ABSTRACT
Carbon dioxide (CO₂) is a colorless, odorless gas that makes up a small fraction of Earth’s atmosphere. Despite its inconspicuous nature, CO₂ plays an integral part in sustaining life on Earth, a part that is largely unknown or underappreciated by the general public. We present a set of activities designed to help students overcome the most common misunderstandings about CO₂, from its sheer existence as a mass-containing molecule to its complementary roles in photosynthesis and respiration. Through these activities, students will be able to apply their knowledge to real-world phenomena, including weight loss and global warming.

Key Words: carbon dioxide; photosynthesis; cellular respiration; fuel combustion; global warming; weight loss.

Introduction
Life on Earth, at its most fundamental, can be described as the acquisition and use of energy for the conversion of smaller, less-organized carbon-based molecules into larger, more organized carbon-based molecules capable of self-propagation. Life works against entropy and, as such, energy needs to be continuously supplied to sustain life’s highly organized structures and allow for its expansion. On Earth’s surface this energy is supplied largely by the sun. Sunlight isn’t acquired directly by all living things, but rather is initially acquired by photosynthetic organisms (plants, algae, and photosynthetic bacteria) that convert sunlight energy into chemical forms, most of which are varied polymers of carbon. These carbon polymers then deliver captured solar energy to nonphotosynthetic organisms, sustaining their lives and allowing them to grow and reproduce.

The general public has a good understanding of the basic concept that humans and other animals get the energy and building materials our bodies need from the carbon-based molecules (carbohydrates, fats, and proteins) in the food we eat. However, most people have a poor grasp of where plants get the building materials that form their bodies, and of the integral role played by a gaseous form of carbon, namely carbon dioxide (CO₂), in life processes in general. This lack of awareness of CO₂’s role in both photosynthesis and respiration has been recorded in popular ad hoc interviews (Veritasium, 2012; Tedx Talks, 2013), as well as in more formal research (Meerman, 2014).

The inability of adults to easily explain the flow of life’s carbon and energy through CO₂ reveals that science education has not been successful in regard to this fundamental topic. The root cause of this misunderstanding stems from CO₂ being invisible. When trying to understand natural phenomena, it is human nature to favor explanations that are readily visible. The most common answer to the question “Where do plants get the material from which they are made?” is “From the soil,” because it appears as if plant roots are drawing all the plant needs from the ground. The most common answer to the question “When a person loses fat, where does that fat go?” is the incorrect “It becomes energy,” followed by an incorrect explanation that fat is lost through sweat, urine, or feces. The correct answer to both questions is CO₂, yet most people have difficulty imagining that a gas can have such a role in the synthesis or decomposition of a solid, living thing.

We describe here a collection of activities designed to overcome fundamental misunderstandings about gases in general and about CO₂ in particular. These activities are designed to help students over the conceptual hurdle that all states of matter are connected, and that a gaseous form of carbon is just as real and important as its more visible polymers. This, in turn, will allow a better understanding of how CO₂ is involved in weight loss, and how CO₂ levels in the atmosphere can be so impactful on surface temperatures and climate.
Learning Activities

The following activities are designed to illustrate and assist conceptualization of the fact that while the gaseous state of matter may be more or less invisible, it actually contains a lot of mass. Students will get practice with the law of conservation of matter through the use of student-constructed models that allow them to visualize and quantify the chemical reactions involved in gasoline combustion, cellular respiration, and photosynthesis. This mass conservation will be further explored by monitoring carbon as it transitions from a solid or liquid form into a gas.

Activity 1: Gas Has Mass

Introduction

This activity is a popular and effective demonstration of air pressure. It dramatically shows that the gases in the atmosphere are quite heavy and are exerting constant pressure on everyone and everything that exists within the atmosphere.

