

Strings Across the Spheres: Modeling Energy and Matter Flows

Investigation question: Where does energy enter Earth's four systems, where does it leave, and why does matter keep going around while energy passes through?

Collaborative systems modeling

Groups of 4

1 session

Setup 5 · Activity 40 · Cleanup 5 min

MS-ESS2-1 · assesses

MS-ETS1-4 · supports

MS-LS2-3 · supports

Scientific purpose

Students build a tabletop or floor model of Earth's four systems plus the Sun, Earth's interior and space, using fifteen process cards and two colors of string (yellow for energy, blue for matter). Each card becomes one or two strings between the systems it links, tagged with the transfer mechanism. Students then count inputs and outputs, test the model with three perturbations (remove the Sun, remove interior heat, seal the model to matter like Biosphere 2) and decide what the model can and cannot show. The product is a systems model that makes the chapter's central claim visible: energy comes in from two sources and leaves as radiation, while matter loops and never leaves.

Why this helps students with this chapter

Diagrams of Earth's systems are usually handed to students finished, with arrows already drawn. Laying the strings themselves forces every decision: which system a process starts in, whether it moves energy, matter or both, and how the energy gets there. Counting the strings at the end makes the asymmetry concrete: yellow strings come in from the Sun and the interior and go out to space, but no blue string ever leaves. The perturbations turn the model into a tool for prediction instead of a poster.

Standards connections

MS-ESS2-1 (assesses, the energy-flow half: a model describing how energy from the Sun and the interior drives the cycling of Earth's materials among its systems): Students develop a model of energy flow and material cycling among Earth's systems, tag every link with its energy source and mechanism, and use the model to predict what stops when a source is removed. This is direct evidence for the energy-flow part of the PE; the rock-forming processes in the clarification statement are modeled in Lesson 17.

MS-ETS1-4 (supports, using a model to test a proposed design): The sealed-dome perturbation asks students to use their systems model to predict what a Biosphere 2 style design would cut off and what would go wrong, which is the reasoning behind iterative model testing without building a testable device.

MS-LS2-3 (supports, energy flow and matter cycling through organisms): Four of the cards trace sunlight through kelp, a consumer, decomposers and heat loss, so students restate the Lesson 6 ecosystem model inside the larger Earth-systems model.

Roles (rotate each session)

- **Cartographer:** Lays out the seven signs (four systems, Sun, interior, space) and keeps the layout readable; redraws the final model on the recording sheet.
- **Card reader:** Reads each card aloud, proposes the starting and ending system, and leads the group to agreement before any string is placed.
- **String runner:** Cuts and tapes the yellow and blue strings, attaches the card number and mechanism flag to each string.
- **Auditor:** Fills in the string log for every card, counts the strings for the tally table, and runs the three perturbation tests by lifting strings.

Materials

Item	Quantity	Per	Note
Printed signs: Geosphere, Hydrosphere, Atmosphere, Biosphere, Sun, Earth's interior, Space	1 set of 7	group	Half-sheet size; Sun and Space go at the edges, the four systems in the middle, Earth's interior under the geosphere.
Process cards 1 to 15 (printed from the recording sheet, cut apart)	1 set	group	
Yellow yarn or string (energy)	about 6 m	group	
Blue yarn or string (matter)	about 6 m	group	
Masking tape	1 roll	group	
Small sticky flags or strips of paper for labeling strings with the card number and mechanism	30	group	
Scissors	1 pair	group	
Large table, or 2 m by 2 m of floor space	1	group	
Recording sheet	1	student	

Estimated cost: 5 to 8 per class (an estimate; Two skeins of yarn (about \$3 each) cover eight groups; index cards, tape, sticky flags and paper are classroom stock.)

Safety

- Scissors only; cut away from fingers and keep them closed on the table when not in use.
- Keep string off the floor walkways between groups so no one trips; tape strings down if the model is built on the floor.
- No heat, chemicals or liquids are used.

Teacher preparation and setup

1. Print and cut one set of 15 process cards and one set of 7 signs per group; laminate if you want to reuse them.
2. Cut yarn into 40 cm lengths in advance (about 15 yellow and 12 blue per group) to save class time, or let the string runner cut to fit.
3. Clear table or floor space so each group's layout can be about a meter across; the model is hard to read when strings are short and crowded.
4. Decide whether to show the chapter's concept-map slide (slide 21) before or after the lab. Showing it after keeps the decisions genuinely the students' own.

