

The Salt That Had No Molecules: How X-rays Revealed Extended Structures

Learning target: I can use evidence from a passage to explain how scientists learned that diamond, graphite and table salt are extended structures, and to describe what each structure looks like at the atomic scale.

Reading with evidence

About 40 min

Individual

MS-PS1-1 · practice

reading

writing

Standards connections

MS-PS1-1 (practice, the extended-structure half): Students read how the models of sodium chloride, diamond and graphite were established and describe each arrangement in their own words. Describing these arrangements accurately is the thinking they will need when they draw the models themselves in Worksheets 4 and 9.

Purpose: build · **Time:** about 40 minutes · **Format:** individual

Answers with reasoning

The Salt That Had No Molecules

[1] In 1772 the French chemist Antoine Lavoisier focused sunlight through a large lens onto a diamond sealed inside a glass jar. The diamond heated, glowed and slowly disappeared, leaving behind a gas that turned limewater cloudy, the same test that carbon dioxide passes. Twenty-five years later, in 1797, the English chemist Smithson Tennant burned a weighed amount of diamond and a weighed amount of charcoal and collected the gas from each. Equal masses gave equal amounts of carbon dioxide. The conclusion was hard to accept: diamond, the hardest material anyone knew, was made of the same thing as charcoal, which is nothing but carbon. One gram of carbon from either source produces about 3.7 grams of carbon dioxide.

[2] That left a puzzle that lasted more than a century. Chemists could measure what a substance was made of, its composition, by burning it or breaking it apart. They could not see how its atoms were arranged. If diamond and graphite, the soft gray form of carbon in a pencil core, had the same composition, then the difference between them had to lie in the arrangement, the structure. But no instrument of the 1800s could show an arrangement of atoms.

[3] The instrument arrived in 1912, when the German physicist Max von Laue showed that a beam of X-rays passing through a crystal comes out as a pattern of sharp spots. The spots meant that the atoms inside a crystal are lined up in neat, repeating rows that scatter the X-rays in an orderly way. In 1913 William Henry Bragg and his son William Lawrence Bragg worked out how to read a spot pattern backward to find where the atoms sit. Among the first structures they solved were table salt and diamond.

[4] The salt result surprised many chemists. The Braggs found that sodium and chlorine alternate in every direction, like the dark and light squares of a three-dimensional checkerboard. Each sodium has

six chlorine neighbors, and each chlorine has six sodium neighbors, all at the same distance. No sodium belongs to any particular chlorine. There is no small, separate particle of salt, no 'molecule' of NaCl, only a pattern that continues to the edge of the grain. The formula NaCl describes a ratio of one to one, not the contents of a particle. Some chemists objected for years; as late as 1927 the English chemist Henry Armstrong complained in the journal *Nature* that a salt with no molecules went against common sense. But the checkerboard model predicted the X-ray spots exactly, and it explained why salt grains tend to grow as tiny cubes. The model won.

[5] Diamond's structure explained its hardness. Every carbon atom is bonded to four neighbors spread evenly around it, and each of those neighbors is bonded to four more. The result is a single rigid network that continues in every direction. To scratch a diamond you must break strong bonds, and there is no direction in which the bonds are weak or missing.

[6] Graphite's structure was solved in 1924 by the British scientist John Desmond Bernal. Each carbon atom is bonded to only three neighbors, and together they form flat sheets of six-sided rings, like chicken wire. The sheets stack one on top of another, but no bonds join one sheet to the next, only weak attractions. The distance between sheets is about 335 picometers, while the distance between bonded atoms inside a sheet is about 142 picometers. The sheets slide apart with a gentle push, which is why a pencil leaves a mark: the paper peels off thin stacks of carbon sheets.

[7] These discoveries settled the puzzle and gave scientists a new way of thinking. The kind of atom is only the beginning. How many atoms join, and how they are connected, decides whether a substance is a tiny separate molecule, a rigid network, a stack of sliding sheets or a long chain. And the arrangement at the atomic scale leaves fingerprints at the human scale: the cube shape of a salt grain, the hardness of a diamond, the gray streak of a pencil. When you build a model with plastic balls, you are doing what the Braggs did with X-rays: showing an arrangement nobody can see.

Questions: cite the passage

1. Paragraph 1 describes two experiments, 25 years apart. What did each one show, and what conclusion did the two together force?

