

Atom Tokens: Taking a Sugar Molecule Apart Without Losing a Piece

Investigation question: When a cell takes one sugar molecule apart with oxygen, where does every atom end up, does the mass change, and how should a model show the energy that is released?

Physical model

Groups of 3

1 session

Setup 5 · Activity 40 · Cleanup 5 min

MS-LS1-7 · assesses

MS-PS1-5 · practice

Scientific purpose

Students build one sugar molecule and six oxygen molecules from colored beads, rearrange exactly those beads into carbon dioxide and water with none left over and none added, and check the mass on a balance before and after. They then scale the model up, run it in the photosynthesis direction, and must decide how to represent energy in a model made of atoms, which forces the idea that energy is not a substance and is not counted with the atoms.

Why this helps students with this chapter

Students hear 'matter is conserved' and nod, but the idea that the carbon in their lunch leaves through their lungs is not real to them. Having to find a home for every one of 36 beads, with the balance confirming nothing was lost, makes conservation a thing they did rather than a rule they heard. The energy-token decision surfaces the misconception that energy is one of the ingredients.

Standards connections

MS-LS1-7 (assesses, developing a model of how a food molecule is broken apart and its atoms rearranged into new molecules while energy is released): The bead model is a direct student-built model of the PE's statement: molecules broken apart, atoms put back together into new molecules, energy released. No reaction steps are required, so the assessment boundary is respected.

MS-PS1-5 (practice, a physical model showing the number of atoms does not change in a reaction): Counting and weighing the beads before and after is the practice this PE calls for, done here with one reaction; the full treatment with several reactions comes in Lesson 13. Students count atoms in a physical model; they do not balance a symbolic equation.

Roles (rotate each session)

- **Builder:** Threads beads onto pipe cleaners to make each molecule according to the molecule mats, and takes molecules apart when the group is ready to rearrange.
- **Counter:** Keeps the atom inventory table, counts each color before and after every step, and refuses to let the group continue until the counts match.
- **Weigher and recorder:** Masses the full set of molecules on the balance before and after rearranging, records every value, and writes the group's energy-token decision.

Materials

Item	Quantity	Per	Note
Black pony beads (carbon)	12	group	Six are needed for one sugar; twelve allow the scaling step.
White pony beads (hydrogen)	24	group	
Red pony beads (oxygen)	36	group	
Pipe cleaners cut to 10 cm (bonds)	30	group	The two-sugar scaling step needs 24 product molecules at once. Twist ties or short lengths of string also work.
Molecule mats: printed outlines showing the shapes of sugar ($C_6H_{12}O_6$), oxygen (O_2), carbon dioxide (CO_2) and water (H_2O)	1 set	group	
Balance reading to 0.1 g	1	group	Groups can share one balance between two tables.
Small tray or paper plate to keep the set together on the balance	1	group	
Blank index cards and a yellow marker (for the energy-token design)	3 cards	group	
Recording sheet	1	student	

Estimated cost: 8 to 12 per class, reusable (an estimate; A 1,000-count bag of mixed pony beads is \$6 to \$8 and supplies ten groups; pipe cleaners are \$3 for 100; balances and index cards are classroom stock. The sets can be bagged and reused every year.)

Safety

- Pony beads are a choking hazard for small children; keep them off the floor and count them back into the bags at the end.
- Pipe cleaner ends have a wire core: fold the tips over so they do not scratch, and do not point them toward faces.
- No chemicals, heat or glass are used.

Teacher preparation and setup

1. Count beads into zip bags per group: 12 black, 24 white, 36 red. Add 30 pipe-cleaner pieces. An extra bead of each color in a separate 'spares' cup lets you catch groups that quietly add atoms.
2. Print the molecule mats. Sugar can be drawn as a ring or chain of six carbons with hydrogens and oxygens attached; the exact shape is not assessed, only the counts, so a simple chain outline with slots is fine.
3. Check that the balance reads the same for a tray of beads whether they are threaded or loose; some pipe cleaners shed fibers, so weigh the full set including all pipe cleaners both times.

4. Decide whether to give the energy-token challenge open-ended or with the three options on the recording sheet; open-ended is better for stronger groups.

Investigation design

Independent variable	Number of sugar molecules reacted (one, then two)
Dependent variable	Number of oxygen molecules needed, number of carbon dioxide and water molecules formed, and the mass of the set before and after
Controlled	Same beads used before and after, none added or removed; Same pipe cleaners included in every mass reading; Same molecule shapes from the mats
Trials	Each group runs the one-sugar reaction once, the two-sugar reaction once, and the reverse (photosynthesis) direction once; the class compares atom counts and mass changes on the board.
Comparison	Respiration direction against photosynthesis direction, using the same beads.

