

Design a Touch Microscope: Map a Surface You Cannot See

Investigation question: What criteria and constraints must a probe-based mapping method meet to produce a trustworthy map of a hidden surface, and how does your method compare with a scanning tunneling microscope?

Engineering design challenge

Groups of 4

2 sessions

Setup 10 · Activity 80 · Cleanup 10 min

MS-ETS1-1 · assesses

MS-PS1-1 · supports

Scientific purpose

Groups face the same kind of problem Rohrer and Binnig faced: produce a map of a surface that cannot be seen, using only a probe. Before building anything, each group must define measurable criteria for a successful map and list the constraints they work within. They then design a probing method (grid spacing, probe technique, how readings become a picture), map a hidden landscape another group built inside a shoebox, test the map against the real surface, and revise. The design is judged by the group's own criteria, which makes the precision of those criteria the heart of the lab.

Why this helps students with this chapter

Students tend to think of microscope images as photographs and of engineering as building first and thinking later. Mapping blind with a skewer shows that an image can be built from numbers, that a sparse grid misses features while a fine grid costs time, and that a design is only successful relative to criteria someone wrote down. Writing those criteria precisely, and discovering that vague ones cannot be tested, is the lesson.

Standards connections

MS-ETS1-1 (assesses, defining criteria and constraints with enough precision to judge success): Students write their own criteria (with numbers) and constraints before designing, then use them to evaluate their map; the written definitions and the evaluation against them are direct evidence for this performance expectation.

MS-PS1-1 (supports, background on how surfaces are mapped at the atomic scale): The shoebox probe is an analogy for the STM, which maps the atoms on a surface; the lab supports the idea that atoms are real, countable objects on a surface without assessing molecule models.

Roles (rotate each session)

- **Design lead:** Runs the criteria and constraints discussion, makes sure every criterion has a number or a clear test, and keeps the group to the agreed probing plan.
- **Prober:** Lowers the probe straight down through each grid point, reads the depth mark at the lid, and calls the value out. Never angles or sweeps the probe.

- **Recorder:** Writes each depth reading in the correct grid cell, converts depths to heights, and keeps the map sheet clean.
- **Mapper and checker:** Shades the height map from the recorded numbers, then at the reveal compares the map with the real surface and scores it against the group's criteria.

Materials

Item	Quantity	Per	Note
Shoebox with lid	1	group	Any box about 30 by 18 by 10 cm. Groups build a landscape for another group, not for themselves.
Landscape pieces: modeling clay, bottle caps, blocks, folded card, a small cup	a handful	group	Three to five objects of different heights, from about 1 cm to 6 cm.
White glue or double-sided tape to fix pieces to the box floor	1	group	
Printed grid sheet matching the lid size, 2 cm squares, labeled A to O across and 1 to 9 down	2	group	One is taped over the open top of the box as the probing surface; one is the map.
Bamboo skewer or thin wooden dowel marked every 0.5 cm from the tip, point blunted	2	group	Blunt the point with sandpaper or cap it with a bead of hot glue before class.
Pushpin or sharp pencil for making probe holes in the grid sheet	1	group	
Masking tape	1 roll	class	
Colored pencils (three shades) for the height map	1 set	group	
Recording sheet	1	student	
Timer	1	group	

Estimated cost: 12 to 20 per class (an estimate; Estimate. Shoeboxes donated; one pack of skewers about \$3; modeling clay about \$8; grid sheets printed; glue, tape and pencils from stock.)

Safety

- Skewers are pointed sticks: use only blunted or glue-capped tips, probe straight down into the box, and never hold a skewer above desk height or point it toward anyone's face. Eye injury is the real risk here.
- Only the teacher uses a hot glue gun, if one is used to cap tips or fix landscape pieces; white glue or tape is the student option.
- Pushpins stay in the lid of their container when not making holes; count them out and back in.
- Keep boxes on the desk, not on laps, while probing.

Teacher preparation and setup

1. Collect one shoebox per group a week ahead. Cut a sheet of 2 cm grid paper to the size of each box opening and label columns A to O and rows 1 to 9 (adjust to your box).
2. Blunt every skewer tip and mark depth lines every 0.5 cm from the tip with a fine marker; a sharp tip is the main hazard in this lab.
3. Do one test box yourself: build a landscape, tape the grid on, probe at 4 cm spacing and then at 2 cm, and see how long each takes. Typical: a 4 cm grid is about 35 points and 8 minutes; a 2 cm grid is about 135 points and 25 minutes.
4. Prepare the two-session plan: session 1 is criteria, constraints, landscape building and design; session 2 is probing, mapping, reveal and revision.
5. Post the compare diagram of the STM team's criteria and constraints from the presentation so groups have a model of the format, not the content.

