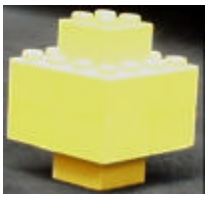
LEGO® Molecular-Scale Models

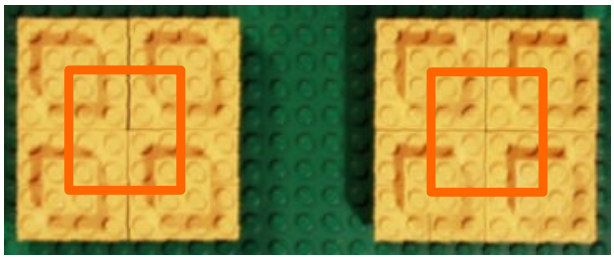
Building Instructions for Structures at the Molecular Scale

Simple Cubic

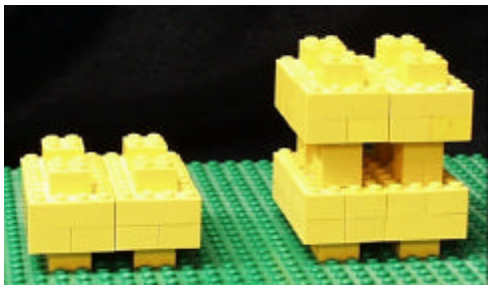
LEGO unit representing atoms in this structure:



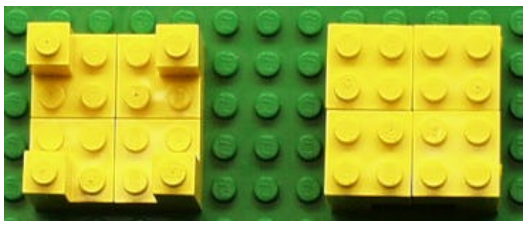
Whole atoms:



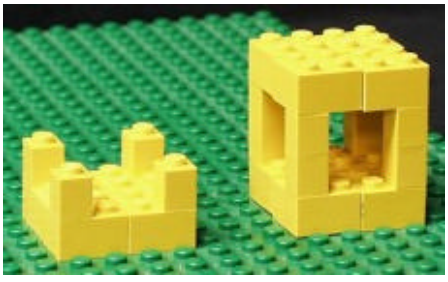
Z=0 **Z=1**



Unit cell:



Z=0 **Z=1**



Body-Centered Cubic (whole atoms)

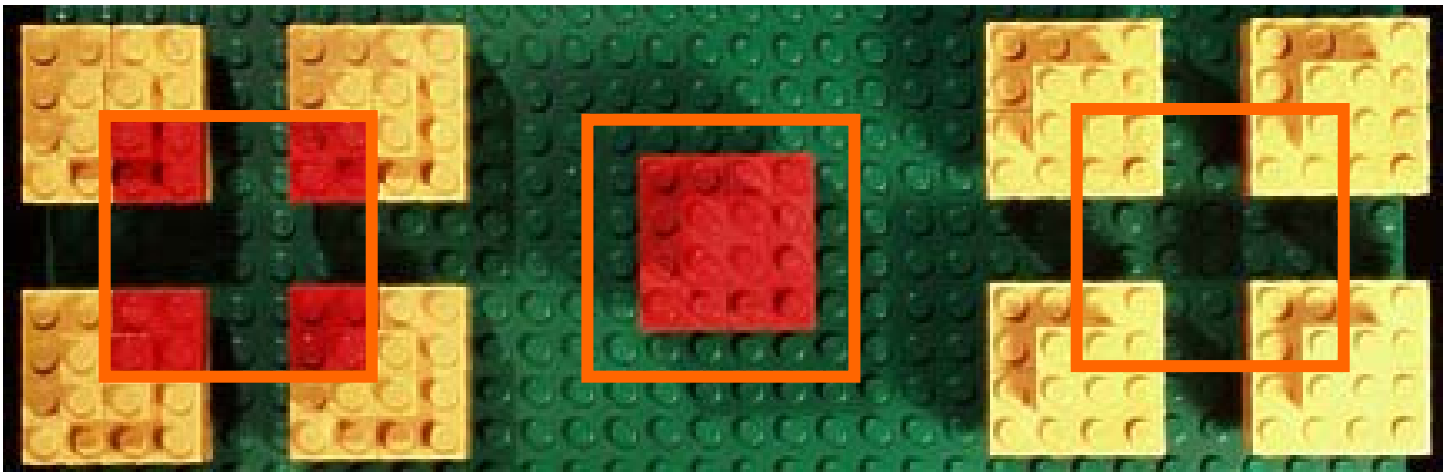
LEGO unit representing atoms in this structure:

<u>This atom model requires:</u>
4 yellow 2x4 bricks
2 yellow 2x2 bricks

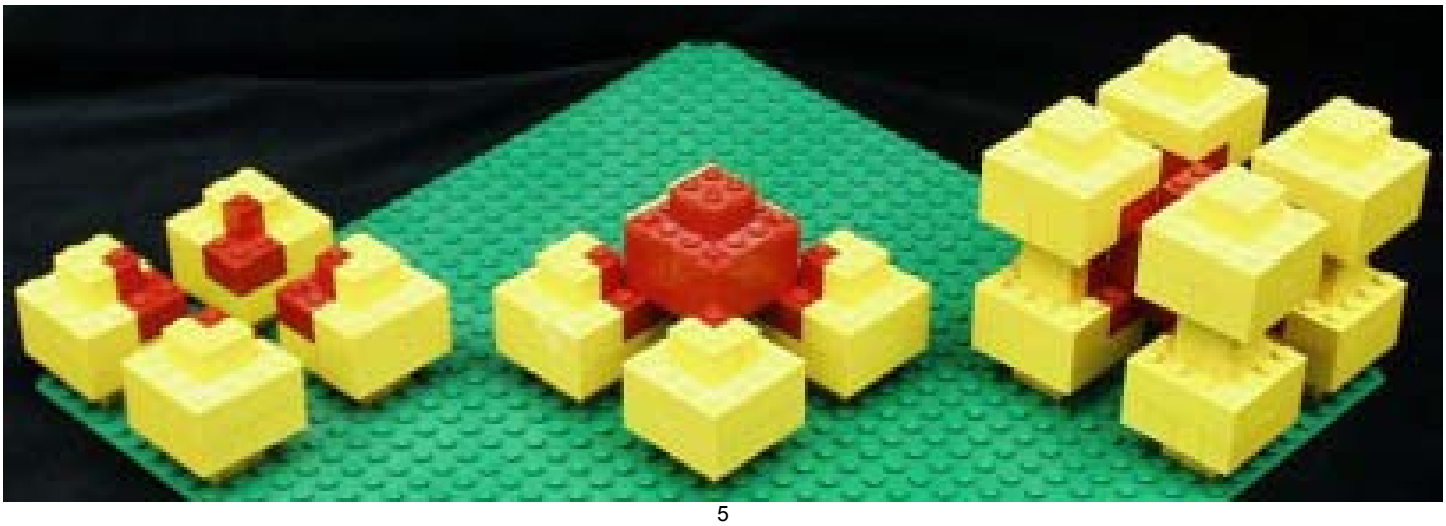
NOTE: The red LEGOs depict portions of the structure within the unit cell.

<u>This model requires:</u>

24 yellow 2x4 bricks	4 red 2x4 bricks
8 yellow 2x2 bricks	6 red 2x2 bricks
8 yellow 1x2 bricks	8 red 1x1 bricks
8 yellow 1x1 bricks	



Z=0 **Z=½** **Z=1**



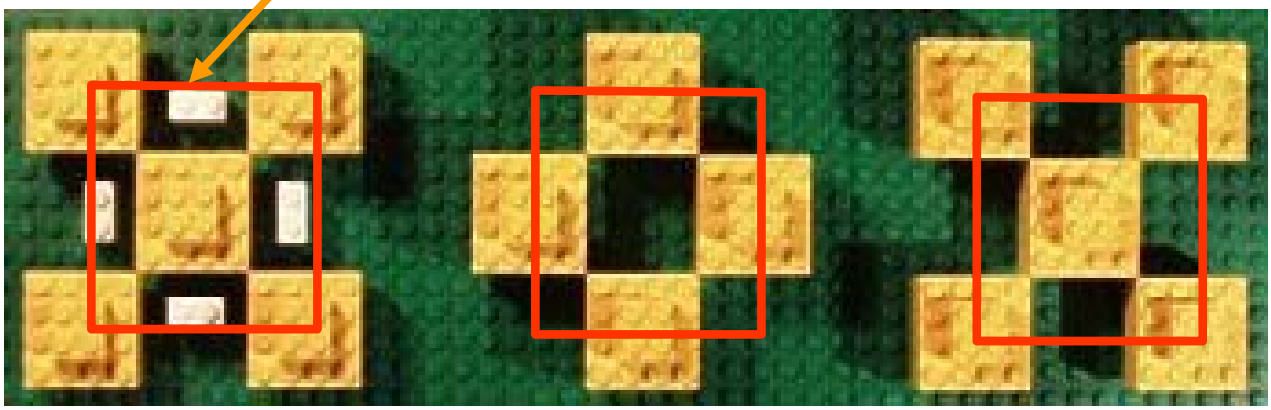
Face Centered Cubic (whole atoms)

LEGO unit representing atoms in this structure:

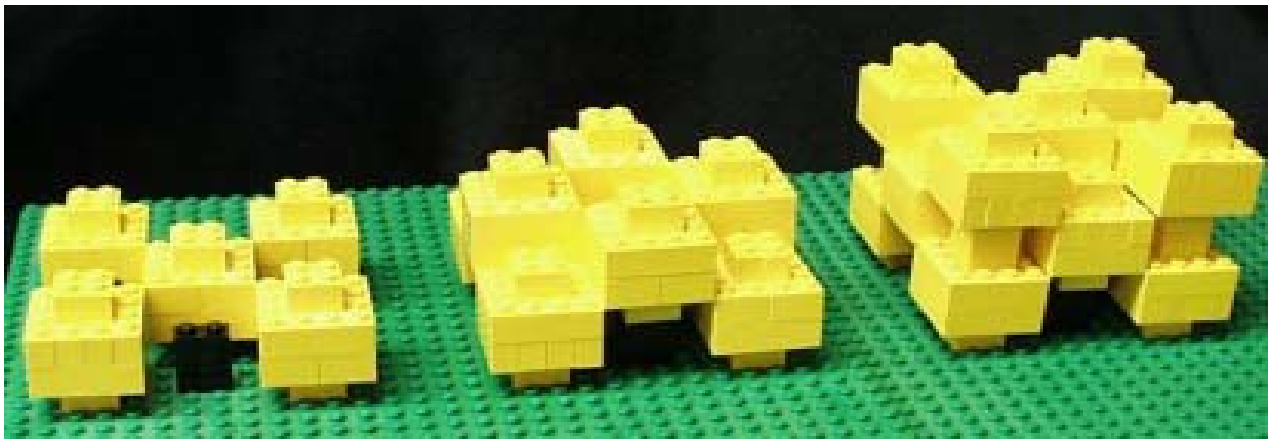
<u>This atom model requires:</u>
4 yellow 2x4 bricks
2 yellow 2x2 bricks

<u>This model requires:</u>
56 yellow 2x4 bricks
28 yellow 2x2 bricks
8 black 1x2 bricks

These are supports made from two 1x2 bricks.



Z=0 **Z=½** **Z=1**

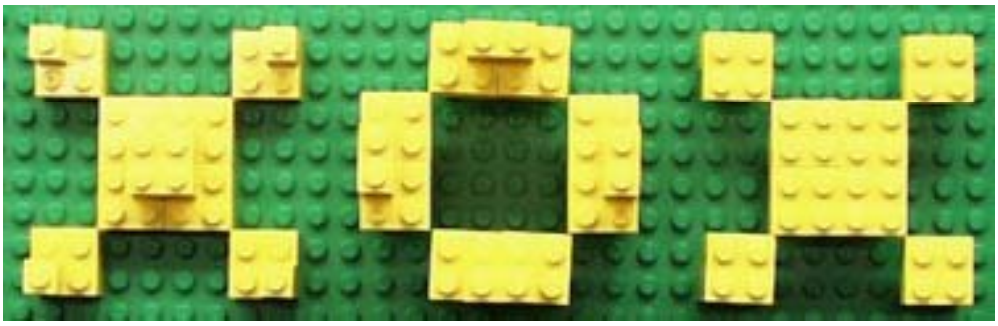


Face Centered Cubic (unit cell)

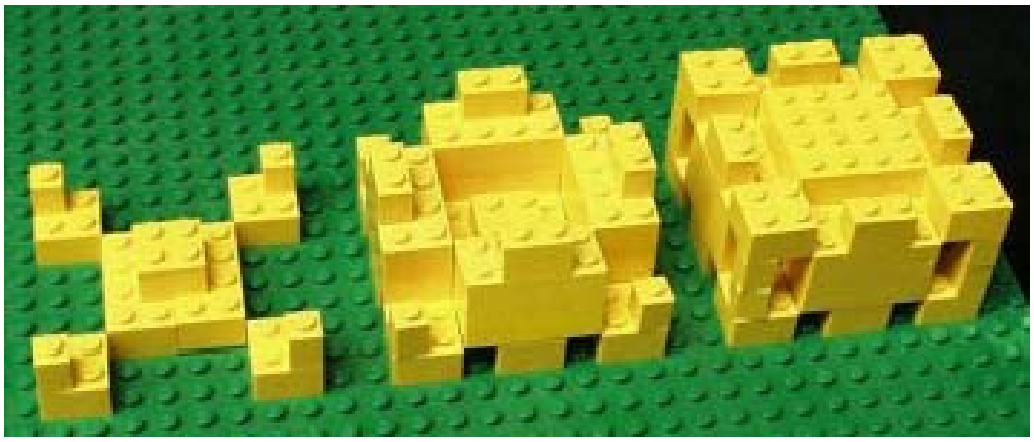
LEGO unit representing atoms in this structure:

<u>This atom model requires:</u>
4 yellow 2x4 bricks
2 yellow 2x2 bricks

<u>This model requires:</u>
14 yellow 2x4 bricks
9 yellow 2x2 bricks
8 yellow 1x2 bricks
8 yellow 1x1 bricks



Z=0 **Z=½** **Z=1**



Hexagonal Close-Packing Layers (whole atoms)

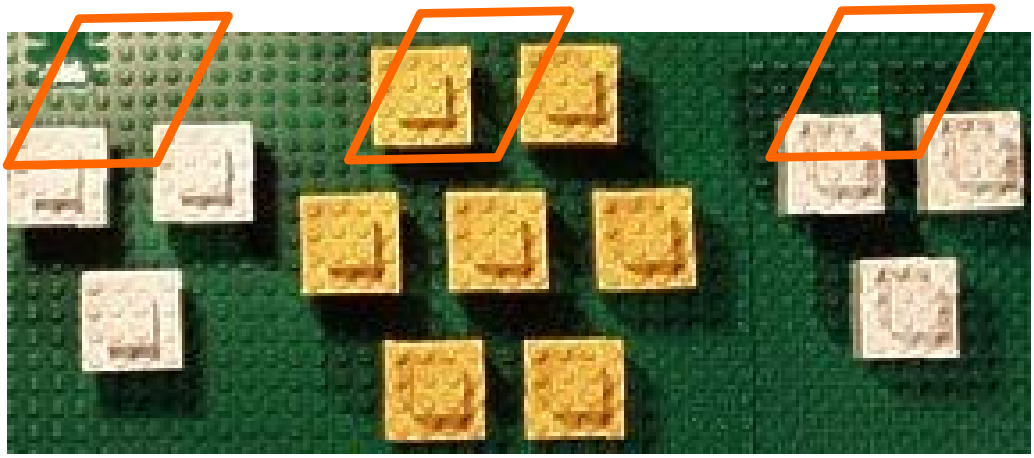
LEGO unit representing atoms in this structure:

<u>This atom model requires:</u>
4 yellow 2x4 bricks
2 yellow 2x2 bricks

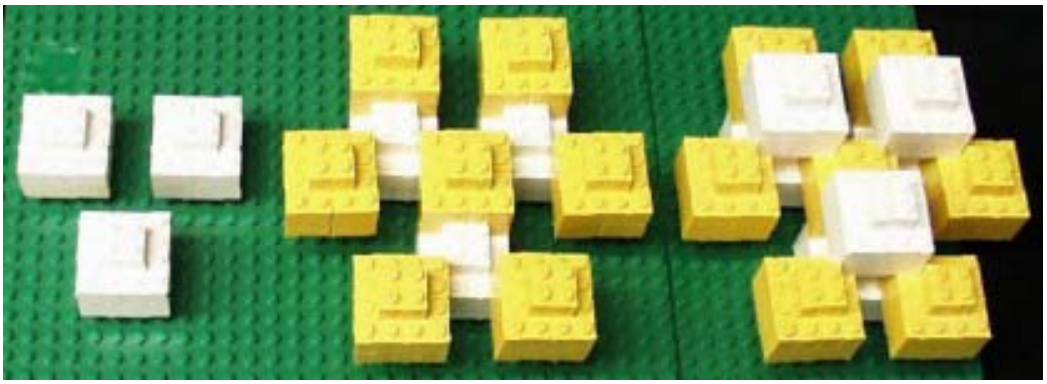
<u>This model requires:</u>

28 yellow 2x4 bricks	24 white 2x4 bricks
14 yellow 2x2 bricks	12 white 2x2 bricks

Note: Colors distinguish layers.



Z=0 **Z=½** **Z=1**



Cubic Close Packing Layers (whole atoms)

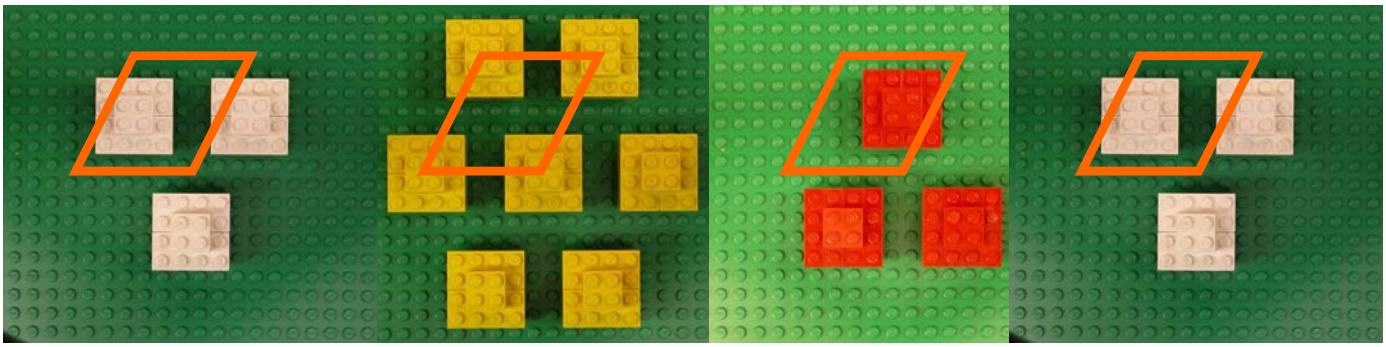
LEGO unit representing atoms in this structure:

This atom model requires:
4 yellow 2x4 bricks
2 yellow 2x2 bricks

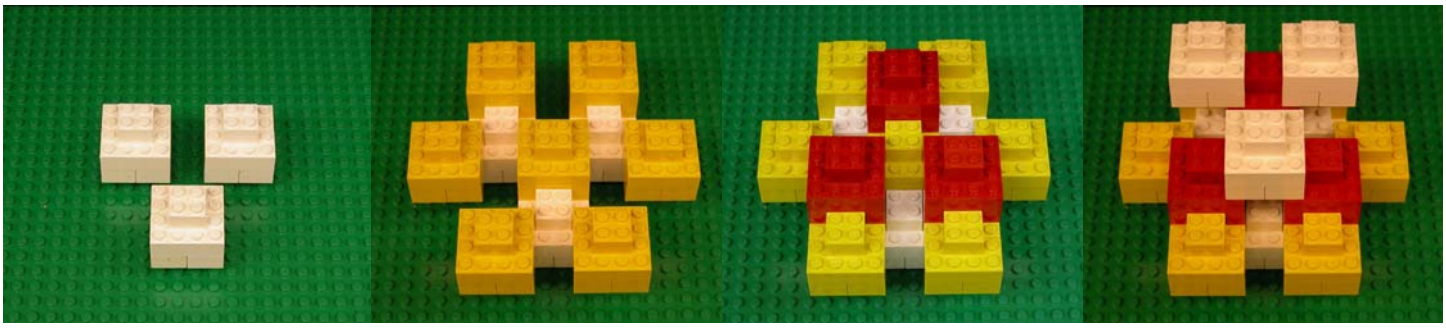
Note: Colors distinguish layers.
Layer A is white,
layer B is yellow,
and layer C is red.

This model requires:

28 yellow 2x4 bricks	24 white 2x4 bricks	12 red 2x4 bricks
14 yellow 2x2 bricks	12 white 2x2 bricks	6 red 2x2 bricks

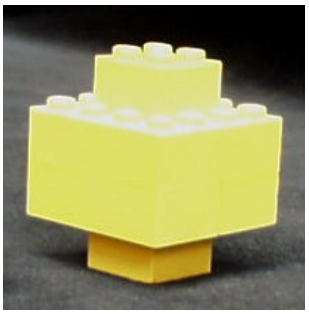


Z=0 **Z=0.333** **Z=0.667** **Z=1**



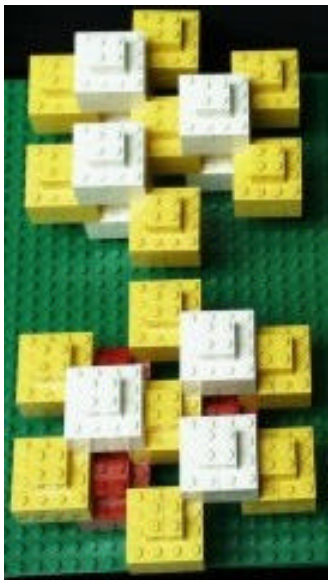
Close-Packed Structures

LEGO unit representing atoms in this structure:



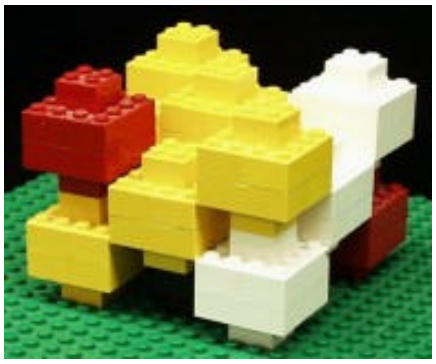
Note: Colors distinguish layers. Layer A is white, layer B is yellow, and layer C is red.

Hexagonal close-packed (ABAB… layers)



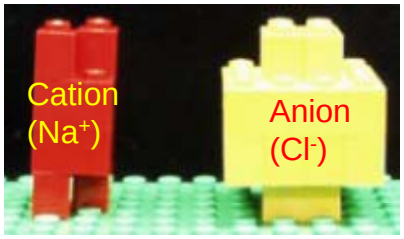
Cubic close-packed (ABCABC… layers)

Note: The cubic close-packed structure is the **same** as the face-centered cubic structure. The layers are simply oriented differently.



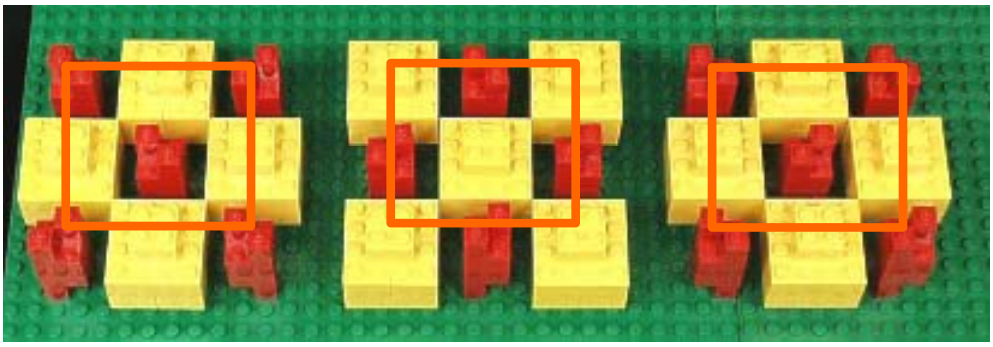
Rock Salt
(whole ions)

LEGO units representing different-sized ions in this structure:

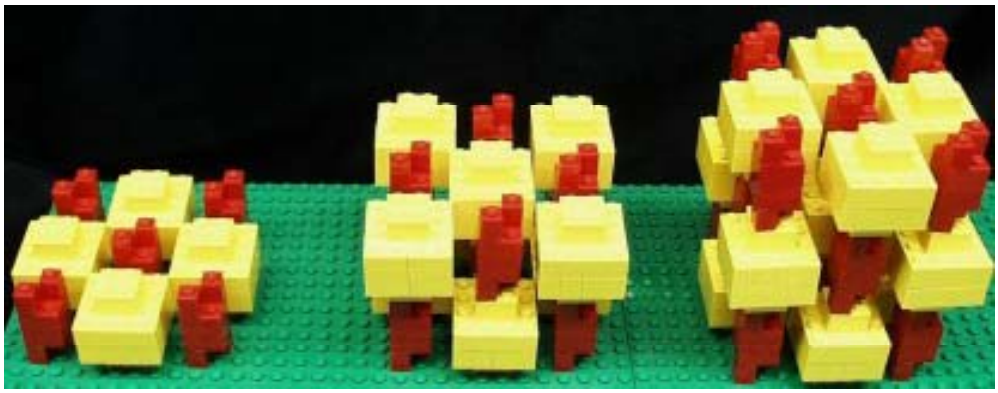


<u>This atom model requires:</u>
4 yellow 2x4 bricks
2 yellow 2x2 bricks
2 red 2x2 bricks
4 red 1x1 bricks

<u>This model requires:</u>
52 yellow 2x4 bricks 28 red 2x2 bricks
26 yellow 2x2 bricks 56 red 1x1 bricks

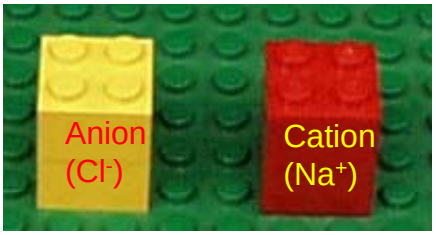


Z=0 **Z=½** **Z=1**



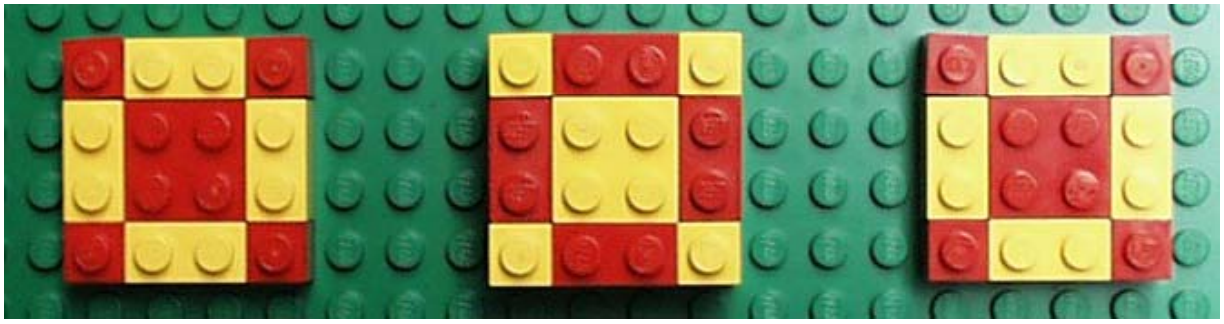
Rock Salt (unit cell)