Student procedure

1. Lay out the molecule mats. Using the beads and pipe cleaners, build one sugar molecule: 6 black (carbon), 12 white (hydrogen) and 6 red (oxygen) beads. Then build six oxygen molecules, each two red beads on a short pipe cleaner.
2. Counter: fill in the 'before' row of the atom inventory with the number of beads of each color actually on the mats, and the total. Weigher: put every molecule and every pipe cleaner on the tray and record the mass.
3. Now 'run the reaction'. Take the molecules apart and use exactly the same beads to build the products: as many carbon dioxide molecules (one black between two red) and as many water molecules (one red between two white) as the beads allow. No beads may be added and none may be left over. If something does not work out, do not borrow from the spares; figure out what went wrong.
4. Counter: fill in the 'after' row. Weigher: put the full set back on the tray and record the mass again. Record how many carbon dioxide and how many water molecules you made.
5. Scaling step: predict how many oxygen molecules and how many of each product two sugar molecules would need and make. Then build the second sugar with the remaining beads and test your prediction by running the reaction again with both sugars. Record the counts.
6. Now run the model in the photosynthesis direction: starting from six carbon dioxide and six water, rebuild one sugar and six oxygen molecules. Note anything that is the same and anything that feels different about doing it this way.
7. Energy decision: your model so far shows only atoms, but respiration releases energy and photosynthesis stores it. As a group, design a way to show energy in the model that does not use a bead and does not get counted with the atoms. Make it with the index cards and write a one-sentence rule for when it appears on the reactant side and when on the product side.
8. Run the respiration reaction one last time with your energy token in play, then answer the recording-sheet questions and the analysis questions individually.

Expected observations

- Before: 6 black, 12 white, 18 red, 36 beads total. After: the same counts, arranged as 6 carbon dioxide and 6 water molecules. Mass identical to within 0.1 g.
- Scaling: two sugars need 12 oxygen molecules and give 12 carbon dioxide and 12 water, 72 beads in all.
- Common first error: groups build carbon dioxide until the red beads run out and are left with unattached hydrogen, which they fix by taking apart one or two carbon dioxide molecules; this is the productive struggle the lab is built for.
- Energy tokens vary: a yellow lightning card, a card labeled 'released energy' placed with the products, a coin placed on whichever side is giving energy.

Likely difficulties

- Students try to make the sugar 'look right' and spend too long on shape; tell them only counts are assessed and a chain of six carbons with the others hung on is fine.
- Groups quietly borrow a bead from the spares cup when the count does not work out; the Counter role and the sealed bag count are the safeguards, and a group that admits borrowing has found the point of the lab.
- Some students expect the mass to fall 'because energy left'. Let the balance answer, then use q5 to make the reasoning explicit.
- Pipe cleaners shed fibers and can change the mass by a tenth of a gram; weigh the whole set including every pipe cleaner each time.

Structured debrief

1. Collect before and after counts from every group: all should read 6, 12, 18 and 36. Ask the groups whose beads did not come out even what they found when they traced the problem; it is almost always an oxygen molecule built with one bead or a water built with the wrong colors.
2. Collect the mass readings. Differences should be zero or within the balance's last digit. Ask what would have to happen for the mass to drop, and connect it to the textbook phrase 'matter is conserved': it is a count of atoms, and the balance is the check.
3. Have two or three groups present their energy tokens. Praise any design that is visibly different from an atom (a card, a color, a sound) and that appears on the product side for respiration and the reactant side for photosynthesis. Make the general point: energy is written in the equation but never counted with the matter.
4. Draw out q7: the bead model cannot show that the two processes happen in different places through different steps, or that the oxygen a leaf releases comes from water rather than carbon dioxide. Students should leave knowing the equations are summaries that are excellent for atom bookkeeping and silent about mechanism.
5. Close with the hill picture from the presentation: sugar and oxygen 'sit higher' than carbon dioxide and water; the model's energy token represents the drop. Remind students that breaking a bond costs energy and that the release comes from the new bonds formed; the token shows the net result only.

Recording sheet: what students fill in

Lab 2 recording sheet: Atom tokens

Black = carbon (C), white = hydrogen (H), red = oxygen (O). Count beads, not molecules, in the inventory. The Counter signs off each row before the group moves on.