Materials

- Aluminum cans (any aluminum beverage can will do)
- Gas or electric heat source
- Large bowl of room-temperature water
- Tongs
- Heat protective gloves

Procedure

Add about a centimeter of water to the bottom of a few aluminum cans and put them on a heat source until the water boils. Allow to boil for about a minute so that the cans fill with steam. Wearing a heat-resistant glove, grab one of the cans with the tongs and, in one smooth motion, invert the can into the bowl of water so that the opening of the can is submerged. Teachers may want to practice this motion with an unheated can first to reduce the chance of dropping the can during the demonstration. If a plastic bowl is used, care should be taken to avoid contact of the can and the bowl. When inverted into the bowl of room-temperature water, the can with boiled water will instantly be crushed by the external air pressure. Repeat a few times while discussing air pressure to get students to realize that gas has mass and the air around us is quite heavy.

Discussing the Science

Earth’s atmosphere is a fluid of loosely packed molecules that extends to ~480 km above the Earth’s surface (by contrast, the solid and liquid portions of the Earth form a sphere with a radius of ~6375 km). The gases in the atmosphere become more densely packed as you get closer to Earth’s surface, and at sea level the collective mass of the gases above exert a pressure of 14.7 pounds per square inch upon everything they surround. A can full of air is not crushed by atmospheric pressure because the air inside the can pushes out with an equal force as the air outside the can is pushing in. When water is boiled inside the can, the air inside the can gets hot and water vapor (steam) displaces some of the other gases. When the can is inverted into a bowl of water, this steam quickly cools and condenses back into a liquid and the remaining gases cool, leaving less air pressure inside the can. Since the air pressure outside the can then exceeds the remaining pressure inside the can, the can is crushed.

To assist and assess learning, teachers can ask students to provide an illustration and explanation of how the cans got crushed, making sure to give gas molecules a physical (perhaps cartoon-like) identity. An example of one such drawing is shown in Figure 1.

Additional Explorations

This activity is quite amenable for experimental investigation of the phenomenon. Questions that can be investigated include the following:

- Would the outcome change if the water in the bowl was hot?
- What if it was ice cold?
- What if the can was heated without water in it?
- What would happen if the hole in the can was plugged with a cork or wad of clay and allowed to cool more slowly?

These and other questions can be included for added scientific inquiry value.

Activity 2: Marshmallow Models of Combustion & Sugar Metabolism

Introduction

Models can be very useful for understanding chemical reactions. Importantly, they show that atoms don’t disappear, but just form different combinations. This activity allows students to build their own molecular models and show what happens as carbon transfers from a fuel to the air (combustion), from the air to a plant (photosynthesis), and from an animal cell to the air (respiration).

Materials

- Standard-size marshmallows
- Miniature marshmallows
- Toothpicks
- Colored chalk, pastels, or watercolor paint (used here)
- Fine-point permanent marker or small and medium label stickers
- “Sun,” “ATP,” and “Fire” energy icons
- “Liquid,” “Air,” “Inside Plant,” and “Inside My Cell” location icons

Procedure

Have students color and label marshmallows to represent carbon, oxygen, and hydrogen. Carbon is made from a standard marshmallow and should be labeled with a “C” and “12.” Oxygen is made from a standard marshmallow and should be labeled with an “O” and “16.” Hydrogen is made from a miniature marshmallow and should be labeled with an “H” and “1.” It turns out that a miniature marshmallow is about 15x lighter than a standard marshmallow, so this does well to reflect the size difference between hydrogen, carbon, and oxygen. Cut toothpicks in half and use to bind atoms together. Tell students that a hydrogen can only have one bond, oxygen has
two bonds, and carbon has four bonds. Once their atoms are colored and labeled, lead them through the following chemical transformations. These reactions will involve building five molecules: \( \text{CO}_2 \), \( \text{H}_2\text{O} \), \( \text{O}_2 \), glucose (\( \text{C}_6\text{H}_{12}\text{O}_6 \)), and heptane (\( \text{C}_7\text{H}_{16} \)). Example marshmallow models of these molecules are shown in Figure 2.

**Gasoline Combustion.** Gasoline can be represented by heptane (\( \text{C}_7\text{H}_{16} \)). The combustion of gasoline involves this chemical reaction: \( \text{C}_7\text{H}_{16} + 11\text{O}_2 \rightarrow 7\text{CO}_2 + 8\text{H}_2\text{O} \).

