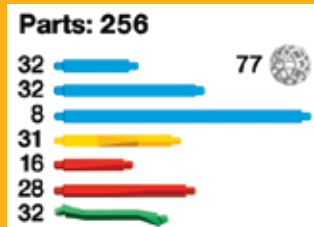


Zometool Project Series: the world's most powerful (and fun!) modeling system. Kids, educators, and Nobel-prize winning scientists all love Zometool:

- it's unique, brilliant, beautiful
- all kits are compatible—more parts, more power!
- guaranteed for life!

"The mind, once stretched by a new idea, never regains its original dimensions." — Oliver Wendell Holmes

# Crystallography



Includes detailed instructions by Dr. Robert Ingel & Dr. Marion Freistadt

Step into the world of crystal and mineral structures! This elegant, simple tool engages students of all ages in hands-on exploration of crystallography.

Build 14 different crystal structures and discover the secrets of:

- Crystal lattices
- Crystal symmetry
- Our crystalline world

Teachers can also use this kit to create models for in-class demonstrations.



## START HERE! What's a crystal?

Which one is crystalline: dull, grey pencil lead or a crystal ball?



Trick question? You bet! Pencil lead is a crystal and glass isn't. This project helps you find out why!

We live in a world of crystals, from delicate water crystals (snow flakes) to super-hard carbon crystals (diamonds) to rare quasi-crystals. Folks even eat crystals (like salt and sugar) every day! So what is a crystal?



Snowflake, diamond and quasicrystal

## A solid arrangement

Matter is everything that makes up the physical world, and usually comes in 3 forms: solid, liquid or gas. Think of ice, water and steam—only ice is a crystal.



### Three forms of water

As a rule, most solids are crystalline, and most crystals are solid (though dish soap is a liquid crystal!) Like a building, its structure—how its building blocks are arranged—makes a crystal solid.

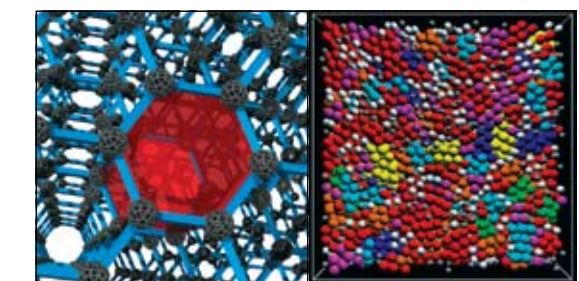
## Atomic building blocks

Atoms are the building blocks of all matter. In crystals, they join in regular patterns. Just like you can build a big cube from little blocks, a crystal's shape often reflects the arrangement of its atoms.

So what's an atom? Imagine you cut a bit of pencil lead in half. Then cut the half in half, and keep going until you get a piece of graphite that can't be cut anymore (without an atom smasher). You'd have a carbon atom! It's small: a carbon atom compared to an orange is about the same as the orange compared to planet earth!



Atoms have energy fields (electron clouds) that hook up with other atoms. In graphite (pencil lead), the carbon atoms line up like stacks of hexagonal bathroom tiles. But with no clearly defined structure, glass (the crystal ball) is amorphous. In fact, it may not even be a solid, but a slow moving fluid!



Graphite's structure (L) and glass's lack of it



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## Make crystal structures!

You can build crystal models in 1, 2 and 3 dimensions, and also explore how they can be seen as shadows of each other. Can you discover what distinguishes the lattices from each other?