Investigation design

Independent variable	The perturbation applied to the model: Sun removed, interior heat removed, or the model sealed to matter
Dependent variable	Which process cards stop, continue or change under each perturbation
Controlled	The same 15 cards and 7 signs for every group; The same string color code: yellow for energy, blue for matter; Each card placed and logged before the next is read
Trials	Three perturbations per group; the class compares which cards each group stopped under each perturbation.
Comparison	Energy strings versus matter strings: how many enter, how many leave, how many loop.

Student procedure

1. Lay out the seven signs: the four systems in a square in the middle, the Sun on one edge, Space on the opposite edge, and Earth's interior tucked under the geosphere sign. Leave hand-widths of space between signs.
2. The card reader reads card 1 aloud. The group decides: where does this process start, where does it end, and does it move energy, matter or both? Record the decision in the string log before placing any string.
3. The string runner tapes a yellow string from the start to the end if energy moves, a blue string if matter moves, or both strings side by side if both move. Attach a flag with the card number and the mechanism (conduction, convection, radiation, or another word such as eating, eruption or gravity).
4. Repeat for cards 2 through 15. A process that stays inside one system gets a string that loops out and back to the same sign; a process with two destinations gets two strings.
5. When all cards are placed, the auditor counts: yellow strings arriving from the Sun or the interior, yellow strings leaving to Space, blue strings leaving to Space, and blue strings that cross from one system to another. Fill in the tally table.
6. Perturbation 1: lift the strings that begin at the Sun. Trace forward: which other cards could no longer happen if those strings stayed lifted? List their numbers. Put the strings back.
7. Perturbation 2: lift the string from Earth's interior. Which cards stop? Put it back.

8. Perturbation 3: imagine a glass dome sealed over the four system signs that lets light and heat through but no matter. Which strings would the dome cut? Which would keep running? Discuss what would happen to the air inside over a year if decomposers kept working.
9. The cartographer draws the finished model on the recording sheet with every string shown as a labeled arrow. Each student answers the recording-sheet questions, then the analysis questions individually.

Expected observations

- Yellow strings fan out from the Sun to the hydrosphere and geosphere (cards 1, 2) and then onward; only one yellow string runs from the interior (card 6), and only card 15 runs out to Space.
- Blue strings form loops: ocean to air to ocean (cards 4, 5), air to kelp to otter to decomposers to air and soil (cards 10 to 12), geosphere to air and surface (card 8). No blue string reaches Space.
- Groups tag cards 3, 4, 7, 9 and 14 as convection; card 6 as conduction; cards 1, 2 and 15 as radiation; cards 8, 10, 11, 12 as other (eruption, photosynthesis, eating, decomposition).

Likely difficulties

- Students try to place card 4 (evaporation) as matter only and forget that the vapor carries energy; ask where the energy that evaporated the water went.
- Groups argue over whether card 11 (otter eats urchin) stays inside the biosphere; it does, and the heat part of it points outward in card 13.
- Card 13 feels like a repeat of 11 and 12; it exists so the biosphere has a visible energy exit. Keep it.
- The model gets crowded and strings cross; let groups stack flags on the sign edges and use longer strings for the Sun and Space links.
- Some groups want a yellow string from decomposers back to producers; q7 and the debrief address it.

Structured debrief

1. Have each group report its tally. The numbers should agree: energy enters by two routes, leaves by one (card 15, plus the heat in card 13 that eventually leaves the same way), and no matter string leaves at all. Write the sentence on the board: energy flows through; matter stays and cycles.
2. Compare the convection lists. Cards 3, 4, 7, 9 and 14 should appear; some groups add 5. Ask what they share: something is warmed at the bottom, becomes less dense, and is pushed up as denser material sinks under gravity. Then ask what each needs: a temperature difference and gravity.
3. Take the perturbations one at a time. Removing the Sun stops cards 1 to 5, 9, 10 to 13 and most of 15; the mantle (6, 7, 8, 14) keeps going. Removing the interior stops 6, 7, 8 and 14 and leaves the surface running. Students should see that Earth has two separate engines.
4. Close on the dome. It cuts nothing marked energy (light still enters and infrared still leaves) and cuts no matter string either, because none leaves Earth, but it stops any exchange with the air outside. Then ask what Biosphere 2 found: oxygen fell because decomposers in the rich soil used it faster than plants made it. The model predicted the risk; the data confirmed it.