LEGO units representing ions in this structure:

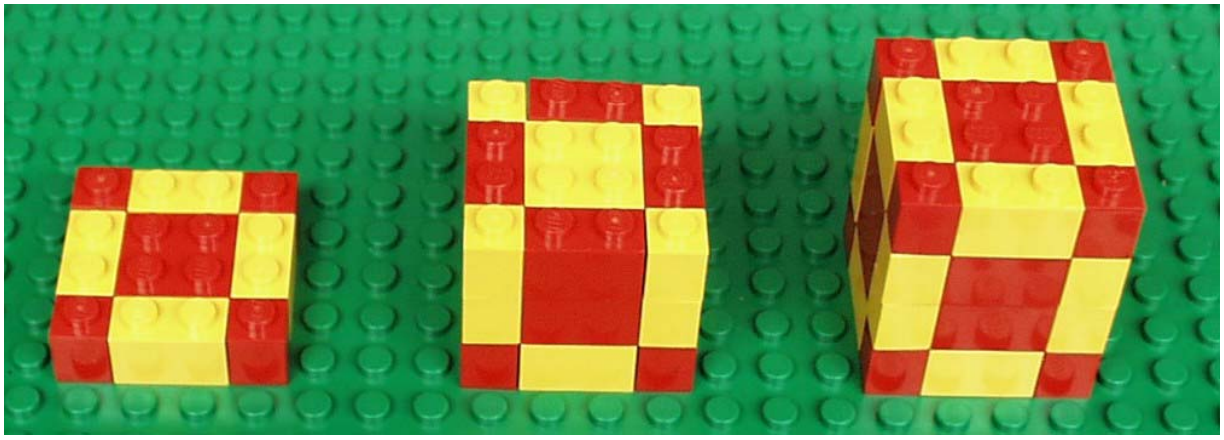


<u>This atom model requires:</u>
2 red 2x2 bricks
2 yellow 2x2 bricks

<u>This model requires:</u>
1 yellow 2x2 brick 2 red 2x2 bricks
8 yellow 1x2 bricks 4 red 1x2 bricks
4 yellow 1x1 bricks 5 red 1x1 bricks

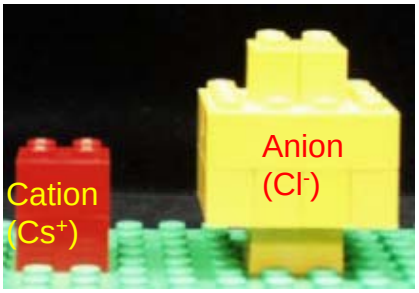


Z=0 **Z=½** **Z=1**



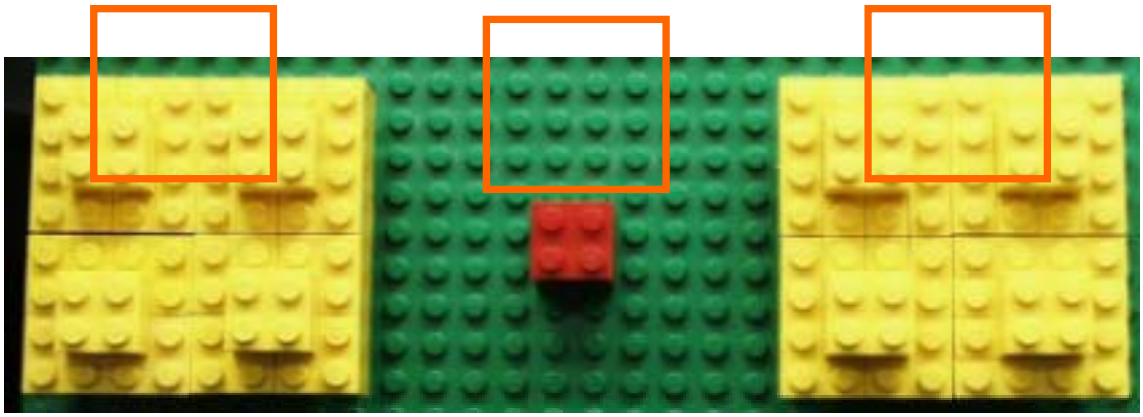
Cesium Chloride (whole ions)

LEGO units representing ions in this structure:

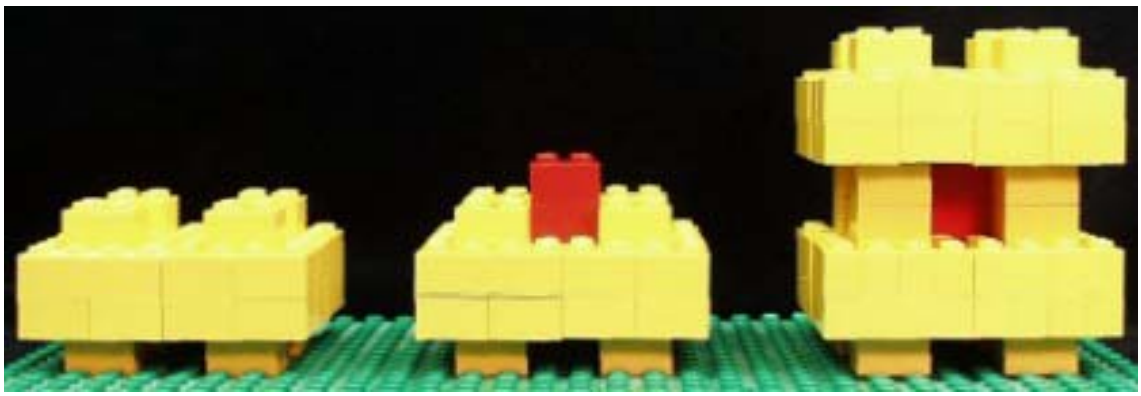


<u>This atom model requires:</u>
4 yellow 2x4 bricks
2 yellow 2x2 bricks
2 red 2x2 bricks

<u>This model requires:</u>
32 yellow 2x4 bricks
16 yellow 2x2 bricks
2 red 2x2 bricks

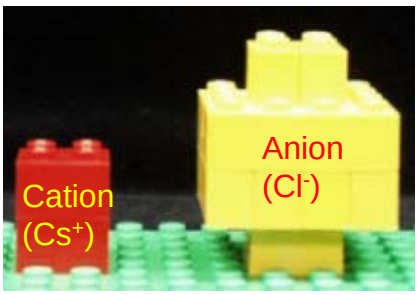


Z=0 **Z=1/2** **Z=0**



Cesium Chloride (unit cell)

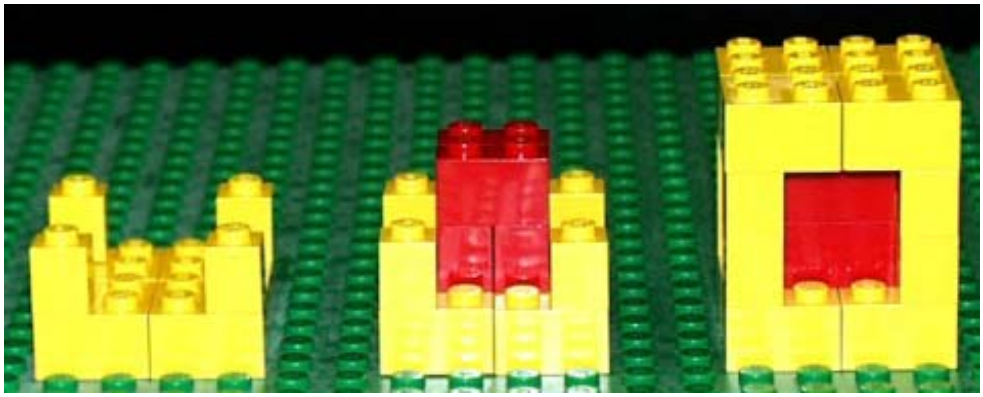
LEGO units representing ions in this structure:



<u>This atom model requires:</u>
4 yellow 2x4 bricks
2 yellow 2x2 bricks
4 red 1x2 bricks

<u>This model requires:</u>
8 yellow 2x4 bricks
8 yellow 1x1 bricks
4 red 1x2 bricks

Z=0 **Z=1/2** **Z=1**

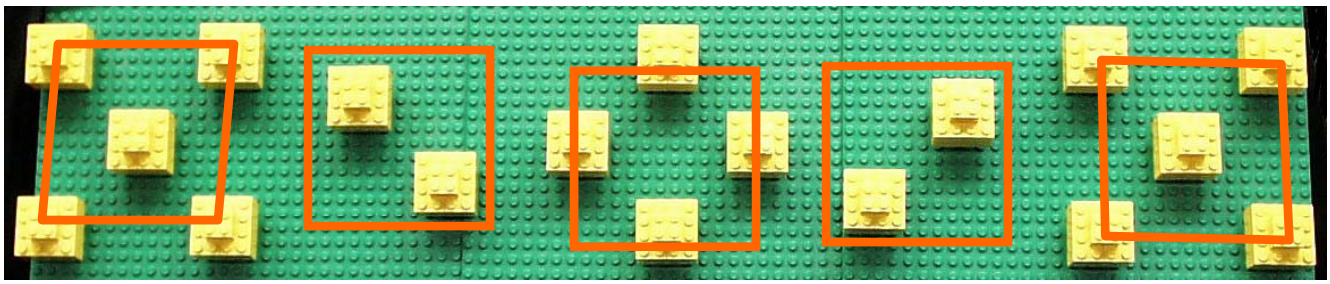


Diamond
(whole atoms)

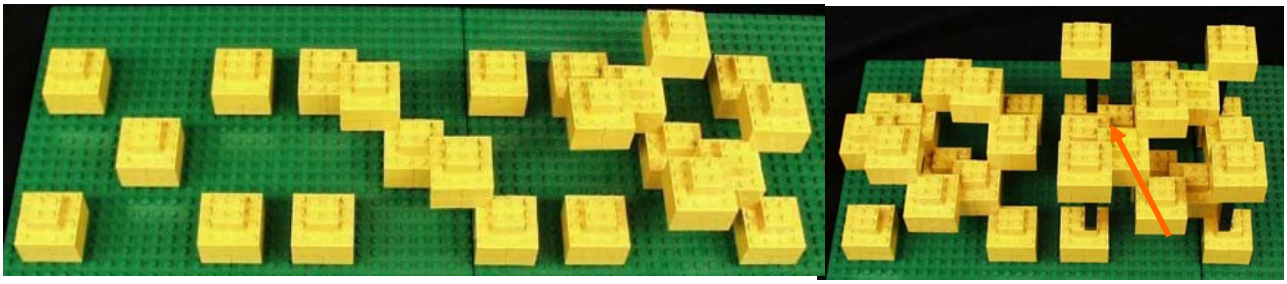
LEGO unit representing atoms in this structure:

<u>This atom model requires:</u>
4 yellow 2x4 bricks
2 yellow 2x2 bricks

<u>This model requires:</u>
72 yellow 2x4 bricks
36 yellow 2x2 bricks
16 black 1x1 bricks

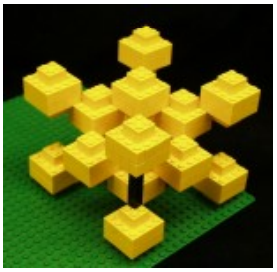


Z=0 **Z=¼** **Z=½** **Z=¾** **Z=1**



These are supports made from four 1x1 bricks.

Side view of diamond structure:



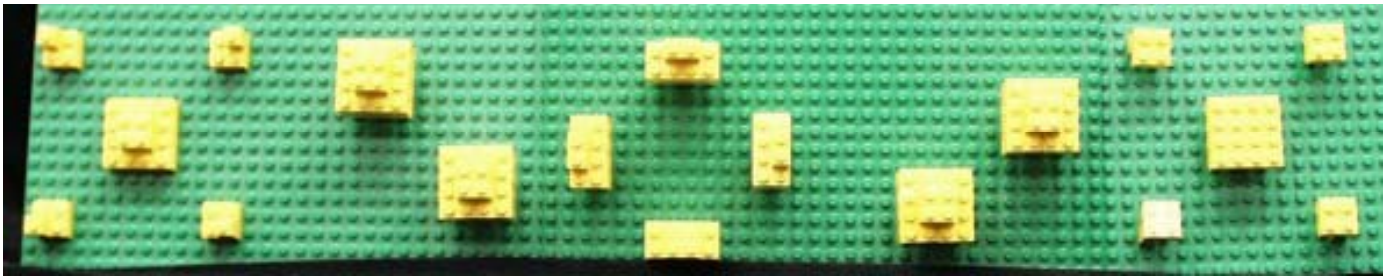
Tetrahedral bonding in diamond structure:

Diamond Unit Cell

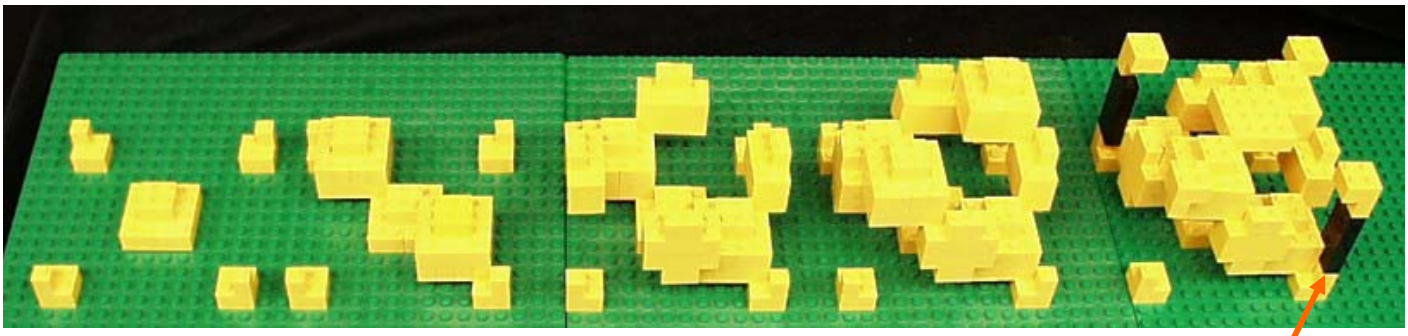
LEGO unit representing atoms in this structure:

<u>This atom model requires:</u>
4 yellow 2x4 bricks
2 yellow 2x2 bricks

<u>This model requires:</u>
28 yellow 2x4 bricks
18 yellow 2x2 bricks
4 yellow 1x2 bricks
8 yellow 1x1 bricks
8 black 1x2 bricks



Z=0 Z=¼ Z=½ Z=¾ Z=1

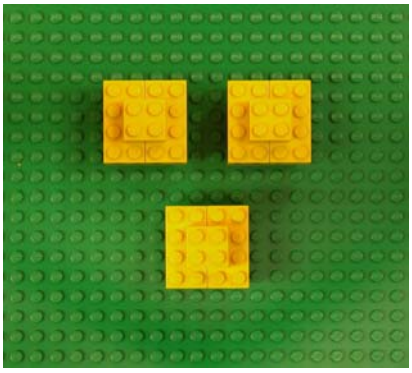


These are supports made from four 1x2 bricks.

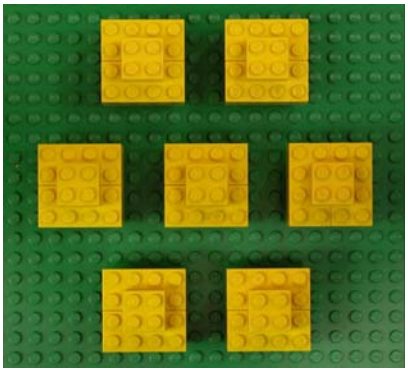
Diamond vs. Lonsdaleite (whole atoms)

LEGO unit representing atoms in this structure:

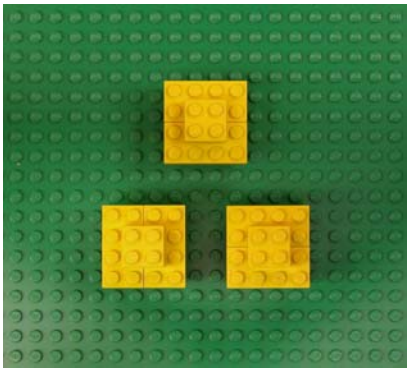
The carbon atoms in both structures are bonded to the other carbon atoms in a tetrahedral geometry:



“A” Layer

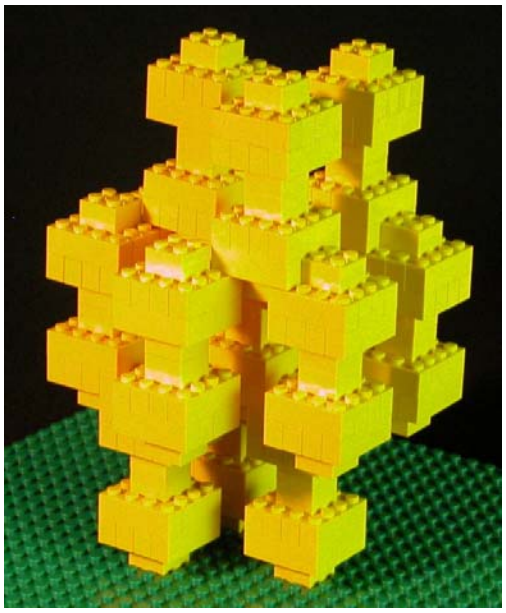


“B” Layer

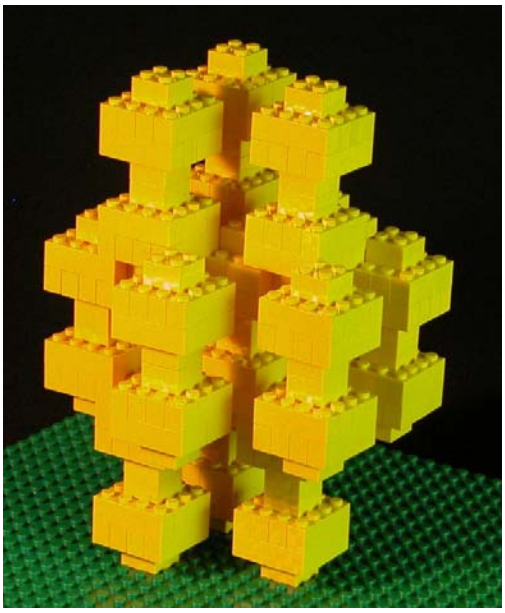


“C” Layer

Angle view of diamond structure (Layers **AABBCC**BBAABBCCBB…):



Angle view of lonsdaleite structure (Layers **AABBAA**BBAABBAA…):

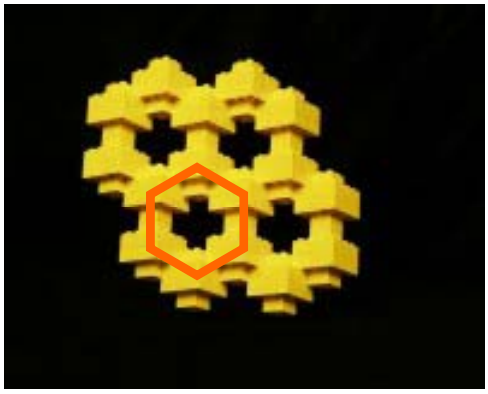


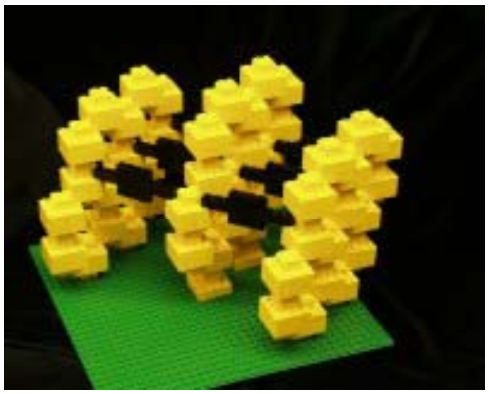
Graphite
(whole atoms)

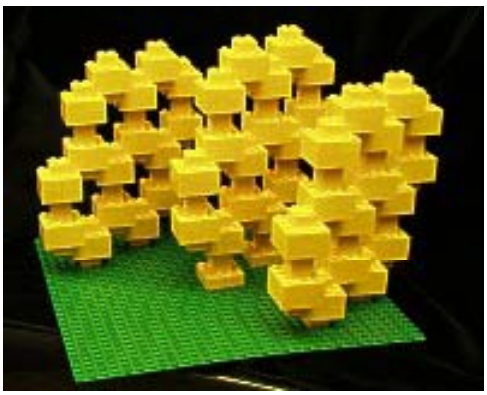
LEGO unit representing atoms in this structure:

Note: The spacers (10 pegs long) should be perpendicular to each layer of graphite to show the scale of spacing between the layers.

<u>This layer requires:</u>
64 yellow 2x4 bricks
32 yellow 2x2 bricks



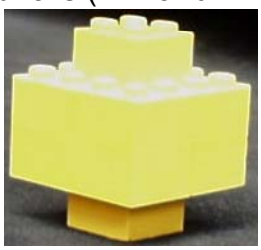




C_{60} and C_{70} Buckminsterfullerenes (whole atoms)

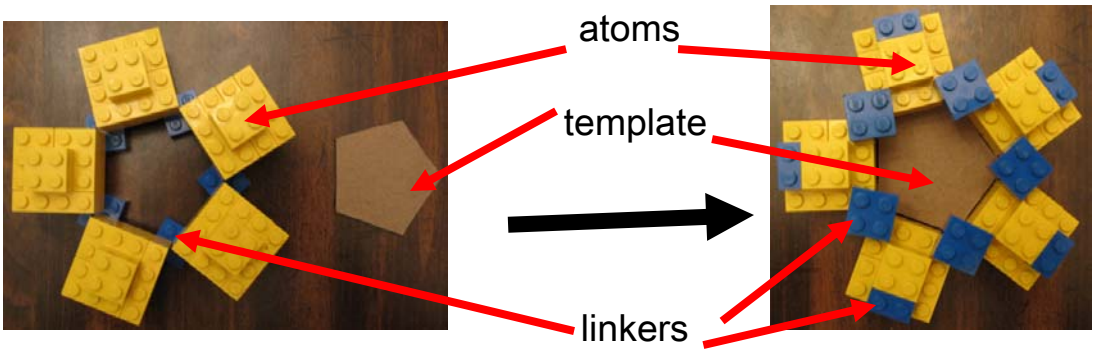
These are the most challenging (and rewarding) builds that I have attempted, and the resulting models have the same atom connectivity as C_{60} and C_{70} molecules. I recommend using fresh bricks with snug tolerances, a careful eye for symmetry, and a good dose of patience. This structure uses both support posts (which one might be able to carefully remove after the fullerene structure is complete and maybe even glued) and small bricks (2x2 and 1x2) to link the atoms together. Enjoy! -DJC-

LEGO unit representing atoms in this structure:



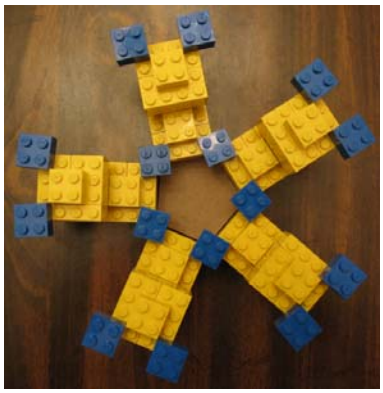
Level 1: 5 atoms, 10 2x2 linkers, 5 1x2 linkers

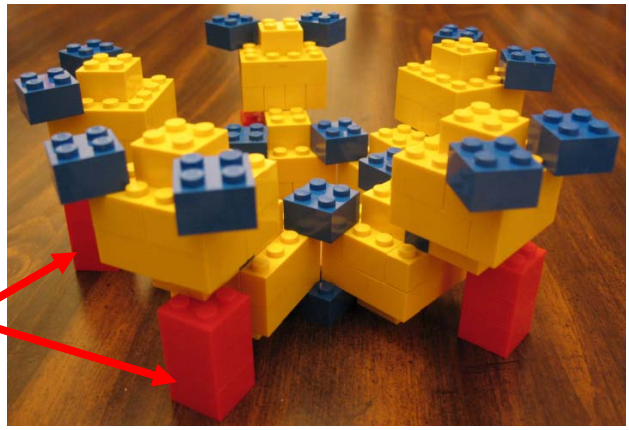
NOTE: Since this is the foundation level, it is helpful to build as perfect of a pentagon of the five atoms as possible. To accomplish this, made a cardboard pentagon template with about 31 mm edges to fit inside the ring of bricks.



Level 2 added: 5 atoms, 10 2x2 linkers, 5 supports (3 bricks high)

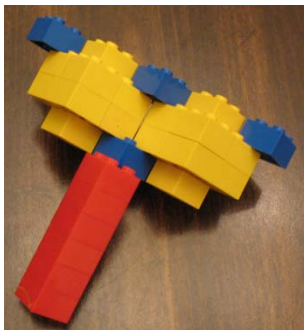
NOTE: Using 2x2 bricks for the supports, and connecting them to the atoms by only one peg, is a trade off between model stability and ease of support removal later on.



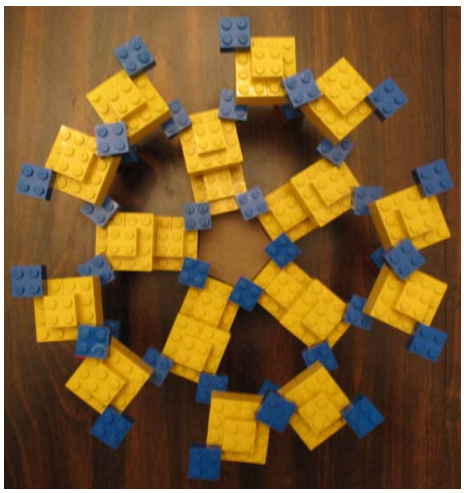


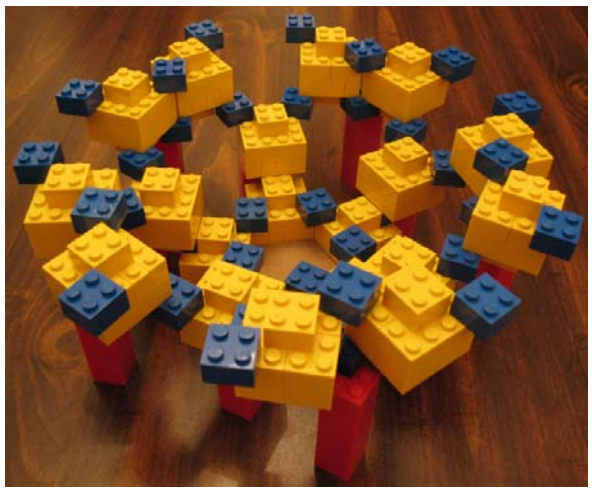
Level 3 added: 10 atoms, 20 2x2 linkers, 5 supports (6 bricks high)

NOTE: The 2x2 linkers must be turned to connect the atoms together. It helps to add atoms in linked pairs.