Have students, individually or in groups, assemble one heptane molecule and 11 oxygen gas molecules following the models shown in Figure 2. On a flat surface, put the heptane and 11 oxygen molecules on the left side of the arrow, and indicate heptane as being a “liquid” and oxygen as being in the “air.” Students should then add up and record the masses of the heptane and oxygen molecules. Have students disassemble the heptane and \( \text{O}_2 \) molecules and reassemble them into seven \( \text{CO}_2 \) and eight \( \text{H}_2\text{O} \) molecules. Place these molecules on the right side of the arrow along with a “fire” energy icon. Have students add up and record the masses of the \( \text{CO}_2 \) and \( \text{H}_2\text{O} \) products along with the total masses (Table 1). A sample combustion model display is shown in Figure 3.

**Cellular Respiration.** When starting with the sugar glucose, cellular respiration involves this chemical reaction: \( \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O} \).

Have students, individually or in groups, assemble one glucose molecule and six oxygen gas molecules following the models shown in Figure 2. On a flat surface, put the glucose and six oxygen molecules on the left side of the arrow, and indicate glucose as being “inside my cell” and oxygen as being in the “air.” Students should then add up and record the masses of the glucose and oxygen. Have students disassemble the glucose and \( \text{O}_2 \) molecules and reassemble them into six \( \text{CO}_2 \) and six \( \text{H}_2\text{O} \) molecules. Place these molecules on the right side of the arrow along with an “ATP” energy icon. Label all the \( \text{CO}_2 \) molecules as being in the “air” and the \( \text{H}_2\text{O} \) and energy as being “inside my cell.” Have students add up and record the mass of the \( \text{CO}_2 \) and \( \text{H}_2\text{O} \) products along with the total masses (Table 1). A sample model display of cellular respiration is shown in Figure 4.

**Photosynthesis.** This energy-requiring reaction does the opposite of cellular respiration as represented by this chemical reaction: \( 6\text{CO}_2 + 6\text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \).

Have students, individually or in groups, assemble six \( \text{CO}_2 \) molecules and six water molecules following the models in Figure 2. On a flat surface, put the six \( \text{CO}_2 \) and six water molecules on the left side of the arrow along with a “sun” energy icon, and indicate \( \text{CO}_2 \) as being in the “air” and water as being “inside plant.” Students should then add up and record the masses of these molecules. Have students disassemble the \( \text{CO}_2 \) and water molecules and reassemble them into one glucose and six \( \text{O}_2 \) molecules. Place these molecules on the right side of the arrow. Label all the glucose as being “inside plant” and the \( \text{O}_2 \) molecules as being in the “air.” Have students add up and record the masses of the glucose and \( \text{O}_2 \) products along with the total masses (Table 1). A sample model display of photosynthesis is shown in Figure 5.

**Discussing the Science**

By taking apart marshmallow molecular models and reassembling them into different forms, students will physically demonstrate the law of conservation of matter. By indicating in what form and location these molecules exist, students will be able to visualize the flow of matter into and out of the air. Teachers can augment this activity by asking students where the glucose in their bodies...
comes from (it comes from plants), where plants get their glucose (they build it from CO₂ in the air), and where the energy in glucose comes from (it comes from the sun). This activity contains the information needed to illustrate the fundamentals of the carbon cycle, as well as how fossil fuel combustion is disrupting the carbon cycle balance by adding CO₂ to the air faster than plants and algae can remove it by photosynthesis.

Additional Explorations
This activity is easily expandable once the students have constructed their marshmallow atoms. Other combustion reactions can be modeled, including with methane (CH₄), propane (C₃H₈), butane (C₄H₁₀), or hydrogen gas (H₂). The respiration of fatty acids can be substituted for glucose by using a short-chain fatty acid as the starting molecule. Larger composite diagrams can also be

Figure 2. Marshmallow models of molecules. From top: CO₂; H₂O; O₂; glucose; heptane.
constructed that show how respiration, photosynthesis, and fuel combustion are connected to make an illustrated poster or mural of the carbon cycle that includes the student-made CO₂, O₂, H₂O, glucose, and gasoline molecules.