Recording sheet: what students fill in

Lab 2 recording sheet: Strings across the spheres

Color code: **yellow string = energy moves**, **blue string = matter moves**. Log every card before you place its string. A process that happens inside one system still gets a string, looping out of that sign and back in.

Process cards

1 Card 1: Sunlight on the sea

Light from the Sun crosses empty space and is absorbed by the surface of the Pacific Ocean, which warms.

2 Card 2: Sunlight on bare ground

Light from the Sun is absorbed by a dry hillside in the Mojave; the rock and soil surface warms.

3 Card 3: Warm ground, warm air

Air touching the hot hillside is warmed by it. The warmed air becomes less dense and is pushed upward by cooler air sinking around it.

4 Card 4: Evaporation

Water leaves the warm ocean surface as invisible vapor and rides upward in warm air, carrying energy with it.

5 Card 5: Clouds and rain

High up, the rising air cools; the vapor condenses into droplets and clouds, and gravity brings rain and snow back to the ocean and the land.

6 Card 6: Heat from the core

Energy from Earth's hot metal core passes into the bottom of the solid mantle, particle to particle.

7 Card 7: Mantle rock rises

Hot, less dense mantle rock creeps upward beneath an ocean ridge, a few centimeters per year, while cooler denser rock sinks elsewhere. The moving rock carries energy with it.

8 Card 8: Eruption

A volcano throws ash, gas and lava from inside Earth into the air and onto the surface.

9 Card 9: Cold salty water sinks

Near Antarctica, surface water loses energy to freezing air and becomes saltier as sea ice forms. The dense water sinks and creeps along the sea floor toward the equator.

10 Card 10: Kelp makes food

Kelp off Monterey captures sunlight and uses carbon dioxide and water from the sea to build sugar, storing energy in it.

11 Card 11: Otter eats urchin

A sea otter eats a sea urchin that ate kelp. Some of the stored energy and some of the matter pass into the otter; the rest leaves the otter as heat and waste.

12 Card 12: Decomposers at work

Bacteria and fungi break down dead kelp and leaves on the shore, releasing carbon dioxide to the air and nutrients to the sand and soil. Energy leaves them as heat.

13 Card 13: Living things give off heat

Every organism, from kelp to otter to bacteria, releases energy as heat into the water or air around it.

14 Card 14: Steam at The Geysers

In Sonoma County, groundwater seeping into hot rock is heated by it and rises as steam through cracks to the surface.

15 Card 15: Earth glows in infrared

Earth's surface and air send invisible infrared light outward into space, day and night.

String log

Card	Starts in	Ends in	Energy, matter or both?	Mechanism (conduction, convection, radiation, other)
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				

-  Draw your finished model: the seven signs and every string as an arrow, yellow (or solid) for energy and blue (or dashed) for matter, each labeled with its card number.

Answer: Seven signs with the four systems in the middle, the Sun and Space at opposite edges and the interior under the geosphere. Energy arrows (solid or yellow): Sun to hydrosphere (1), Sun to geosphere (2), geosphere to atmosphere (3), hydrosphere to atmosphere (4, paired with matter), interior to geosphere (6), a loop inside the geosphere (7, paired with matter), a loop inside the hydrosphere (9, paired with matter), Sun or hydrosphere to biosphere (10, paired with matter), a loop inside the biosphere (11, paired with matter), biosphere outward as heat (13), geosphere to hydrosphere (14, paired with matter rising), Earth to Space (15). Matter arrows (dashed or blue): 4, 5, 7, 8, 9, 10, 11, 12, 14. No matter arrow reaches Space.

Why: The drawing must match the string log; the key check is that every arrow has a card number, energy and matter are distinguishable, and nothing but energy leaves to Space.

- All 15 cards appear as labeled arrows
- Energy and matter arrows are visually distinct
- Only energy arrows reach Space

String tally

What you are counting	Number of strings	Card numbers
Energy strings arriving from outside the four systems (Sun or interior)		
Energy strings leaving to Space		
Matter strings leaving to Space		
Matter strings crossing from one system to a different system		
Strings tagged convection		

1. Which card was hardest to place, and what did your group disagree about? How did you settle it?

Answer: Group-specific. Common choices are card 4 (energy and matter together), card 11 (inside one system) and card 13 (an energy exit that does not go to a named system).

