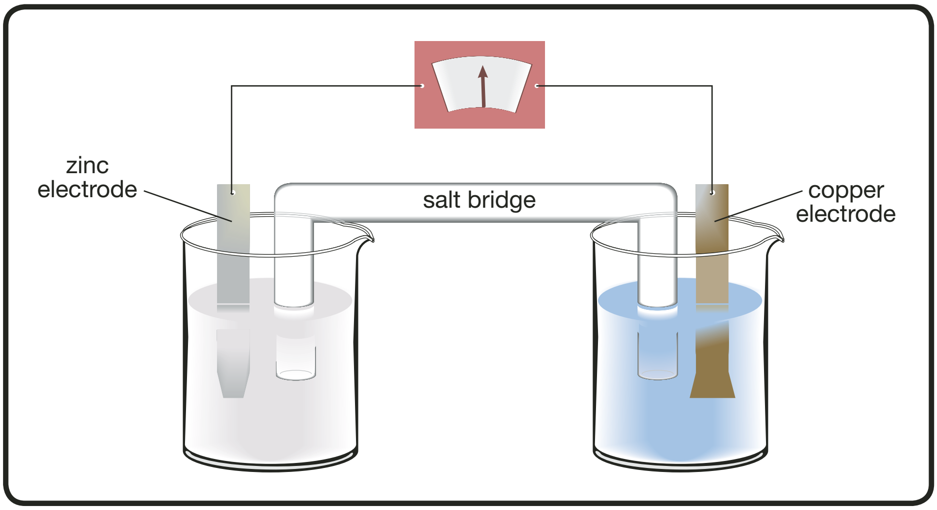
11. Describe the changes you observed to the electrodes or to the solutions. Use the half-reactions stated earlier to assist you in suggesting reasons for the changes you observed.

Analyzing How a Voltaic Cell Works

Earlier in this chapter you investigated the activity series for metals and metal ions. This series describes oxidation reactions, where metal atoms lose electrons to become metal ions. The chart also describes reduction reactions, where metal ions gain electrons to become metal atoms. Placing a metal that readily loses electrons into a solution that contains metal ions that readily gain electrons results in a spontaneous reduction-oxidation (redox) reaction.

The voltaic cell featured in the "Building a Voltaic Cell" investigation used these principles to transform chemical energy into the electrical energy measured by the voltmeter. The following analysis shows how a voltaic cell can produce a steady electric current to an external circuit.

step 1: Identify the electrode where oxidation occurs, and label it.



Locate each metal used in the electrodes in the activity series. These metal atoms are located on the right side of the series. Recall that the metal atoms located closest to the bottom of the chart have the greatest tendency to be oxidized or lose electrons. In this case, zinc is located below copper; so, the zinc electrode is the one that loses electrons or is oxidized. This electrode is called the **anode**.

The copper electrode is the one that will be receiving electrons, or is reduced. This electrode is called the **cathode**.

Here's a memory device you can use to help remember the labelling of the electrodes:

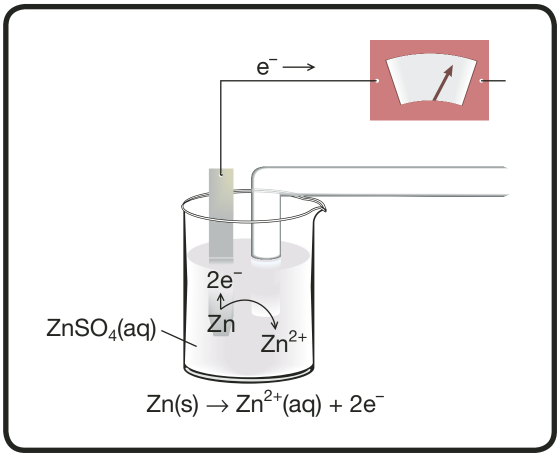
Anode and *oxidation* both begin with vowels.

