

Design Challenge: A Hallway Model of the Atomic Scale

Learning target: I can define precise criteria and constraints for a scale-model exhibit, use calculations about the atomic scale to compare design options, and justify a design decision.

Transfer and design

About 50 min

Pairs

MS-ETS1-1 · assesses

MS-PS1-1 · supports

engineering design

data analysis

writing

Standards connections

MS-ETS1-1 (assesses): Students write criteria and constraints with numbers attached, take scientific principles (scale ratios) and impacts on people (young visitors, accessibility) into account, and show how those definitions limit the possible designs. This is the PE as written.

MS-PS1-1 (supports): Reasoning about how far atoms are from everyday sizes is background for modeling molecules and extended structures; the challenge does not produce a molecular model.

Purpose: extend · **Time:** about 50 minutes · **Format:** pairs

Answers with reasoning

The brief from the science club — 'We want visitors, including younger brothers and sisters, to walk away able to say how an atom compares in size with things they know. The exhibit must live in the main hallway, which is 40 meters long and 3 meters wide, and must be set up and taken down the same evening. The club can give you \$25 for materials and two class periods of building time. Nothing may be taped higher than 2 meters, and nothing may block the hallway for wheelchairs or strollers.'

Real sizes (rounded) of the objects to model

Object	Typical width	Width in picometers (pm)
One atom (carbon)	about 150 pm	150
One bacterium	about 1.5 micrometers	1,500,000
One human hair	about 75 micrometers	75,000,000
One grain of sand	about 0.5 millimeters	500,000,000
One basketball	about 24 centimeters	240,000,000,000

Part A: Do the math before you design

1. Complete the table. First divide each object's width by the atom's width (150 pm) to find how many atoms would fit across it. Then convert: if one atom is drawn as a 1 mm dot, the model of each object is that many millimeters wide. Write the model sizes in meters or kilometers where that is easier to read. Show one calculation below the table.

Answer: Bacterium: $1,500,000 \div 150 = 10,000$ atoms wide; model = 10,000 mm = 10 m. Human hair: $75,000,000 \div 150 = 500,000$ atoms; model = 500,000 mm = 500 m. Grain of sand: $500,000,000 \div 150 \approx 3,330,000$ atoms; model $\approx 3,330$ m ≈ 3.3 km. Basketball: $240,000,000,000 \div 150 = 1,600,000,000$ atoms; model = 1,600,000 m = 1,600 km.

Why: Each ratio is width divided by 150 pm; because one atom is drawn 1 mm wide, the model width in millimeters equals the ratio. Students should convert to meters and kilometers to see the problem: only the bacterium fits in a hallway.

Also acceptable: Accept 3,333,333 atoms or 3.3 km for the sand grain, and 1.6×10^9 atoms or 1,600 km for the basketball.

2. Using your table, which of the four objects could be shown at the 1 mm-atom scale inside a 40 m hallway? What does this tell you about using a single scale for the whole exhibit?

Answer: Only the bacterium (10 m) fits in the 40 m hallway. The hair would be 500 m, the sand grain over 3 km and the basketball 1,600 km. A single scale cannot show all four objects in one hallway; either the atom must be drawn smaller than anyone can see, or the exhibit needs more than one scale.

Why: This is the core insight: the atomic scale spans so many powers of ten that one ratio cannot cover it in a classroom-sized space.

Also acceptable: A student who proposes shrinking the atom to a smaller dot should note that a 0.01 mm dot would be invisible, which is the same problem in reverse.

- Identifies the bacterium as the only object that fits
- Concludes that one scale cannot cover the whole range

Part B: Define the problem precisely

A vague requirement cannot be tested. 'Visitors should understand scale' is vague. 'A visitor can state, within one minute, that a hair is about half a million atoms wide' can be tested. Write your criteria and constraints so that someone could check each one with a yes or no.

3. Write three **criteria** for a successful exhibit. Each must include a number or a clear test (for example, how many objects are compared, how accurately, how fast a visitor can answer a question about it).

Answer: Examples of precise criteria: (1) The exhibit compares the atom with at least three everyday objects. (2) Every size ratio shown is accurate to within 10 percent of the data table. (3) After viewing for two minutes, a visitor can answer 'about how many atoms wide is a human hair?' to within a factor of ten. (4) A six-year-old can read or be read every sign (letters at least 5 cm tall, placed below 1.5 m).

Why: Each criterion must be checkable with a number or a yes/no test. 'Visitors understand' without a test does not earn full credit.

Also acceptable: Any three testable success statements that fit the brief.

- Three criteria
- Each contains a number or a clear yes/no test
- Each describes success, not a limit

4. Write four **constraints** from the brief, each with its number or limit. Then add one constraint of your own that protects people (visitors or builders) and say why it matters.