Why: The question surfaces the reasoning behind the hardest tags; any card with a real disagreement and a stated resolution earns credit.

- Names a card
- States the disagreement and how it was resolved using the card text

2. Perturbation 1: list the cards that stop when the Sun's strings are lifted. Perturbation 2: list the cards that stop when the interior's string is lifted.

Answer: Sun lifted: cards 1, 2, 3, 4, 5, 9, 10, 11, 12, 13 stop, and 15 shrinks to only the interior's share. Interior lifted: cards 6, 7, 8 and 14 stop.

Why: Every surface process traces back to the Sun's strings; the four geosphere cards trace back to card 6.

Also acceptable: Accept lists that keep card 5 running briefly (clouds already formed would still rain) or keep card 13 for a while (organisms keep breathing until stored food runs out), with that reasoning stated.

Analysis questions: answer key

3. Use your tally. How many energy strings enter the four systems, how many leave, and how many matter strings leave? Explain what this pattern says about energy and matter on Earth.

Answer: Energy enters by two routes: from the Sun (cards 1 and 2, and card 10 if the group ran the kelp's string from the Sun) and from the interior (card 6), so three or four strings. One energy string leaves, card 15, with the heat from card 13 eventually leaving the same way. Zero matter strings leave. Energy passes through Earth: it comes in from the Sun and the interior and goes out to space as infrared light. Matter stays on the planet and goes around and around, which is why we say energy flows and matter cycles.

Why: Accept 2 to 4 for the entering count depending on whether the group counts routes or strings and where it started card 10; the exit count of one and the matter exit of zero are the key results.

- Reports the tally consistently with the log
- States that energy enters and leaves while matter does not leave
- Uses the words flow (energy) and cycle (matter) or equivalent

4. List every string you tagged convection. What do all of those processes have in common, and what two things does each one need in order to keep going?

Answer: Cards 3, 4, 7, 9 and 14 (some groups add 5 for the rising air). In each one, material is warmed where it sits, becomes less dense, and is pushed upward as cooler, denser material sinks under gravity; the moving material carries energy with it. Each needs a temperature difference (warm below, cool above) and gravity.

Why: This is the chapter's central mechanism restated from the students' own model.

- Lists at least four of the convection cards
- Names density change and gravity as the common mechanism
- Names temperature difference and gravity as the two requirements

5. Perturbation 3: a sealed glass dome lets light and heat through but no matter. Which of your strings does it cut? Using cards 10, 12 and 13, explain what could go wrong with the air inside over a year, and connect it to what happened in Biosphere 2.

Answer: The dome cuts no energy strings: sunlight still enters and infrared still leaves. It cuts no string that leaves Earth, because no matter string leaves anyway, but it stops any exchange with the air and water outside the dome. Inside, card 10 (kelp and plants) makes oxygen and takes in carbon dioxide; cards 12 and 13 (decomposers and all organisms) use oxygen and give off carbon dioxide and heat. If decomposers and breathing use oxygen faster than the plants replace it, the oxygen in the sealed air falls month after month and cannot be replaced from outside. That is what Biosphere 2's data showed: oxygen fell from about 21% to about 14% in sixteen months, mainly because of microbes in the rich soil, and the team had to pump oxygen in.

Why: The model predicts the direction of the problem; the data from the real physical model confirmed it. Students should connect the sealed-to-matter, open-to-energy idea.

- States that light and heat still cross but matter cannot
- Uses cards 10, 12 and 13 to argue oxygen could fall
- Connects to the Biosphere 2 oxygen decline

6. Follow cards 10, 11, 12 and 13 with your finger. Where does the energy that started as sunlight end up? Where does the carbon end up? Explain why we say energy flows through the biosphere while matter cycles.

Answer: The energy that started as sunlight is stored in the kelp's sugar (card 10), part passes to the urchin and otter (card 11), part to the decomposers (card 12), and at every step some leaves as heat (card 13), which eventually radiates to space (card 15). The carbon goes from the air and sea into kelp, into the urchin and otter, into the decomposers, and back to the air as carbon dioxide, where kelp can take it in again. Energy ends up outside the biosphere as heat and must be replaced by new sunlight, so it flows through; the carbon atoms are never used up and return to the start, so matter cycles.