Investigation design

Independent variable	Grid spacing of the probe points (for example every 2 cm versus every 4 cm) and the probing technique chosen by the group
Dependent variable	Map quality measured against the group's criteria: number of hidden objects correctly located, height error in cm, and time to complete
Controlled	Same box and landscape for both probing passes; Same probe and depth marks; Probe always vertical; Lid grid never lifted before the reveal
Trials	One full map at the planned spacing, then one revised pass on a 6 by 6 region after the reveal; groups compare the two against their criteria.
Comparison	Map versus the builder's hidden sketch, and coarse-grid versus fine-grid results across the class.

Student procedure

1. Session 1, define first. Before touching any material, write the problem in your own words: produce a map of a surface you cannot see, using a probe through a grid. Then write at least three criteria, each with a number or a clear test (for example: 'the map shows the location of every object taller than 1 cm to within one grid square'; 'the map's height values are within 1 cm of the real heights'; 'the map is finished in 20 minutes or less').
2. List at least three constraints you must work within: materials you have, time, the rule that the lid grid may not be lifted until the reveal, the probe may only go straight down, and anything about the box itself. Record both lists in the criteria and constraints table.
3. Build a landscape for another group: fix three to five objects of different heights to the floor of your box with glue or tape. Sketch it on a hidden sheet, measure each object's height, and give the sheet to your teacher in a sealed envelope. Tape the grid sheet over the open top of the box and swap boxes with another group.
4. Design your probing method. Decide the grid spacing (every square, every other square, or coarser), how you will read depth (which mark on the skewer lines up with the grid sheet), how you will turn depth into

height (height = box depth minus probe depth), and how you will shade the map. Write the plan and predict how many probe points you will take and how long it will take.

5. Session 2, map. Set the timer. The prober pushes the skewer straight down through the grid at each planned point until it stops, reads the depth mark at the grid sheet, and calls it out. The recorder writes the number in the matching cell of the map grid.
6. When the planned points are done, stop the timer and record the time. Convert each depth to a height and shade the map: one color for floor level, a second for 1 to 3 cm, a third for above 3 cm (or your own scheme). Mark where you think each object is and how tall it is.
7. Reveal. Open the envelope from the group that built your box and compare your map with their sketch and heights. Score your map against each of your own criteria: met or not met, with the evidence.
8. Revise. Choose one change to your method that would improve the result on the criterion you missed most (for example, probing every square in one region, or reading the skewer at eye level), and if time allows, re-probe one 6 by 6 region with the revised method.
9. Compare your method with the scanning tunneling microscope: list two ways they are alike and two ways they differ. Complete the analysis questions individually.

Expected observations

- Groups probing every 4 cm take about 8 to 10 minutes and usually locate tall objects but miss or missshape objects narrower than 4 cm; groups probing every 2 cm take 20 to 25 minutes and catch nearly everything but often run out of time.
- Height errors of about 0.5 cm are common from reading the skewer at an angle or from a probe that lands on a sloped clay edge.
- First-draft criteria are usually vague ('accurate', 'detailed'); after session 1 discussion most groups produce criteria with numbers such as 'every object taller than 1 cm located within one square'.
- At the reveal, students are often surprised that a correctly recorded grid can still produce a misleading picture when the spacing is too coarse.

Likely difficulties

- Groups want to build before defining. Hold the materials until the criteria and constraints table is checked.
- The prober angles the skewer to 'feel around', which breaks the grid logic; the design lead should call it out and the controlled-variable rule is the reason.
- Students confuse depth and height; the conversion line (height = box depth minus probe depth) should be written at the top of the map.
- Landscape builders make objects too small or too crowded, so nothing can be resolved; the prep note of three to five objects from 1 to 6 cm tall prevents this.
- Groups who finish fast with a coarse grid may feel they 'won'; the scoring table against their own criteria is the corrective.

Structured debrief

1. Post each group's criteria. Sort them as a class into testable and not-yet-testable. Rewrite two of the vague ones together. The point to land: a criterion you cannot test cannot tell you whether you succeeded, which is why the STM team wrote '100 picometers' instead of 'see atoms'.
2. Compare maps from coarse and fine grids. Fine grids found small objects; coarse grids finished fast. Ask which is better, and insist on 'better for which criterion?' as the only acceptable answer.
3. Go back to the STM flow diagram: the shoebox probe touches and measures depth; the STM probe never touches and measures a current that depends on distance. Both sweep in a pattern, both build an image from numbers. Name this as an analogy with a known breakdown.
4. Ask what a constraint from the natural world looks like at the atomic scale: footsteps shaking the building, air molecules bumping the probe, heat making atoms jiggle. The STM team worked at night and, later, in vacuum and cold for exactly these reasons.

