

# Passport of a Carbon Atom: Where Do the Atoms Pile Up?

**Investigation question:** When carbon atoms move among the air, water, living things, soil and fossil fuels by chance at each step, which reservoirs end up holding the most atoms, and what changes when people start burning fossil fuels?

Collaborative systems modeling

Groups of 3

1 session

Setup 8 · Activity 35 · Cleanup 5 min

MS-LS2-3 · assesses

MS-LS1-6 · supports

## Scientific purpose

Students become carbon atoms in a room-sized model of the carbon cycle. Six stations stand for reservoirs, and a die roll at each station decides where the atom goes next, following rules that mirror the real processes. Each student records a passport of their own journey, and the class pools everyone's final positions into a bar chart. A second run changes one rule, fossil fuels can now be burned, and the class compares the two charts. The lab turns a static cycle diagram into a system with rates, randomness, storage and a human-caused change.

## Why this helps students with this chapter

A cycle diagram on a page looks like one loop every atom follows in order. Walking the cycle with a die makes three things visible that the page hides: atoms take different routes, some reservoirs hold atoms for many rounds while others pass them on at once, and the number of atoms in the whole system never changes no matter how they shuffle. Changing a single rule and re-running shows how people shift a cycle without creating or destroying anything.

## Standards connections

**MS-LS2-3** (assesses, developing and using a model of matter cycling among living and nonliving parts of an ecosystem, with the boundary of the system defined): Students run, record and then revise a model of carbon cycling among producers, consumers, decomposers, soil, water, air and fossil fuels, state the boundary of the modeled system, and use the pooled data to explain conservation of matter and the effect of fossil-fuel burning. No chemical reactions are used, which respects the assessment boundary.

**MS-LS1-6** (supports, photosynthesis as the entry point for carbon into producers): The producers station's incoming arrow is photosynthesis; students use it as a process name without being asked to explain its mechanism.

## Roles (rotate each session)

- **Atom (every student):** Rolls the die at each station, reads the rule, records the round in their own passport and moves to the next station. Every student is an atom; the group roles below are extra jobs.

- **Station keeper:** One member of each group also keeps a station: reads the rule aloud for anyone unsure, keeps the die at the station, and counts the atoms present at the end of each run.
- **Tally recorder:** One member of each group collects the group's three passports after each run, checks they have ten rounds, and reports the group's final stations to the class tally on the board.
- **Grapher:** One member of each group copies the class tally into the recording sheet and draws the two bar charts for the group to analyze.

## Materials

| Item                                                          | Quantity                               | Per     | Note                                                                                                                 |
|---------------------------------------------------------------|----------------------------------------|---------|----------------------------------------------------------------------------------------------------------------------|
| Six-sided dice                                                | 1 per station (6 total), plus 2 spares | class   | Large foam dice are easier to read across a room.                                                                    |
| Station cards printed from the rules table, one per reservoir | 6                                      | class   | Print the natural-run rules on one side and the fossil-fuel-era rules on the other, so the change takes ten seconds. |
| Passport recording sheet                                      | 1                                      | student |                                                                                                                      |
| Painter's tape or cones to mark station areas on the floor    | 1 roll                                 | class   |                                                                                                                      |
| Whiteboard or chart paper for the class tally                 | 1                                      | class   |                                                                                                                      |
| Colored pencils for the bar charts                            | 2 colors                               | group   |                                                                                                                      |

**Estimated cost:** 6 to 10 per class, reusable (an estimate; A set of eight large foam dice costs about \$6; station cards and passports are printed; tape and chart paper are classroom stock.)

## Safety

- Students walk between stations; clear bags and chairs from the paths and set a walking-only rule. Mark station areas with tape so groups do not crowd a corner.
- Foam or large plastic dice only; no throwing dice across the room.
- No chemicals, heat or sharp tools are used.

## Teacher preparation and setup

1. Print and post six station cards around the room with space for students to stand: Atmosphere, Water, Producers, Consumers, Soil and decomposers, Fossil fuels. Put the natural rules on the front and the fossil-fuel-era rules on the back.
2. Decide the starting spread: divide the class evenly across the six stations for run 1 (for 30 students, 5 per station). Keep the same spread for run 2 so the two runs can be compared fairly.
3. Draw the class tally table on the board before class: six station rows, two run columns, and a row for the total that should equal the class size every time.

4. Run three rounds yourself with a die to check that the rules read clearly; most confusion comes from students moving before recording.