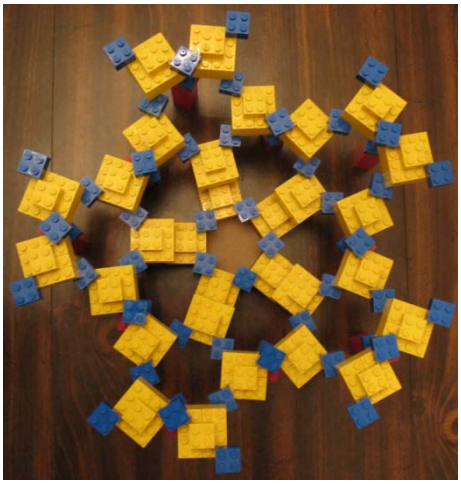


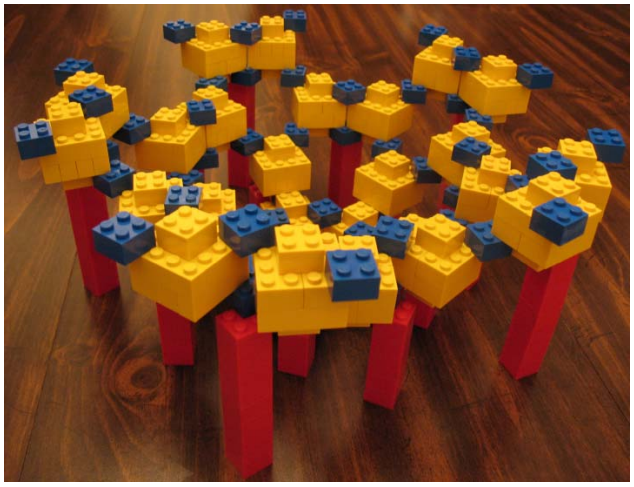
Linked pair
and support





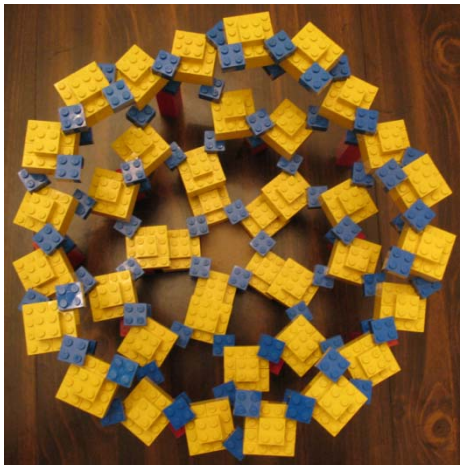
Level 4 added: 10 atoms, 20 2x2 linkers, 5 supports (9 bricks high)

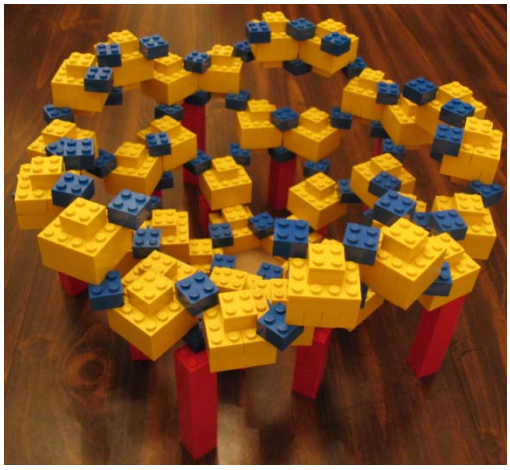




Level 5 added: 10 atoms, 20 2x2 linkers

NOTE: The pattern of atoms in Level 5 is similar to that of Level 4, only rotated by 36°.
Levels 4 and 5 contain the “equator” of the structure and should make as uniform of a ring together as possible.



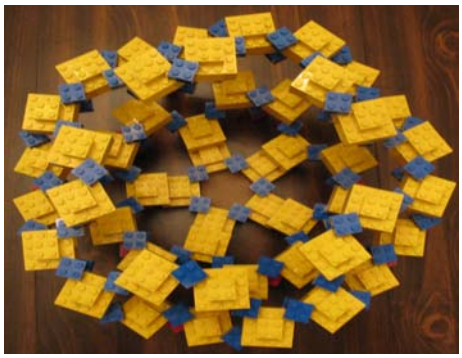


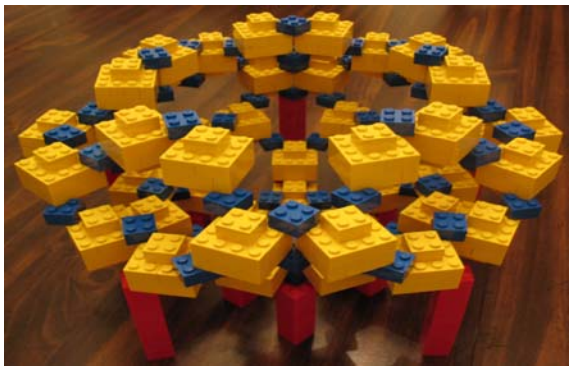
Levels 4 and 5
together make a ring

Modifications to make C_{70} are described on the last page.

Level 6 added: 10 atoms, 10 2x2 linkers

NOTE: The pattern of atoms in Level 6 is similar to that of Level 3, only rotated by 36°.

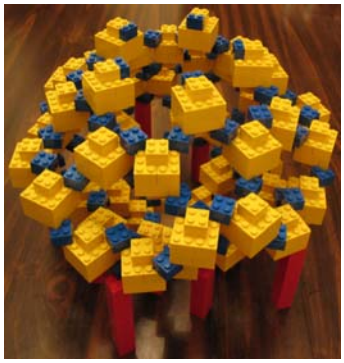




Level 7 added: 5 atoms, 10 2x2 linkers, 5 1x2 linkers

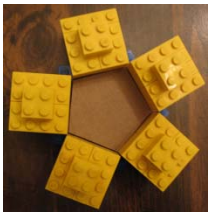
NOTE: It helps to add atoms as the units shown. The pattern of atoms in Level 7 is similar to that of Level 2, only rotated by 36°.

One atom
and 3 linkers

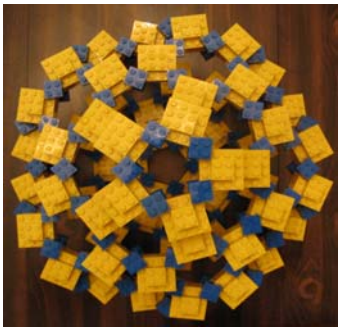


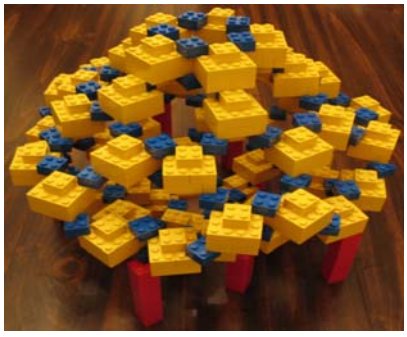
Level 8 added: 5 atoms, 10 2x2 linkers

NOTE: It helps to add this level by building a 5-atom ring and then adding the entire level at once. The level should just be able to rest in place, but fastening this level down to Level 7 makes for a stronger and better-looking structure. The pattern of atoms in Level 8 is similar to that of Level 1, only rotated by 36°.



A template
can help
build the
pentagon

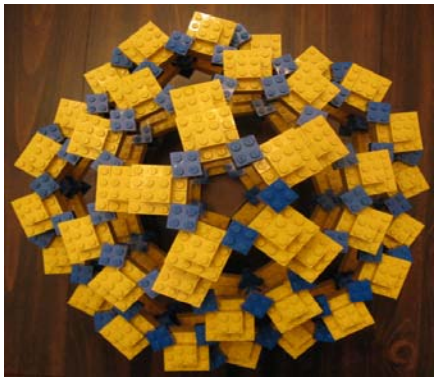


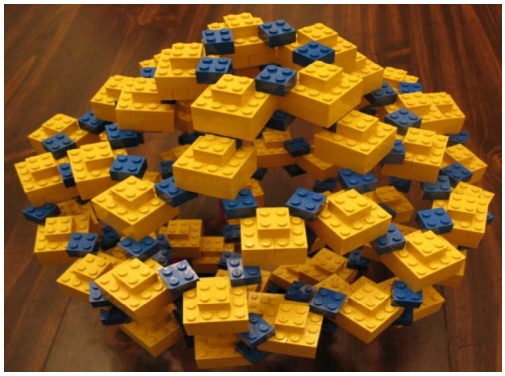


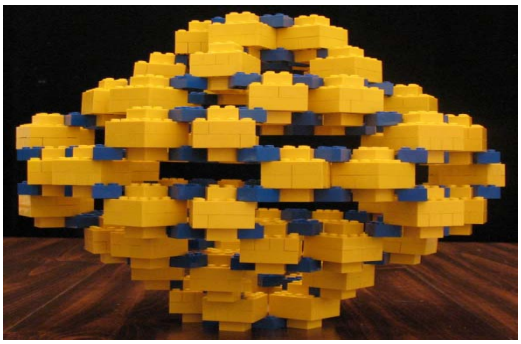
<u>This model (C_{60}) requires:</u>
240 yellow 2x4 bricks
120 yellow 2x2 bricks
90 red 2x2 bricks
110 blue 2x2 bricks
10 blue 1x2 bricks

To make C_{70}, add a Level "5 and a half": 10 atoms, 20 2x2 linkers

This level would look like Level 4. If this extra level is used, Levels 6, 7, and 8 would not be rotated by 36° from Levels 3, 2, and 1.





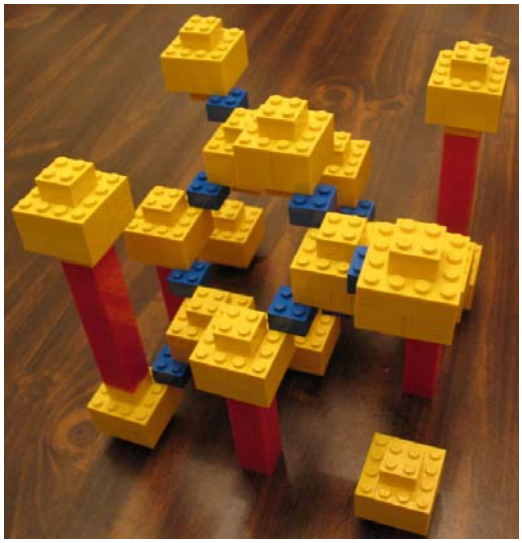


Remember that these structures are fragile.

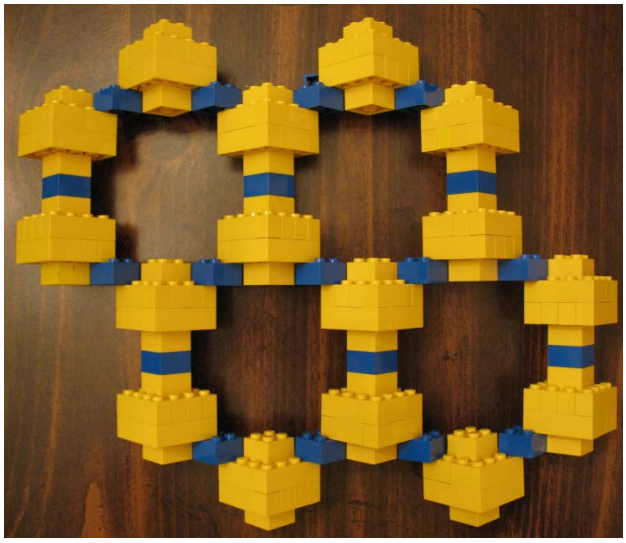
This model (C_{70}) requires:

280 yellow 2x4 bricks
140 yellow 2x2 bricks
90 red 2x2 bricks
130 blue 2x2 bricks
10 blue 1x2 bricks

Diamond and graphite models with linking bricks between the atoms can also be made for comparison to the fullerenes.



Diamond

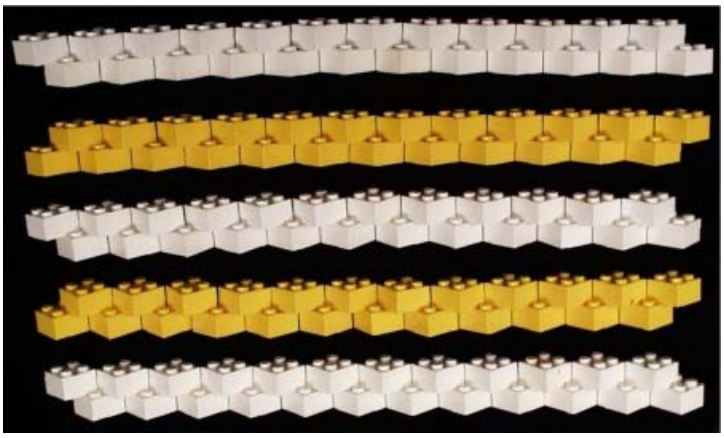


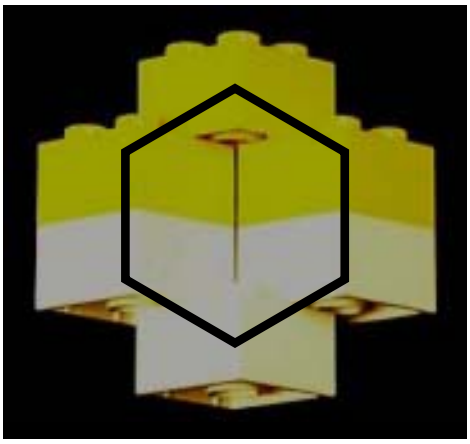
Graphite

Buckytubes
(whole atoms)

Carbon nanotubes, also known as buckytubes, can be thought of as a rolled-up graphite sheet. A simple representation of a flat graphite sheet is shown below. (For more sophisticated models of graphite, see the graphite building instructions.)

To build a simple graphite structure, build corner-connected chains of 2x2 bricks. Then stack several chains as shown.

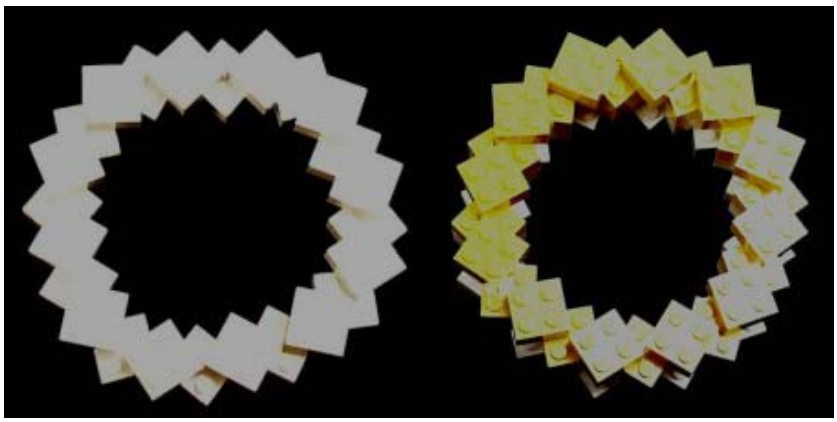


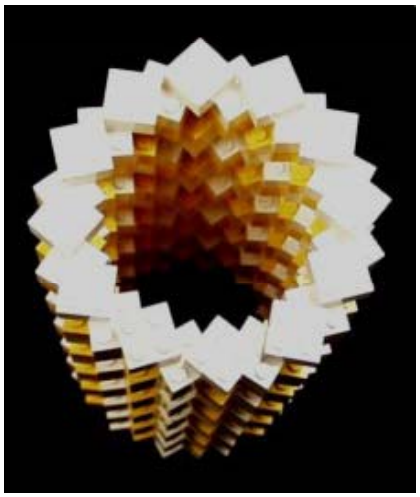


These six 2 peg x 2 peg bricks represent a hexagon of carbon atoms, a fundamental part of graphite and buckytube structure. The different colors are used simply to distinguish individual bricks (atoms).

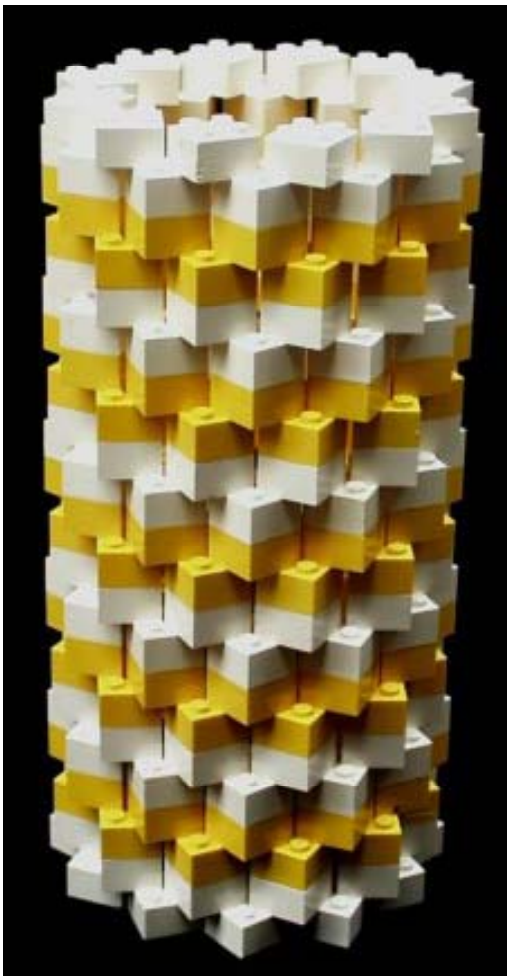
<u>This model requires:</u>
Approximately 264
2x2 bricks

Building the graphite structure above into a tube makes a portion of a buckytube structure.



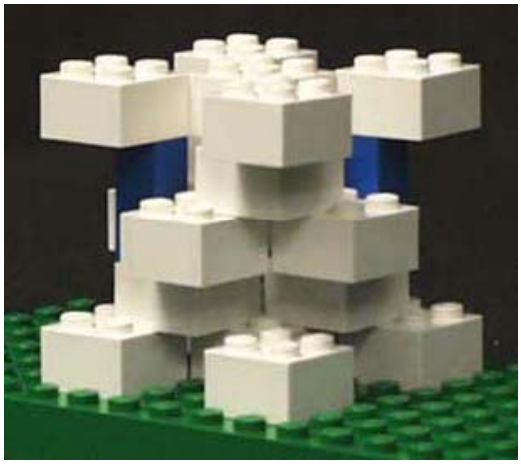


One chain Two chains Eleven chains



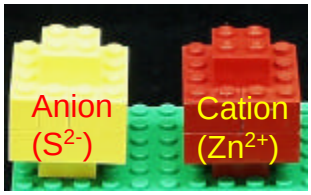
If each brick represents a carbon atom, then in real life this tube would be about a nanometer in diameter.

Note how different the graphite and buckytube structures are from the diamond structure. (For more sophisticated models of diamond, see the diamond building instructions.)

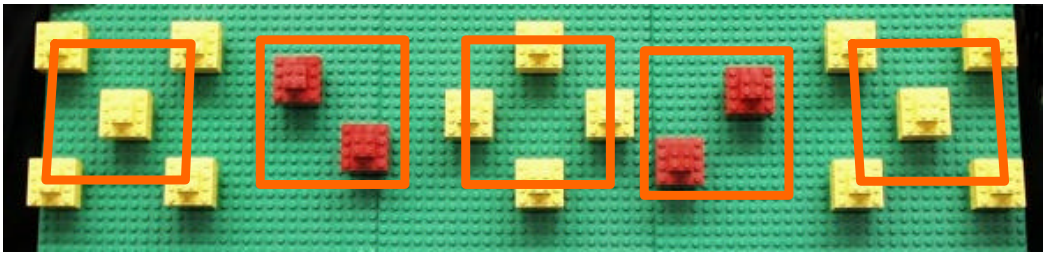


Zinc Blende

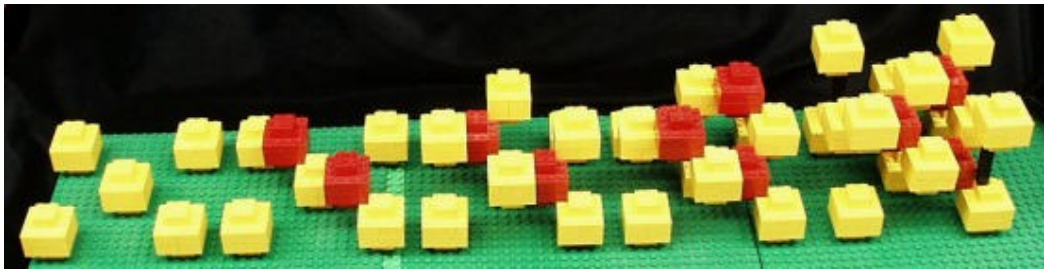
LEGO unit representing ions in this structure:



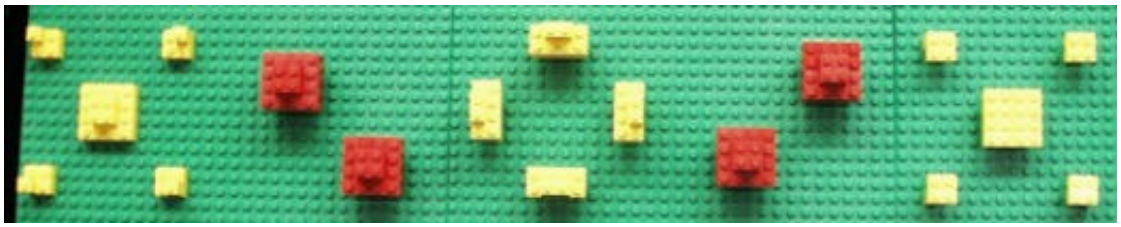
Whole ions:



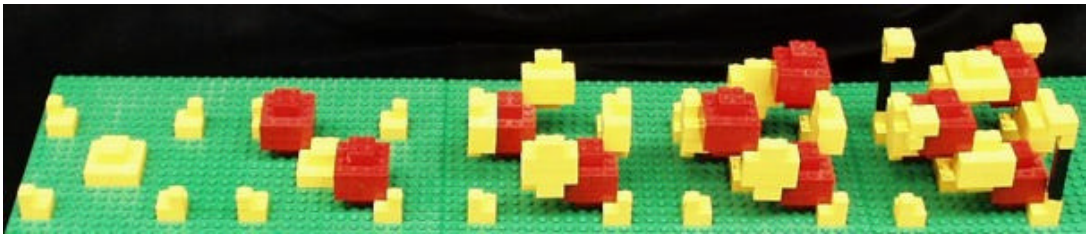
Z=0 Z=¼ Z=½ Z=¾ Z=1



Unit cell:

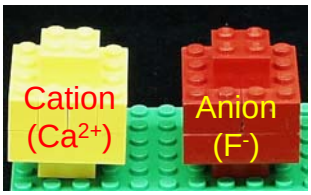


Z=0 Z=¼ Z=½ Z=¾ Z=1

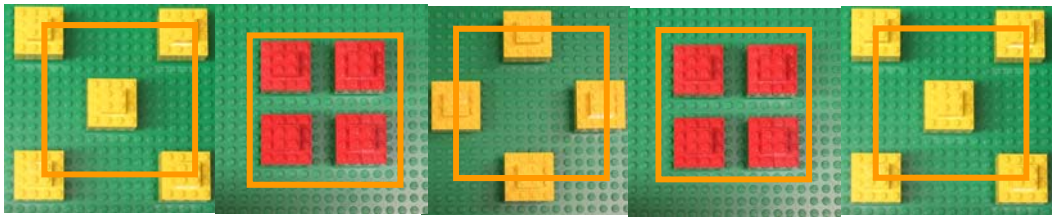


Fluorite

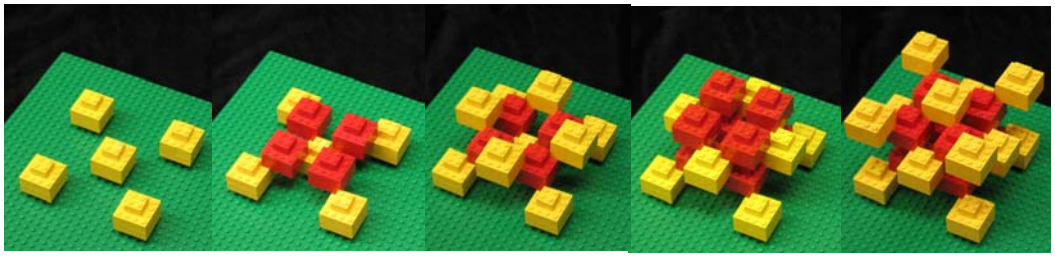
LEGO unit representing ions in this structure:



Whole ions:



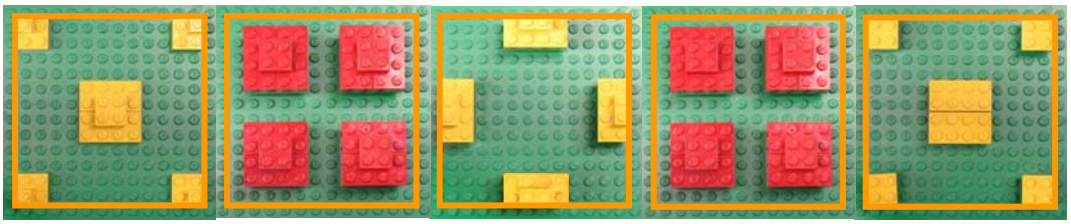
Z=0 **Z=¼** **Z=½** **Z=¾** **Z=1**



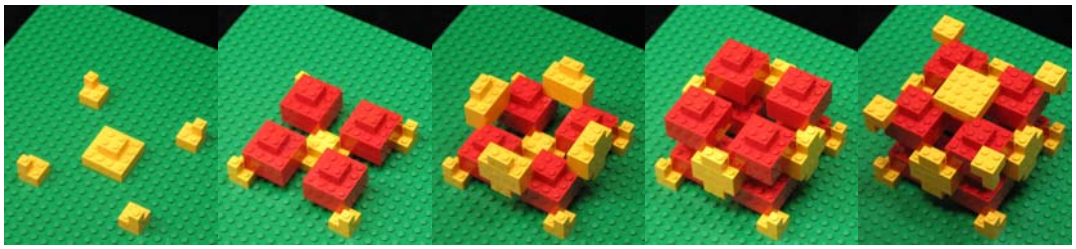
This model Whole ion requires:
56 yellow 2x4 bricks
28 yellow 2x2 bricks
32 red 2x4 bricks
16 red 2x2 bricks

This model Unit cell requires:
12 yellow 2x4 bricks
10 yellow 2x2 bricks
8 yellow 1x2 bricks
8 yellow 1x1 bricks
32 red 2x4 bricks
16 red 2x2 bricks

Unit cell:

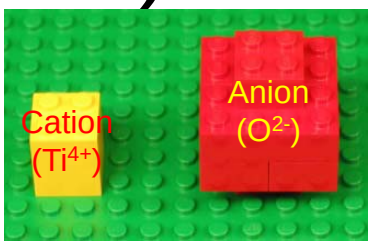


Z=0 **Z=¼** **Z=½** **Z=¾** **Z=1**

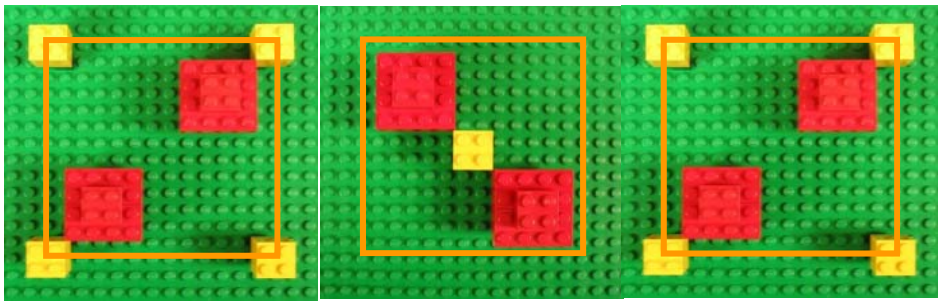


TiO_2 (rutile form)

