

Sheets or Networks: Build a Structure That Survives

Investigation question: Which arrangement of connections, flat stacked sheets or a three-dimensional network, best resists a load, a sideways push and a drop, and what does that tell us about graphite and diamond?

Engineering design challenge

Groups of 4

1 session

Setup 5 · Activity 45 · Cleanup 5 min

MS-PS1-1 · practice

MS-ETS1-2 · practice

MS-ETS1-3 · practice

Scientific purpose

Students first build two reference structures from gumdrops and toothpicks, a stack of flat sheets and a three-dimensional network, and test both with a push, a load and a drop. Then they take on a design brief with criteria (hold a 500 g bottle, limit top movement under a push, survive a 30 cm drop) and constraints (a toothpick and gumdrop budget, at most four connections per gumdrop, a time limit), test their design, analyze the data and build an improved version. The macroscopic tests make the lesson's claim about structure physical: atoms bonded in all directions resist forces that stacked sheets cannot.

Why this helps students with this chapter

Students accept that diamond is hard and graphite flakes, but 'because of its structure' stays a slogan until they feel a stack of sheets slide under a fingertip and a braced network refuse to. The design brief adds the engineering habit of defining success before building, and the budget rule that each gumdrop can hold at most four toothpicks mirrors the fact that a carbon atom can form only four bonds, so the strongest designs are found the same way nature finds them: by using every available connection in different directions.

Standards connections

MS-PS1-1 (practice, modeling extended structures of one element (graphite sheets, diamond network) with 3-D ball-and-stick builds): The reference builds are physical models of the two carbon structures, and the design phase keeps the 'limited connections per atom' rule, so students are modeling extended structures while they engineer. It is practice rather than assessment because the design tower is not a model of any particular substance.

MS-ETS1-2 (practice, evaluating competing designs against stated criteria and constraints): Each group tests two reference structures and two designs of its own against the same three criteria under the same constraints, records pass or fail, and ranks them. This builds the systematic-evaluation practice; a full assessment would need a more open problem with social and environmental impacts weighed.

MS-ETS1-3 (practice, analyzing test data from several designs to identify the best features and combine them): In the debrief the class pools test results, names the features shared by the structures that passed (triangles, connections in three directions, four-connection nodes) and groups use them in a second build. The textbook lesson has no engineering strand; this lab supplies the practice.

Roles (rotate each session)

- **Builder:** Assembles the reference structures and the group's designs, keeping to the four-toothpicks-per-gumdrop rule.
- **Tester:** Runs the push, load and drop tests exactly as written, in the same order for every structure, and calls out the results.
- **Recorder:** Counts materials used, measures height, writes every test result in the data table and sketches the designs.
- **Design lead:** Keeps the criteria and constraints checklist in front of the group, proposes the change between Design 1 and Design 2 based on the data, and manages the build time.

Materials

Item	Quantity	Per	Note
Round toothpicks	100	group	34 for the two reference builds (22 for the sheets, 12 for the octahedron), up to 30 per design; reuse undamaged ones.
Mini marshmallows or small gumdrops	45	group	Foam craft balls (2 cm) make a reusable, allergy-safe kit.
Full 500 mL water bottle (about 500 g) for the load test	1	group	Any object of about 500 g with a flat base works; check on a balance.
30 cm ruler	1	group	Used for the push test and to set the 30 cm drop height.
Printed criteria and constraints card	1	group	
Recording sheet	1	student	
Paper cup for broken toothpicks	1	group	
Timer or clock visible to the class	1	class	

Estimated cost: 8 to 12 per class (an estimate; Two boxes of 500 toothpicks (about \$2 each) and two bags of mini marshmallows (about \$2 each) supply eight groups; water bottles and rulers are classroom stock. A foam-ball kit costs about \$12 once and is reusable.)

Safety

- Toothpick points are an eye hazard. Build and test at desk level, keep faces back from structures being tested, and never flick or throw a structure.
- Drop tests are from 30 cm onto the desk only, measured with the ruler, with hands and faces clear of the landing zone.
- The load bottle can tip and roll off a failing structure; the tester keeps a hand ready beside the bottle (not on it) to catch it.

- No eating marshmallows or gumdrops; pierced candy is not food and allergies may be present. Wash hands afterward, as marshmallow sugar is sticky.
- Broken toothpicks go in the cup immediately; do not leave splinters on desks or floors.