Answer: From the brief: hallway 40 m by 3 m; budget \$25; two class periods to build and set up and take down the same evening; nothing taped above 2 m; the walkway must stay clear for wheelchairs and strollers (a clear-width constraint, for example at least 1.5 m kept open). Student-added examples: no small loose parts within reach of toddlers (choking risk); no tape on the floor that could trip visitors; no ladders used during setup; no materials that scratch the floor.

Why: Four brief constraints with numbers plus one safety constraint with a reason. Note that 'wheelchairs and strollers' is in the brief, so a student may count it as one of the four and add a different one of their own.

Also acceptable: Accept 'same evening setup and takedown' as a time constraint separate from the two periods.

- Four constraints from the brief with their numbers or limits
- One added constraint that protects people, with a reason

5. Pick one of your criteria and one of your constraints and explain how each one rules out at least one possible design.

Answer: Examples: the criterion 'compares the atom with at least three objects' rules out a design that only models the bacterium. The constraint '40 m hallway' rules out Design 1's plan to model the hair at 500 m, and the constraint 'nothing above 2 m' rules out hanging a 3 m basketball strip vertically.

Why: Students must show that a precise definition actively limits the design space, which is the point of MS-ETS1-1.

Also acceptable: Any accurate pairing earns credit.

- One criterion linked to a design it eliminates
- One constraint linked to a design it eliminates

Part C: Compare three candidate designs

Candidate designs

1 Design 1: One Ruler

A single scale for everything: one atom = a 1 mm dot on a card at the hallway entrance. Tape measures and arrows run down the hallway to the bacterium model (a 10 m chalk circle on butcher paper). Signs at the far end say how far away the hair, sand grain and basketball models would be at this scale ('the hair would be at the park, 500 m away'). Cost: about \$10. Build time: one period.

2 Design 2: Zoom Ladder

Three posters along the wall, each with its own scale. Poster A: one atom = 1 mm, bacterium = 10 m strip along the wall. Poster B: one bacterium = 1 mm, hair = 50 mm, sand grain = 33 cm circle. Poster C: one hair = 1 mm, basketball = 3.2 m strip. Each poster's legend says 'this poster is zoomed out 10,000 times from the last one' (or the true factor). Cost: about \$20. Build time: two periods.

3 Design 3: Count Jar

A jar holding about 10,000 1 mm beads sits on a table with a card: 'If each bead were an atom, this jar holds the atoms in a line across one bacterium. You would need 50 of these jars for a hair and about 330 for a sand grain.' No lengths are modeled; only numbers are shown. Cost: about \$15. Build time: half a period.

6. Score each design against each of your criteria: 2 = fully meets, 1 = partly, 0 = fails. In the constraints row, write yes or name the constraint the design breaks. Add a total.

Answer: Scores depend on the student's criteria, but with criteria like those in q3: Design 1 scores low on 'three objects compared' (only the bacterium is actually modeled; the others are described in words) and may fail a criterion about visitors stating ratios; it meets all constraints. Design 2 scores high on objects compared, accuracy and visitor understanding; it meets all constraints if the 10 m strip and 3.2 m strip run along the wall and the posters stay under 2 m, and it uses most of the budget and both periods. Design 3 scores high on cost and time but low on a criterion about seeing size ratios, since it shows only counts; a loose-bead jar may also fail the added safety constraint if small children can open it. A typical total: Design 2 highest, Designs 1 and 3 lower.

Why: Grade the consistency between the student's criteria and their scores, not the particular totals.

Also acceptable: A student whose criteria value speed and cost may rank Design 3 highest; that is acceptable if the scoring is consistent and the safety issue is addressed.

- Every cell filled
- Scores follow logically from the student's criteria
- Constraint row identifies any failure accurately

7. Check Design 2's numbers: at the Poster B scale (one bacterium = 1 mm), is a 50 mm hair and a 33 cm sand grain correct? Use the data table and show your work.

Answer: Hair ÷ bacterium = $75,000,000 \div 1,500,000 = 50$, so a hair is 50 bacteria wide; at 1 mm per bacterium the hair is 50 mm. Correct. Sand ÷ bacterium = $500,000,000 \div 1,500,000 \approx 333$, so the sand grain is about 333 mm $\approx$ 33 cm. Correct.

Why: Checking a design's numbers before building is part of engineering practice.

Also acceptable: Accept 333 mm or 33.3 cm.

Part D: Decide and justify

8. Which design do you recommend, or what change to one of them? Justify your decision using your scores, at least one calculation from Part A, and at least one impact on people. Explain the strongest argument **against** your choice and why you still chose it.

Answer: Model response: I recommend Design 2, the Zoom Ladder, with one change: add a short sentence on each poster that chains the factors together ('one hair = 50 bacteria = 500,000 atoms'). It scored highest because it is the only design that models all four objects at a size people can see; Part A showed a single scale would need 1,600 km for the basketball, so zooming is the only way to meet the hallway constraint. Impact on people: posters at 1.2 m height and a 10 m wall strip keep the 3 m hallway open for wheelchairs and strollers and let small children read along. Strongest argument against: three different scales can confuse visitors, who may think a hair is 'only' 50 mm wide. I still chose it because the legend on each poster states the zoom factor, and the chaining sentence lets a visitor multiply back to the atom, which Design 1 cannot do beyond the bacterium and Design 3 cannot do at all.