Answer: Lavoisier (1772) burned a diamond with focused sunlight and showed that the gas produced was carbon dioxide (it turned limewater cloudy). Tennant (1797) burned equal masses of diamond and charcoal and got equal amounts of carbon dioxide. Together they forced the conclusion that diamond is made of carbon, the same substance as charcoal.

Why: Both experiments appear in paragraph 1; the conclusion sentence is 'diamond ... was made of the same thing as charcoal, which is nothing but carbon.'

Also acceptable: Accept 'diamond and charcoal are the same element' for the conclusion.

- Describes the burning diamond and the carbon dioxide test
- Describes the equal-masses comparison
- States that diamond is carbon

2. Paragraph 1 says one gram of carbon produces about 3.7 grams of carbon dioxide. How much carbon dioxide should 2.5 grams of diamond produce? How much should 2.5 grams of charcoal produce? Show your work, then say in one sentence why getting the same two answers mattered to Tennant.

Answer: Diamond: $2.5 \text{ g} \times 3.7 \text{ g per gram} = 9.25 \text{ g}$ of carbon dioxide (about 9.3 g). Charcoal: $2.5 \text{ g} \times 3.7 = 9.25 \text{ g}$, the same. The equal results mattered because if diamond contained anything other than carbon, it would have produced a different amount of carbon dioxide from the same mass; the match showed that all of the diamond's mass was carbon.

Why: The multiplication is the same for both because the passage says the 3.7 figure holds for carbon from either source. The reasoning sentence should connect equal results to identical composition.

Also acceptable: Accept 9.25 g or 9.3 g. Accept 'it proved diamond is pure carbon' for the final sentence.

3. According to paragraph 2, what could chemists of the 1800s measure, and what could they not see? Write the two words the passage uses for these two things.

Answer: They could measure what a substance was made of (its composition) by burning or breaking it apart. They could not see how its atoms were arranged (its structure). The two words are composition and structure.

Why: Paragraph 2 defines both words in context.

Also acceptable: None; both words are required.

- Names composition as what could be measured
- Names structure as what could not be seen

4. What evidence convinced scientists that the atoms inside a crystal are arranged in repeating rows? Quote or closely paraphrase paragraph 3.

Answer: In 1912 von Laue showed that X-rays passing through a crystal come out as a pattern of sharp spots, and the spots meant the atoms are 'lined up in neat, repeating rows that scatter the X-rays in an orderly way' (paragraph 3).

Why: The spot pattern is the evidence; the repeating rows are the inference. Students should give the evidence, not just the conclusion.

Also acceptable: A close paraphrase is acceptable.

- Names the X-ray spot pattern
- Links it to repeating rows of atoms

5. Paragraph 4 says there is 'no molecule of NaCl.' Explain in your own words what the Braggs found inside salt, what the formula NaCl means if it is not a molecule, and why the passage says 'the model won' even though some chemists objected.

Answer: The Braggs found sodium and chlorine alternating in every direction, each with six neighbors of the other kind at equal distance, so no sodium pairs with one particular chlorine; the pattern simply continues to the edge of the grain. The formula NaCl therefore means a ratio, one sodium for every one chlorine, not a particle containing one of each. The model won because it did what a scientific model must do: it predicted the X-ray spot pattern exactly and explained the cube shape of salt grains, and objections based on 'common sense' could not match that evidence.

Why: Full credit needs all three parts: the arrangement, the meaning of the formula, and the evidence-based reason the model was accepted over Armstrong's objection.

Also acceptable: Accept 'three-dimensional checkerboard' as the description of the arrangement.

- Describes alternating sodium and chlorine with six neighbors each
- Explains NaCl as a 1:1 ratio, not a particle
- Explains that the model was accepted because it predicted and explained evidence

6. Using the two distances in paragraph 6, calculate how many times farther apart the graphite sheets are than the bonded atoms within a sheet. Round to one decimal place. Then say what this number suggests about the attraction between sheets compared with the bonds inside a sheet.

Answer: $335 \text{ pm} \div 142 \text{ pm} = 2.36$, about 2.4 times farther apart. Bonded atoms inside a sheet sit close together because strong bonds hold them; the much larger gap between sheets suggests that only weak attractions, not bonds, hold the sheets to each other, which is why they slide apart.

Why: The ratio is a straightforward division; the interpretation links distance to strength of attraction, which paragraph 6 states directly ('no bonds join one sheet to the next, only weak attractions').