Teacher preparation and setup

1. Build both reference structures yourself and run the three tests so you know what the sheet stack and the octahedron network do; the sheet stack should slide apart under the push and the network should hold. Neither reference meets the 8 cm height criterion; they are there to show the two kinds of connection, not to pass the brief.
2. Pre-count toothpicks and marshmallows into zip bags per group; a 30-toothpick, 16-marshmallow design budget is strict enough that groups must plan.
3. Weigh the load bottles; anything from 450 to 550 g is fine, but all groups should use the same load.
4. Print the criteria and constraints card: Criteria: (1) at least 8 cm tall, (2) holds the bottle for 10 s, (3) top moves no more than 1 cm under a ruler push and nothing slides off, (4) survives a 30 cm drop onto the desk losing no more than 2 connections. Constraints: at most 30 toothpicks and 16 gumdrops, at most 4 toothpicks in any gumdrop, 12 minutes per build, no tape or glue.
5. Clear a drop zone on each desk and set the rule that drops happen only from a ruler-measured 30 cm, never from standing height.

Investigation design

Independent variable	The arrangement of connections: flat stacked sheets versus a three-dimensional network, and in the design phase the pattern chosen (triangles or squares, connections between layers, connections per node)
Dependent variable	Whether the structure holds the 500 g load for 10 s, how far the top moves under the push (cm) and whether anything slides off, and how many connections come apart in the 30 cm drop
Controlled	Same toothpicks and marshmallows for every build; Same load bottle and the same 30 cm drop height for every test; Same order of tests (push, then load, then drop) and the same gentle push with the ruler; Same material budget and 12-minute build limit for Design 1 and Design 2
Trials	Each structure is tested once in each test; the class pools the results of all designs on the board so that patterns across eight or more designs can be seen.
Comparison	Sheet stack versus network reference, then Design 1 versus Design 2 against the same criteria.

Student procedure

1. Build the sheet reference: make a flat honeycomb of 10 marshmallows and 11 toothpicks (two hexagons sharing one side) so that every inner marshmallow has 3 toothpicks and the sheet lies flat. Build a second identical sheet and lay it on top of the first with no toothpicks joining the layers.

2. Build the network reference: make a square of 4 marshmallows and 4 toothpicks, add a fifth marshmallow above the middle joined to all four corners (a square pyramid), then turn it over and add a sixth marshmallow below the middle joined to the same four corners. You now have an octahedron: 6 marshmallows, 12 toothpicks, every face a triangle, and every marshmallow holding exactly 4 toothpicks that point in different directions. Stand it on any triangular face; the opposite face is a flat triangle on top, about 5 cm up, where the bottle will sit.
3. Test both references in the same order and record each result. Push test: lay the ruler flat against the top layer and push sideways gently; measure how far the top moves and note whether anything slides off. Load test: set the bottle on top and count 10 seconds. Drop test: hold the structure 30 cm above the desk (ruler held upright beside it), release, and count the connections that came apart.
4. Read the criteria and constraints card aloud. Design lead sketches a Design 1 on the sheet using what the reference tests showed; the group agrees before any building starts. Count materials as you take them: no more than 30 toothpicks and 16 marshmallows, no marshmallow with more than 4 toothpicks.
5. Build Design 1 in 12 minutes. Measure its height, count the materials actually used, and run the three tests in the same order. Record pass or fail against every criterion.
6. Look at your data and at the structures that passed on nearby desks. Name the one feature you will change (for example add a diagonal, replace a square with two triangles, add connections between layers) and write it on the sheet with a reason.
7. Build Design 2 in 12 minutes under the same constraints, reusing undamaged materials. Measure, count, test and record exactly as before.
8. Draw Design 2 in the drawing box and circle the feature you added. Answer q1 and q2 on the sheet, then the analysis questions individually.

Expected observations

- Sheet stack: the top sheet slides off under a light push (movement well over 1 cm), the flat stack holds the bottle only because it is lying flat and fails the height criterion, and the drop usually separates the layers and pops one or two connections.
- Network: the top moves little under the push (often under 1 cm), the octahedron resting on a face holds the bottle on its flat top triangle for 10 s in most builds, and the drop typically costs zero to two connections.
- Design 1 commonly fails one criterion, most often the push (towers built from squares lean) or the drop (tall, lightly braced towers). Design 2 with added diagonals or inter-layer connections typically meets three or four criteria within the budget.
- Marshmallows soften with handling; tests run late in the period show more movement than early ones.