Atom inventory for one sugar molecule

Step	Black (C)	White (H)	Red (O)	Total beads	Mass of the set (g)	Molecules on the mats
Before: 1 sugar + oxygen molecules						
After: carbon dioxide + water						

Scaling up: two sugar molecules

	Oxygen molecules needed	Carbon dioxide made	Water made	Total beads
Prediction				
Result				

-  Draw the 'before' and 'after' sets side by side using circles labeled C, H and O, with the energy token you designed in its correct place. Write the word equation underneath.

Answer: Before: one cluster of 6 C, 12 H, 6 O (sugar) and six O–O pairs. After: six O–C–O groups and six H–O–H groups. The energy token drawn with the products. Word equation: sugar + oxygen → carbon dioxide + water + energy.

Why: The drawing is the student's model of the PE statement. Counts and placement of the energy token matter; molecular shape does not.

- Correct atom counts on both sides (6 C, 12 H, 18 O)
- Products drawn as CO₂ and H₂O groupings
- Energy token on the product side and clearly not an atom
- Word equation written correctly

1. Describe your energy token and write your group's rule for which side it goes on in respiration and in photosynthesis.

Answer: Group-specific. Example: a yellow lightning card labeled 'energy released'. Rule: in respiration it sits with the products because the reaction gives energy off; in photosynthesis it sits with the reactants because light energy must be put in.

Why: Any token that is visibly not an atom and follows the side rule earns credit; the rule is the understanding being checked.

- Token is not a bead and is not counted with the atoms
- Rule places energy with the products for respiration
- Rule places energy with the reactants for photosynthesis

2. Did the balance reading change between before and after? Write the two values and the difference, and explain the result in terms of beads.

Answer: No change (or a difference within 0.1 g). Example: before 28.4 g, after 28.4 g, difference 0.0 g. The same beads and pipe cleaners were on the tray both times; they were only regrouped, so the mass had to be the same.

Why: Numeric: students write both readings and subtract. A difference of one balance digit is measurement noise, not a lost atom.

Also acceptable: If a group lost a bead, accept 'the difference equals one bead because we dropped one' with the explanation.

Analysis questions: answer key

3. Every carbon bead from the sugar ended up in a carbon dioxide molecule and every hydrogen bead ended up in water. Where did the 18 oxygen beads end up? Give the split between the two products and show that it adds to 18.

Answer: 12 oxygen beads in the six carbon dioxide molecules (2 each) and 6 oxygen beads in the six water molecules (1 each). $12 + 6 = 18$.

Why: Oxygen is the atom that gets split between products, which is why groups run short of red beads if they build only carbon dioxide first.

Also acceptable: Accept the same split written as $6 \times 2 + 6 \times 1 = 18$.

4. Use the model to explain to a younger student why the mass of the set did not change, and then explain what that means for the sugar in a squirrel's acorn: where is that sugar's mass an hour after the squirrel eats it?

Answer: Every bead that was on the tray before is still on the tray after; we only moved them into new groups, so the balance cannot read anything different. In the squirrel, the acorn's sugar is taken apart the same way: its carbon atoms are now in carbon dioxide molecules the squirrel breathes out, its hydrogen atoms are in water, and the oxygen atoms are shared between the two. An hour later the sugar's mass is mostly in the air around the squirrel and in water in its body, not gone.

Why: Full credit needs both halves: the bead explanation for a younger student and the real-world location of the atoms.

- Explains unchanged mass as the same atoms regrouped
- States that the sugar's carbon leaves as carbon dioxide (breathed out)
- States that hydrogen leaves in water; the matter is not destroyed

5. Why can energy not be a bead in this model? Give two reasons, one about what beads represent and one about what would happen to the mass if energy were a bead.

Answer: First, a bead stands for an atom, a piece of matter that has mass and must be counted; energy is not matter, it is a property of how the atoms are arranged, so a bead would be the wrong kind of thing. Second, if energy were a bead and it left during respiration, the mass after would be lower than before; the balance showed the mass did not change, so whatever left was not matter.

Why: The second reason uses the lab's own evidence; the first uses the meaning of the model. Both are required.

- Energy is not matter so cannot be an atom token
- Uses the unchanged mass as evidence that energy is not a substance that left

6. A cell in a running muscle takes apart 5 sugar molecules in a short time. How many oxygen molecules does it need and how many carbon dioxide molecules does it give off? Show the pattern you used.

Answer: 30 oxygen molecules needed and 30 carbon dioxide molecules given off (and 30 water). Pattern: one sugar needs 6 O₂ and gives 6 CO₂, so five sugars need 5 × 6 = 30 and give 5 × 6 = 30.