Also acceptable: Accept 2.3 or 2.4 depending on rounding; accept 'the sheets are only weakly attracted' as the interpretation.

7. Compare diamond (paragraph 5) and graphite (paragraph 6): how many bonded neighbors does each carbon atom have, and in which directions do the bonds point? Which single feature of graphite explains why a pencil leaves a mark?

Answer: Diamond: each carbon is bonded to four neighbors spread evenly around it, so the bonds point in every direction and form one rigid network. Graphite: each carbon is bonded to only three neighbors, all within a flat sheet, so the bonds point sideways within the sheet and none point up or down to the next sheet. The feature that explains pencil marks is that the sheets are held together only by weak attractions (no bonds between sheets), so they slide off onto the paper.

Why: The contrast of four neighbors in all directions versus three neighbors in a plane is the heart of the structure-property link. The passage's own cause for the pencil mark is the sliding of weakly held sheets.

Also acceptable: Accept 'the sheets slide apart' as the single feature.

- Four neighbors versus three
- All directions versus within a flat sheet
- Names weak attraction between sheets (or sliding sheets) as the cause of the mark

8. Paragraph 7 claims that the arrangement of atoms 'leaves fingerprints at the human scale.' Using evidence from at least two other paragraphs, explain what this means and whether the passage supports the claim.

Answer: The claim means that something you can see or feel (a shape, a hardness, a streak) is caused by the pattern of atoms you cannot see. The passage supports it with evidence: paragraph 4 says the alternating checkerboard pattern explains why salt grains grow as tiny cubes; paragraph 5 says the rigid network of four-way bonds explains diamond's hardness; paragraph 6 says sliding sheets explain the pencil's mark. In each case a visible property is traced to an atomic arrangement, so the claim is supported.

Why: Full credit requires an explanation of the claim plus evidence from at least two paragraphs. Students should connect each piece of evidence to a visible property.

Also acceptable: A student who argues the claim is supported but notes that salt grains only 'tend to' grow as cubes (the passage's own hedge) is reading carefully and deserves full credit.

- Explains 'fingerprints at the human scale' in the student's own words
- Evidence from at least two paragraphs, each linking an arrangement to a visible property
- States whether the claim is supported

Teacher notes

The passage is just under 700 words and is historically grounded: Lavoisier's diamond combustion (1772), Tennant's equal-mass comparison (1797), von Laue's X-ray diffraction (1912), the Braggs' structures of salt and diamond (1913), Bernal's graphite structure (1924), and Armstrong's 1927 objection in *Nature* are all documented. The 3.7 g figure is the real mass ratio of carbon dioxide to carbon ($44 \div 12$). The 142 pm and 335 pm distances are standard values for graphite. Two accuracy notes: the sodium and chlorine in salt are charged particles (ions), which the passage and the lesson leave out because MS-PS1-1 excludes the ionic nature of subunits from assessment; and the passage says salt grains 'tend to' grow as cubes because real grains are often chipped or irregular. If students ask what X-rays are, say they are a kind of light with waves short enough to be scattered by atoms. Extension: in a 5 by 5 alternating layer there are 13 of one kind and 12 of the other; each inside square touches four neighbors of the other kind in the layer, and the remaining two of its six neighbors sit directly above and below it in the next layers, which also alternate; the 13-to-12 imbalance shrinks to nothing as the grain grows to billions of atoms.

Scaffold offered to students: Paragraph map

Before answering, write one phrase beside each paragraph number on scrap paper: 1 = burning diamond; 2 = the puzzle (composition versus structure); 3 = X-rays; 4 = salt; 5 = diamond; 6 = graphite; 7 = the big idea. Every question names its paragraph, so find the phrase, reread only that paragraph, and underline the sentence that answers the question before you write.

Extension: Model the salt checkerboard

Paragraph 4 says each sodium in salt has six chlorine neighbors at the same distance. Using grid paper, draw one flat layer of the checkerboard, 5 squares by 5, and label the squares Na and Cl so that they alternate. Count how many neighbors of the other kind each inside square touches edge to edge, then explain where the remaining neighbors (to make six) must be (hint: think about the layers above and below) and why a flat drawing can show only part of the pattern. Finally, count the Na and Cl squares in your 5 by 5 layer and explain why the counts are not exactly equal even though the ratio for a whole grain is 1:1.