Likely difficulties

- Groups ignore the four-toothpick limit and pack six toothpicks into a hub marshmallow. Have the recorder count every node before testing; a structure that breaks the constraint fails the brief even if it passes every test.
- The push test is done with different force by different groups. Standardize: the ruler is laid flat against the top, pushed with one finger until it just moves the structure, and movement is read against the

desk edge.

- Towers built to exactly 8 cm from two toothpick lengths are fragile at the joint; suggest a wider base rather than a taller single column.
- Groups try to glue or lick marshmallows to improve grip. Remind them the constraint stands and that real atoms cannot borrow glue either.
- Time runs away during Design 1. Call out 6-minute and 2-minute warnings; an unfinished design is still tested and recorded.

Structured debrief

1. Pool every design's results in one class table: height, toothpicks, marshmallows, criteria met. Ask the class to find what the designs that met three or four criteria have in common. Expect triangles, diagonal braces, connections between layers and nodes with four toothpicks pointing in different directions.
2. Return to the reference builds: the sheet stack slid because nothing joined the layers and all connections lay in one plane; the octahedron held because its connections pointed in three directions and every face was a triangle, so a push in any direction met a toothpick in tension or compression. Name them: graphite and diamond. (Diamond's real pattern is four bonds per atom pointing to the corners of a tetrahedron; the octahedron copies the four-connections-in-different-directions rule, not diamond's exact geometry.)
3. Make the atom connection explicit: a carbon atom can form four bonds. Graphite spends three in a sheet and none between sheets; diamond spends all four in different directions. The design that used all four connections per marshmallow in three directions was doing what diamond does.
4. Close on the engineering practice: the groups that improved most did not build bigger; they changed one feature in response to one test result. That is what MS-ETS1-3 means by using test data to combine the best characteristics into a new solution.

Recording sheet: what students fill in

Lab 3 recording sheet: Sheets or networks?

Test every structure in the same order: push, load, drop. Record what you measured, not what you expected. A structure passes a criterion only if it meets the number on the card.

- ☐ Criterion 1: at least 8 cm tall (measure from desk to top marshmallow).
- ☐ Criterion 2: holds the 500 g bottle on top for 10 seconds.
- ☐ Criterion 3: under a gentle sideways push with the ruler, the top moves no more than 1 cm and nothing slides off.
- ☐ Criterion 4: survives a 30 cm drop onto the desk losing no more than 2 connections.
- ☐ Constraint: no more than 30 toothpicks and 16 marshmallows.
- ☐ Constraint: no marshmallow holds more than 4 toothpicks (an atom has a limited number of bonds).
- ☐ Constraint: 12 minutes per build; no tape, glue or anything but toothpicks and marshmallows.

Reference builds

Structure	Toothpicks per marshmallow (most common)	Directions of connections (flat or 3-D)	Push test: top movement (cm) and anything slide off?	Load test: held 10 s?	Drop test: connections lost
Sheet stack					
Network					

Design tests

Design	Toothpicks used	Marshmallows used	Height (cm)	Push: movement (cm), slide off?	Load: held 10 s?	Drop: connections lost	Criteria met (list numbers)
Design 1							
Design 2							

-  Draw Design 2 (marshmallows as circles, toothpicks as lines). Circle the feature you added after testing Design 1 and label it with the criterion it was meant to fix.

Answer: Group-specific. A clear line drawing of Design 2 with marshmallows as circles and toothpicks as lines, no circle showing more than 4 lines, one feature circled (for example a diagonal brace, a toothpick joining two layers, a wider triangular base) and labeled with the criterion it targets (for example 'criterion 3, push' or 'criterion 4, drop').

Why: The drawing documents the design and the data-driven change; it should agree with the materials counts in the design table.

- Drawing matches the materials counts recorded for Design 2 within a few toothpicks
- No node shows more than 4 connections
- One added feature is circled and labeled with the criterion it was meant to fix

1. What one feature did you change between Design 1 and Design 2, and which test result made you change it?

Answer: Group-specific. Typical: 'We added diagonal toothpicks to turn each square face into two triangles because the top moved 3 cm in the push test,' or 'We joined the two layers with toothpicks because the drop pulled the layers apart.'