Cathode and *reduction* both begin with consonants.

anode: the electrode in a cell where the oxidation half-reaction occurs

cathode: the electrode in a cell where the reduction half-reaction occurs

step 2: Describe the oxidation process at the anode.



Write the half-reaction that describes the oxidation process at the anode.

$Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$

The zinc strip will decrease in mass and become smaller over time because the zinc atoms are turning into zinc ions.

Electrons lost by the zinc electrode travel to the external circuit. From the point of view of the voltmeter, the zinc electrode is the negative electrode because it is a source of electrons.

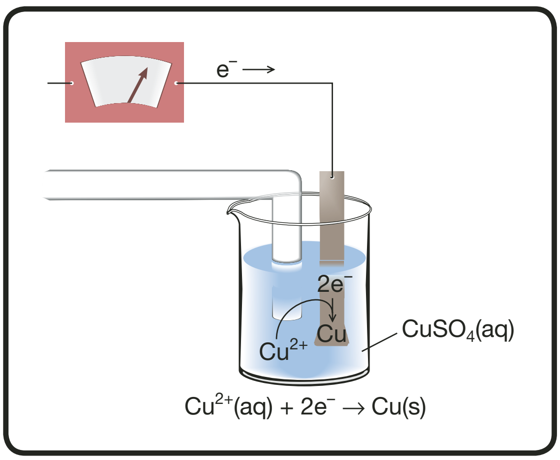
Here's a memory device to help you remember the charge of the anode as seen by the external circuit:

A_node is negative.
(Read as: "A no is negative.")

Here's another memory device to help you remember which way the electrons flow in the external circuit:

Electrons flow from Anode **to C**athode.
(Read as: "Electrons flow from A to C.")

step 3: Describe the reduction process at the cathode.



Write the half-reaction that describes the reduction process at the cathode.

$Cu^{2+} + 2e^- \rightarrow Cu(s)$

The copper(II) ions in the surrounding solution are attracted to the electrons, thus gaining electrons to become reduced copper atoms.

Copper(II) ions precipitate on the copper metal strip, causing the mass of the Cu(s) to increase.

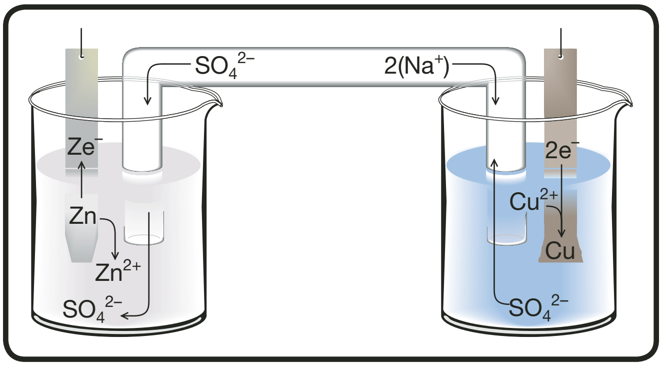
As the cell operates, the intensity of the blue colour of the copper(II) ion solution in the beaker decreases as copper(II) ions are being reduced.

Electrons are conducted from the external circuit to the copper cathode. From the point of view of the voltmeter, the cathode is the positive electrode because it is attracting the electrons.

Here's a memory device to help you remember the charge of the cathode as seen by the external circuit:

A cathode **is pos**itive.
(Read as: "A cat's paws.")

step 4: Describe how the salt bridge completes the circuit.



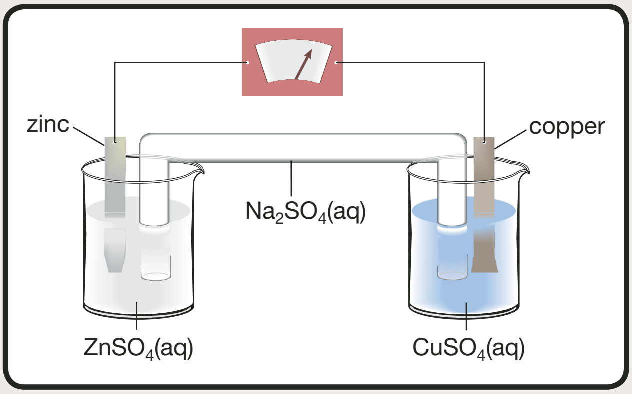
The previous steps described the flow of negative charge in the form of electrons from the zinc anode to the copper cathode. This situation is not sustainable because electrons cannot be produced at the anode without limit. The charges must be replenished. The salt bridge provides a path for ions to complete the circuit.