### 1D lattices

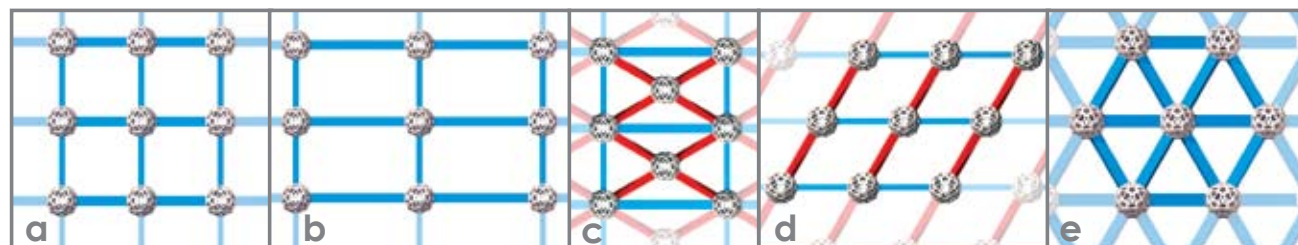
Build a 1-dimensional lattice (a line) using short blue struts and balls. Since the "atoms" are all in a line, the only thing you can change is the distance between them (use a different strut.)



A line of equally spaced balls is like a one-dimensional lattice. Notice that all the balls are oriented the same.



Adding a new line (red) defines a plane. Now you are working in two dimensions!



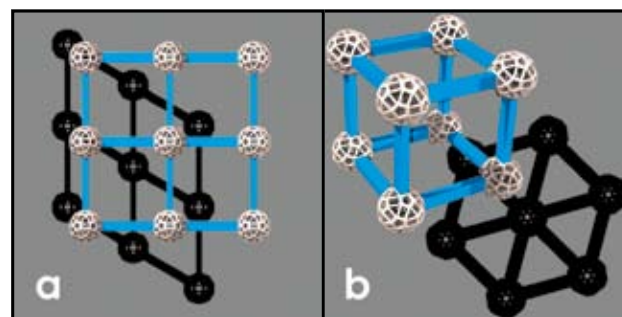
Five 2-dimensional lattices: simple square (a), simple rectangular (b), centered rectangular (c), simple oblique (d) and simple hexagonal (e).

### 2D lattices

Take your blue line and stick any strut in any ball. When 2 lines cross, they define a plane and can form the basis of a 2-dimensional lattice. There are 5 kinds (above), which combine to form the 3D crystal lattices shown on the other side. Try making the 2D lattices above to see how they relate to 3D lattices.

### 3D lattices

You can combine 2 planes to make 3D lattices (see other side). There are 7 kinds of "primitive (P) space lattices" with one atom at each corner, and 7 variations.



Shadows show how crystal lattices are related: a square turns oblique (a) and a cube becomes a hexagon (b)

Using sunlight and white cardboard, you can cast shadows to discover relationships among the lattices!

## Beyond 7 simple lattices

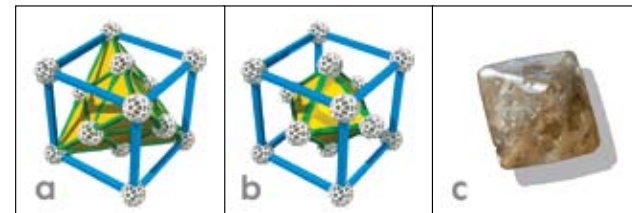
You can expand the primitive crystal structures to include other shapes.

### Centered Lattices

Crystals also form with atoms in the middle or on the faces of the simple lattice, called body-centered (I) and face-centered (F) lattices. The 7 simple shapes plus their 7 variations are called 14 Bravais lattices.

### Tetra- and octahedra

Some elements crystallize as tetrahedra (a pyramid with a triangular base) or octahedra (two square pyramids joined at the base). These are both related to body-centered and face-centered lattices.

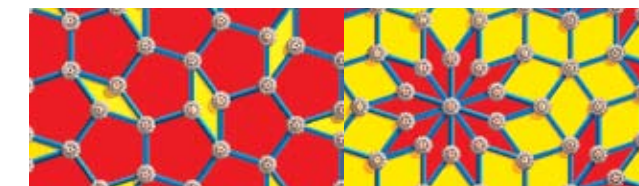


Tetrahedron (a) and octahedron (b) inside a face-centered cube; rough diamond (c)

### Multiple unit cells

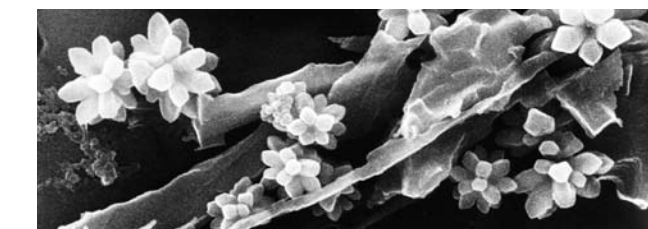
The models that you can build on the other side are "unit cells," the simplest way to picture crystals. There are about  $1.2 \times 10^{18}$  unit cells in a single grain of salt, so it would take about 100x the age of the universe to produce Zometool parts to build a model of it!