## Investigation design

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|                             |                                                                                                                                                                                                    |
|-----------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Independent variable</b> | The rule set at the Fossil fuels station: natural (atoms never leave) versus fossil-fuel era (rolls of 4, 5 or 6 send the atom to the Atmosphere by combustion)                                    |
| <b>Dependent variable</b>   | The number of atoms at each station after ten rounds, especially the Atmosphere count                                                                                                              |
| <b>Controlled</b>           | Same starting spread of atoms across stations in both runs; Ten rounds per run; One roll per atom per round; All other station rules unchanged; Boundary: no atoms enter or leave the six stations |
| <b>Trials</b>               | One run of each rule set per class; pool results across periods if several classes run it, because chance makes small classes noisy.                                                               |
| <b>Comparison</b>           | Run 1 (natural) versus run 2 (fossil-fuel era) tallies, station by station.                                                                                                                        |

## Student procedure

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1. Stand at your starting station and write it in round 0 of your passport. The class should be spread evenly across all six stations. Agree on the boundary of the model: the six stations are the whole system, and no atom may leave the room or join from outside.
2. Round 1: roll the die at your station once. Read the rule for your roll on the station card. In your passport write the round number, the station you are at, the number you rolled, the process named on the card and the station you are going to. If the card says stay, write 'stays' as the process and your current station as the destination.
3. Move to your destination station only after you have written the row. Wait there until the teacher calls the next round. Everyone rolls once per round.
4. Repeat for ten rounds. At the end of round 10 stay where you are. Station keepers count the atoms at their station and report the count; the tally recorder writes the group's three final stations on the board tally. Check that the class total equals the number of students.
5. Return to your run 1 starting station. The teacher flips every station card to the fossil-fuel-era side. The only rule that changes is at the Fossil fuels station, where rolls of 4, 5 or 6 now send the atom to the Atmosphere by combustion. Run ten more rounds exactly as before and record them in the run 2 passport table.
6. At the end of run 2, count and tally again. Check the total.
7. In your group, copy both tallies into the recording sheet and draw two bar charts, one per run, with the same vertical scale so they can be compared by eye.
8. Count how many rounds of your own passport you spent in each reservoir across both runs and fill in the personal summary table.
9. Answer the analysis questions on your own, then compare answers in your group and revise anything you now disagree with.

## Expected observations

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- In run 1 the Fossil fuels station gains atoms slowly and never loses them, so its count rises over ten rounds while the Water station holds a steady group; Atmosphere and Producers trade atoms back and forth every round.
- In run 2 the Atmosphere count after round 10 is higher than in run 1 and the Fossil fuels count is lower, because half of each round's fossil-fuel rolls now release atoms by combustion. With a class of about 30, expect a difference of several atoms rather than a dramatic one; pooling across periods sharpens it.
- Every total equals the class size. Any mismatch means an atom was miscounted or moved before recording, which is itself a good conservation check.

## Likely difficulties

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- Students move before writing the row, then cannot remember their roll. Call rounds slowly and require pencils down before anyone walks.
- Students at a stay rule sometimes think they rolled wrong or do not record the round. A stay is a legitimate row: the process is 'stays' and the destination is the same station.
- Small classes give noisy tallies, and run 2 may by chance look no different. Have students compute the expected direction from the rules (q5) and compare with the actual, which is how scientists judge a noisy result.
- Some students argue that the Soil-to-Fossil fuels rule (one in six) is 'wrong' because real burial is rare. They are right; use it to discuss why a model exaggerates a rate to make a slow process visible in ten rounds.

## Structured debrief

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1. Put both class bar charts side by side. Ask what the one changed rule did to the Atmosphere bar, and why the Fossil fuels bar fell. Then ask the question that matters: did the total change? It cannot; every student is still in the room. That is conservation of matter, and the planet works the same way with its atoms.
2. Ask which reservoirs were 'sticky' in run 1 (Fossil fuels, where nobody could leave; Water, with a one-in-two stay rule) and which were 'fast' (Consumers, where half the rolls go straight to the air). Connect stickiness to residence time: real fossil fuels hold carbon for hundreds of millions of years, and a mouse holds it for months.
3. Lay a few passports next to each other and show that no two journeys match. The cycle diagram is a map of possible routes, not a track. Ask who skipped a reservoir entirely in ten rounds, and who bounced between two stations.
4. Name the model's limits in students' own words: real chances differ by season and by place, real reservoirs are vastly different in size (the ocean holds far more carbon than the air), the model has no rocks and no energy, and the fossil-fuel burial rule is far too fast. Then ask why the model is still useful: it shows direction of change correctly when one rule changes, which is what we needed to know.