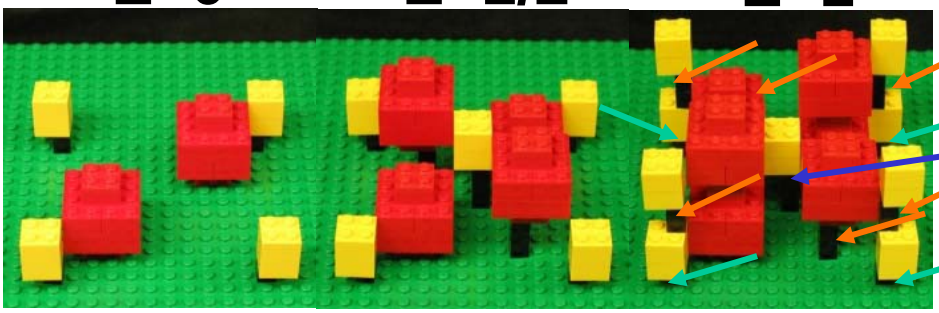
LEGO units representing ions in this structure:



Whole ions:



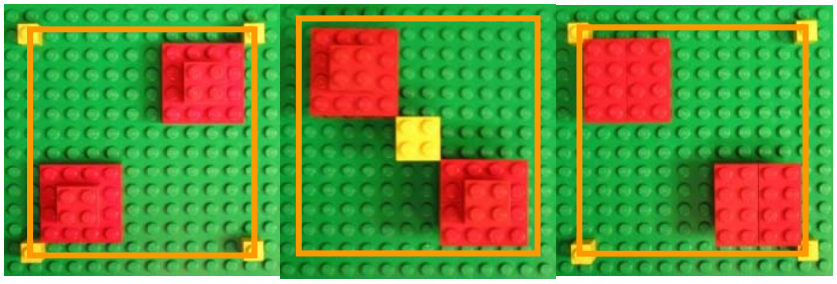
Z=0 **Z=1/2** **Z=1**



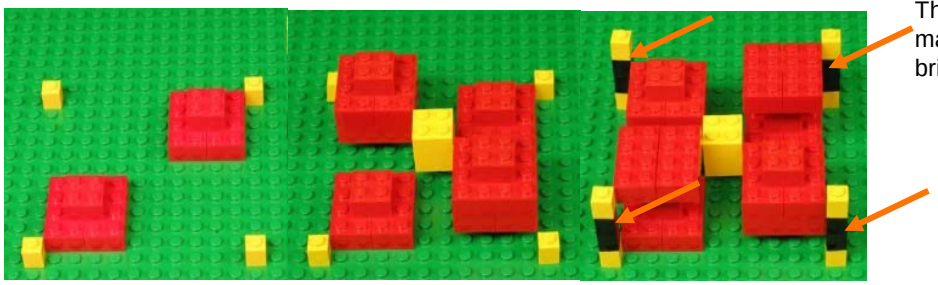
<u>This model Whole ion requires:</u>
17 black 1x1 bricks
18 yellow 2x2 bricks
24 red 2x4 bricks
12 red 2x2 bricks

<u>This model Unit cell requires:</u>
6 yellow 1x1 bricks
2 yellow 2x2 bricks
8 black 1x1 bricks
8 red 2x2 bricks
16 red 2x4 bricks

Unit cell:

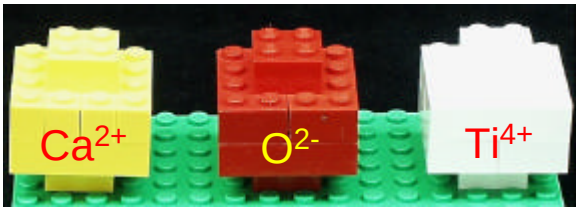


Z=0 **Z=1/2** **Z=1**

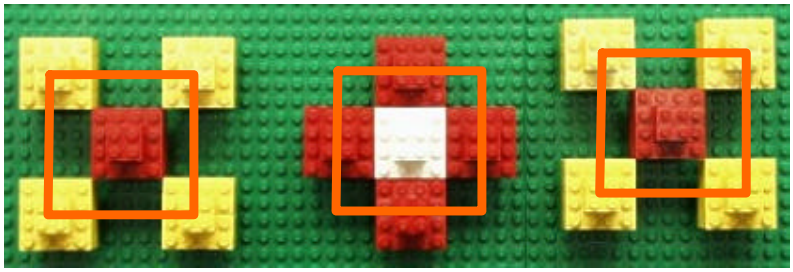


Perovskite: $CaTiO_3$

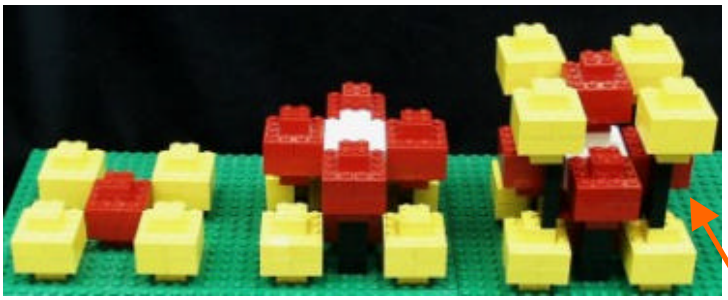
LEGO units representing ions in this structure:



Whole ions:

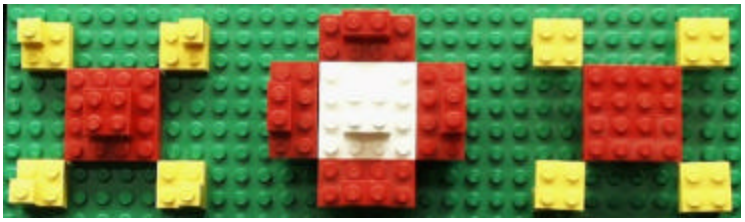


Z=0 **Z=½** **Z=1**

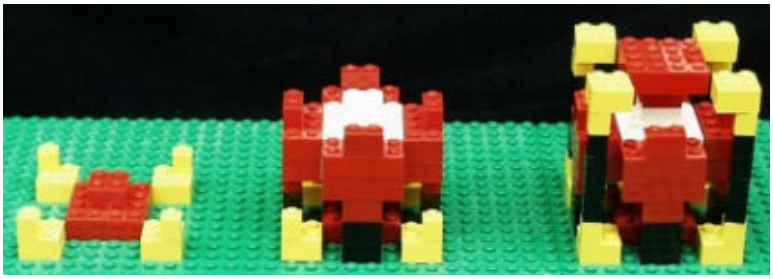


These are supports made from four 1x1 bricks.

Unit cell:

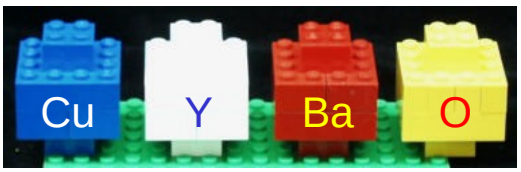


Z=0 **Z=½** **Z=1**



$YBa_2Cu_3O_7$ (whole ions)

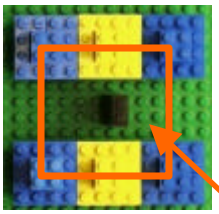
LEGO units representing ions in this structure:



A mixture of Cu^{2+} and Cu^{3+},Y^{3+}, Ba^{2+} and O^{2-}

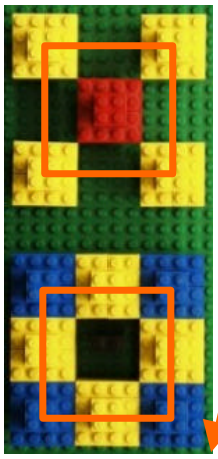
Note: All supports are four 1x2 bricks.

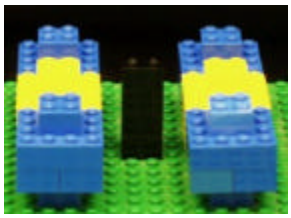
Z= 0

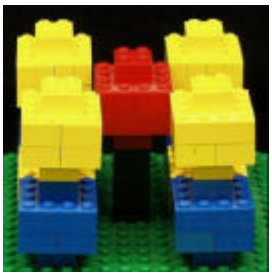


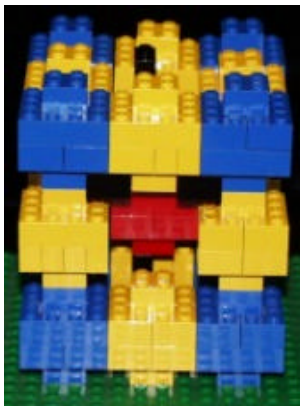
Z= 0.167

Z= 0.333







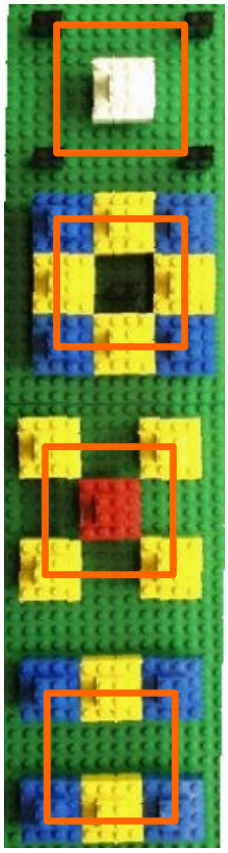


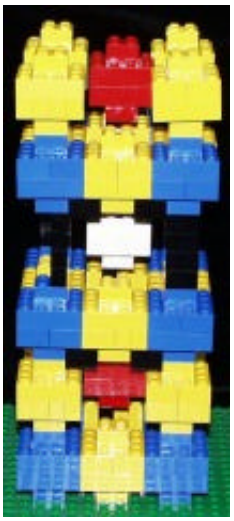
Z= 0.5

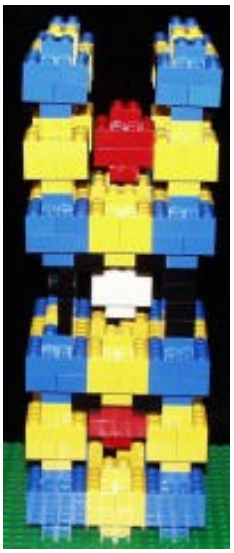
Z= 0.667

Z= 0.833

Z= 1

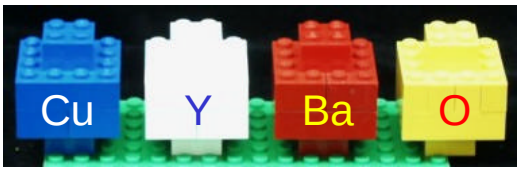




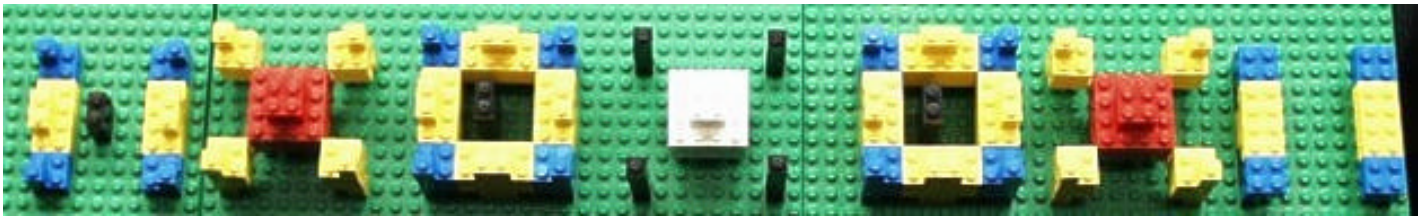


$YBa_2Cu_3O_7$ unit cell

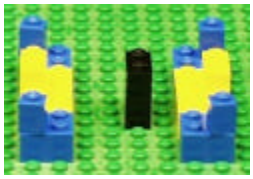
LEGO units representing ions in this structure:

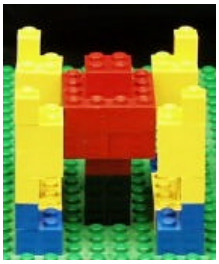


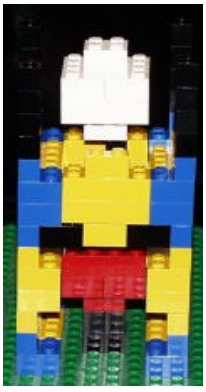
Y^{3+}, Ba^{2+}, O^{2-} and a mixture of Cu^{2+} and Cu^{3+}

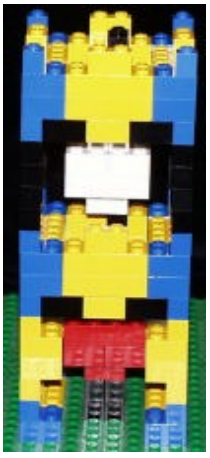


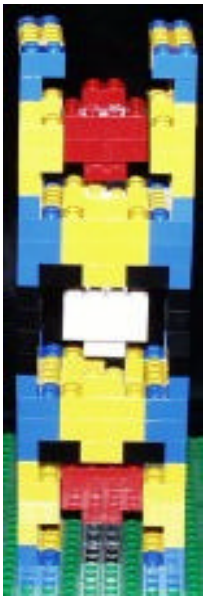
Z=0 **Z=0.167** **Z=0.333** **Z=0.5** **Z=0.667** **Z=0.833** **Z=1**





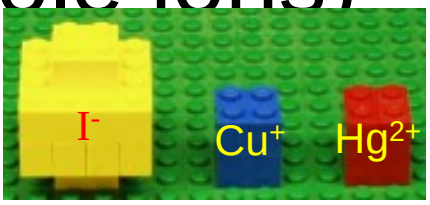




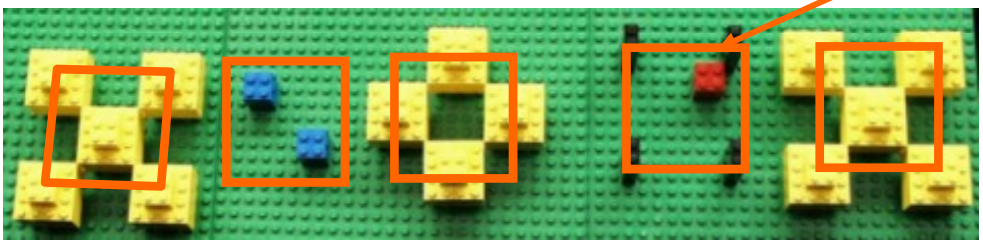


Cu_2HgI_4 low temperature phase (whole ions)

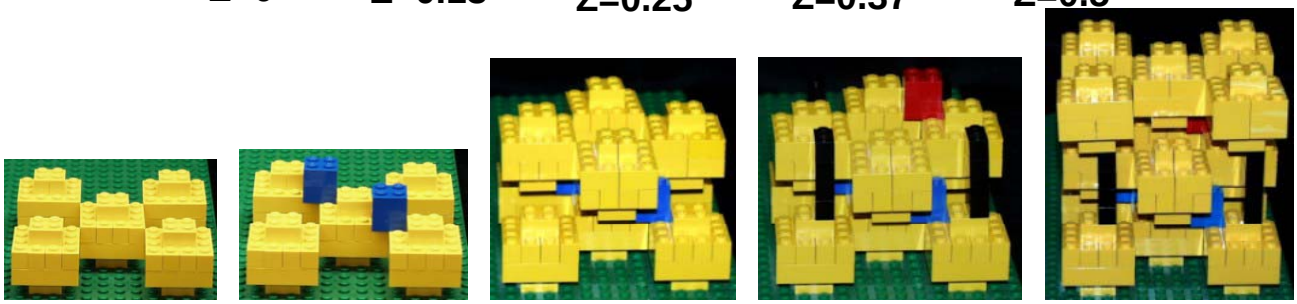
LEGO units representing ions in this structure:

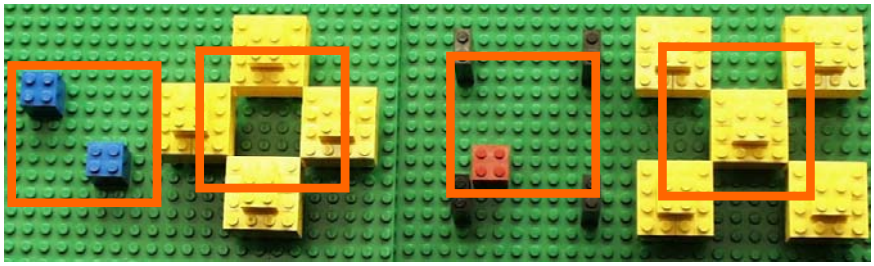


These are supports made from two 1x2 bricks.



Z=0 **Z=0.13** **Z=0.25** **Z=0.37** **Z=0.5**



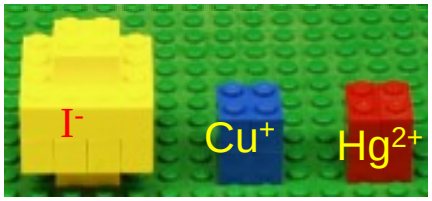


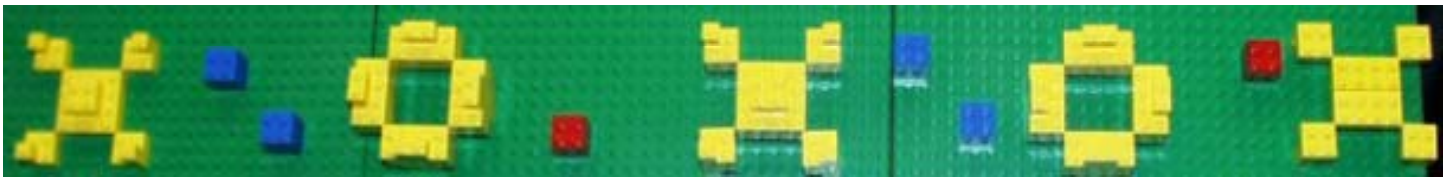
Z=0.63 **Z=0.75** **Z=0.87** **Z=1**

<u>This model requires:</u>
92 yellow 2x4 bricks
46 yellow 2x2 bricks
4 red 2x2 bricks
8 blue 2x2 bricks
16 black 2x1 bricks

Cu_2HgI_4 low temperature phase unit cell

LEGO units representing ions in this structure:

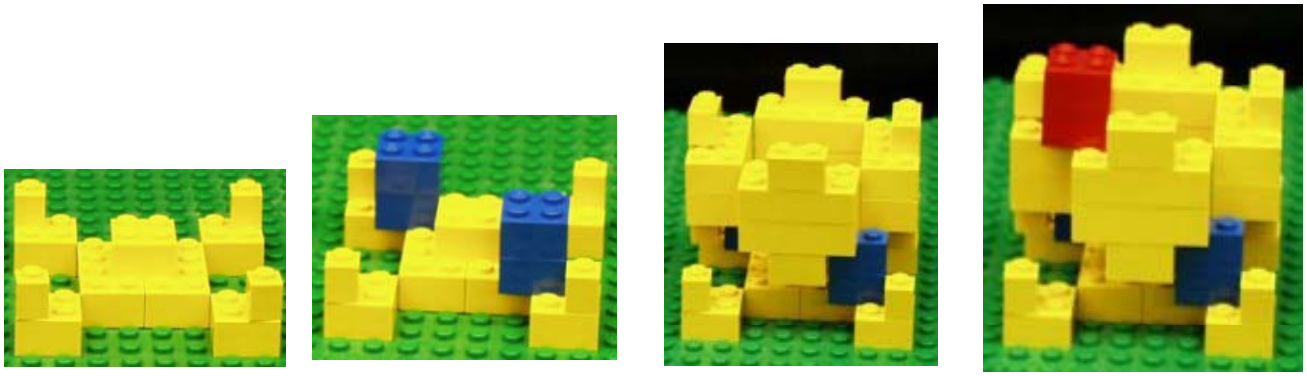


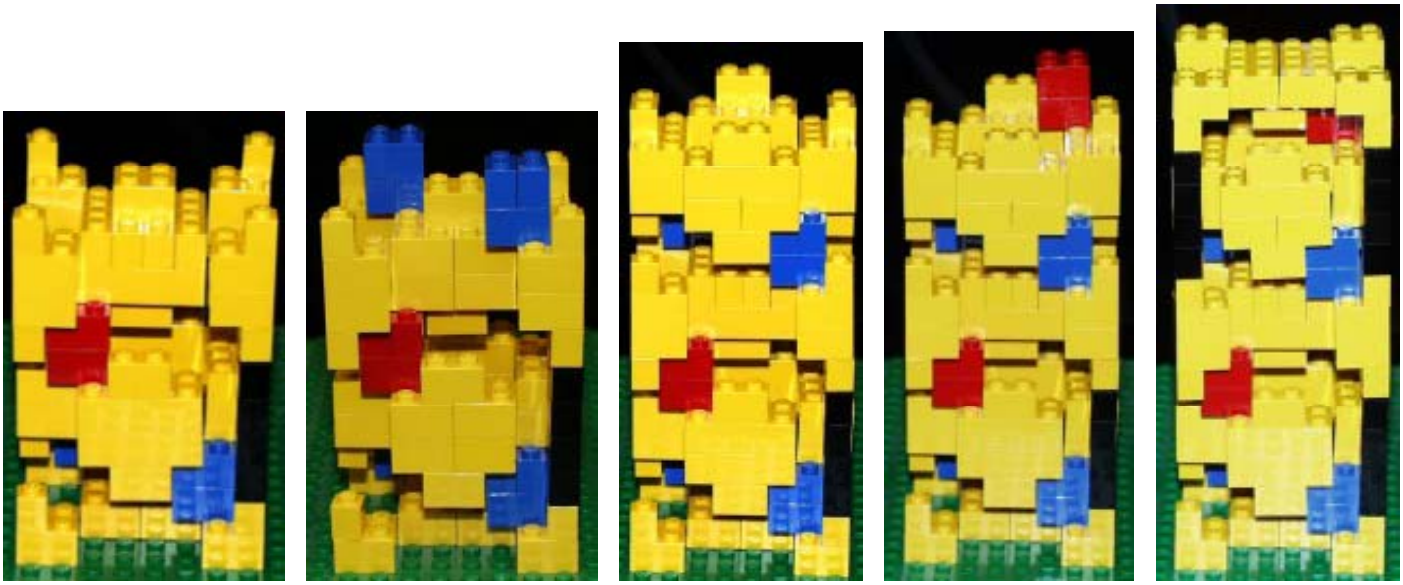


Z=0 **Z=0.13** **Z=0.25** **Z=0.37** **Z=0.5** **Z=0.63** **Z=0.75** **Z=0.87** **Z=1**

This model requires:

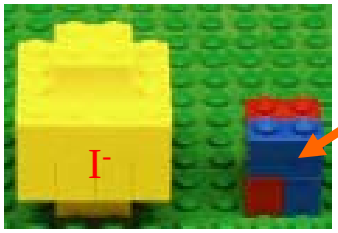
20 yellow 2x4 bricks	4 red 2x2 bricks
10 yellow 2x2 bricks	8 blue 2x2 bricks
8 yellow 1x2 bricks	8 yellow 1x1 bricks



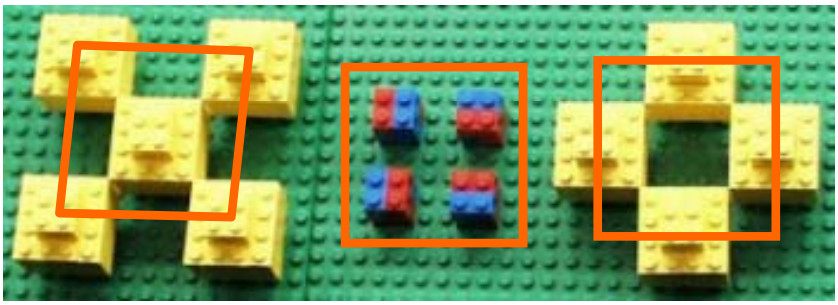


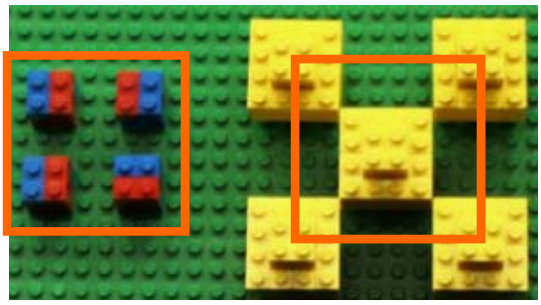
Cu_2HgI_4 high temperature phase (whole ions)

LEGO units representing ions in this structure:



Cu^+,Hg^{2+}, or hole



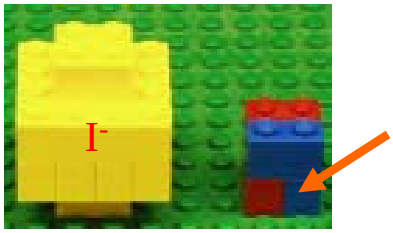


Z=0 **Z=¼** **Z=½** **Z=¾** **Z=1**

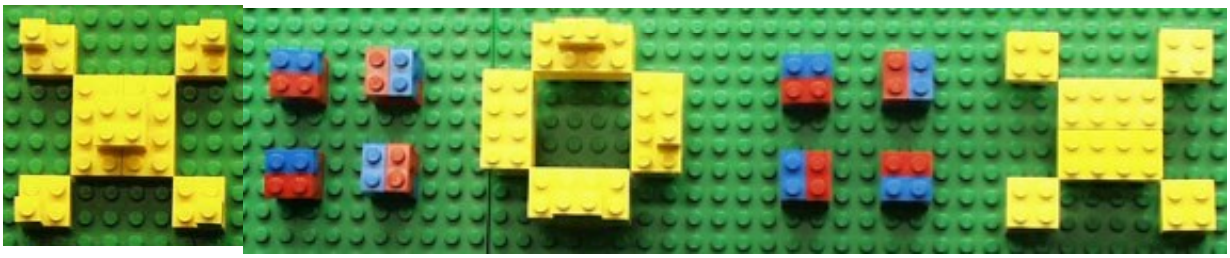
This model requires:
56 yellow 2x4 bricks
28 yellow 2x2 bricks
16 red 1x2 bricks
16 blue 1x2 bricks

Cu_2HgI_4 high temperature phase unit cell

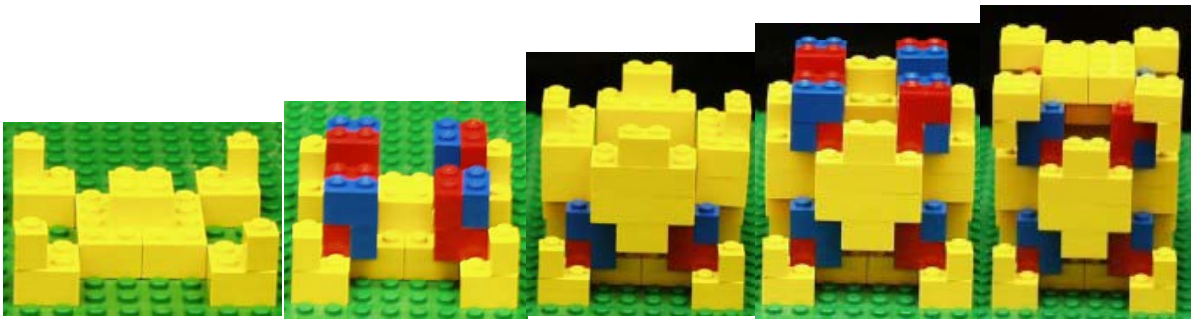
LEGO units representing ions in this structure:



Cu^{+},Hg^{2+}, or hole

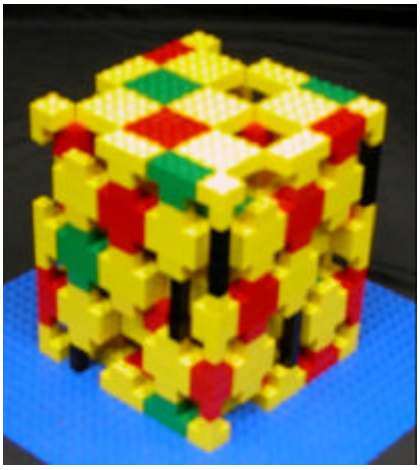


Z=0 **Z=¼** **Z=½** **Z=¾** **Z=1**

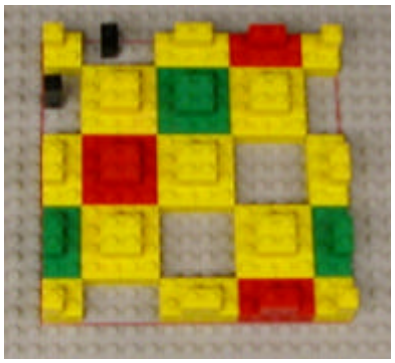
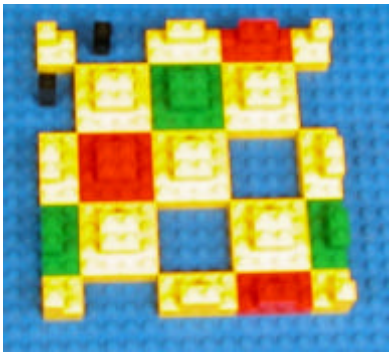
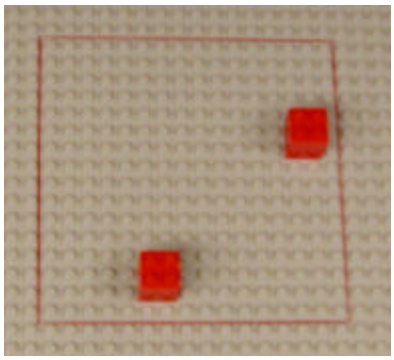
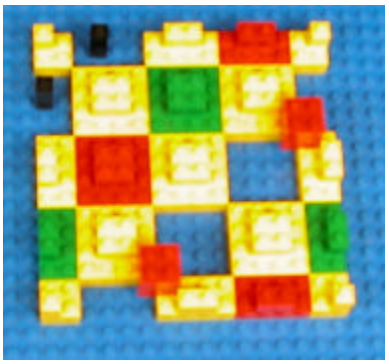
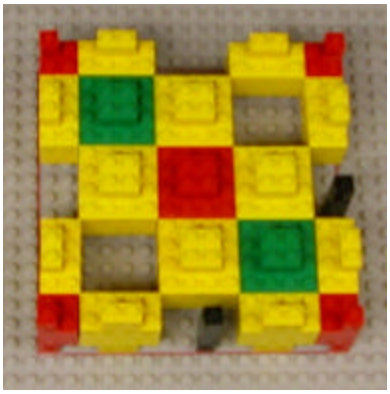


<u>This model requires:</u>
12 yellow 2x4 bricks
10 yellow 2x2 bricks
8 yellow 1x2 bricks
8 yellow 1x1 bricks
16 red 1x2 bricks
16 blue 1x2 bricks

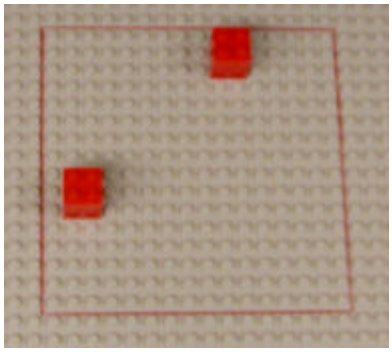
Magnetite (Fe_3O_4) Unit Cell



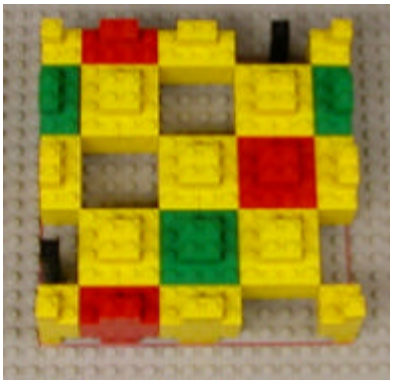
yellow = O^{2-}, red = Fe^{3+}
green = Fe^{2+}, black = spacers

	Layer	Build-up
Z=0		
Z=0.125		
Z=0.25		

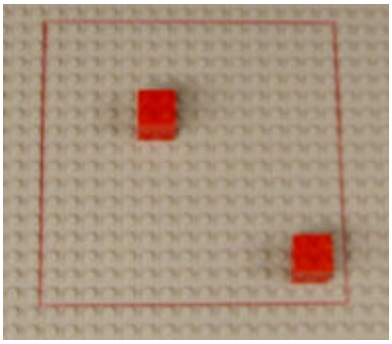
Z=0.375



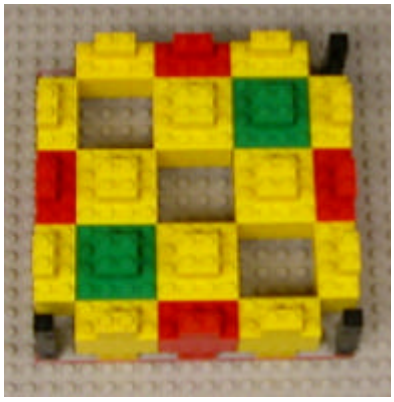
Z=0.5



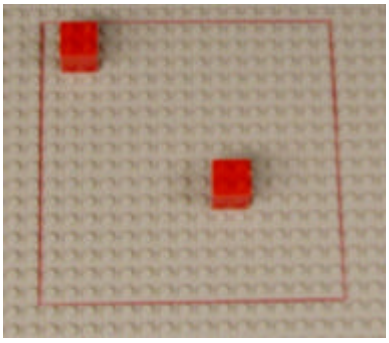
Z=0.625



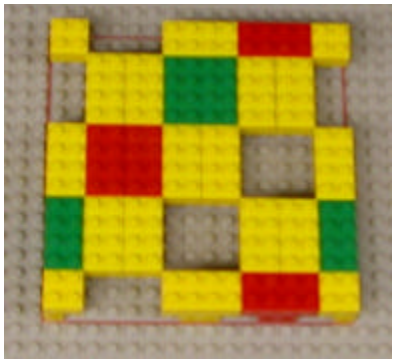
Z=0.75



Z=0.875



Z=1



Bricks required to build structures

Partial atoms

Color	Type (pegs)	Number needed
Yellow	2x4	120
	2x2	52
	1x2	48
	1x1	16
Red	2x4	28
	2x2	30
	1x2	16
	1x1	8
Green	2x4	32
	2x2	12
	1x2	8
Black	1x1	32*
Baseboard	16x16	1

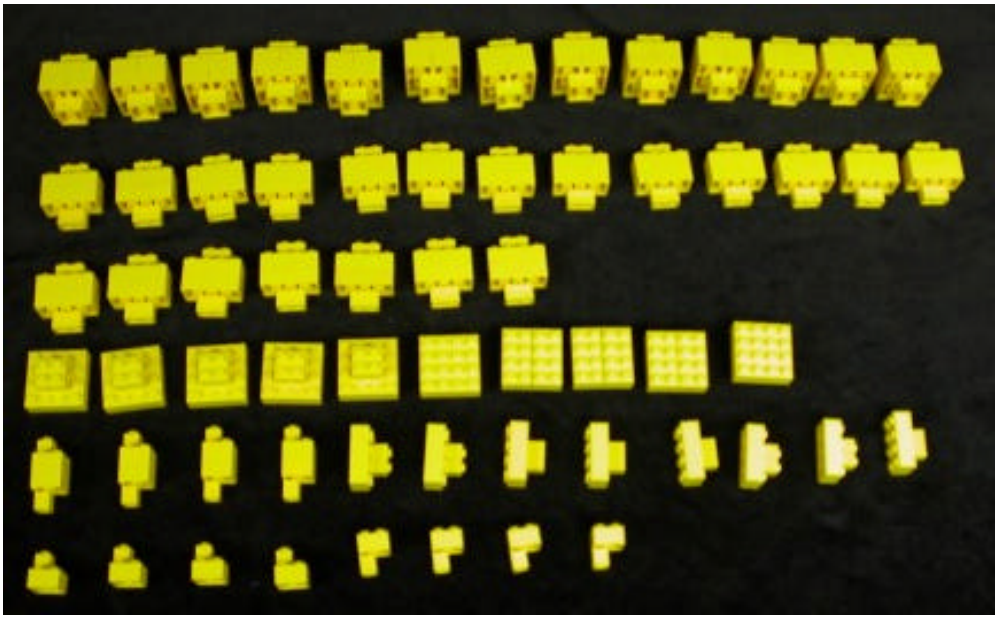
Full atoms (not shown)

Color	Type (pegs)	Number needed
Yellow	2x4	252
	2x2	126
Red	2x4	72
	2x2	52
Green	2x4	52
	2x2	26
Black	1x1	?
Baseboard	18x18	1

*This is a minimum number. The structure will be more sturdy with more support bricks, but the visibility of the interior of the structure will be diminished.

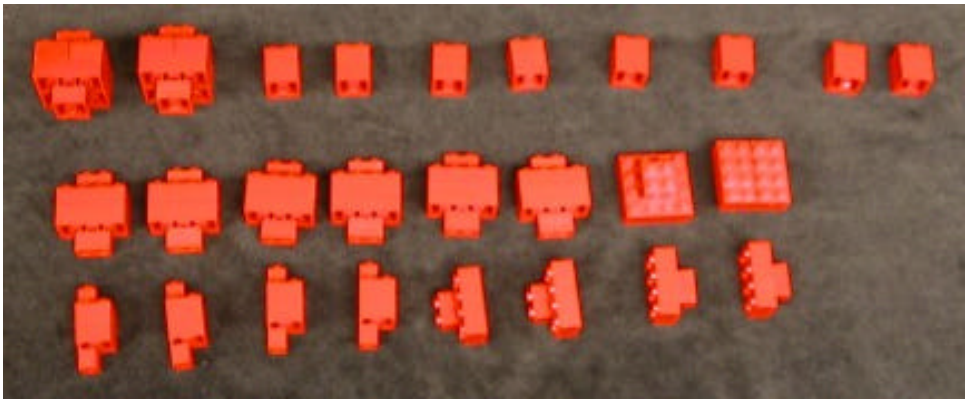
The stoichiometry of magnetite, Fe_3O_4, can be extracted from the unit cell model.

32 total O^{2-} ions



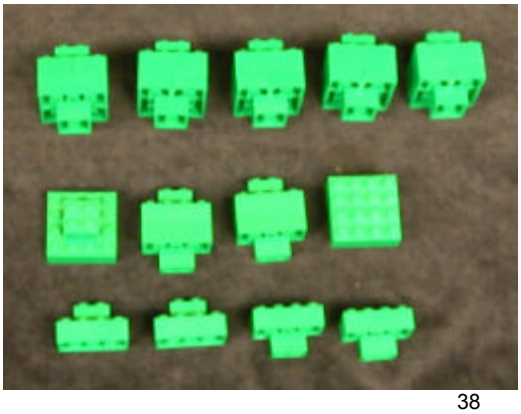
13 whole = 13 ions
30 half = 15 ions
12 quarter = 3 ions
8 eighth = 1 ion
32 total ions

16 total Fe^{3+} ions



10 whole = 10 ions
8 half = 4 ions
8 quarter = 2 ions
16 total ions

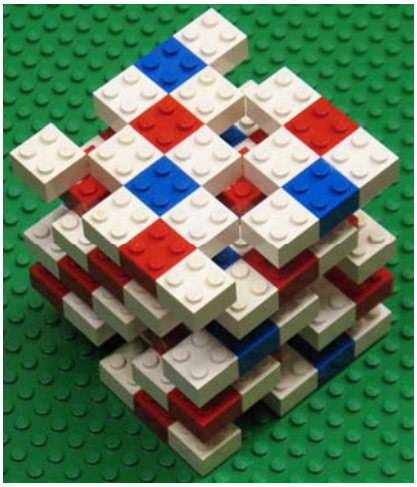
8 total Fe^{2+} ions



5 whole = 5 ions
4 half = 2 ions
4 quarter = 1 ions
8 total ions

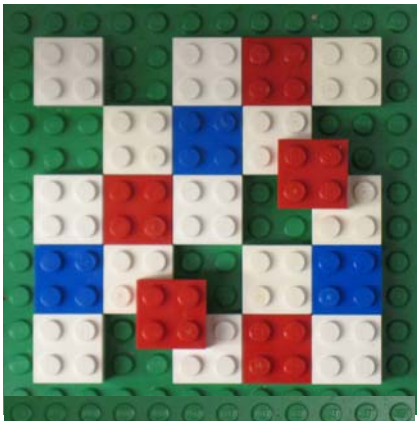
Magnetite (Fe_3O_4) whole small atoms

Fe^{3+}
O^{2-}
Fe^{2+}

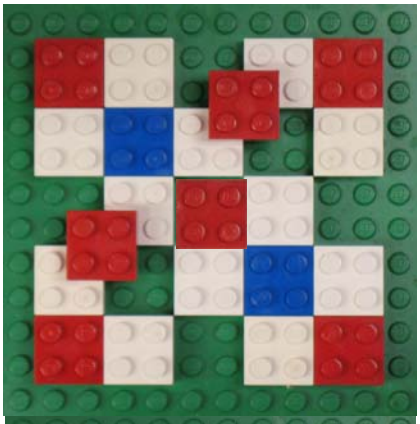


Layer Sequence

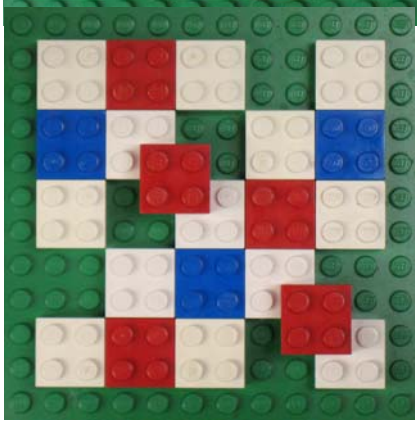
Z = 0 & 0.125



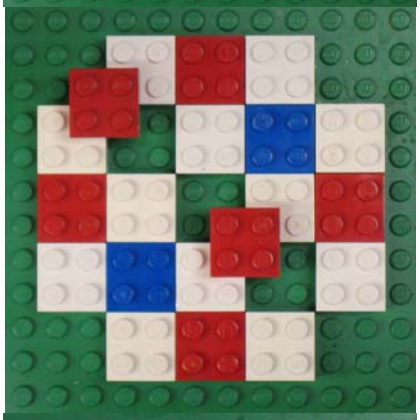
Z = 0.25 & 0.375



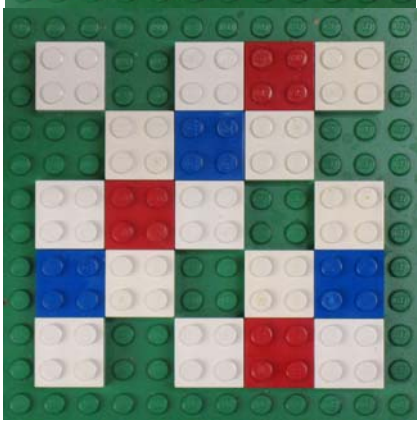
Z = 0.5 & 0.625



Z = 0.75 & 0.875



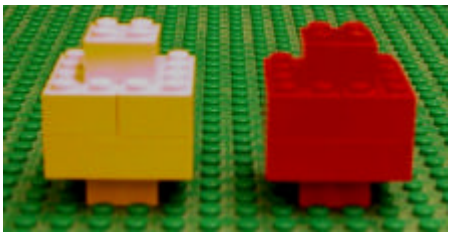
Z = 1

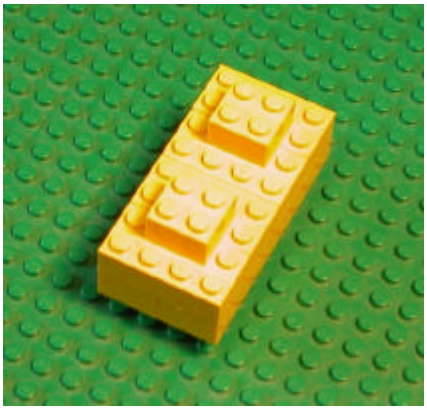


<u>This model requires:</u>
26 red 2x2 bricks
63 white 2x2 bricks
13 blue 2x2 bricks
***If glued, no support necessary

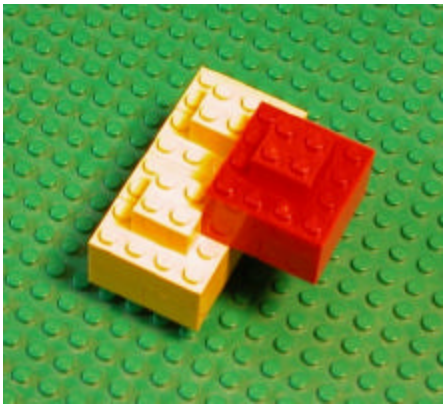
NiTi Low Temperature Martensite Phase (whole atoms; small cell)

LEGO unit representing atoms in this structure: (Different colors represent different elements.)

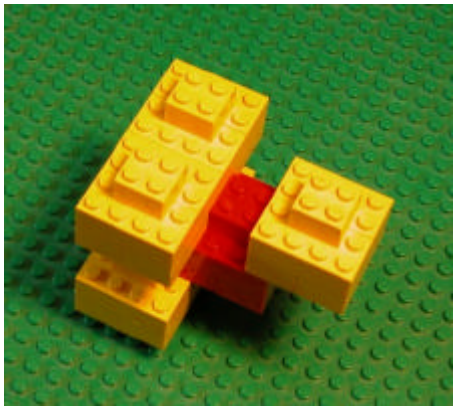




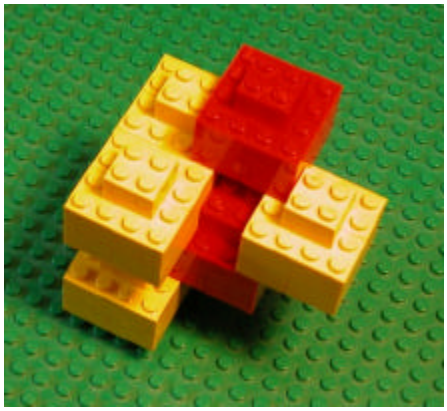
Step 1



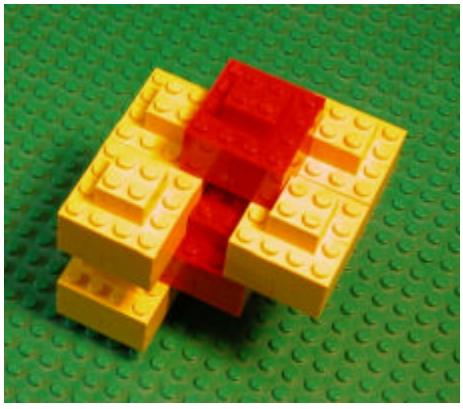
Step 2



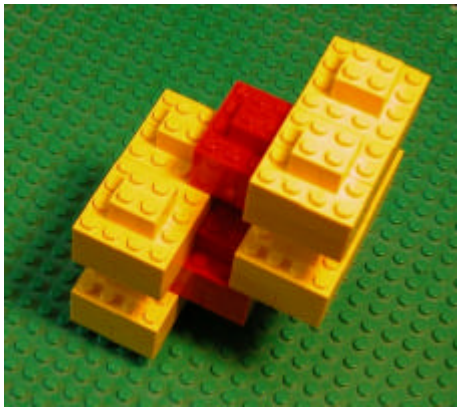
Step 3



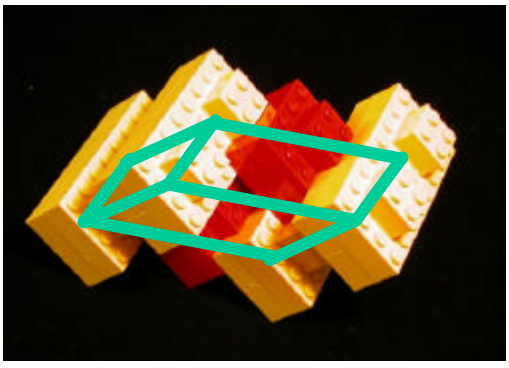
Step 4



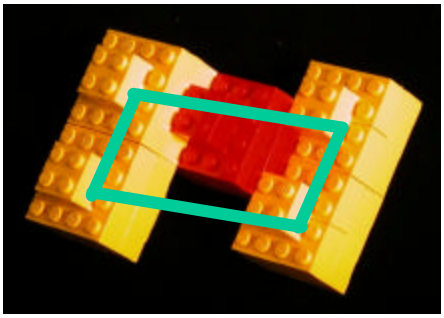
Step 5



Step 6



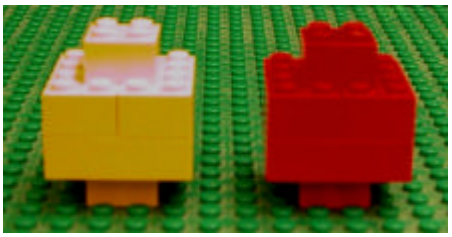
Lines represent approximate boundaries of the unit cell.



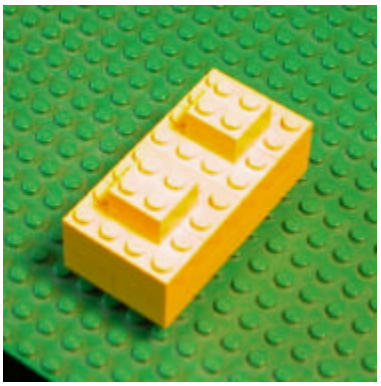
Layers: Z = 0,1

NiTi Low Temperature Martensite Phase (whole atoms; large cell)

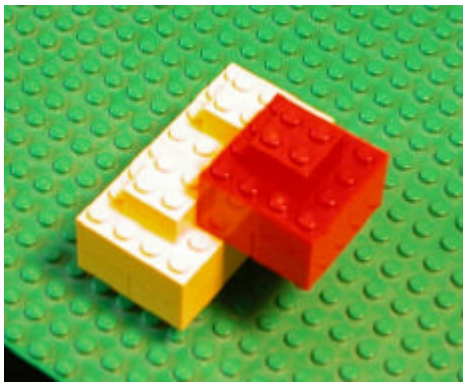
LEGO unit representing atoms in this structure: (Different colors represent different elements.)



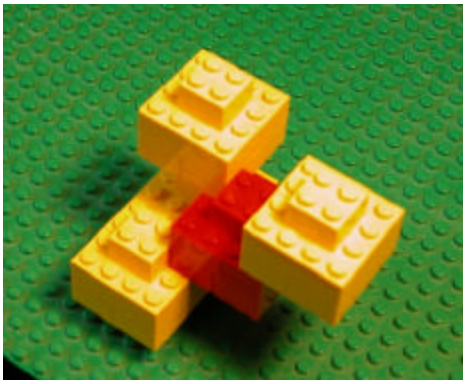
NOTE: The unit cell represented by this structure has atoms that are not parallel to the bottom face of the unit cell. The structure may be built in the following series of steps and then later tilted.



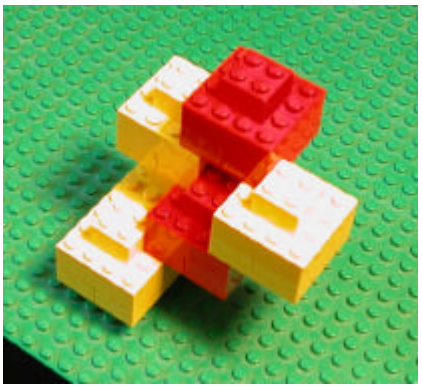
Step 1



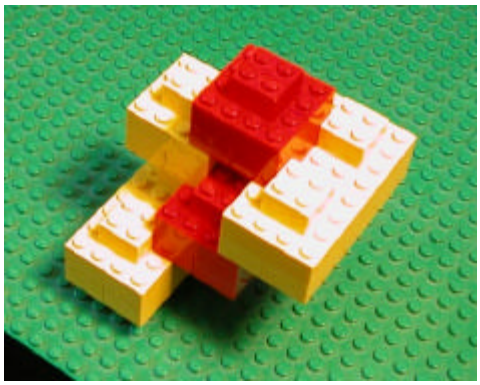
Step 2



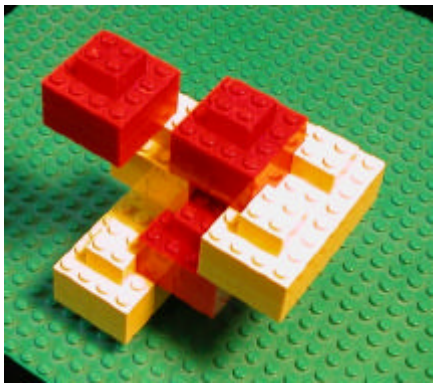
Step 3



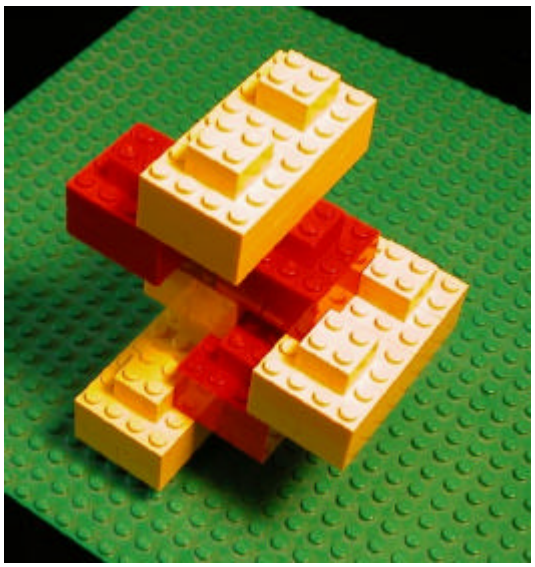
Step 4



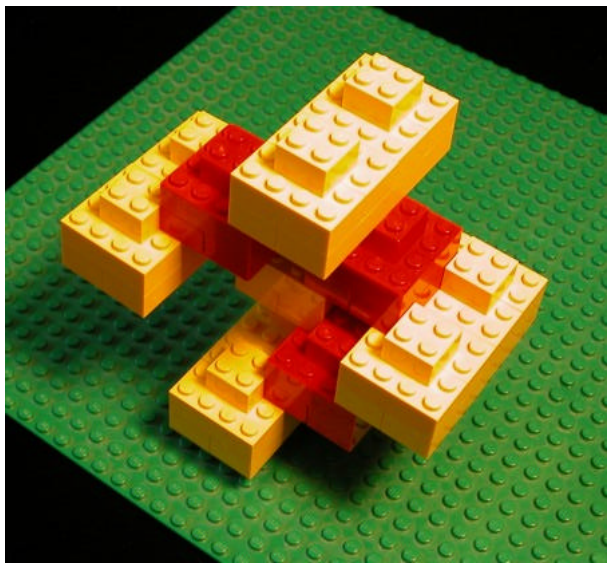
Step 5



Step 6

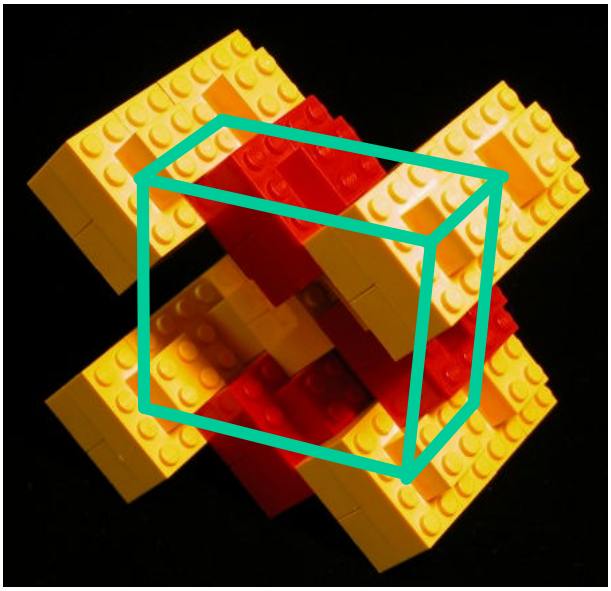


Step 7



Step 8

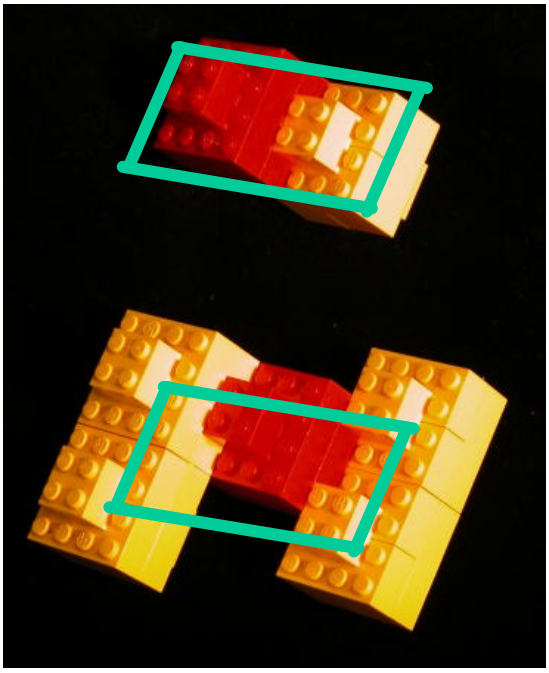
Lines represent approximate boundaries of the unit cell.