### Quasicrystals



It's easy to tile a plane with squares, but if you try to fill a plane with pentagons, you will get gaps between your tiles. So crystallographers used to think that crystals based on number 5 were impossible.

But you can tile a plane with two different "shadows" of squares in a way that reflects the number 5.



Not an apple blossom, but an aluminum alloy: quasicrystal's 5-fold symmetry conveys a strange life-like quality

Likewise, space can be filled with shadows of cubes in a way that also shows 5-fold symmetry. Theorized for decades by artists and mathematicians, in 1984, "quasicrystals" were discovered and blew the lid off crystallography (see "Snapshots" below)!

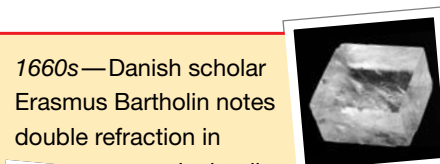
### GLOSSARY

- 5-fold symmetry** – the quality of being made up of 5 exactly similar parts around an axis, so if turned one fifth way around (72°), object lines up with itself.
- Amorphous** – non-crystalline, having neither clear form nor apparent structure
- Atom** – the basic unit of a chemical element, from Greek atomos, 'indivisible'
- Dimension** – a line in space, always perpendicular to any other dimension(s), which can be used to locate points in space
- Electron** – stable negatively charged subatomic unit, considered a cloud around the nucleus of an atom, that causes chemical bonding
- Graphite** – grey, crystalline carbon used as lubricant, in pencils, and composites
- Lattice** – regularly repeating 3-dimensional arrangement of atoms or molecules
- Liquid crystal** – a substance that exhibits a phase of matter that has properties between those of a conventional liquid and those of a solid crystal
- Matter** – whatever occupies space, considered to constitute physical universe
- Molecule** – two or more atoms bonded together; also called chemical compound
- Plane** – a flat surface defined by the intersection of two straight lines
- Projection** – image of an object on a "surface" of one or more dimensions with a linear correspondence between its points and points on the image
- Rhombus** – any parallelogram with sides of equal lengths: a "squashed" square
- Solid** – one of three basic states of matter in which a substance's atoms or molecules are usually arranged in a crystal lattice
- Structure** – systematic arrangement of parts in a substance, body, or whole
- Tiling** – a repeating pattern with translational symmetry; if the object is moved in one or more directions it lines up with itself.
- Unit cell** – the smallest group of atoms, ions or molecules whose repetition at regular intervals in three dimensions produces a crystal lattice.

### Some historical snapshots



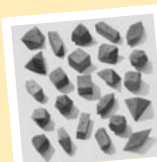
5th century B.C.—Greek philosophers Leucippus and Democritus lay the basis of crystallography by imagining matter chopped into the tiniest bits, "atoms."



1660s—Danish scholar Erasmus Bartholin notes double refraction in Icelandic calcite crystals. Nicolaus Steno sets forth his "first law of crystallography" from studying quartz.

1781—Upon accidentally shattering acalcite crystal, University of Paris professor Abbé René Just Haüy surmises that the external form of crystals is a reflection of inner regularity, due to the of arrangement of constituent building blocks.

19th century—Careful measurement, reasoning, guesswork lead scientists to the startling realization that most solids are crystals. In nature's bounty of solid materials there are only 7 major divisions of crystals (see other side)!



1895—Wilhelm Roentgen at the University of Würzburg, Germany, discovers x-rays. By 1912, Max von Laue uses x-rays to see the arrangement of atoms in a solid, reasoning that rays may be diffracted like light through a prism.