## Recording sheet: what students fill in

### Lab 1 recording sheet: Passport of a carbon atom

You are a carbon atom. At each station, roll once, find your number on the station card, write the row, and only then move. The rules below are a model: the chances are invented for teaching, but every arrow is a real process in the carbon cycle.

**Station rules (reference). Run 1 natural rules; run 2 changes only the Fossil fuels row.**

*Simulated teaching dataset: the numbers are invented to be realistic, not measured.*

| Station (reservoir)                   | Roll 1                                        | Roll 2                                        | Roll 3                                        | Roll 4                                     | Roll 5                                     | Roll 6                                                    |
|---------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|--------------------------------------------|--------------------------------------------|-----------------------------------------------------------|
| Atmosphere (carbon dioxide in air)    | Producers: photosynthesis                     | Producers: photosynthesis                     | Producers: photosynthesis                     | Water: dissolves into the ocean or pond    | Stays in the air                           | Stays in the air                                          |
| Water (carbon dioxide dissolved)      | Producers: photosynthesis by algae            | Producers: photosynthesis by algae            | Atmosphere: escapes to the air                | Stays dissolved                            | Stays dissolved                            | Stays dissolved                                           |
| Producers (plants, algae)             | Atmosphere: cellular respiration              | Atmosphere: cellular respiration              | Consumers: eaten                              | Consumers: eaten                           | Soil and decomposers: dies or drops a leaf | Stays, stored in wood                                     |
| Consumers (animals)                   | Atmosphere: cellular respiration              | Atmosphere: cellular respiration              | Atmosphere: cellular respiration              | Soil and decomposers: wastes               | Soil and decomposers: dies                 | Stays in the body                                         |
| Soil and decomposers                  | Atmosphere: decomposers' cellular respiration | Atmosphere: decomposers' cellular respiration | Atmosphere: decomposers' cellular respiration | Stays stored in soil                       | Stays stored in soil                       | Fossil fuels: buried under sediment for millions of years |
| Fossil fuels, run 1 (natural)         | Stays buried                                  | Stays buried                                  | Stays buried                                  | Stays buried                               | Stays buried                               | Stays buried                                              |
| Fossil fuels, run 2 (fossil-fuel era) | Stays buried                                  | Stays buried                                  | Stays buried                                  | Atmosphere: dug up and burned (combustion) | Atmosphere: dug up and burned (combustion) | Atmosphere: dug up and burned (combustion)                |

**Run 1 passport (natural rules). Starting station for round 0: \_\_\_\_\_**

| Round | Station I am at | Roll | Process on the card | Station I go to |
|-------|-----------------|------|---------------------|-----------------|
|-------|-----------------|------|---------------------|-----------------|

| Round | Station I am at | Roll | Process on the card | Station I go to |
|-------|-----------------|------|---------------------|-----------------|
| 1     |                 |      |                     |                 |
| 2     |                 |      |                     |                 |
| 3     |                 |      |                     |                 |
| 4     |                 |      |                     |                 |
| 5     |                 |      |                     |                 |
| 6     |                 |      |                     |                 |
| 7     |                 |      |                     |                 |
| 8     |                 |      |                     |                 |
| 9     |                 |      |                     |                 |
| 10    |                 |      |                     |                 |