Recording sheet: what students fill in

Lab 3 recording sheet: Design a touch microscope

Session 1: fill in the problem statement, the criteria and constraints table and the design plan before you probe anything. Session 2: fill in the map grid, the scoring table and the questions.

Criteria and constraints (write at least three of each; every criterion needs a number or a clear test)

Criteria: what a successful map must do	How we will test it	Constraints: limits we must work within	Why it limits us

Design plan

Grid spacing (cm)	Predicted number of probe points	Predicted time (min)	How we read depth	How we turn depth into height	Shading scheme

Map grid: write the probe depth (cm) in each cell you probe; leave skipped cells blank

Row	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1															
2															
3															
4															
5															
6															
7															
8															
9															

-  Shade your height map here (or shade the grid above). Mark each object you think is present, label its estimated height, and add a key for your colors.

Answer: A shaded height map with a color key, objects outlined where the readings cluster above floor level, and an estimated height written beside each. The map should match the recorded grid cell for cell.

Why: The drawing is the reconstructed image; grade it for consistency with the numbers in the grid, not for matching the real box, which is what the scoring table is for.

- Color key present and used consistently
- Each shaded region corresponds to recorded readings
- Objects labeled with an estimated height in cm

Scoring against our own criteria (after the reveal)

Criterion	Met? (yes/no)	Evidence from the comparison	What change would help

1. Time taken for the first full map: ___ minutes. Number of probe points: ___. Number of objects in the box: ___. Number your map found: ___.

Answer: Group-specific. Typical: 4 cm grid, about 35 points, 8 to 10 minutes, finds 3 of 4 objects; 2 cm grid, about 135 points, 20 to 25 minutes, finds 4 of 4.

Why: The numbers feed q3; check that points and time are consistent with the chosen spacing.

Also acceptable: Any internally consistent set of values.

2. Which of your criteria was hardest to write with a number? Rewrite it here in its final, testable form.

Answer: Group-specific. A good final form includes a number and a test, for example 'the map locates every object taller than 1 cm to within one grid square, checked against the builder's sketch.'

Why: Students usually struggle most with 'accuracy'; the rewrite should name what is compared and the allowed error.

- Final criterion contains a number or a clearly testable condition
- Names how it will be checked

Analysis questions: answer key

3. Explain the trade-off between grid spacing and time using your own numbers. If you doubled the number of probe points, what would improve and what would get worse?

Answer: Doubling the probe points roughly doubles the time but halves the spacing in one direction, so smaller objects are caught and edges are placed more precisely. What improves: fewer missed objects, better shape, smaller position error. What worsens: time, fatigue, more reading errors, and a greater chance of missing the time criterion. The right spacing depends on which criterion matters most.

Why: Full credit requires the group's own numbers (points and minutes) and both sides of the trade-off.

- Uses the group's actual point count and time
- Names at least one gain in map quality
- Names time or error as the cost
- Connects the choice to the criteria

4. Your map was built from a table of numbers, not from a picture. Describe how the numbers became an image, and name one way the image could be wrong even if every reading was correct.

Answer: Each cell's depth was subtracted from the box depth to get a height, and heights were sorted into bands and shaded, so the shading pattern is the image. Even with perfect readings the image can be wrong because the grid only samples the surface: an object narrower than the spacing can be missed, an object's edge can appear a full square off, and a sloped edge can read as a step. The image is a reconstruction, not a photograph.

Why: Mirrors the STM: the picture is built from numbers and inherits the sampling limits of the scan.

- Describes the depth-to-height-to-shade chain
- Names a sampling error (missed object, shifted edge, false step) despite correct readings

5. A classmate writes the criterion 'the map should be good.' Explain why that criterion cannot be used to judge a design, and rewrite it so it can.

Answer: 'Good' cannot be tested: two people could look at the same map and disagree. A usable criterion says what to measure and how close is close enough, for example 'every object taller than 1 cm appears on the map within one grid square of its true position, and estimated heights are within 1 cm of the real ones.'

Why: This is the core of MS-ETS1-1: precision in criteria makes success judgeable.

- Explains that the vague criterion cannot be tested
- Rewrites it with a measurable quantity and a comparison

6. Which of your constraints came from the physical world (the box, the probe, the objects) and which came from people (time, rules, materials budget)? Give one of each and explain how it limited your design.