Layers:

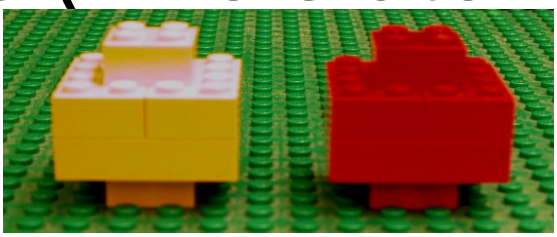
Z = ½

Z = 0,1

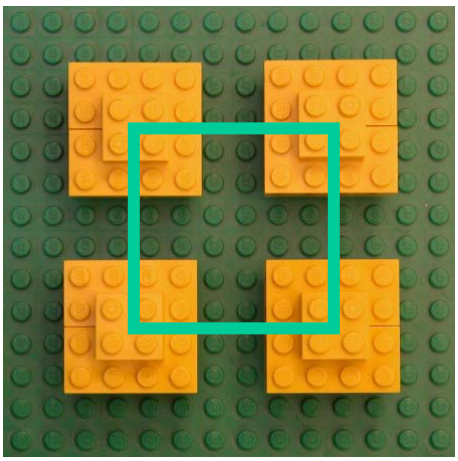


NiTi High Temperature Austenite Phase (whole atoms)

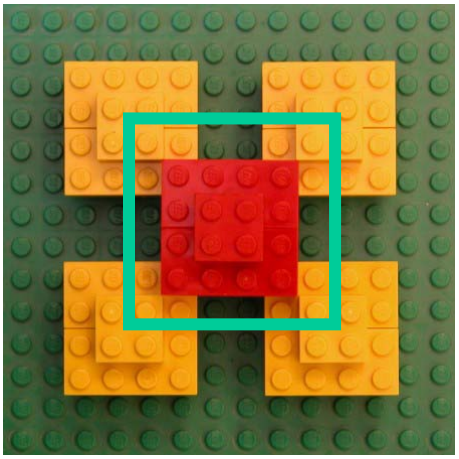
LEGO unit representing atoms in this structure: (Different colors represent different elements.)



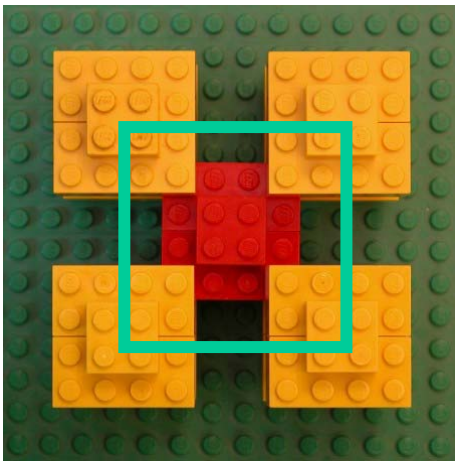
This model requires:
32 yellow 2x4 bricks
16 yellow 2x2 bricks
4 red 2x4 bricks
2 red 2x2 bricks



Z=0

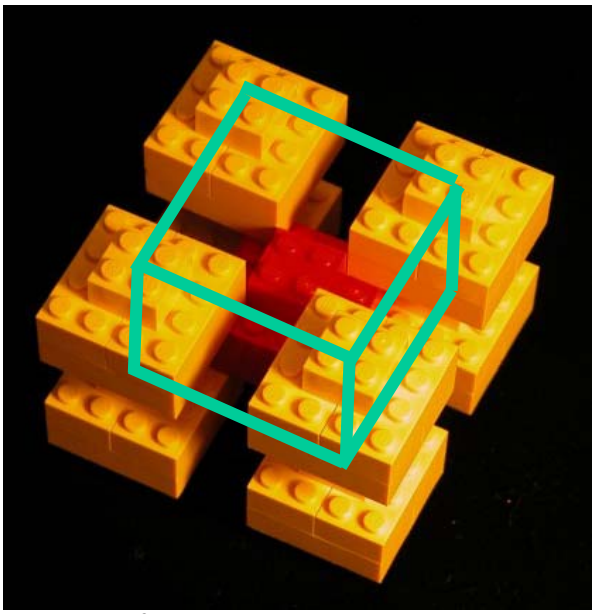


Z=½



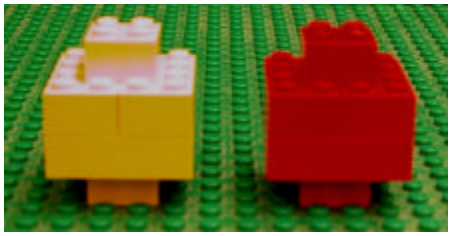
Z=1

Lines represent approximate boundaries of the unit cell.

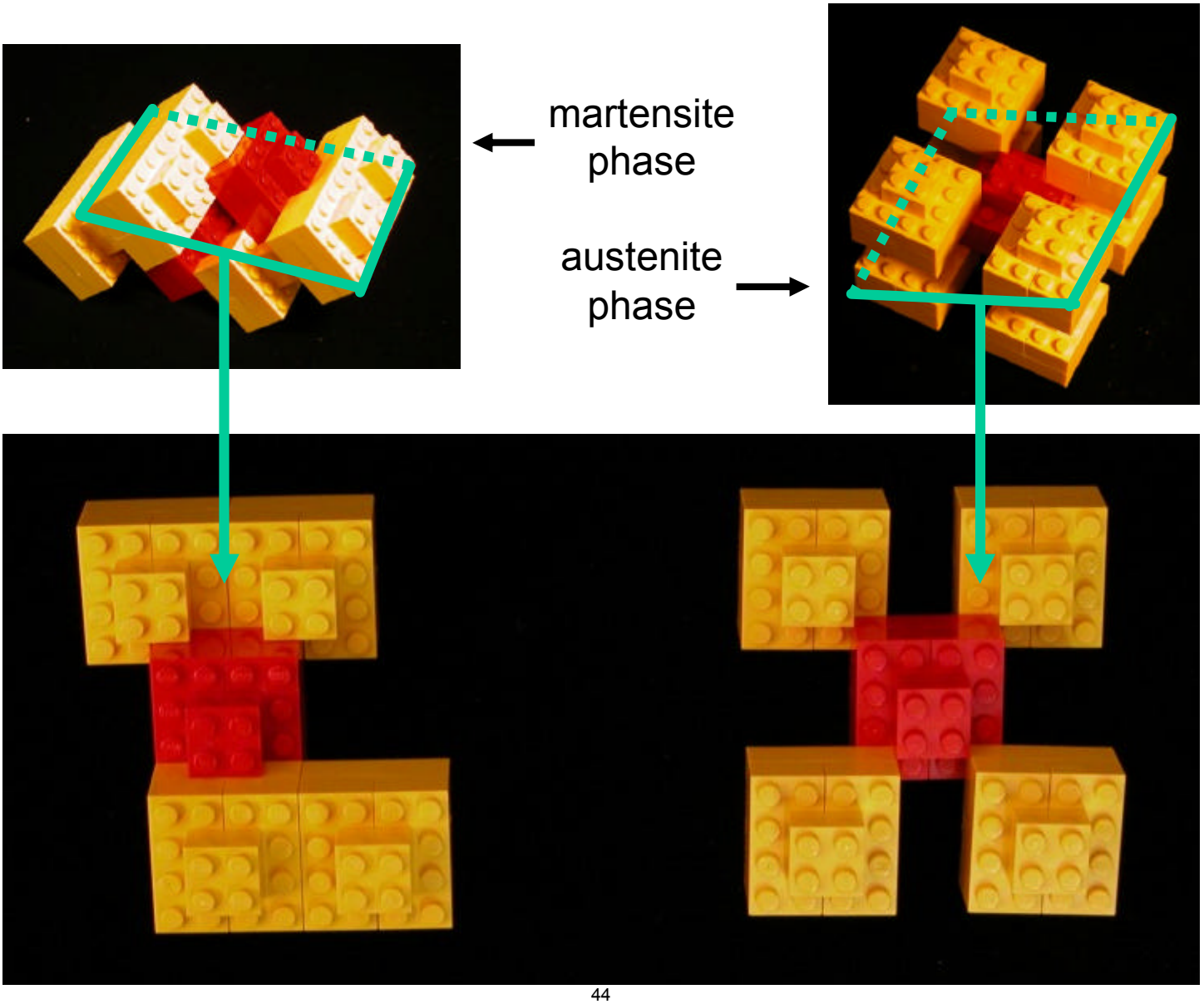


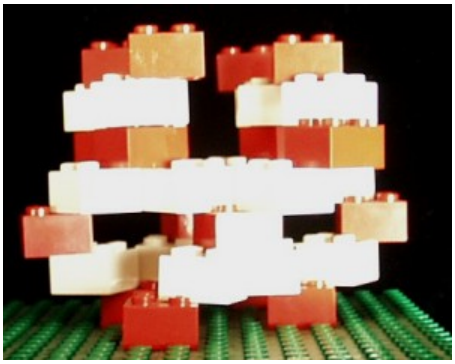
NiTi Low Temperature Martensite Phase vs. High Temperature Austenite Phase

LEGO unit representing atoms in this structure: (Different colors represent different elements.)



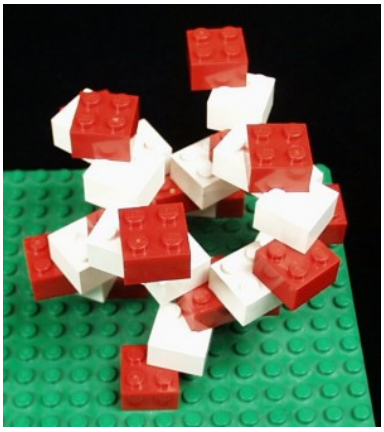
The structures can be represented as planes of Ni and Ti atoms. The lines represent the planes of atoms.



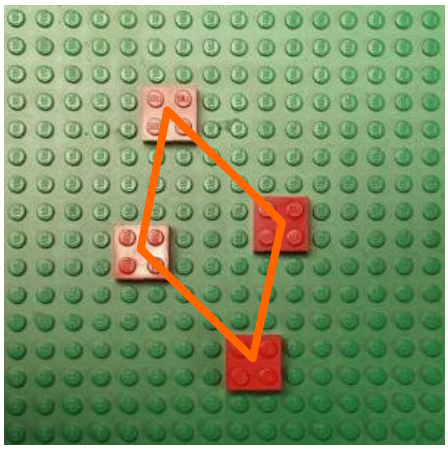


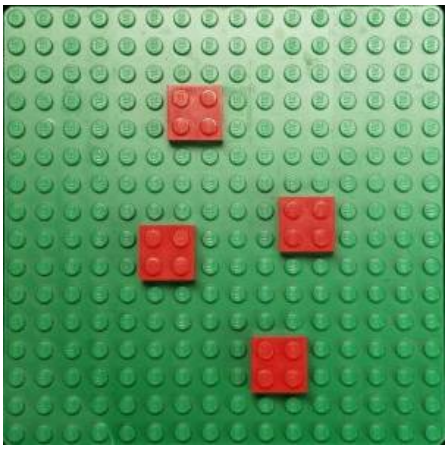
red = Si white = O

Quartz (whole atoms)

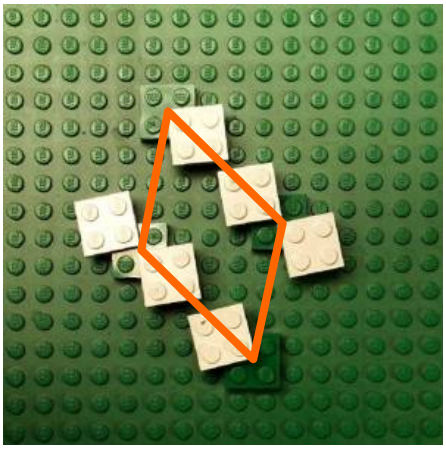


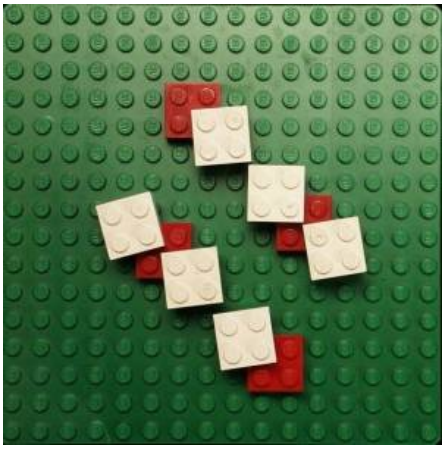
Z=
0,1



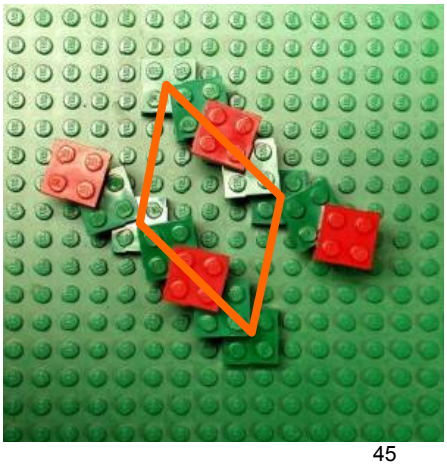


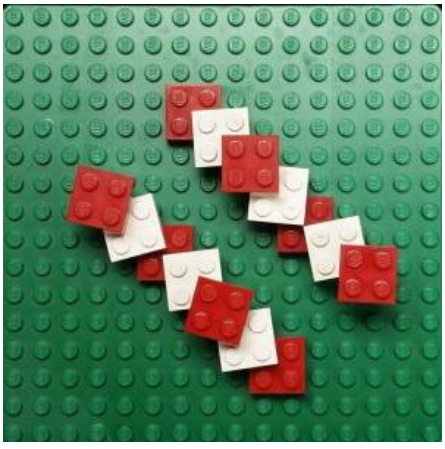
Z=
0.167,
0.833



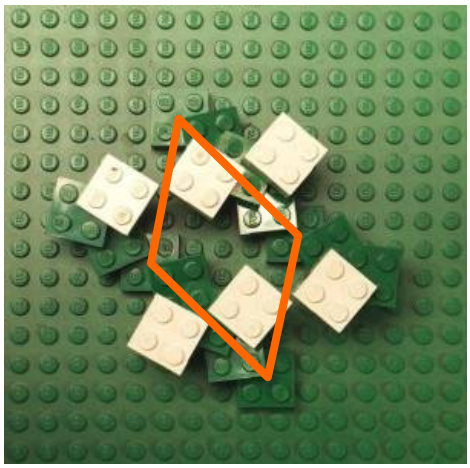


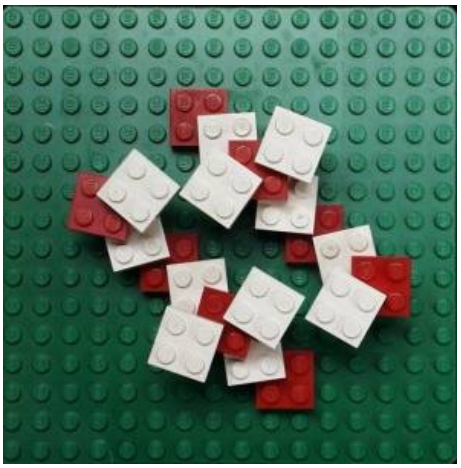
Z=
0.333,
0.667



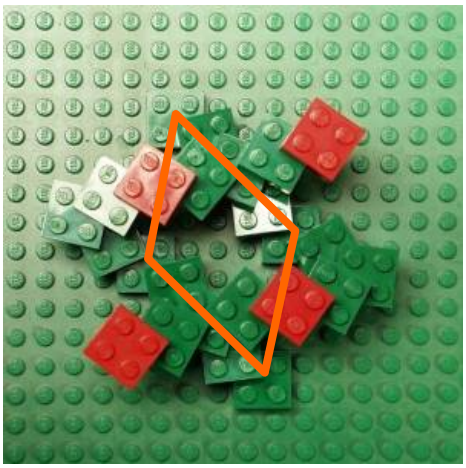


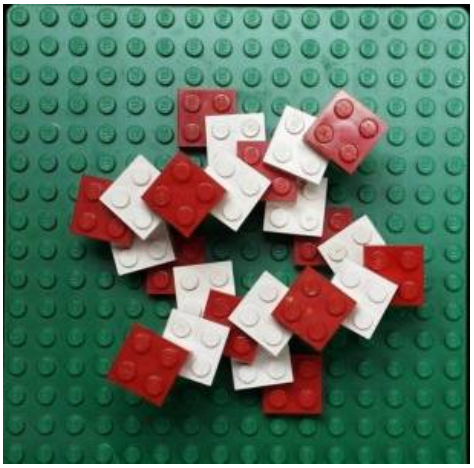
Z=
0.5



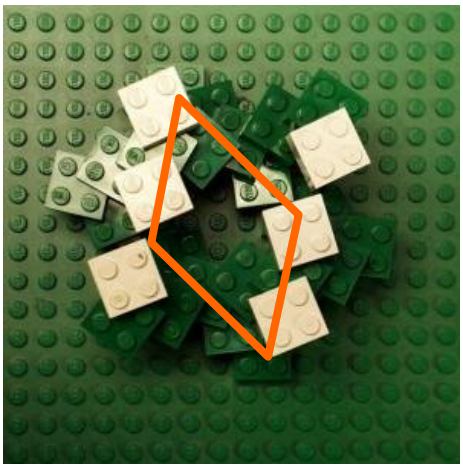


Z=
0.333,
0.667

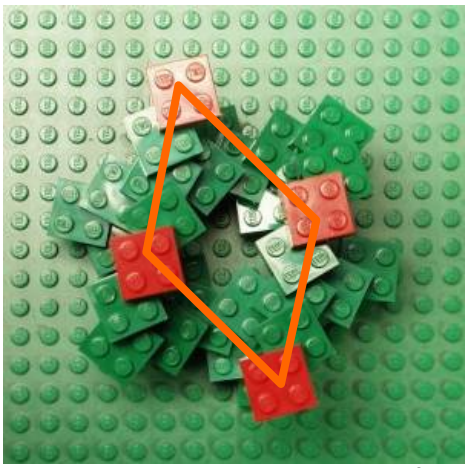




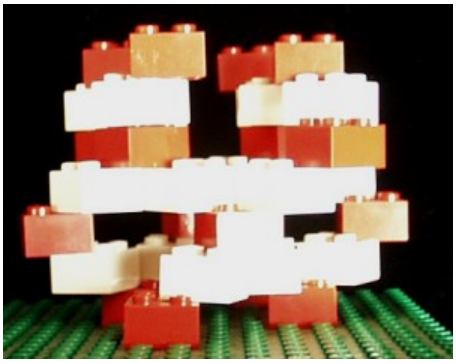
Z=
0.167,
0.833



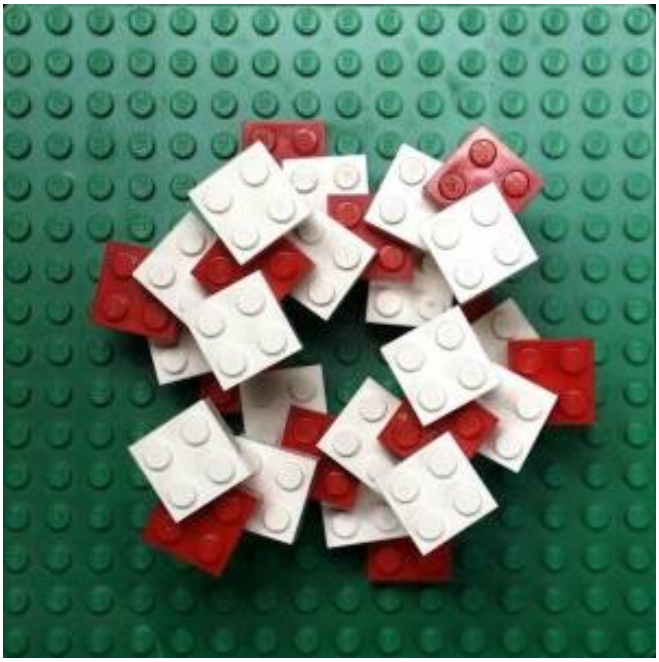
Z=
0,**1**



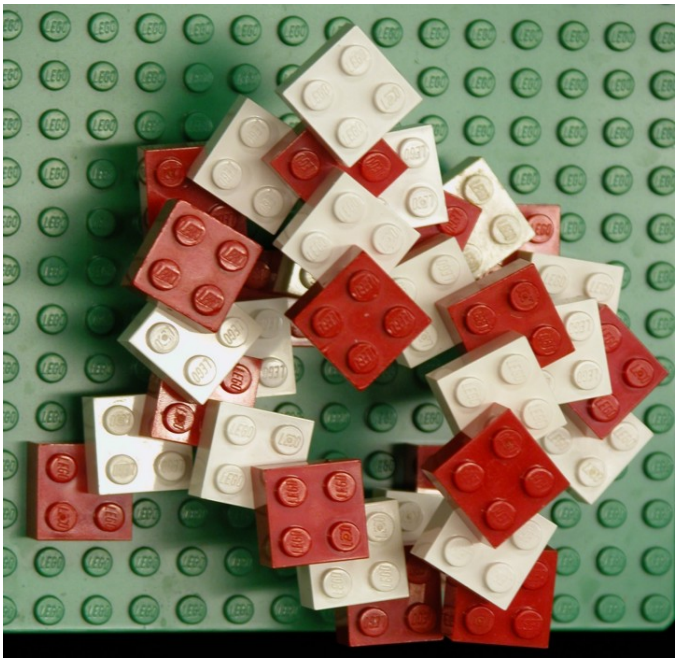
Crystalline vs. Amorphous Quartz (whole atoms)



red = Si white = O



Crystalline

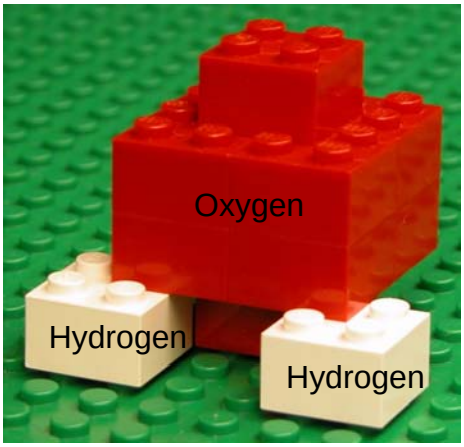


Amorphous

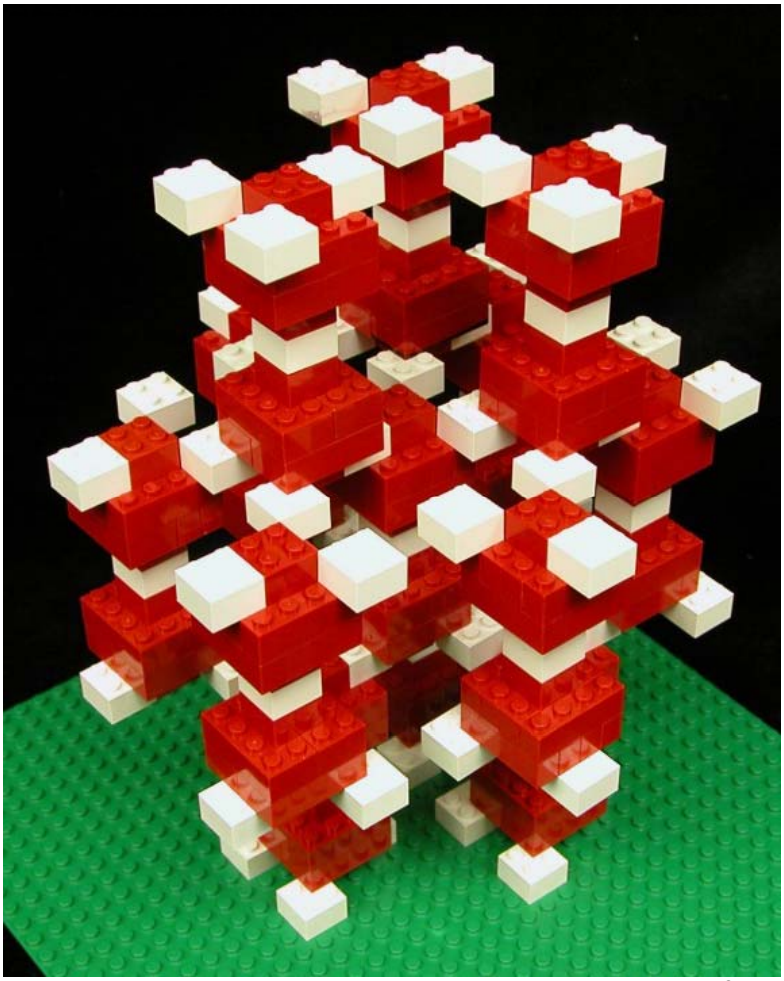
Note in both structures that the rules for bonding are the same: each Si atom is attached to four O atoms and each O atom is attached to two Si atoms. However, the atoms are organized in three-dimensional patterns in the crystalline phase. In the amorphous (glassy) phase, that order is not present. The atoms in the amorphous phase show a liquid-like disorder, yet they do not move about and the material is a solid.