Why: The ratio is fixed by the atom counts: each carbon in sugar leaves in its own carbon dioxide, and each needs one oxygen molecule's worth of oxygen overall.

Also acceptable: Accept 30 and 30 with the multiplication shown in any form.

7. When you ran the beads in the photosynthesis direction, the atoms worked out exactly the same. List two ways real photosynthesis is not just real respiration run backward, and say which of them your bead model can show.

Answer: Two ways: (1) they happen in different places by different steps, photosynthesis in chloroplasts and respiration in the cell fluid and mitochondria, not one path run backward; (2) the oxygen gas released in photosynthesis comes from splitting water, not from carbon dioxide; (3) photosynthesis needs light energy put in, while respiration gives energy out, and in a leaf both run at the same time. The bead model can show the energy direction with the token, but it cannot show the different places or steps, and it does not show which oxygen atoms become the oxygen gas.

Why: Students should take any two of the three and correctly judge the model's reach. The energy-direction difference is the one the model shows.

- Two genuine differences stated
- Correctly identifies which the bead model can and cannot show

8. Name one thing about cellular respiration that the bead model shows well and one thing it hides or gets wrong. For the hidden one, say what a better model would need.

Answer: Shows well: that all atoms are conserved and regrouped, and that the oxygen is split between two products. Hides or gets wrong: the many steps, the mitochondria, that bonds are not identical sticks and that breaking them costs energy, where the released energy goes (cell work and heat), or that it happens in water inside a living cell. A better model would need stages (several mats in sequence), a way to show energy captured versus energy lost as heat, or bonds that show different strengths.

Why: Any correct pair with a sensible improvement earns full credit; the point is that students judge the model rather than trust it.

- One accurate strength named
- One accurate limitation named
- A specific feature a better model would need

Individual evidence of learning

Each student submits their own recording sheet (inventory table, scaling table, the before-and-after drawing with the energy token, q1 and q2) and written answers to q3 through q8. The drawing plus q4 are the primary evidence for the MS-LS1-7 model; q3 and q6 are the evidence for conservation and scaling.

Assessment criteria

Criterion	Proficient looks like
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Atom conservation	Inventory shows 6 C, 12 H, 18 O before and after; masses recorded and the difference explained as no beads added or lost.
Model of the reaction	Drawing shows the correct molecules before and after, the word equation beneath, and the energy token placed on the product side with a stated rule.
Scaling and ratio reasoning	Correctly predicts and verifies the two-sugar counts and extends the pattern to five sugars.
Limits of the model	Names at least one thing the model shows well and one it hides (steps, location, where the oxygen comes from, the cost of breaking bonds) with a sensible improvement.

Accessibility adaptations

- Use large beads and thick pipe cleaners, and let a partner thread while the student directs and counts; counting and deciding are the thinking, not the threading.
- Provide the inventory table with the 'before' row pre-filled and a color legend with the element symbol beside each bead color for students who need more support or who do not distinguish red from black easily; use three distinct shapes (round, cube, oval) if color is a barrier.
- Accept a photographed bead layout with the energy token in place instead of the drawing, and a spoken explanation for q4 and q7.
- Offer a multilingual card for reactant, product, conserved, molecule and energy, and allow the group rule for the energy token to be written in any language and read aloud in English.

Low-cost alternative

Use colored paper circles with the symbol written on them and tape or paper clips as bonds; or three colors of dried beans in sandwich bags, with a molecule drawn as beans arranged on a printed mat. If no balance is available, replace the mass check with the total bead count, which is the same evidence.

Model limitations

Beads show atoms as identical hard balls and pipe cleaners show bonds as sticks, which hides that bonds hold energy differently and that breaking them costs energy. The model shows a one-step swap, while real respiration is dozens of steps in the cell fluid and mitochondria, and it cannot show that the oxygen released by photosynthesis comes from water. The energy token represents only the net energy released, not where it goes (cell work and heat). This activity has not been physically tested by the authors; the 40-minute timing assumes groups have used bead models before.

Teacher notes

The reaction will not come out even if groups build the oxygen molecules with one bead or the water with two red beads; walk the room during the build step and check the oxygen pairs before anyone 'runs' the reaction. If a group finishes early, give them the yeast puzzle: in bread dough with little oxygen, yeast still releases energy from sugar and gives off carbon dioxide; ask them to try to build the products with no O₂ beads and discover that the carbons cannot all leave as carbon dioxide, which is why a different product (alcohol) forms. Keep the energy tokens; the best ones make a good display beside the word equation.