1915—Father and son team William and Lawrence Bragg are awarded the Nobel Prize for mathematically interpreting X-ray diffraction patterns to discover the actual structure of various crystals. Their work launches the field of solid-state physics.



1984—Israeli scientist Daniel Shechtman of the (US) National Bureau of Standards discovers a new form of "quasiperiodic" crystals with 5-fold symmetry, shattering crystallographers' belief such "quasicrystals" are impossible.



Zometool Models

Cubic	Tetragonal	Orthorhombic	Monoclinic
<b>P</b> 	<b>P</b> 	<b>P</b> 	<b>P</b> 
<b>I</b> 	<b>I</b> 	<b>I</b> 	<b>C</b> 
<b>F</b> 	<b>F</b> 	<b>F</b> 	<b>C</b> 

**Legend**

- P** = Primitive lattice: the lattice points are on cell corners only
- I** = Body-centered lattice: one lattice point is at the center of each cell
- F** = Face-centered lattice: one more lattice point is in the center of each face of each cell
- C** = Centered on a single face: one more lattice is in the center of one of the faces of each cell
- = Projected along a blue (2-fold) symmetry axis
- = Projected along a yellow (3-fold) axis

*"Be glad of water, but don't forget  
The lurking frost in the earth beneath  
That will steal forth after the sun is set  
And show on the water its crystal teeth."  
- Robert Frost*

Triclinic	Rhombohedral	Hexagonal
<b>P</b> 	<b>P</b> 	<b>P</b> 

Shadows

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Examples

<b>SALT</b> 	<b>TIN</b> 	<b>URANIUM</b> 	<b>GYPSUM</b> 	<b>TURQUOISE</b> 	<b>ARSENIC</b> 	<b>GRAPHITE</b> 
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ZOMETOOL RULES!

- If it works, it works perfectly.**  
...and if it doesn't work, it doesn't work at all. Don't force Zometool components. You can bend a strut to fit it into a tight spot, but struts in finished models are always straight, never under tension. Hint: you can tell which strut fits between two balls in a model by lining up the balls and looking through the holes. The holes show you the shape of the strut that fits!
- Don't break it apart; take it apart!**  
Take models apart by grasping a strut with your fingers and pushing the ball straight off with your thumb. Twisting balls, pulling models apart or crushing them can cause parts to break! To disassemble a large model quickly, remove all the longest struts of one color first, and work your way down!
- Leave the place cleaner than you found it.**  
It's always a good idea to clean up when you're done, so the next person can enjoy Zometool too. If we work together, we can make the world better for all.

*We replace accidentally broken parts for free: visit [www.zometool.com/](http://www.zometool.com/) warranty for details.*

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- make learning fun
- create value
- build a better world

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Zometool Crystallography Project—thanks to Dr. Robert Ingel (Department of Physics and Optical Science, UNC Charlotte) and Marion Freistadt, MBA, PhD, concept and copywriting; Dr. Scott Vorthmann, vZome software used for renderings; Anni Wildung, graphic design; Paul Hildebrandt, project management, etc. Images, page 1: Froebel blocks – Norman Brosterman, Inventing Kindergarten, Abrams, 1997; carbon atom – Wikibooks, New Atomic Model of the Carbon and Oxygen Atoms, Pcfjr9; glass – courtesy of Paddy Royall, University of Bristol; pages 2-3: Wooden crystal models – Brosterman (above), Roentgen hand x-ray – American College of Radiology; page 4 (inside) Robert Frost, *Two Tramps in Mud Time*, Oxford Book of American Poetry, 2006; "Fat Man" uranium bomb – Los Alamos Scientific Laboratory; Arsenic and Old Lace – courtesy of Jerry Telfer and Masquers Playhouse, [www.masquers.org](http://www.masquers.org). Contact [paulh@zometool.com](mailto:paulh@zometool.com). © 2009 Zometool Inc. Based on the 31-zone system discovered by Steve Baer, Zomeworks Corp., USA.

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