Ice Ih (typical phase) (whole atoms)

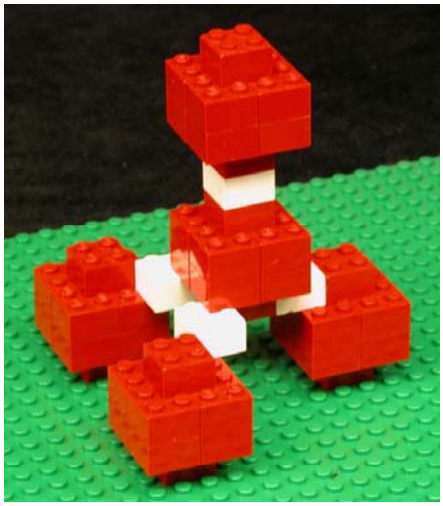
LEGO® unit representing H_2O in this structure:



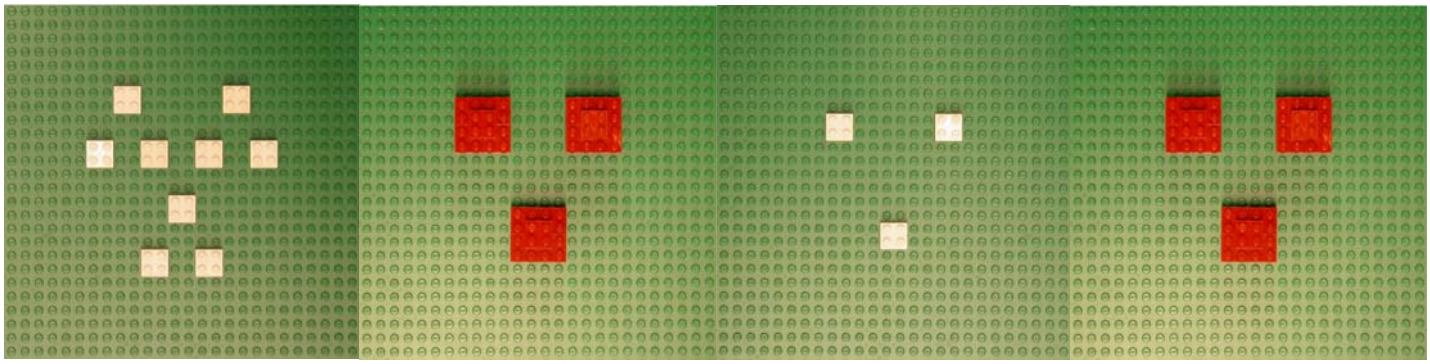
The oxygen atoms are connected to the other oxygen atoms in a tetrahedral geometry via covalent and hydrogen bonds to hydrogen atoms. Note in this representation the hydrogen atoms are shown as equally distant from the oxygen atoms that they bridge. In reality, the hydrogen atoms are closer to the oxygen atoms to which they are covalently bonded and further from the oxygen atoms to which they are hydrogen bonded.



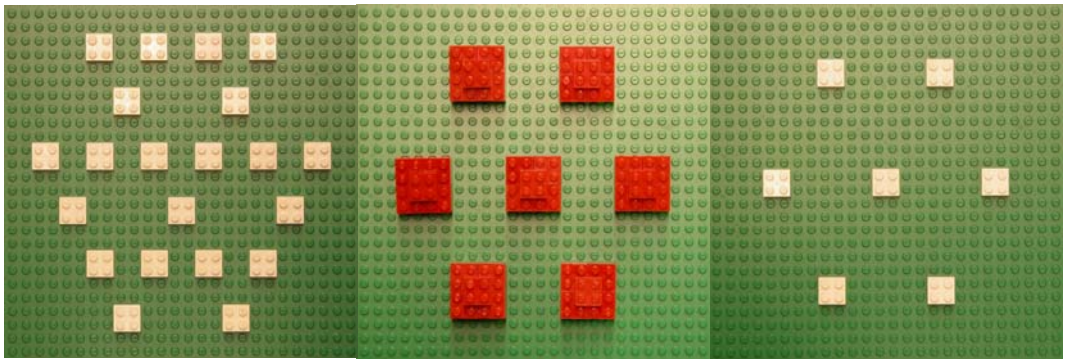
<u>This model requires:</u>
73 white 2x2 bricks
104 red 2x4 bricks
52 red 2x2 bricks



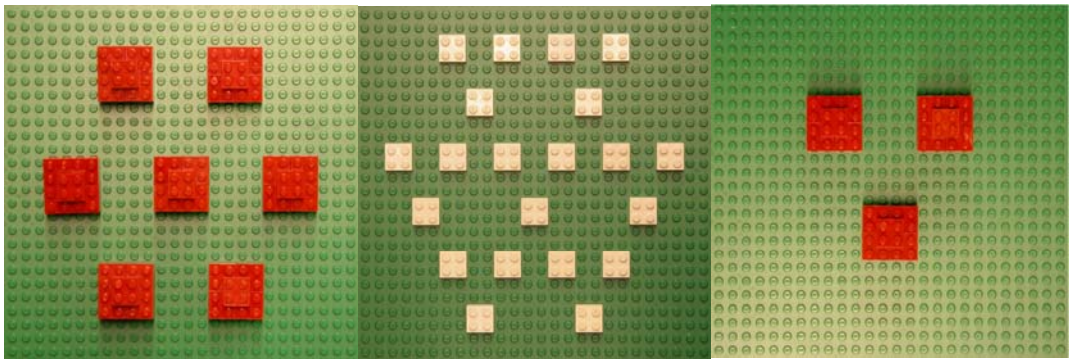
Angle view of the Ice Ih structure (The relative oxygen atom positions are similar to the londsdaleite structure.)



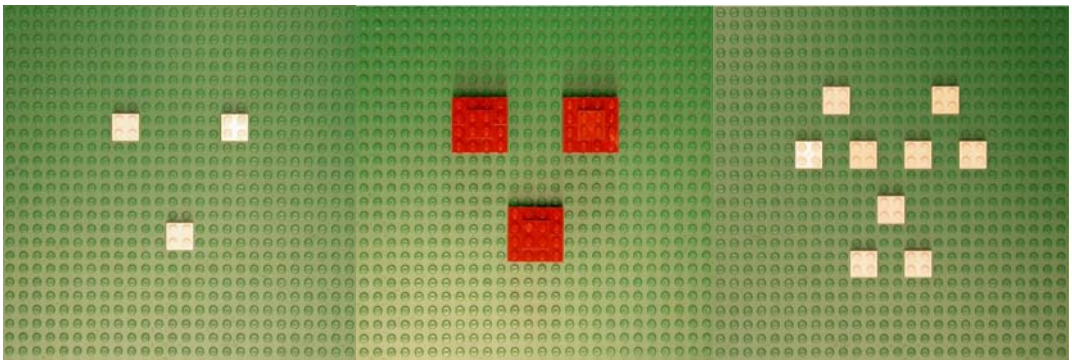
Layer 1 (bottom) Layer 2 Layer 3 Layer 4



Layer 5 Layer 6 Layer 7



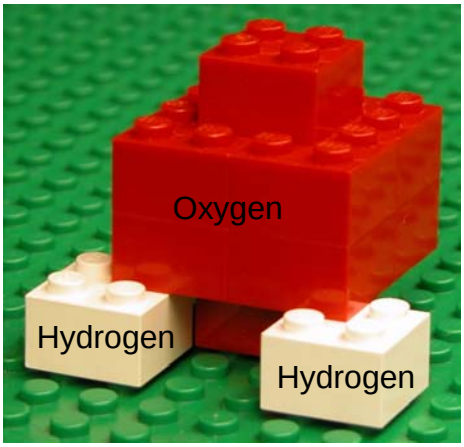
Layer 8 Layer 9 Layer 10



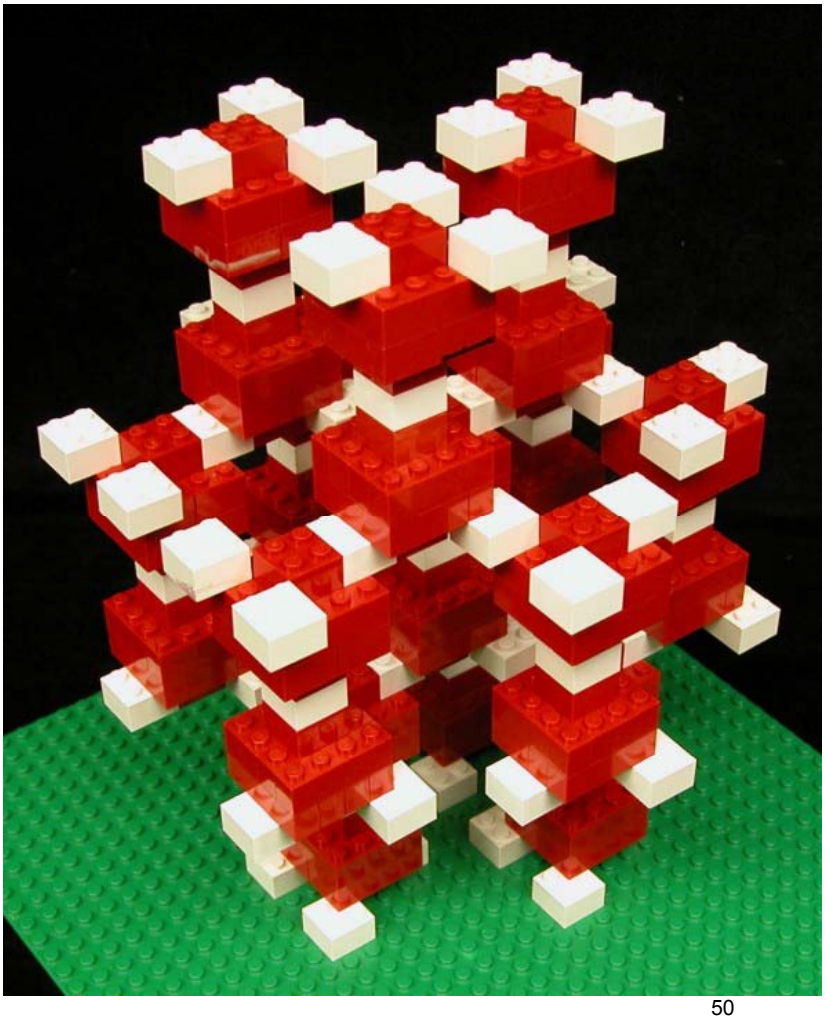
Layer 11 Layer 12 Layer 13 (top)

Ice Ic (a low-temperature phase) (whole atoms)

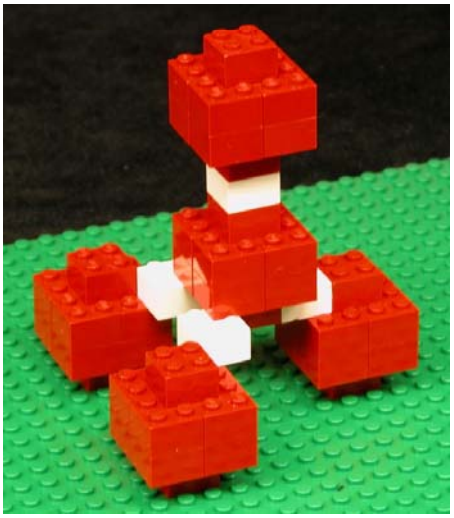
LEGO® unit representing H_2O in this structure:



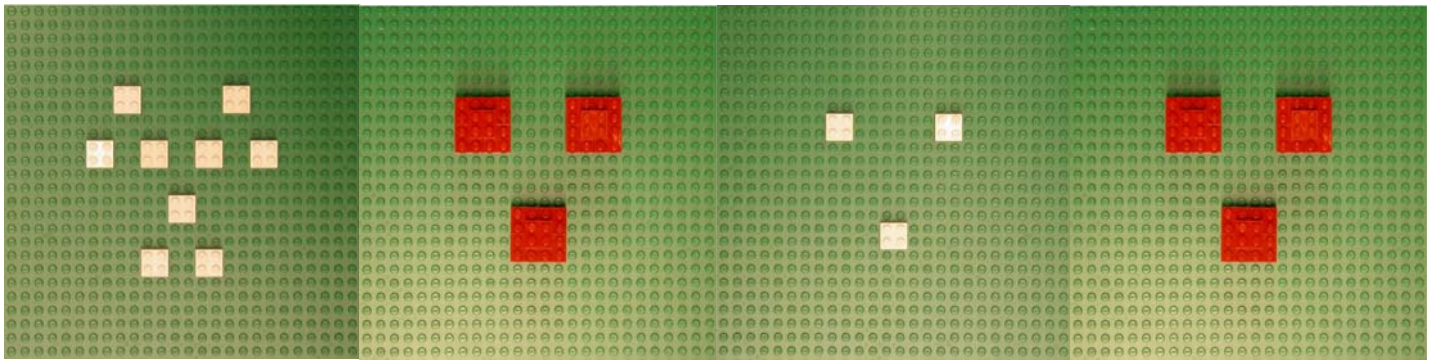
The oxygen atoms are connected to the other oxygen atoms in a tetrahedral geometry via covalent and hydrogen bonds to hydrogen atoms. Note in this representation the hydrogen atoms are shown as equally distant from the oxygen atoms that they bridge. In reality, the hydrogen atoms are closer to the oxygen atoms to which they are covalently bonded and further from the oxygen atoms to which they are hydrogen bonded.



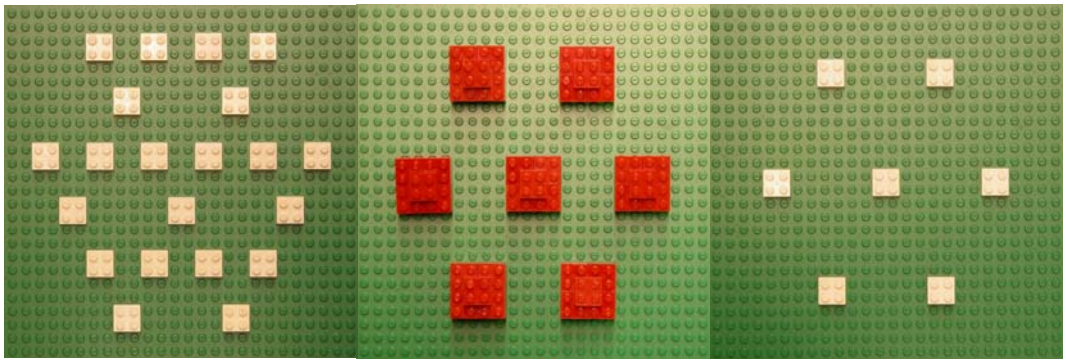
<u>This model requires:</u>
73 white 2x2 bricks
104 red 2x4 bricks
52 red 2x2 bricks



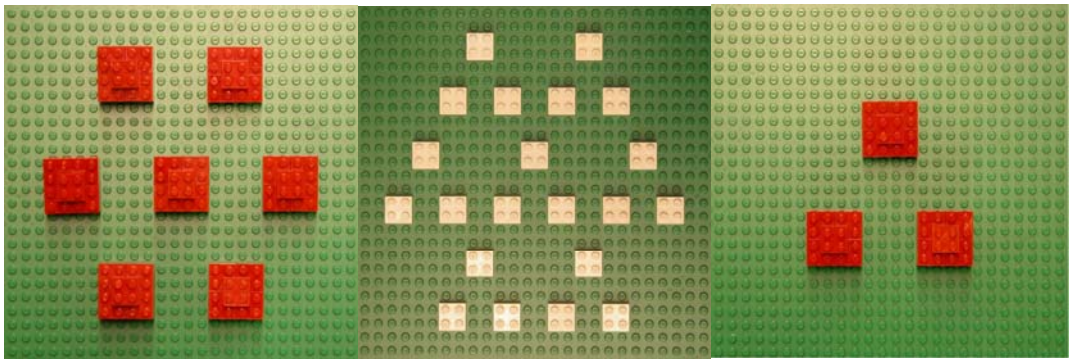
Angle view of the Ice Ic structure (The relative oxygen atom positions are similar to the diamond structure.)



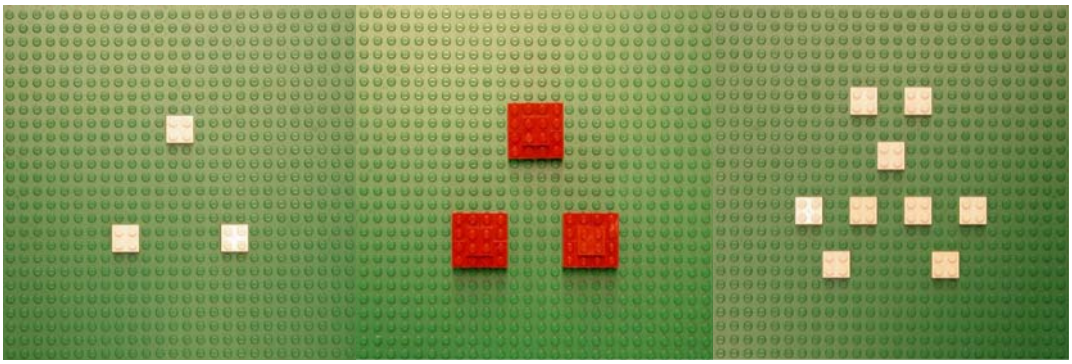
Layer 1 (bottom) Layer 2 Layer 3 Layer 4



Layer 5 Layer 6 Layer 7



Layer 8 Layer 9 Layer 10

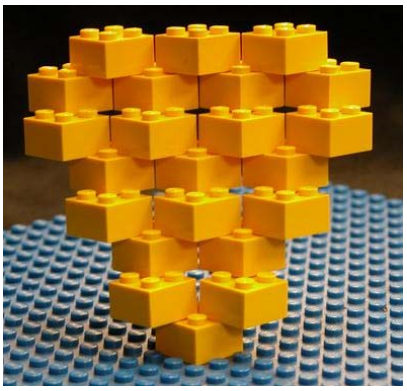


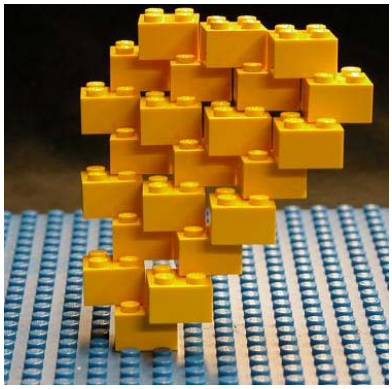
Layer 11 Layer 12 Layer 13 (top)

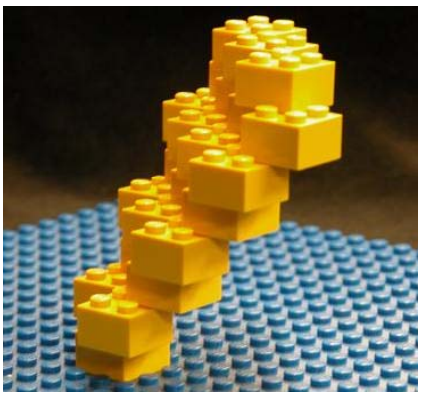
Arsenic
(whole atoms)

LEGO unit representing atoms in this structure:

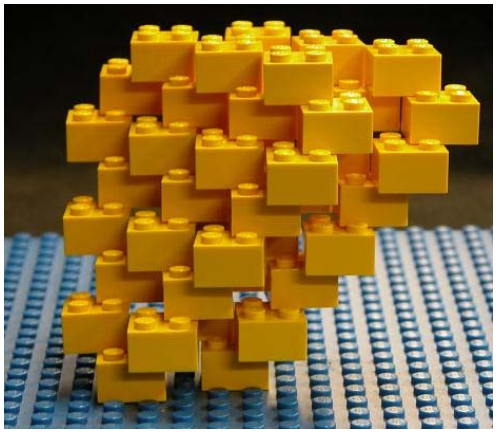
One layer – sheet of hexagons







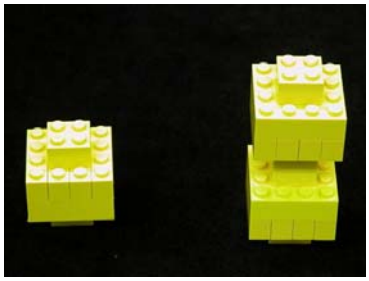
Two layers

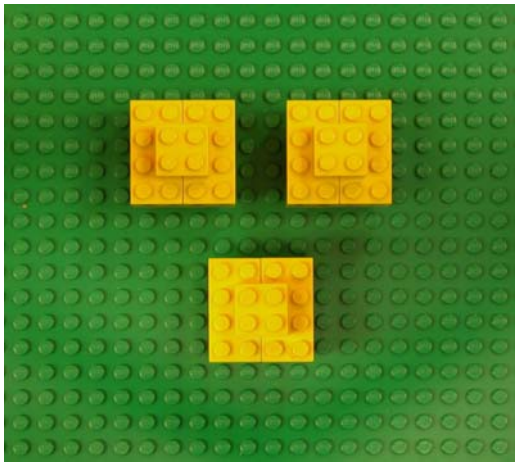


<u>This model requires:</u>
44 yellow 2x2 bricks

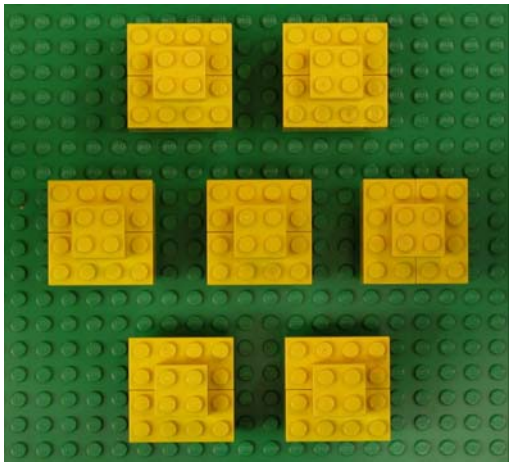
Nitrogen
(whole atoms)

LEGO unit representing atoms in this structure:



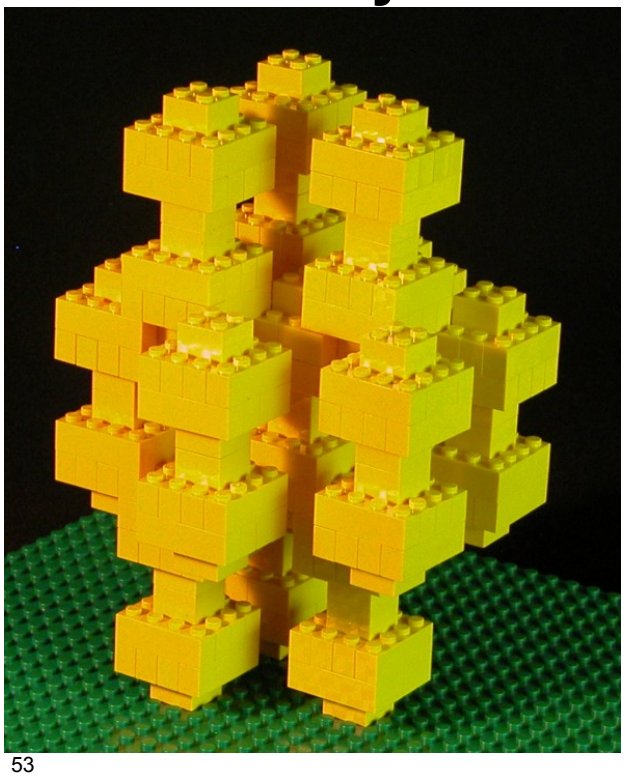


“A” Layer



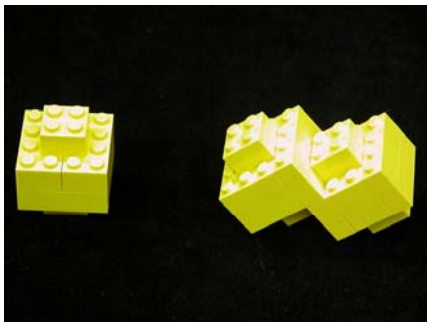
“B” Layer

Angle view of nitrogen structure (Layers **ABA**BABA…):



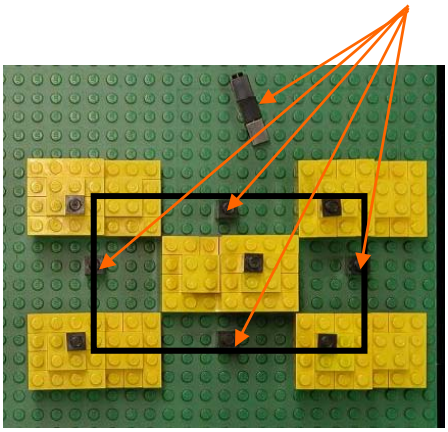
Iodine Structure (whole atoms)

LEGO unit representing atoms in this structure:

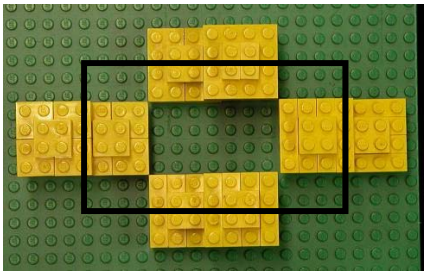


<u>This model requires:</u>
112 yellow 2x4 bricks
56 yellow 2x2 bricks
20 black 1x1 bricks

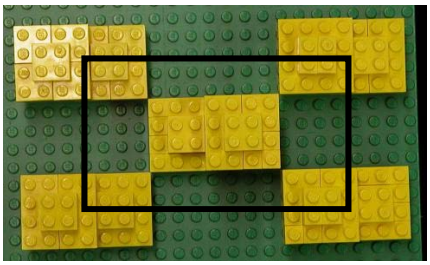
These are supports made from three 1x1 bricks.