Why: Students trace both quantities along the same four cards and see that only one of them comes back.

- Traces energy to heat leaving the organisms
- Traces carbon back to the air or sea and into producers again
- Explains the flow-versus-cycle difference

7. Another group added a yellow energy string from the decomposers in card 12 back to the kelp in card 10. Is that string correct? Explain what should connect decomposers to kelp, if anything.

Answer: No. Decomposers lose energy as heat; they do not pass energy to kelp. The correct link from decomposers to kelp is a blue matter string: carbon dioxide and nutrients released by decomposers are taken up by producers. The only energy string arriving at the kelp comes from the Sun.

Why: This is the decomposer-arrow misconception from the textbook figure, repaired in the students' own model.

- Rejects the energy string
- Names matter (carbon dioxide, nutrients) as the real link
- States that the kelp's energy comes only from sunlight

8. Name two things about the real Earth that this string model cannot show, and say for each why it matters.

Answer: Any two of: the model shows no amounts, so the Sun's huge input and the interior's small one look the same; it shows no rates, so mantle convection over millions of years and air convection in minutes look the same; the signs are separate when real systems overlap (water vapor is in two at once); each card is one event when the real processes run continuously; it leaves out small sources such as tidal energy from the Moon. Each matters because a reader could wrongly conclude the sources are equal, the speeds are similar, or the systems have sharp borders.

Why: Model-limits reasoning is a systems and system models practice; any two valid limits with consequences earn credit.

- Names two real limits
- Explains why each could mislead

Individual evidence of learning

Each student submits a completed string log, the model drawing, the tally table and answers to q1 through q8. The tally plus q3 is the evidence for the energy-in, energy-out, matter-loops target; q4 for convection; q5 for using a model to predict a design problem; q6 and q7 for energy flow versus matter cycling.

Assessment criteria

Criterion	Proficient looks like
Model accuracy	All 15 cards logged with the correct starting and ending systems, the correct energy/matter tag and a sensible mechanism; the drawing matches the log.
Inputs and outputs	Correctly counts two energy inputs and one energy exit, zero matter exits, and states the energy-flows-through, matter-cycles pattern in their own words.
Using the model to predict	Lists the cards that stop under each perturbation with reasoning, and uses cards 10, 12 and 13 to predict falling oxygen under a sealed dome.
Model limits	Names two real limits of the string model (such as no amounts, no rates, no overlap of systems, every process shown as one event) and why each matters.

Accessibility adaptations

- Provide cards with the starting system already printed for students who need more support, leaving the ending system and the energy/matter tag to decide.
- Use thick cord and clothespins instead of yarn and tape for students with limited fine-motor control; the model can be built on a pegboard or a magnetic whiteboard with magnets.
- Pair multilingual learners with a card reader who paraphrases each card; supply a picture icon on each card (sun, wave, volcano, kelp) and a two-word home-language gloss for energy and matter.
- Allow the model drawing to be a photograph of the built model with labels added, and accept q3 through q6 as a recorded explanation while pointing at the model.

Low-cost alternative

Build the model on a whiteboard with dry-erase markers in two colors instead of string, with the cards taped on; or give each group a printed map of the seven signs and have them draw colored arrows with pencils.

Model limitations

The string model shows that a link exists, not how much energy or matter moves or how fast; a single string stands for the Sun's enormous input and another for the interior's much smaller one. It shows each process as one event between two signs when real processes are continuous and many systems overlap (water vapor is both hydrosphere and atmosphere). It does not show that convection moves energy and matter together inside a single loop, and it leaves out small contributions such as tidal energy from the Moon. This activity has not been physically tested by the authors; the card set and the 40-minute pacing are estimates.

Teacher notes

If a group logs card 6 as convection, ask what is moving: the energy crosses from the core into the mantle without the rock itself flowing, so it is conduction; card 7 is where convection begins. Card 13 is deliberately an energy exit with no single destination; let groups run it to the atmosphere, the hydrosphere or straight to Space and accept any as long as it is yellow. Keep one finished model on display for the concept-map slide (slide 21) and the Biosphere 2 task (slide 22).