The salt bridge allows the SO_4^{2-}—negative ions or anions—to move to the solution containing the zinc anode. The negative ions are attracted to the excess positive zinc ions accumulating in this solution. Sodium ions will migrate to the cathode side, where the solution has lost positive ions as the $Cu^{2+}(aq)$ ions are reduced. This closes the loop and completes the circuit.

The absence of a salt bridge to balance the charges on both sides of the voltaic cell inhibits the reduction and oxidation reactions, thus not allowing the voltaic cell to function.

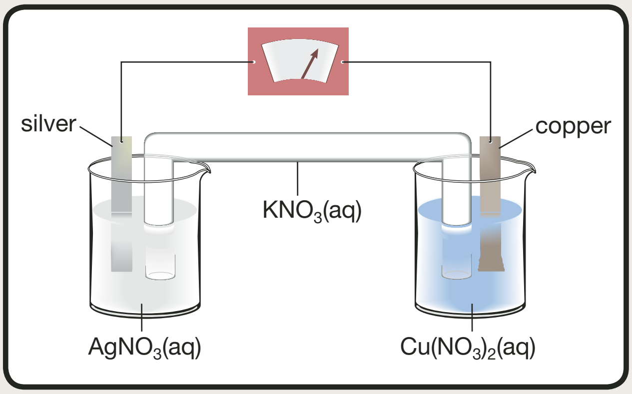
Practice

36. Copy the following diagram into your notebook or obtain the handout "Voltaic Cell Diagram" from the Science 20 Textbook CD.



Add labels to this diagram that illustrate how this voltaic cell works. Attempt to do this without looking at the four steps outlined previously. Then use the four steps to check your diagram.

37. Study the following diagram carefully; then answer questions 37.a. to 37.d.



a. Identify the electrode where oxidation occurs.

b. Describe the oxidation process at the anode.

c. Describe the reduction process at the cathode.

d. Describe how the salt bridge completes the circuit.

38. Explain the statement, "In simple terms, a voltaic cell is an electron pump."

39. A voltaic cell cannot run forever. In time, the cell begins to lose its ability to supply electrical energy to an external circuit. Identify some of the circumstances that would cause a cell to eventually stop circulating electrons through an external circuit.

A Concise Way to Represent Voltaic Cells

The detailed diagram showing a voltaic cell is useful for explaining all of the components of the cell's operation. However, sometimes it is useful to communicate the essential features of a voltaic cell in a more abbreviated format. This is concisely illustrated as follows.

salt bridge

$$Zn(s)\,|\,Zn^{2+}(aq)\,||\,Cu^{2+}(aq)\,|\,Cu(s)$$

anode — cathode

oxidation — reduction

This format, $Zn(s)|Zn^{2+}(aq)||Cu^{2+}(aq)|Cu(s)$, is called **cell notation**. In this arrangement, one electrode is always put on the left side and the other electrode is put on the right side. The vertical line | represents a boundary between a metal and its ion in the solution. The double lines || represent the salt bridge.

cell notation: a concise description of a voltaic cell

Example Problem 2.6

A voltaic cell is assembled using a copper electrode in a copper(II) nitrate solution, a silver electrode in a silver nitrate solution, a salt bridge containing potassium nitrate, and a number of connecting wires attached to a voltmeter. Describe this voltaic cell using cell notation.