Answer: Physical constraint example: the probe can only go straight down, so overhangs or the sides of objects cannot be mapped; or the 2 cm grid holes fix the smallest spacing. Human constraint example: the 20 minute limit forced a coarser grid than we wanted; or the rule against lifting the lid meant we could not check partway. Each limited the design by ruling out some methods.

Why: Students should see that constraints come from both nature and people, as they did for the STM team (available technology versus the need to show progress).

- One physical constraint with its effect
- One human constraint with its effect

7. The scanning tunneling microscope sweeps a probe over a surface and records a current that grows when the probe is closer to the surface. List two ways your method is like the STM and two ways it is different, including what the STM probe never does.

Answer: Alike: both sweep a probe across a surface in an ordered pattern; both build an image from a table of readings rather than from light; both have a resolution set by how closely the probe samples. Different: the STM probe never touches the surface and reads a current that grows as the gap shrinks, while ours touches and reads depth; the STM works at a scale about a hundred million times smaller; real STMs usually move the probe to keep the current constant and record the height, and they must deal with vibration and jiggling atoms.

Why: Two likenesses and two differences are required; the non-touching probe must appear.

- Two likenesses (scan pattern, image from numbers, resolution)
- Two differences including that the STM probe does not touch
- Mentions current depending on distance

8. An object in the box was 2 cm wide and your grid spacing was 4 cm. Could your map have missed it entirely? Explain, and connect this to why the STM inventors set a criterion of about 100 picometers of resolution.

Answer: Yes. With probe points every 4 cm, a 2 cm object can sit entirely between two points and never be touched, so the map shows floor where the object is. The resolution of a scan is set by its spacing: you cannot see features smaller than the gap between samples. Atoms are about 100 to 300 pm apart, so the STM team required the ability to tell apart features about 100 pm apart; a coarser instrument would blur neighboring atoms into one bump, just as our coarse grid blurred or missed small objects.

Why: Links the sampling idea to the criterion in the textbook's engineering spread.

- Says the object could be missed and why
- Defines resolution in terms of spacing
- Connects to the 100 pm criterion for atoms

Individual evidence of learning

Each student submits their own criteria and constraints table, the scoring table against those criteria, and individual answers to q1 through q8. The criteria table with the 'how we will test it' column completed and q5 are the primary evidence for MS-ETS1-1; q7 and q8 show the link to the STM and to resolution.

Assessment criteria

Criterion	Proficient looks like
Criteria defined with precision	At least three criteria, each with a number or a clear test, written before building, and used to score the map afterward.
Constraints identified and explained	At least three constraints, including one from the physical setup and one from time, rules or materials, each with a sentence on how it limited the design.
Design, test and revise	A written probing plan with predicted points and time, a completed map, an honest score against the criteria and one specific revision tied to a missed criterion.
Connecting to the STM	Names two likenesses and two differences, including that the STM probe does not touch and that the image is reconstructed from readings, and explains why resolution (grid spacing) was a criterion.

Accessibility adaptations

- Let a partner operate the probe while a student with limited fine-motor control calls grid positions and interprets the map; the design and scoring roles carry the learning.
- Provide a criteria sentence frame ('The map must ___ within ___') and a word bank for constraints (time, materials, rules, box size, probe).
- Use a raised-line grid or tactile markers on the grid sheet for students with low vision, and allow the height map to be built with stacked blocks instead of shading.
- Allow q3 and q7 to be answered orally or as a labeled sketch, and provide a multilingual glossary card for criterion, constraint, probe, grid and resolution.

Low-cost alternative

Use cereal boxes laid flat with the top cut off, pencils as probes with marks every 1 cm, and a grid drawn by hand on scrap paper with 3 cm squares. Landscape pieces can be erasers, bottle caps and folded card.

Model limitations

The shoebox probe touches the surface and measures depth directly; the STM never touches and measures a current that depends on the gap. Our objects are centimeters wide while the STM resolves features a hundred picometers apart, a difference of a hundred million times. A clay landscape does not jiggle, but atoms do, which is one reason real STMs are often run cold. The activity has not been physically tested by the authors; probing times and error sizes are estimates from the geometry of a typical box and should be checked in the teacher's trial run.

Teacher notes

Grade the criteria table before session 2 and send back any criterion without a number or test; the lab's evidence for MS-ETS1-1 lives there. During probing, the most common error is angling the skewer; a quick demonstration of vertical probing at the start of session 2 prevents most of it. If a landscape has an object narrower than the group's grid spacing, do not fix it; the missed object is the best possible lead-in to q8.