Table 1. Masses of reactants and products of heptane combustion, glucose respiration, and photosynthesis. Mass is based on molecular mass using the most common isotopes of hydrogen, carbon, and oxygen.

| Reaction                        | Reactants | Mass | Form | Products | Mass | Form |
|--------------------------------|-----------|------|------|----------|------|------|
| Combustion of heptane          | Heptane (C₇H₁₆) | 100  | Liquid | 7 CO₂ | 308  | In air |
|                                | O₂        | 352  | In air | 8 H₂O | 144  | In air |
| Total                          |           | 452  | Total  | 452     |      |      |
| Respiration of glucose         | Glucose (C₆H₁₂O₆) | 180  | In cells | 6 CO₂ | 264  | In air |
|                                | O₂        | 192  | In air | 6 H₂O | 108  | In cells |
| Total                          |           | 372  | Total  | 372     |      |      |
| Photosynthesis                 | CO₂       | 264  | In air | Glucose | 180  | In cells |
|                                | H₂O       | 108  | In cells | O₂ | 192  | In air |
| Total                          |           | 372  | Total  | 372     |      |      |

Figure 3. Marshmallow model of heptane combustion reaction.

Figure 4. Marshmallow model of cellular respiration.

Figure 5. Marshmallow model of photosynthesis.

Activity 3: From Solid Mass to Gas Mass

Introduction

As illustrated with the marshmallow molecular models, the combustion of carbon-based fuels involves their combination with oxygen to form CO₂ and H₂O. This releases energy in the form of heat and light (fire). This also results in the loss of mass of the fuel as the CO₂ and H₂O molecules formed become part of the atmosphere. This activity allows students to observe, measure, and plot the rate of this reaction by following the loss of mass by a fuel source through combustion.

Materials

- Birthday candles (longer varieties work best, but short candles also will do)
- Lighter (use with instructor supervision)
Procedure
Prepare a small support structure to hold a birthday candle in a vertical position (we used a marshmallow). Get an initial weight of the candle plus support, then light the candle and start the timer. Weigh the candle once a minute for 8–10 minutes, then extinguish the candle. Have students prepare a table and graph of weight loss over time for this activity (example shown in Figure 6). Having students work on their graph while the candle is burning will keep them engaged while collecting their data points.

Discussing the Science
Combustion reactions break down carbon-based fuels with the assistance of oxygen gas to form CO₂ and H₂O. Combustion of liquid fuels (such as gasoline) or solid fuels (such as candle wax) result in the conversion of the carbons in the fuel into a gas. The fuel seems to disappear, but it actually becomes part of the atmosphere. To assist and assess student learning, teachers can ask their students these questions (all of which have the same answer, “Into the air”):

- Where did the mass of the candle go?
- When a car uses gasoline, where does the gasoline mass go?
- When a log is burned in a campfire, where does the wood mass go?
- When coal is burned to make electricity, where does the coal mass go?

The discussion of how fuels become CO₂, which gets added to the mass of the air, is an opportune time to explain that CO₂ acts like an invisible blanket over the surface of the Earth. The more CO₂ gets added to that blanket, the warmer the Earth’s surface becomes. Currently, the human burning of fossil fuels is adding ~1.2 million kg of CO₂ to the Earth’s atmosphere every second (Harvey, 2018).

Additional Explorations
This activity sets the table for student consideration of the many energy sources being used to power human communities. Some fuels (coal, petroleum, natural gas, and biofuels) are combusted to release energy, and the carbon components of these fuels become CO₂ in the atmosphere and add to global warming. Other energy sources (hydrogen gas, solar, wind, hydropower, geothermal, and nuclear energy) do not rely on burning carbon and do not directly add CO₂ to the atmosphere. With this awareness, teachers can have students consider what alternative energy sources are available in their communities and how they can be integrated to reduce CO₂ production from energy generation.

Figure 6. Data on mass loss over time from candle wax combustion activity.