Solution

According to the activity series for metals and metal ions, copper metal has a greater tendency to lose electrons compared to silver—copper appears closer to the bottom of the series. This means that the copper is oxidized and will form the anode.

The silver ions are the most reactive of the two metal ions listed. Therefore, the solid silver, Ag(s), placed in the solution of silver ions, $Ag^+(aq)$, will be the cathode. The two electrodes can then be written on either side of the equation. It does not matter which is written first.

$$Cu(s) \qquad Ag(s)$$

Add the metal ions and the salt bridge to complete the cell notation.

$$Cu(s)|Cu^{2+}(aq)||Ag^+(aq)|Ag(s)$$

Example Problem 2.7

A salt bridge containing potassium nitrate is used in the following voltaic cell:

$Zn(s)|Zn^{2+}(aq)||Al^{3+}(aq)|Al(s)$

a. Identify the substance being oxidized and the substance being reduced.

b. Identify the anode and the cathode in this cell.

c. Identify the anions, and describe the motion of these particles within the cell.

d. If wires and a voltmeter were connected to this voltaic cell, describe the direction of electron flow between the two electrodes.

Solution

a. Aluminium appears below zinc in the activity series, indicating that aluminium has a greater tendency to oxidize than zinc. Therefore, the aluminium is being oxidized and the zinc ion is being reduced.

b. Because the aluminium is being oxidized, it is the anode. The zinc ions are the most reactive of the two metal ions listed. Therefore, the solid zinc, Zn(s), placed in the solution of zinc ions, $Zn^{2+}(aq)$, will be the cathode.

c. The anions are the nitrate ion, $NO_3^-(aq)$. They complete the circuit by flowing to the solution containing the anode.

d. If wires and a voltmeter were connected to this voltaic cell, the electrons would flow from the aluminium anode, where they are produced by oxidation, to the zinc cathode, where they complete the process of reduction.

DID YOU KNOW?

A 9-volt battery is made up of a series of six connected voltaic cells that are connected anode to cathode in series. These batteries go dead when a cell loses a reactant. Voltaic cells are a closed system and will cease to function unless more reactants are added.

Practice

40. Study the following voltaic cell closely. Assume the salt bridge contains a solution of potassium nitrate, $KNO_3(aq)$.

$Au(s)|Au^{3+}(aq)||Pb^{2+}(aq)|Pb(s)$

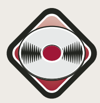
a. Identify which metal would be oxidized and which metal ion would be reduced.

b. Identify the anode and the cathode.

c. Write the half-reactions that will occur in the cell.

d. Draw the voltaic cell. Label the direction of the flow of electrons and anions within the cell.

Note: Feel free to use the handout "Voltaic Cell Diagram" on the Science 20 Textbook CD whenever you need to draw a voltaic cell.



41. Study the following voltaic cell closely. Assume the salt bridge contains a solution of potassium nitrate, $KNO_3(aq)$.

$Zn(s)|Zn^{2+}(aq)||Ni^{2+}(aq)|Ni(s)$

a. Identify which metal would be oxidized and which metal ion would be reduced.

b. Identify the anode and the cathode.

c. Write the half-reactions that will occur in the cell.

d. Draw the voltaic cell. Label the direction of the flow of electrons and anions within the cell.