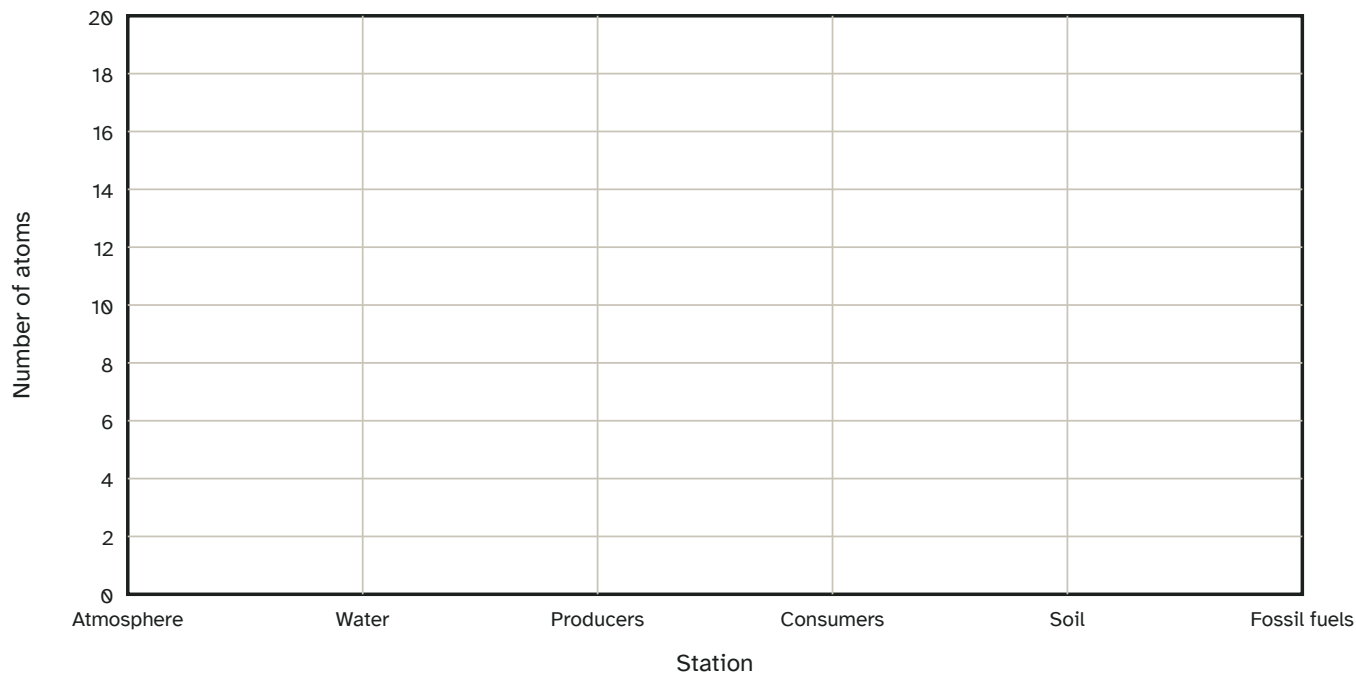
**Run 2 passport (fossil-fuel era). Starting station for round 0: \_\_\_\_\_**

| Round | Station I am at | Roll | Process on the card | Station I go to |
|-------|-----------------|------|---------------------|-----------------|
| 1     |                 |      |                     |                 |
| 2     |                 |      |                     |                 |
| 3     |                 |      |                     |                 |
| 4     |                 |      |                     |                 |
| 5     |                 |      |                     |                 |
| 6     |                 |      |                     |                 |
| 7     |                 |      |                     |                 |
| 8     |                 |      |                     |                 |
| 9     |                 |      |                     |                 |
| 10    |                 |      |                     |                 |

Class tally: atoms at each station after round 10

| Station                           | Run 1 count (natural) | Run 2 count (fossil-fuel era) | Change (run 2 minus run 1) |
|-----------------------------------|-----------------------|-------------------------------|----------------------------|
| Atmosphere                        |                       |                               |                            |
| Water                             |                       |                               |                            |
| Producers                         |                       |                               |                            |
| Consumers                         |                       |                               |                            |
| Soil and decomposers              |                       |                               |                            |
| Fossil fuels                      |                       |                               |                            |
| Total (must equal the class size) |                       |                               |                            |

Atoms at each station after ten rounds, run 1 and run 2 (draw two bars per station,



### My own journey: rounds spent in each reservoir (count rows from both passports, 20 rounds total)

| Reservoir            | Rounds in run 1 | Rounds in run 2 | Total rounds |
|----------------------|-----------------|-----------------|--------------|
| Atmosphere           |                 |                 |              |
| Water                |                 |                 |              |
| Producers            |                 |                 |              |
| Consumers            |                 |                 |              |
| Soil and decomposers |                 |                 |              |
| Fossil fuels         |                 |                 |              |

1. Which reservoir held you for the most rounds, and which card rule explains why it was hard to leave?

**Answer:** Student-specific. The most common answers are Fossil fuels (in run 1 no roll lets an atom leave; in run 2 only 4, 5 and 6 do), Water (rolls 4, 5 and 6 stay, a one-in-two chance each round) and Soil and decomposers (rolls 4 and 5 stay).

**Why:** The student should connect their own count to the share of stay rolls on that station's card rather than to luck alone.

- Names a reservoir with the highest personal round count
- Cites the stay rule on that card as the reason

2. Compare your run 1 passport with a groupmate's. Name one reservoir you visited that they did not, and one process that moved you that never moved them.