Figure 7. Data on mass loss over time from yeast respiration activity.

Table: Candle Combustion

| Time (min.) | Mass (g) |
|------------|----------|
| 0          | 9.85     |
| 1          | 9.78     |
| 2          | 9.72     |
| 3          | 9.64     |
| 4          | 9.60     |
| 5          | 9.52     |
| 6          | 9.48     |
| 7          | 9.41     |
| 8          | 9.35     |

Table: Yeast Respiration

| Time (min.) | Mass (g) |
|------------|----------|
| 0          | 163.21   |
| 10         | 163.01   |
| 20         | 162.74   |
| 30         | 162.49   |
| 40         | 162.25   |
| 50         | 162.03   |
| 60         | 161.80   |
○ Activity 4: From Living Mass to Gas Mass

Introduction
As illustrated with the marshmallow molecular models, cellular respiration converts energy-containing carbon polymers such as glucose into CO₂ so as to release the energy these fuels contain for sustaining life. As cellular respiration occurs, oxygen gas is brought into cells while CO₂ gas is released. Since CO₂ has greater mass than O₂, there is a net loss of mass in the cell or organism as it respires. This activity allows students to measure and plot the rate of mass loss of a yeast cell solution as it undergoes cellular respiration.

Materials
- Dried yeast (1 tablespoon)
- Yeast growth solution (1 cup apple juice plus 1/3 cup sugar)
- Hot plate or microwave oven
- Funnel
- Digital balance with 0.01 g accuracy
- Lightweight growth container (e.g., plastic bottle)

Procedure
Prepare enough yeast growth medium to allow student groups to carry out the activity (each group will need about ½ cup of the solution). Warm up the growth solution to ~42°C (108°F) and pour ~60 mL (¼ cup) into two separate growth containers. Add ~1 tablespoon of dried yeast to one of the containers and swirl it until yeast are well dissolved and distributed. The second container without yeast will serve as a control. Measure the weight of each of the containers and start the timer. Weigh the containers again every 10 minutes for one hour. Have students create a table and graph showing weight loss over time for each container (example shown in Figure 7).

During this activity, have students come up with predictions about how mass will change based on the respiration marshmallow modeling activity. Students can also be asked to complete activities in the “Discussing the Science” section below while yeast data points are being collected.

Discussing the Science
Cellular respiration releases energy contained in sugar molecules by converting the carbons in the sugar to CO₂ with the assistance of O₂. The end products of this reaction are the same as those of fuel combustion (CO₂ and H₂O), but the water produced stays in the cells or the surrounding solution. The CO₂ produced during sugar respiration goes into the air and results in the observed weight loss. In our bodies, sugars, fats, and proteins are all used for energy by converting them into CO₂. The CO₂ produced in our cells is carried to our lungs, which eliminate it from our bodies by exhalation. This results in gradual weight loss. To assist and assess learning, teachers can have students put the following processes in the correct order, connecting them with arrows:

- CO₂ made in cells enters the blood
- The body loses weight
- Fats are converted to CO₂ for energy
- CO₂ leaves the lungs by exhalation
- CO₂ moves from the blood to air in the lungs

Students can also be asked to calculate how quickly the body loses weight by breathing. Let students know that for a body at rest, ~15 mg of fat fuel is used to make the CO₂ released into the atmosphere with every breath. Thus, every exhaled breath represents the loss of ~15 mg of body weight. Have students measure their normal respiratory rate at rest and use this to approximate weight loss per minute, per hour, and per day using the average of 15 mg of fuel converted to CO₂ per breath. Students can also be asked to predict how exercise will affect the rate of weight loss by considering what happens to respiratory rate and volume when a person does various exercises.

○ Conclusions
These activities are well suited for demonstrations and classroom active learning about CO₂. They would also serve well as science fair exhibits, where students can explain to their classmates (and to their parents) how a gaseous form of carbon connects animals and fossil fuels to plants. These activities can serve as a foundation for explaining and understanding carbon cycling, weight loss, global warming, and other natural phenomena tied to CO₂.

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