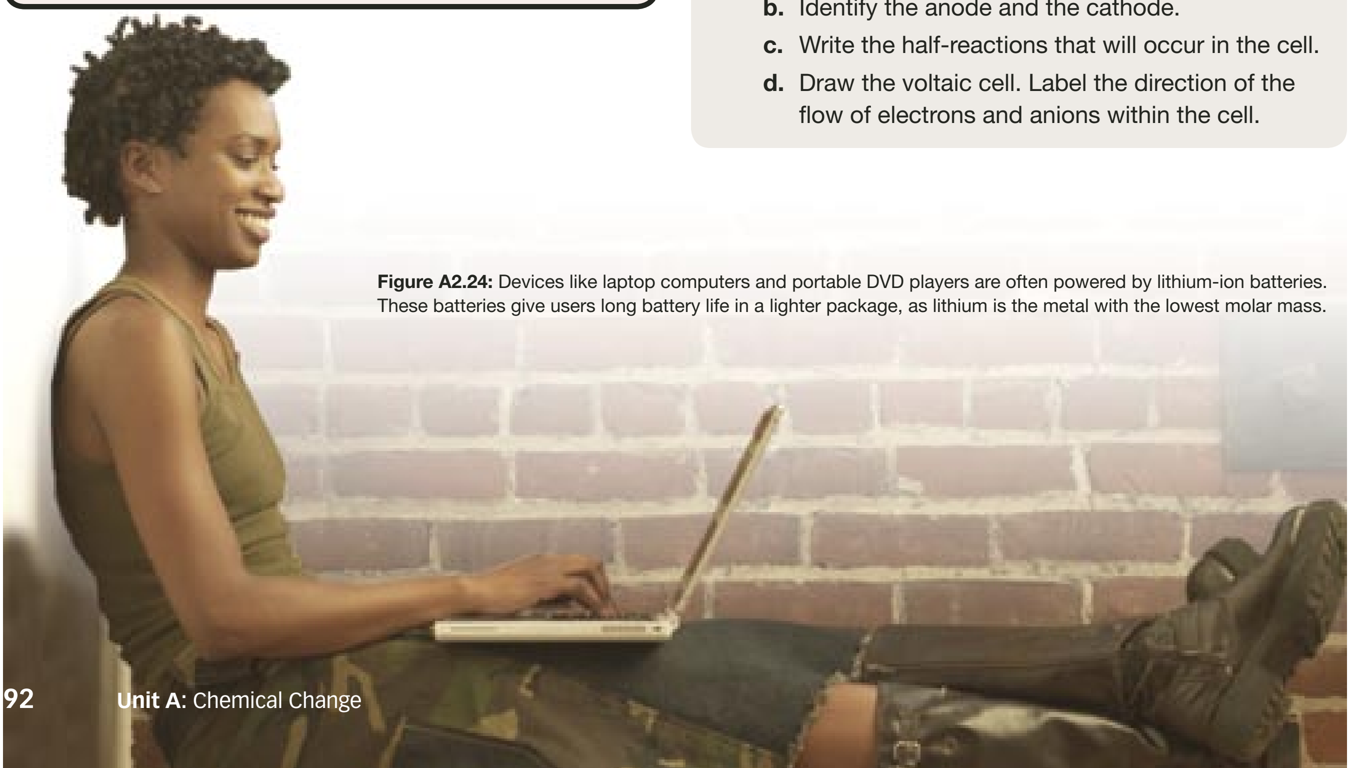


Figure A2.24: Devices like laptop computers and portable DVD players are often powered by lithium-ion batteries. These batteries give users long battery life in a lighter package, as lithium is the metal with the lowest molar mass.

Investigation

Designing Voltaic Cells

Science Skills

✓ Initiating and Planning

Given a list of metals and solutions containing metal ions, it is possible to design a number of voltaic cells using different combinations of materials. Which combination would you select to build a cell that creates the maximum output on a voltmeter? Which would create the minimum output?

Metal Electrode	Solution
$Fe(s)$	$Fe(NO_3)_2(aq)$
$Cu(s)$	$Cu(NO_3)_2\ (aq)$
$Mg(s)$	$Mg(NO_3)_2\ (aq)$
$Zn(s)$	$Zn(NO_3)_2\ (aq)$

Purpose

You will design voltaic cells that create the maximum and minimum output on a voltmeter.

Procedure

Consider the list of metals and solutions that could be used for this experiment. Consider the position of each of these metals and metal ions in the activity series. You will choose substances from the materials list to build a voltaic cell that produces the maximum output on a voltmeter. To ensure that your design, in fact, provides the maximum output, you should include plans to build three other voltaic cells, including the voltaic cell that provides the minimum output. Assume the salt bridge contains a solution of potassium nitrate, $KNO_3(aq)$.