Why: Full credit requires one feature and the specific test result that prompted it; a vague 'we made it stronger' is partial credit.

- Names one specific structural feature
- Names the test result (with a number or pass/fail) that motivated the change

2. Which criterion was hardest to meet within the constraints, and what did the constraints force you to give up?

Answer: Group-specific. Common: the push test (criterion 3) was hardest, and the budget forced the group to give up height or to use fewer braces; or the drop test was hardest and the group gave up a wide base to save toothpicks for connections between layers.

Why: Checks that students experienced the criteria/constraints tension, which is the heart of the design brief.

- Names a criterion
- Names something the constraints forced them to give up

Analysis questions: answer key

3. Compare the two reference builds in the push test. Which one slid, and what about its connections allowed that? Name the real carbon structure each reference stands for.

Answer: The sheet stack slid: its connections all lay flat within each sheet and nothing joined one sheet to the next, so a sideways push met no toothpick that could resist it. The network barely moved because its connections pointed in three directions, so any push was resisted by toothpicks in line with it. The sheet stack stands for graphite; the network stands for diamond.

Why: The core structure-explains-behavior idea at the macroscopic scale, with the names attached.

- Identifies the sheet stack as the one that slid
- Explains it by connections in one plane and nothing between layers
- Names graphite and diamond correctly

4. Use the sheet-stack model to explain what happens when a pencil is dragged across paper. Then explain why the same thing cannot happen with the network model, and what that means for diamond.

Answer: In graphite each carbon atom is bonded to three neighbors in a flat sheet, and the sheets are stacked with only weak attraction between them, like our two honeycombs lying on each other. Dragging a pencil across paper is a sideways push: sheets shear off the stack and stick to the paper, leaving a gray mark. In diamond each carbon is bonded to four neighbors in different directions, like our network, so there are no separate sheets and nothing can slide off; a sideways push is resisted by bonds in every direction. To leave a mark, bonds would have to break, which friction with paper cannot do, so diamond leaves no mark and is instead hard enough to scratch almost anything.

Why: Students must transfer the push-test result to the pencil and then negate it for diamond, using bonds per atom and directions.

- Explains the pencil mark as sheets sliding off because of weak attraction between layers
- Explains that the network has no layers and resists pushes in all directions
- Concludes diamond leaves no mark and is hard

5. With 16 marshmallows and at most 4 toothpicks each, what is the largest number of toothpicks a design can contain? If a design used all 30 toothpicks, what was the average number of toothpicks per marshmallow? Show the arithmetic.

Answer: Maximum 32 toothpicks: 16 marshmallows $\times$ 4 toothpicks each = 64 toothpick ends, and each toothpick has 2 ends, so $64 \div 2 = 32$. A design using 30 toothpicks has 60 ends shared among 16 marshmallows, an average of $60 \div 16 = 3.75$ toothpicks per marshmallow.

Why: Students often forget that each toothpick uses two ends; 64 is the common wrong answer for the first part.

Also acceptable: Accept 3.8 for the average; accept 32 with the two-ends reasoning in words.

6. Structures made only of triangles usually passed the push test, but they use more toothpicks for the same height. Describe this trade-off and explain how the material budget shaped your Design 2.

Answer: Triangles cannot change shape without a toothpick changing length, so triangle-braced structures resist the push, but turning each square into two triangles costs an extra toothpick per face and a tall triangle tower uses more toothpicks than a tall square tower of the same height. With only 30 toothpicks, we had to choose where triangles mattered most (for example, bracing the faces that faced the push and the joint between layers) and accept squares or fewer marshmallows elsewhere, or build a shorter, wider structure that still met 8 cm.

Why: The trade-off between rigidity and material budget is the engineering content; specific choices will vary.

- States that triangles resist deformation but use more material
- Describes a specific choice the budget forced in Design 2

7. Look at the class results on the board. Name two features shared by the designs that met the most criteria, and describe a Design 3 that combines the best feature of your design with the best feature of another group's.