**Answer:** Student-specific. For example: 'I went to Fossil fuels and my partner never did; I was moved by burial and they were never moved by burial.'

**Why:** The point is that passports differ, so the cycle is a map of possible routes, not one loop every atom follows.

- Names a reservoir not in the partner's passport
- Names a process not in the partner's passport

### Analysis questions: answer key

3. Look at the class tally for run 1. Which reservoir had the most atoms after ten rounds? Use the station rules to explain why atoms pile up there.

**Answer:** Class-specific. Most often Fossil fuels or Water. Fossil fuels: once an atom arrives by a Soil roll of 6, no run 1 roll lets it leave, so its count can only grow. Water: three of six rolls stay, and atoms arrive from the Atmosphere on a 4, so it holds a steady group. A class that started with few atoms in Soil may instead see Atmosphere or Producers highest because those two trade atoms every round.

**Why:** Accept any reservoir the tally actually shows, provided the explanation uses the stay and arrival rules on the cards.

- Names the station the tally shows as highest
- Explains with the stay rolls and incoming arrows for that station

4. In run 1, what fraction of the Soil and decomposers rolls send an atom to Fossil fuels, and what fraction of the Fossil fuels rolls let an atom leave? Show the two fractions and explain what they mean for how long an atom stays buried.

**Answer:** Soil and decomposers to Fossil fuels: 1 roll out of 6, so  $1/6$  of rolls (about 17 percent). Fossil fuels leaving in run 1: 0 out of 6, so 0. Meaning: an atom reaching Fossil fuels in run 1 stays for the rest of the run, which models carbon locked away for millions of years; in the real cycle the burial fraction is far smaller than  $1/6$ , but the 'never leaves' rule captures the long storage time.

**Why:** Two fractions read off the card, then interpreted as residence time. Students should see that a zero exit chance means infinite stay within the model.

*Also acceptable: Accept 'one in six' and 'none' in words with the interpretation.*

5. Compare the run 2 tally with run 1. Which station changed the most, in which direction, and which single rule caused it? Use numbers from the class tally.

**Answer:** Class-specific numbers. Expected pattern: Atmosphere rises and Fossil fuels falls, with the Atmosphere gaining roughly what Fossil fuels lost (some of those atoms then move on to Producers or Water). The single cause is the run 2 Fossil fuels rule that sends rolls of 4, 5 and 6 to the Atmosphere by combustion.

**Why:** Students should quote the change column and name the one rule changed. If chance produced no visible difference in a small class, full credit for stating the expected direction from the rule and noting the sample was too small.

- Uses numbers from the tally change column
- Names Atmosphere up and Fossil fuels down (or explains a noisy result)
- Attributes the change to the combustion rule only

6. Add the counts in each run column. What do you notice about the totals, and which law does that illustrate? Explain why the total could not have changed no matter how the dice fell.

**Answer:** The totals in both columns equal the class size. This illustrates the law of conservation of matter: atoms move between reservoirs but none are created or destroyed. The total could not change because the boundary of the model was the six stations and every student stayed inside it; dice only decide which station an atom goes to, never whether it exists.

**Why:** The key link is boundary plus conservation. A student who says 'because we counted right' has missed that the model forbids creation and loss by design.

- States totals are equal to the class size
- Names conservation of matter
- Explains that the rules only move atoms, with no entry or exit across the boundary

7. State the boundary of the system this model represents. Name one real flow of carbon that crosses the boundary of a real ecosystem but could not happen in the model.

**Answer:** The boundary is the set of six stations, that is, one ecosystem's air, water, producers, consumers, soil with decomposers, and its fossil-fuel deposits; nothing outside the room counts. Real cross-boundary flows the model cannot show include carbon dioxide blowing in from another region's air, a river carrying dissolved carbon out to the sea, animals migrating in or out, or wood being hauled away.

**Why:** MS-LS2-3's clarification asks for the boundary to be defined. Any real import or export of carbon earns credit.

- States the boundary as the six stations / one ecosystem
- Gives one real flow across an ecosystem boundary that the model excludes

8. The die gives each arrow a fixed chance. Name two ways this is different from how carbon really moves, and say whether each difference makes the model's answer to our question better, worse or unchanged.