Designs

1. Using the list of materials, describe the voltaic cell that will produce the maximum output on the voltmeter. Provide a concise explanation and a diagram to support your answer.
2. Using the list of materials, describe the voltaic cell that will produce the minimum output on the voltmeter. Provide a concise explanation and a diagram to support your answer.
3. Using the list of materials provided, describe a possible voltaic cell that will produce neither the maximum nor the minimum output on the voltmeter.

Voltaic Cells for Consumer Use

Although the set-up with the two beakers and the salt bridge is ideal for learning about the operation of a voltaic cell, this apparatus is not suitable for everyday use. Most people use voltaic cells that are conveniently packaged in small, sealed containers like the consumer cell shown in Figure A2.25. Even though these cells are called "dry cells," they actually contain a moist paste as the electrolyte—if these cells were completely dry, they would not work.

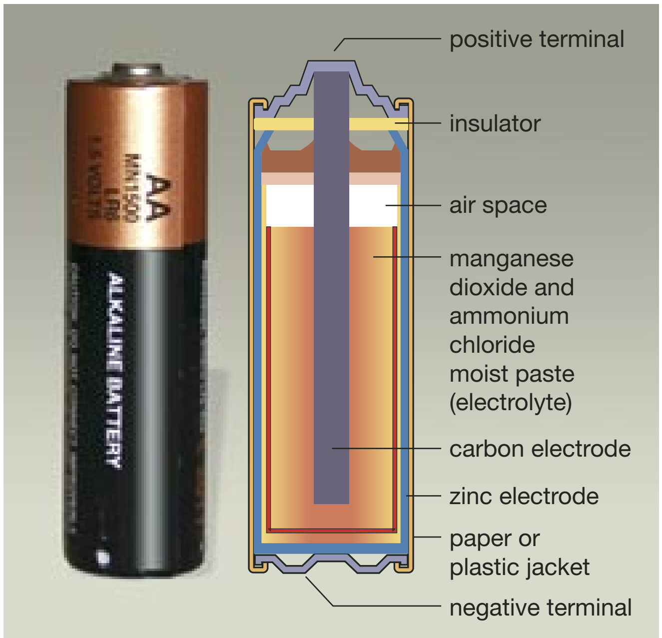


Figure A2.25: This is an artist's diagram of the inside of a standard consumer cell.

The small cells consumers use operate on the same principles of oxidation and reduction that you have been applying throughout this lesson. The oxidation reaction is straightforward and can be found in the activity series for metals and metal ions. The reduction reaction is more complex, requiring a number of interconnected steps.

Oxidation and Reduction in a Standard Consumer Cell
Oxidation
$Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$
Reduction
$2\ NH_4^+(aq) + 2\ MnO_2(s) + 2e^- \rightarrow Mn_2O_3(s) + NH_3(g) + H_2O(l)$

In North America, about three billion consumer cells are purchased every year. The metals and electrolytes that enable these cells to produce an electric current are harmful if released into the environment. You can help keep these substances out of landfills by sending spent cells to local recycling centres. Another strategy is to use rechargeable cells, which dramatically reduces the number of cells needed over a product's lifetime.