Why: Full credit requires a decision, use of the scores, a Part A calculation, an impact on people, and a fair counterargument that is answered.

Also acceptable: Design 1 with the hair model shortened to fit, or Design 3 with a sealed jar plus a wall strip, are defensible if the justification meets all five criteria.

- Clear recommendation (a design or a specified modification)
- Cites the decision matrix scores
- Uses at least one calculation from Part A
- Names at least one impact on people
- States the strongest counterargument and answers it

9. Sketch your recommended exhibit as a top view of the hallway (40 m by 3 m). Label the scale used at each place, the clear path for wheelchairs and strollers, and where a visitor would stand to read each sign.

Answer: A labeled top view: a 40 m by 3 m rectangle; for Design 2, three posters spaced along one wall with the 10 m bacterium strip beside Poster A and the 3.2 m basketball strip beside Poster C; the scale factor written at each poster; a clear path of at least 1.5 m marked down the middle or the opposite wall; standing spots in front of each poster.

Why: The sketch should match the recommended design and show the constraints being honored (height is implied by a top view, so the clear path is the key constraint to show).

Also acceptable: A sketch of Design 1 or 3 is fine if it is the student's recommendation and the labels are present.

- Top view with the hallway dimensions
- Scale labeled at each element
- Clear path for wheelchairs and strollers marked
- Visitor standing positions shown

Scoring rubric

Criterion	4 • Exemplary	3 • Proficient	2 • Developing	1 • Beginning
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Criteria defined with precision	Three criteria, each testable with a number or a yes/no check, each describing success rather than a limit.	Three criteria; one lacks a number or test.	Criteria are vague ('people learn a lot') or mixed with constraints.	Criteria missing or copied from the brief without change.
Constraints defined with precision	Four constraints from the brief with their numbers plus one added constraint that protects people, with a reason.	Four constraints with numbers; the added constraint is missing or lacks a reason.	Constraints listed without numbers, or fewer than four.	Constraints missing or confused with criteria.
Use of scientific principles	Part A calculations correct and used to explain why one scale fails; Design 2's numbers checked correctly in q7.	Calculations mostly correct with one arithmetic slip; the single-scale problem is identified.	Calculations attempted but not connected to the design decision.	Calculations missing or incorrect throughout.
Decision and justification	Decision follows from the scores, cites a calculation and an impact on people, and answers the strongest counterargument.	Decision follows from the scores with a calculation or an impact, but the counterargument is weak or missing.	Decision stated with general reasons not tied to the scores.	No decision or a decision that contradicts the student's own matrix.

Teacher notes

The size data are typical rounded values: a carbon atom is about 150 pm across (reported atomic radii of about 70 pm give a diameter near 150 pm), bacteria 1-2 micrometers, hair 50-100 micrometers, sand 0.1-1 mm, a basketball 24 cm. The key insight of Part A is that a single scale cannot span the atomic to the everyday in a hallway; the zoom-ladder idea mirrors how scientists actually present scale. The decision matrix is only as good as the student's criteria, so grade consistency. The extension's arithmetic: 5×10^{19} balls $\times 34 \text{ cm}^3 = 1.7 \times 10^{21} \text{ cm}^3 = 1.7 \times 10^{15} \text{ m}^3$; divided by $4 \times 10^{12} \text{ m}^3$ gives about 400 canyon-fulls, not hundreds of thousands, so the textbook's comparison overstates by roughly a thousandfold. This has not been built or tested physically; if students go on to build it, check that floor strips do not create a trip hazard.

Scaffold offered to students: Criteria versus constraints, one more time

A criterion answers 'What must it DO to be a success?' A constraint answers 'What limits are we stuck with?' If a sentence starts with 'must show', 'must let visitors', or 'must be accurate to', it is probably a criterion. If it starts with 'no more than', 'only', 'cannot', or 'must fit', it is probably a constraint. The brief contains at least four constraints hiding in its sentences: find the length, the money, the time and the height.

Extension: The Grand Canyon check

The textbook says that if every atom in a grain of sand were as big as a ping-pong ball, they would fill the Grand Canyon hundreds of thousands of times. Test that claim. A ping-pong ball is 40 mm across (volume about 34 cm^3); a sand grain contains roughly 5×10^{19} atoms; the Grand Canyon's volume is roughly $4 \times 10^{12} \text{ m}^3$. Compute how many times the balls would fill the canyon, state whether the textbook's claim holds, and write two sentences about why engineers and writers must check scale comparisons with arithmetic rather than instinct.