**Answer:** Examples: (1) Real chances change with season and conditions; photosynthesis is faster in summer, so an atom in the air in July is more likely to enter a plant than in January. The model's fixed chances make the answer less accurate in detail but unchanged in direction. (2) Real reservoirs differ hugely in size; the ocean holds far more carbon than the air, and burial into fossil fuels is far rarer than one in six. This makes the model's sizes wrong but the direction of change after the combustion rule still right. (3) Atoms in reality do not move one at a time by chance; a whole leaf's carbon moves together when a deer eats it. This changes the pattern of individual passports but not the totals. (4) The model has no energy flow, so it cannot show that the cycles run on sunlight; that leaves the question of where atoms pile up unchanged.

**Why:** Full credit needs two real differences and a judgment for each about the model's answer to the lab question (where atoms pile up, and what burning changes).

- Names two concrete differences between dice rules and real carbon movement
- Judges the effect of each on the model's answer (better, worse or unchanged) with a reason

9. Propose a rule change for a run 3 that models a large reforestation project. Say which station's rule you would change, how, and what you predict would happen to the Atmosphere count after ten rounds.

**Answer:** Change the Atmosphere card so that more rolls go to Producers by photosynthesis, for example rolls 1 through 4 instead of 1 through 3, and change the Producers card so that roll 6 'stays, stored in wood' becomes rolls 5 and 6 staying, because growing trees hold carbon longer. Prediction: after ten rounds the Atmosphere count drops and the Producers count rises compared with run 2. A strong answer adds that if a later rule allowed fire or logging at Producers, the stored carbon would return to the Atmosphere.

**Why:** The student uses the model to predict the direction of a change, which is the modeling skill in the standard. Any rule change that increases flow from Atmosphere to Producers or increases storage in Producers earns credit.

*Also acceptable: Accept adding a new station such as 'Long-lived trees' with a high stay chance fed from Producers.*

- Names a specific station and the exact roll change
- Links the change to photosynthesis or storage in wood
- Predicts the direction of the Atmosphere count

## Individual evidence of learning

Each student submits their own two passports, personal summary table and written answers to q1 through q9. The passports show the student can record a model's state and the process on every move; q6 and q7 are the evidence for conservation of matter and system boundary; q9 is the evidence for using the model to predict the effect of a change.

## Assessment criteria

| Criterion                      | Proficient looks like                                                                                                                                          |
|--------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Model use and recording</b> | Both passports complete for ten rounds with the process named on every move, stays included; personal summary totals 20 rounds.                                |
| <b>Data analysis</b>           | Class tallies and bar charts correct, change column computed, and the run 1 versus run 2 comparison explained with numbers and the single rule that caused it. |

|                                        |                                                                                                                                                                                                         |
|----------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Conservation and boundary</b>       | States that totals are equal because no atoms enter or leave the defined system, names the model's boundary, and gives a real cross-boundary flow the model excludes.                                   |
| <b>Model evaluation and prediction</b> | Names at least two differences between dice rules and real rates with their effect on the model's answer, and proposes a reforestation rule change with a predicted direction for the Atmosphere count. |

## Accessibility adaptations

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- Use large foam dice and large-print station cards; a station keeper can read the rule aloud for any atom who asks.
- A student who cannot move between stations can stay seated as a station keeper and run an atom on a tabletop version with a small token, or roll for a partner who walks.
- Provide a passport with rounds 1 and 2 filled in as a worked example and a word bank of the six process names.
- Accept a spoken explanation recorded on a device for q8 and q9, and allow the bar charts to be built with stacked sticky notes on the board instead of drawn.

## Low-cost alternative

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Run it at the tables instead of around the room: each group lays out six paper station cards, uses one die and three coins as atoms, and rolls for each coin in turn. The class tally then pools the groups' coin positions. One die per group and a sheet of paper is the entire cost.

## Model limitations

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The chances on the cards are invented so that every reservoir is visited within ten rounds; real rates differ by season, by ecosystem and by orders of magnitude (burial that leads to fossil fuels is extremely rare, and the ocean holds far more carbon than the air). The model has equal-sized reservoirs, leaves out rocks such as limestone, shows no energy flow, and treats each atom as moving independently. Combustion of wood and wildfire are absent from the natural rules. The model is good for direction of change and for conservation, not for how large a real change would be. This activity has not been physically tested by the authors; the expected tallies are estimates from the rules.

## Teacher notes

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Check q4 as two fractions read from the cards, not as a probability calculation. For q3 and q5 grade against your class's actual tally; if chance produced an odd result, a correct explanation of what the rules predict and why the sample was small earns full credit. Keep both tallies on the board for the misconception slide: the unchanged total is the best answer to 'fire destroys matter.' If you run several periods, add the tallies together and show students how the pooled chart is smoother than any one class's chart.