Practice

42. Consider the oxidation reaction that occurs in a standard consumer cell.

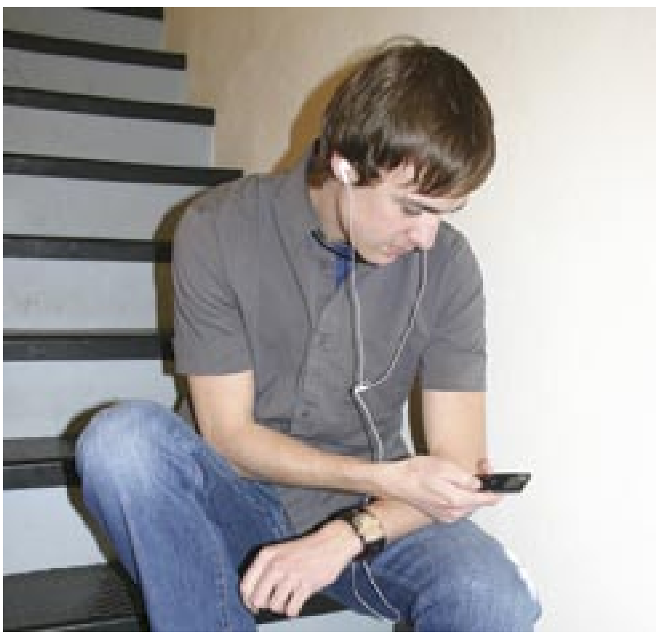
- **a.** Explain how this reaction indicates that the zinc electrode is the anode.
- **b.** Carefully examine the diagram of the standard consumer cell in Figure A2.24. Explain how this diagram verifies your answer to question 42.a.

43. Consider the reduction reaction that occurs in a standard consumer cell.

- **a.** Explain why both the manganese and the ammonium are considered to be reduced in this reaction.
- **b.** If the reduction-half reaction for the manganese dioxide were to be placed in the activity series for metals and metal ions, would it be placed above or below the reaction for zinc? Explain.

2.4 Summary

Electrical devices, like MP3 players and portable CD players, require energy from electrons in order to function. A voltaic cell uses spontaneous oxidation and reduction reactions to create an electrical current. The activity series for metals and metal ions can be used to predict which electrode will be the anode and which will be the cathode. Oxidation occurs at the anode, which is the source of electrons for an external circuit. The electrons flow from the anode, through the external circuit, to the cathode, where reduction occurs. To keep a voltaic cell working, the reactants need to be replenished.



2.4 Questions

Knowledge

1. Define the following terms.

- **a.** battery
- **b.** voltaic cell
- **c.** electrode
- **d.** anode
- **e.** cathode
- **f.** anion
- **g.** cation

2. Draw a detailed diagram of a voltaic cell that uses zinc and copper electrodes, a solution of sodium sulfate in the salt bridge, and other materials. Label all the essential parts that explain how the operation of the cell is based upon oxidation and reduction.

3. Explain the importance of the salt bridge in a voltaic cell.

4. Outline the path of electrons within an external circuit connected to a voltaic cell.

Applying Concepts

5. Answer the following questions regarding the following voltaic cell. Assume the salt bridge contains a solution of potassium nitrate, $KNO_3(aq)$

$$Mg(s)|Mg^{2+}(aq)||Ag^{+}(aq)|Ag(s)$$

- **a.** Identify which metal is oxidized and which metal ion is reduced.
- **b.** Identify the anode and the cathode of the voltaic cell.
- **c.** Write the half-reactions that will occur in the cell.
- **d.** The solutions in this cell are magnesium nitrate in the beaker on the left, silver nitrate in the beaker on the right, and potassium nitrate in the joining salt bridge. Draw the voltaic cell and label the direction of the flow of electrons and anions within the cell.

6. Lithium voltaic cells are very common today. Use the activity series for metals and metal ions to explain why lithium metal would be a useful metal for voltaic cells, especially for one producing a high voltage.

7. You notice that the voltaic cells running your portable stereo have "died." Explain why your voltaic cells are no longer able to provide your device with the energy it needs to operate. Use the terms *metal*, *metal ion*, *anode*, *cathode*, *oxidation*, and *reduction* in your explanation.

8. Obtain the handout "Voltaic Cell Diagram" from the Science 20 Textbook CD.

- **a.** Explain how this cell works by adding detailed labels and a description of the chemical reactions to the illustration on the handout.
- **b.** Check your answer to question 8.a. by watching "The Voltaic Cell" applet on the Science 20 Textbook CD. Be sure to use the pause button if you need to make additions or changes to your work.

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Legend: t = top, m = middle, b = bottom, l = left, r = right

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