Answer: Class-specific. Typical shared features: diagonal braces or all-triangle faces; toothpicks joining layers; nodes with four toothpicks pointing in different directions; a base wider than the top. A Design 3 might combine one group's wide triangular base (passed load and push) with another group's braced upper pyramid (passed the drop), within the 30-toothpick budget.

Why: This is the MS-ETS1-3 move: identify best characteristics across several solutions and combine them.

- Names two features supported by the pooled class data
- Proposes a Design 3 that combines a feature from the student's own design with one from another group's
- Stays within the constraints

8. In graphite, nothing joins the sheets except weak attraction, and in diamond every atom has exactly four bonds. Name two ways the marshmallow model matches these facts and two ways it does not.

Answer: Matches: in graphite three connections per atom lie in one flat sheet and nothing bonds the sheets, which our stacked honeycombs copy; in diamond every atom has four connections in different directions, which our four-toothpick limit and the octahedron (four toothpicks in every marshmallow) copy; both are repeating patterns with no fixed size. Does not match: real bonds are not rigid sticks and do not pop out; real graphite sheets are held by a weak attraction, not by nothing at all; diamond's hardness comes from strong bonds in every direction, not from triangle shapes; the sizes and the forces (a bottle, a drop) are nothing like atomic scales; marshmallows soften and real atoms do not.

Why: Model evaluation; any two accurate matches and two accurate mismatches earn full credit.

- Two accurate ways the model matches (connections per atom, directions, repeating pattern, nothing between sheets)
- Two accurate ways it does not (rigid sticks, weak attraction not nothing, hardness from bonds not triangles, scale)

Individual evidence of learning

Each student submits their own completed reference table, design table, Design 2 drawing with the changed feature circled, and written answers to q1 through q8. The design table with q1 is the evidence for using test data to improve a design; q3 and q4 are the evidence for connecting structure to the behavior of graphite and diamond.

Assessment criteria

Criterion	Proficient looks like
Testing against criteria	All tests run in the stated order for both references and both designs; every result recorded with a number or a clear pass/fail; constraints checked and recorded for both designs.
Data-driven revision	q1 names one specific feature changed and the specific test result that motivated it; the drawing shows the feature and labels the criterion it targets.
Structure explains behavior	q3 and q4 correctly explain sliding from connections in one plane with nothing joining layers, and rigidity from connections in three directions, and name graphite and diamond.
Combining best features	q7 identifies two features shared by the most successful class designs from the pooled table and proposes a Design 3 that combines features from two groups.

Accessibility adaptations

- Provide a printed template of a triangle and a pyramid at actual toothpick size so students with limited fine-motor control can lay toothpicks on the template before adding marshmallows; allow foam balls, which hold toothpicks more firmly.
- Let a partner run the drop test for a student who cannot hold the structure steady at 30 cm, while that student measures and records.
- Offer the criteria and constraints card in large print with icons (ruler, bottle, hand, arrow down), and with home-language translations of criterion, constraint, load and connection.

- Accept a photographed Design 2 with a voice recording explaining the changed feature instead of the drawing, and a spoken answer for q7.

Low-cost alternative

Use pipe-cleaner pieces and clay balls, or straws and paper clips, with the same four-connections rule; replace the bottle with a textbook of known mass and the drop with a 20 cm tilt-and-release onto the desk. The reference builds alone, with the push test, carry the graphite-versus-diamond idea if time is short.

Model limitations

Marshmallows and toothpicks model the geometry of connections, not chemical bonds: real bonds are not rigid rods, they do not pop out, and diamond's hardness comes from strong bonds in all directions rather than from triangles. The sheet stack models graphite's weak attraction between layers as nothing at all, which overstates how easily sheets slide; real graphite sheets are held together weakly, not loosely stacked. The design towers are not models of any real substance, and the load, push and drop tests are stand-ins for forces at the atomic scale that act very differently. This activity has not been physically tested by the authors; the expected results are based on the standard behavior of toothpick-and-marshmallow structures and should be confirmed with the reference builds before class.

Teacher notes

Check q5 first; the two-ends error (64 instead of 32) is the most common mistake and is quick to fix at the board. When grading q1, require the test number: 'the top moved 3 cm' earns full credit where 'it was wobbly' does not. Photograph the pooled class table for the next class period; the features list is reused in W9's transfer task. If a group's Design 2 did worse than Design 1, that is still full credit if the change was motivated by data and the result is recorded honestly.