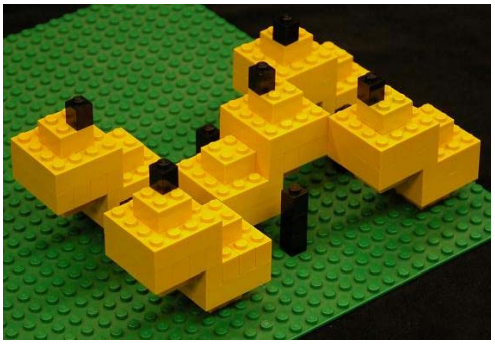
Z=0

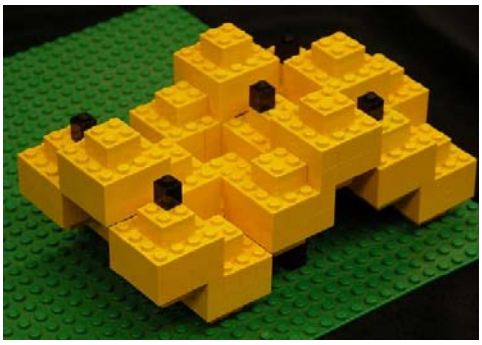


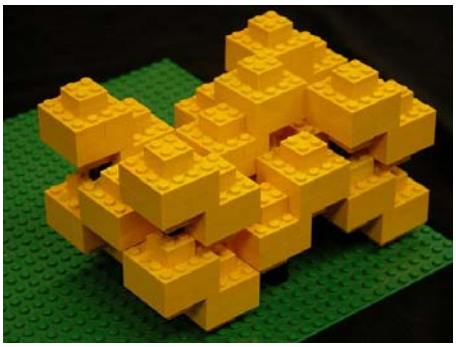
Z=½



Z=1



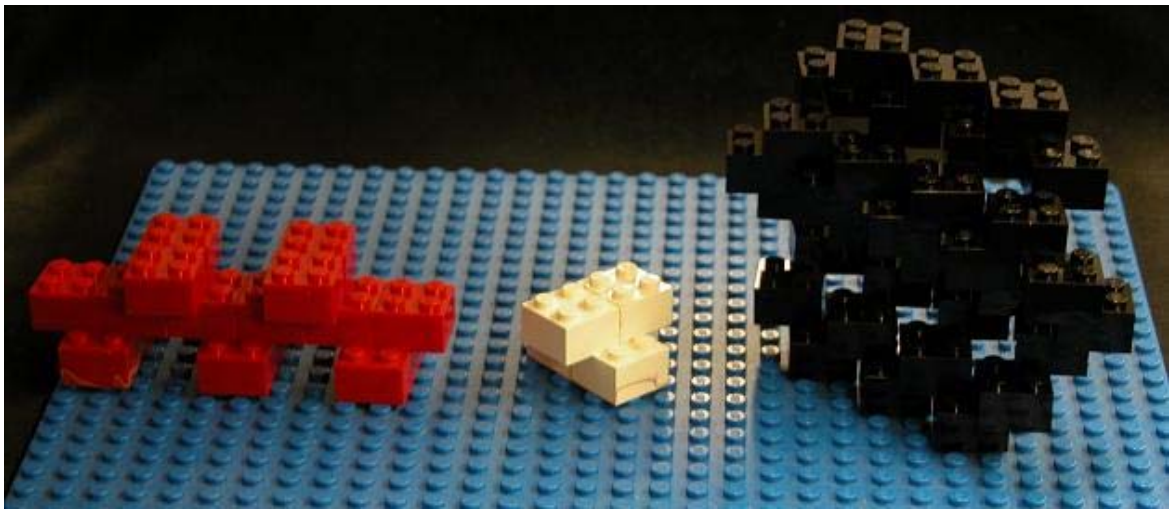




Phosphorus
(whole atoms)

LEGO unit representing atoms in this structure:

Red Allotrope White Allotrope Black Allotrope

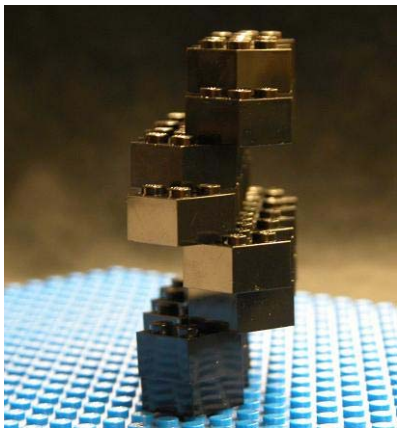


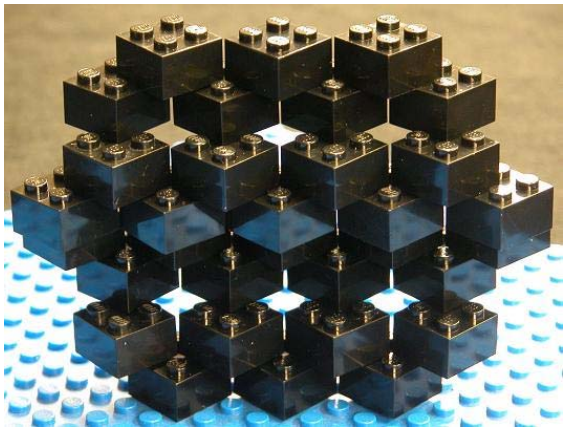
Chains of four-atom groups

Four-atom group

Rippled sheets of hexagons

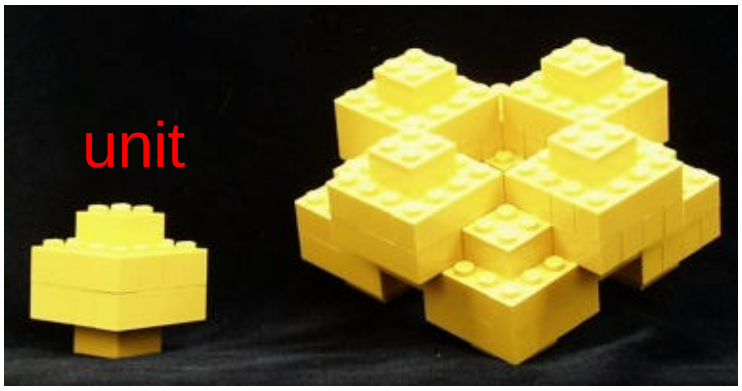
Black phosphorus detail

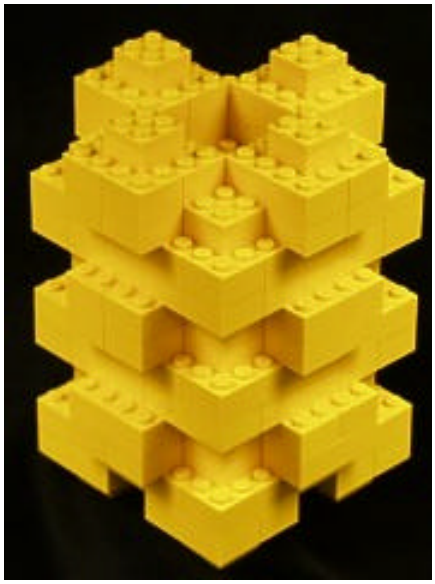




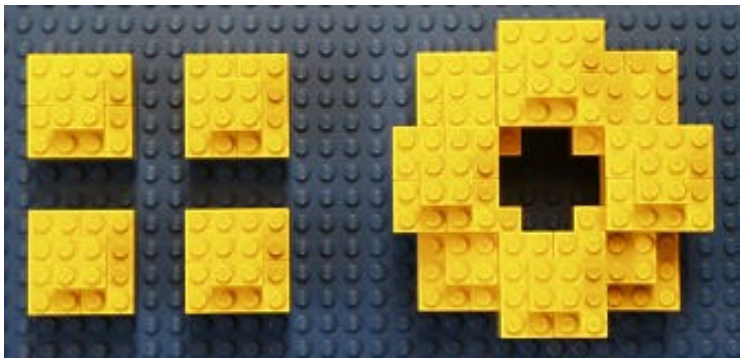
Sulfur
(whole atoms)

Rhombic/Orthorhombic Sulfur





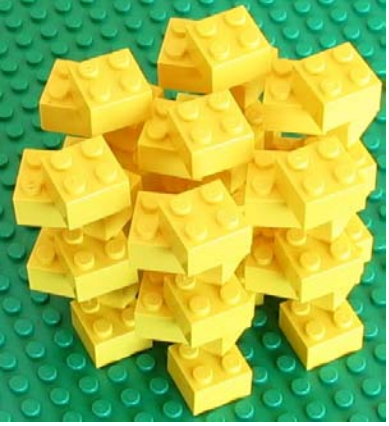
Build Up Sequence



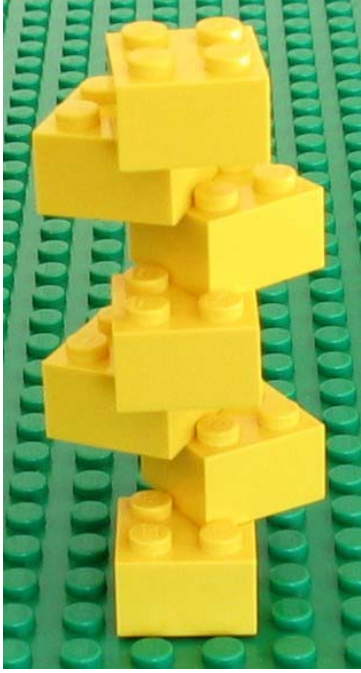
Level 1 Level 2

Monoclinic Sulfur

Trigonal Selenium (whole atoms)



yellow = Se

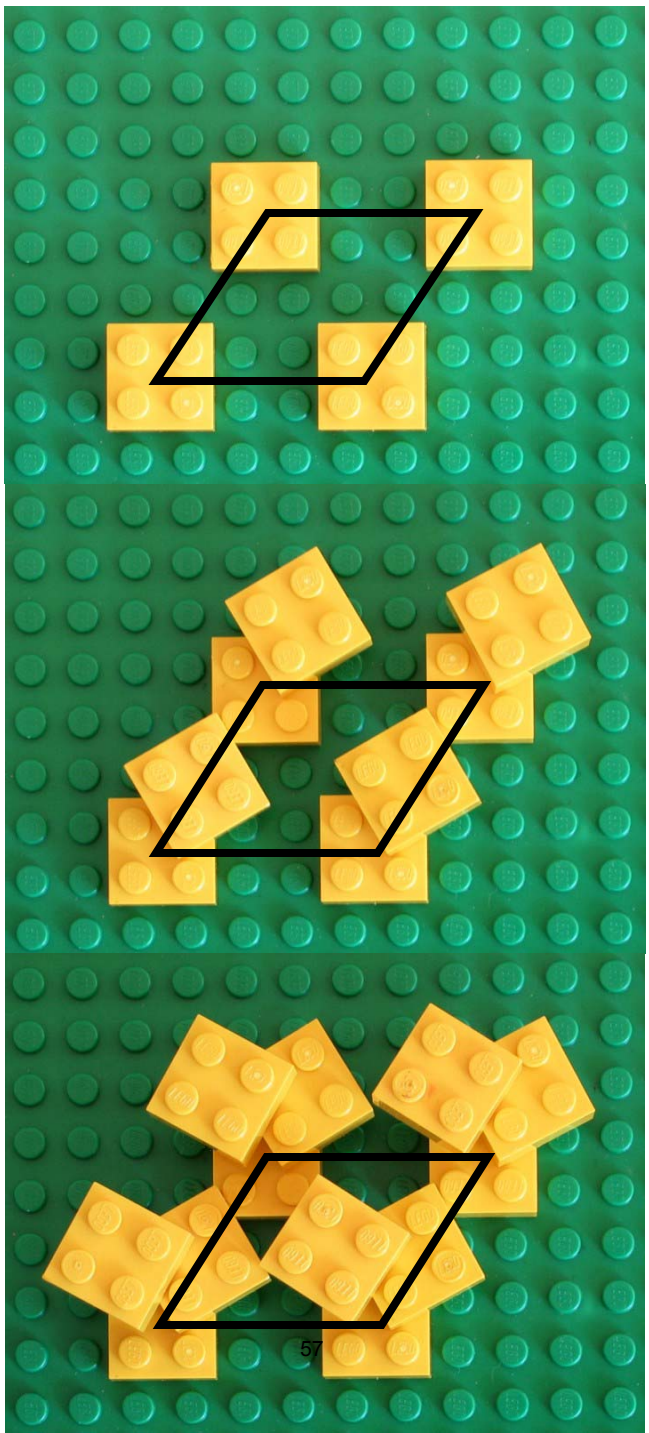


Helix of seven atoms

Z=0,1

Z=0.333

Z=0.667

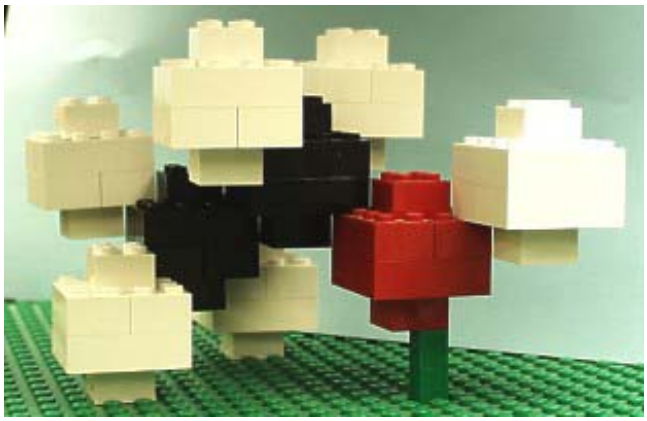


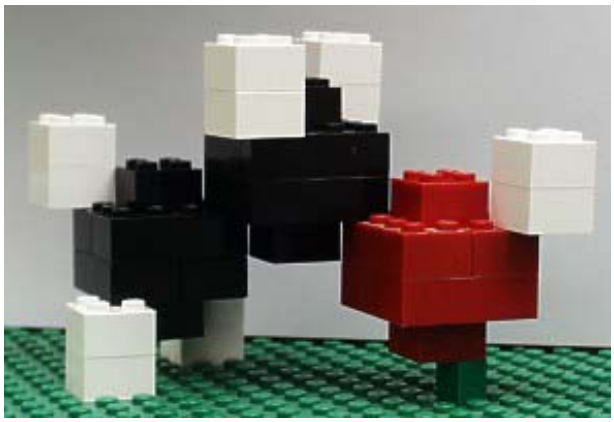
Organic Compounds

Models of organic compounds can be made from tetrahedral bonded LEGO® bricks.

Tetrahedral Bonding

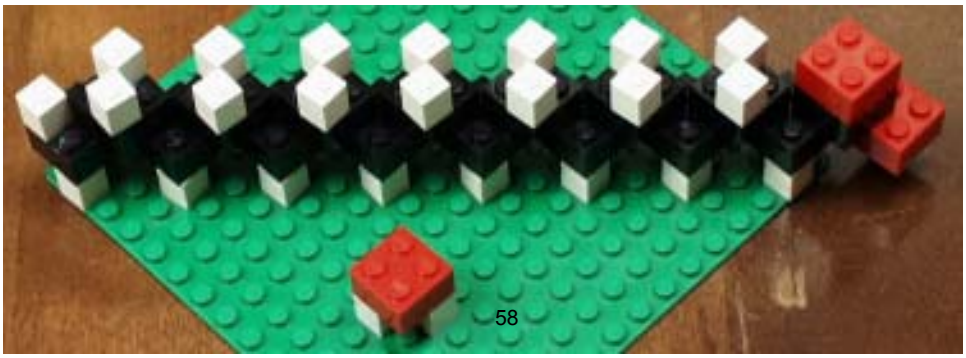
Ethanol





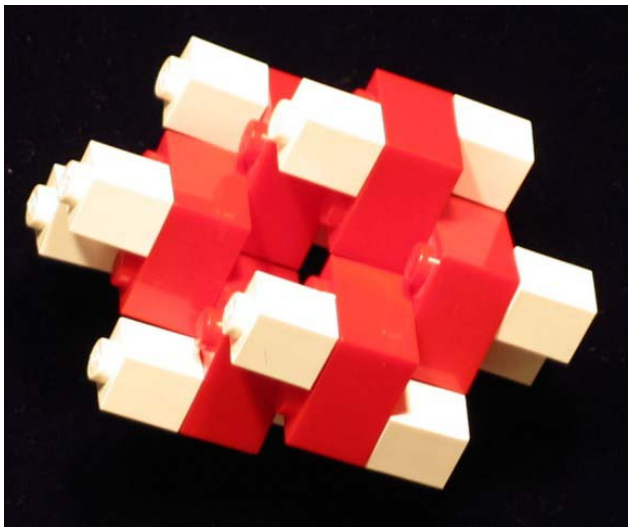
Like many organic chemistry models:
black = carbon, white = hydrogen, red = oxygen

Soap (palmitate ion) and Water

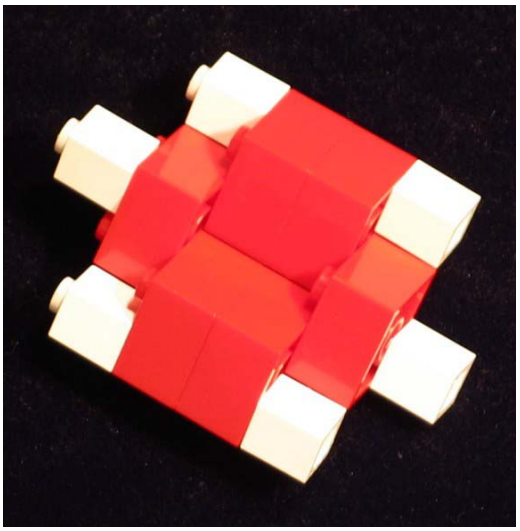


Organic Compounds

Cyclohexane

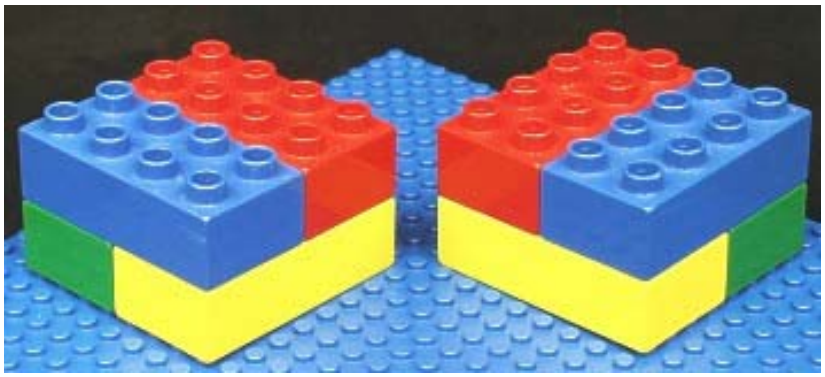


Benzene

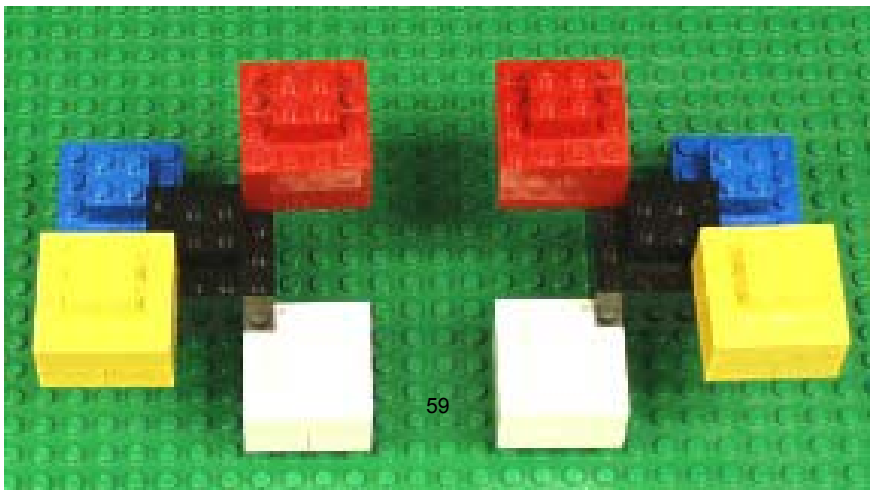


Chiral Structures

Simplest Structure



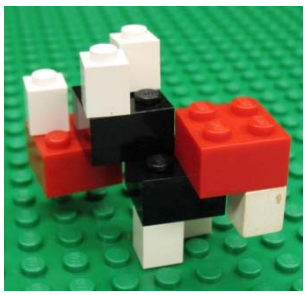
Tetrahedral Bonded Structure



Polyethylene terephthalate (PET, 1)

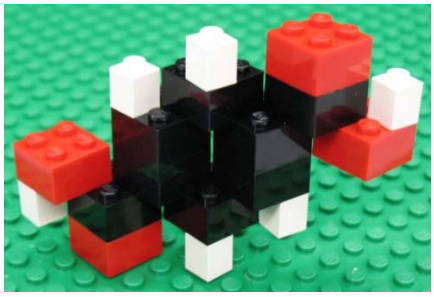
Color key:
black = carbon
white = hydrogen
red = oxygen

Monomers for the condensation polymerization:



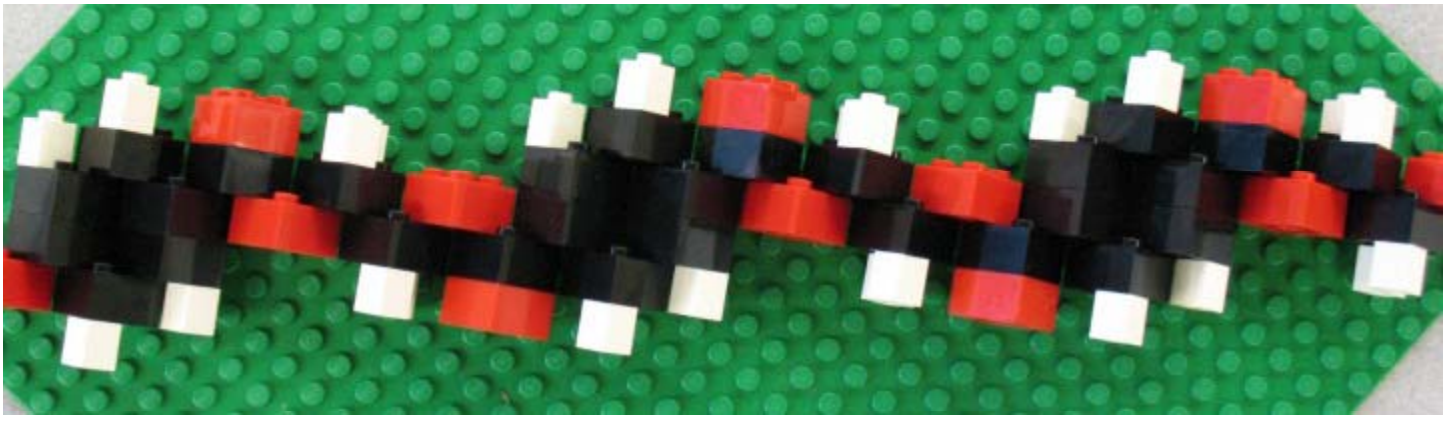
This model requires:
2 red 2x2 bricks
2 black 2x2 bricks
6 white 1x1 bricks

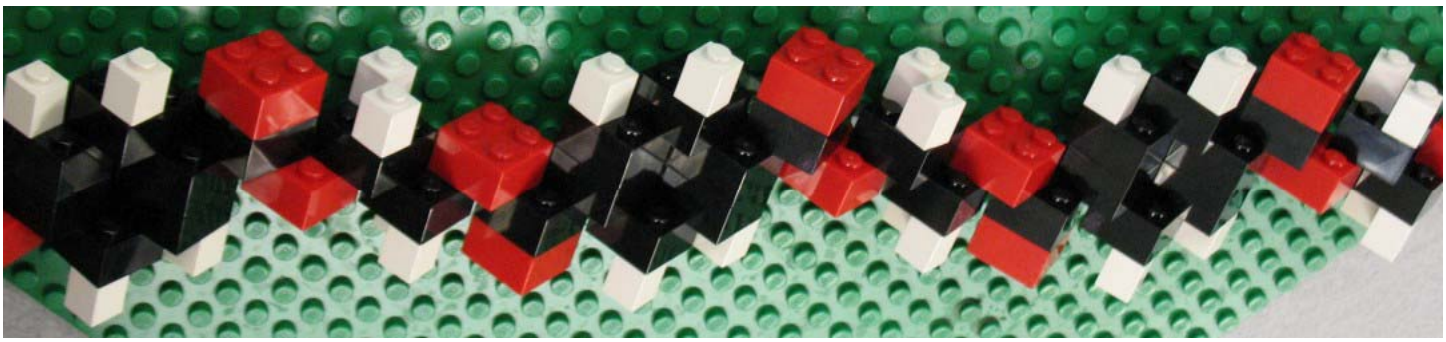
ethylene glycol
(1,2-ethanediol)



This model requires:
8 black 2x2 bricks
4 red 2x2 bricks
6 white 1x1 bricks

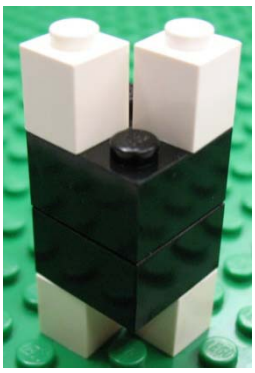
terephthalic acid





High Density Polyethylene (HDPE, 2)

Monomer for the addition polymerization:

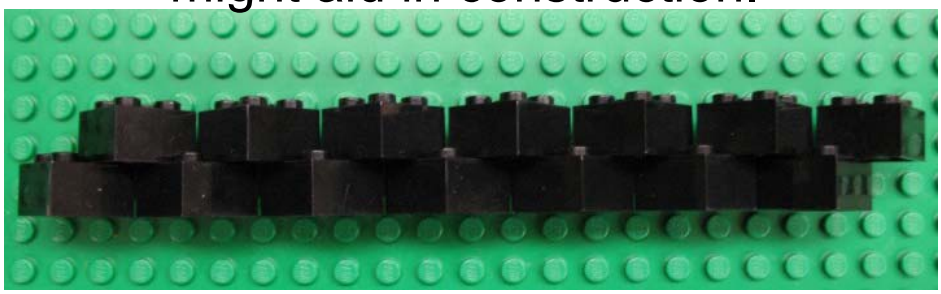


ethylene (ethene)

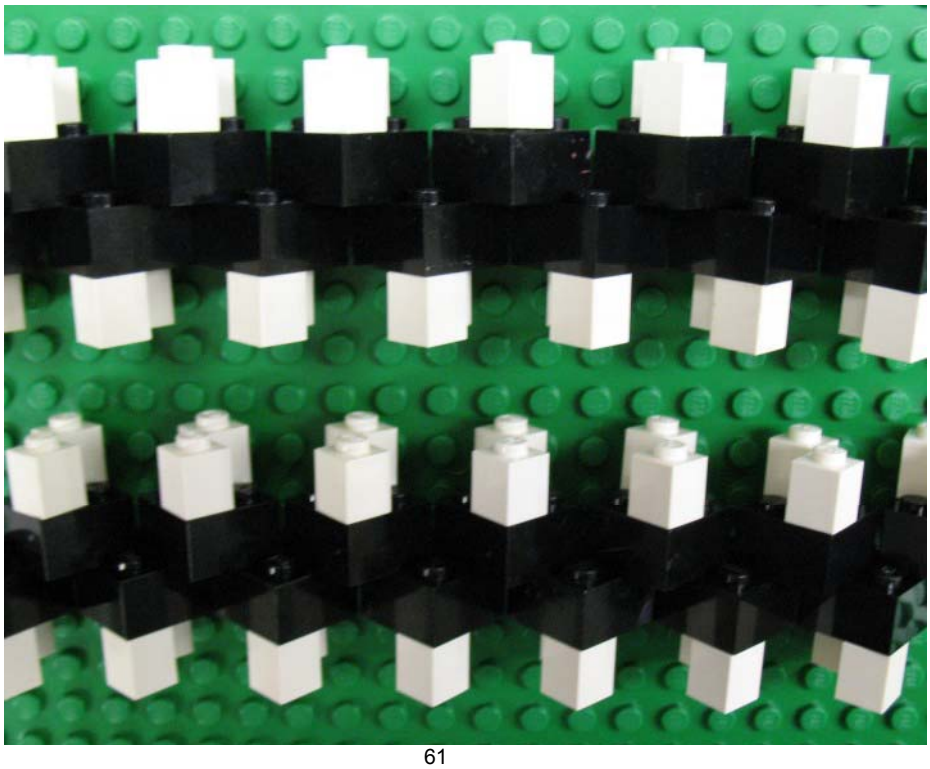
<u>This model requires:</u>
2 black 2x2 bricks
4 white 1x1 bricks

<u>Color key:</u>
black = carbon
white = hydrogen

Building the carbon backbone first might aid in construction.

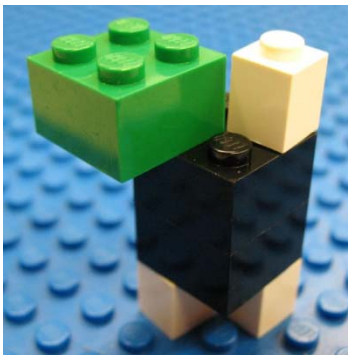


The linear polymer chains can pack together closely, causing the polymer to have a higher density than low density polyethylene.



Polyvinyl chloride (PVC, 3)

Monomer for the addition polymerization:

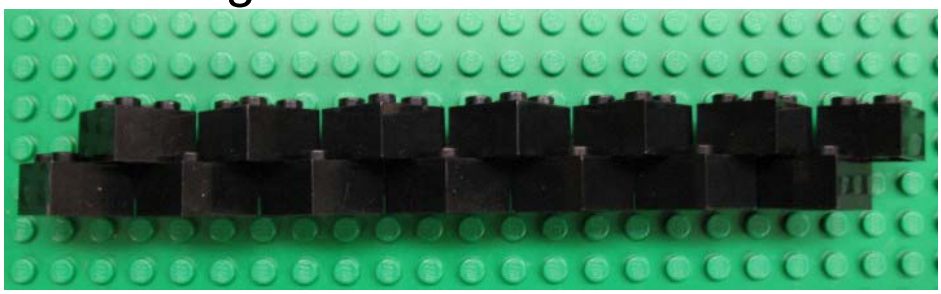


vinyl chloride (chloroethene)

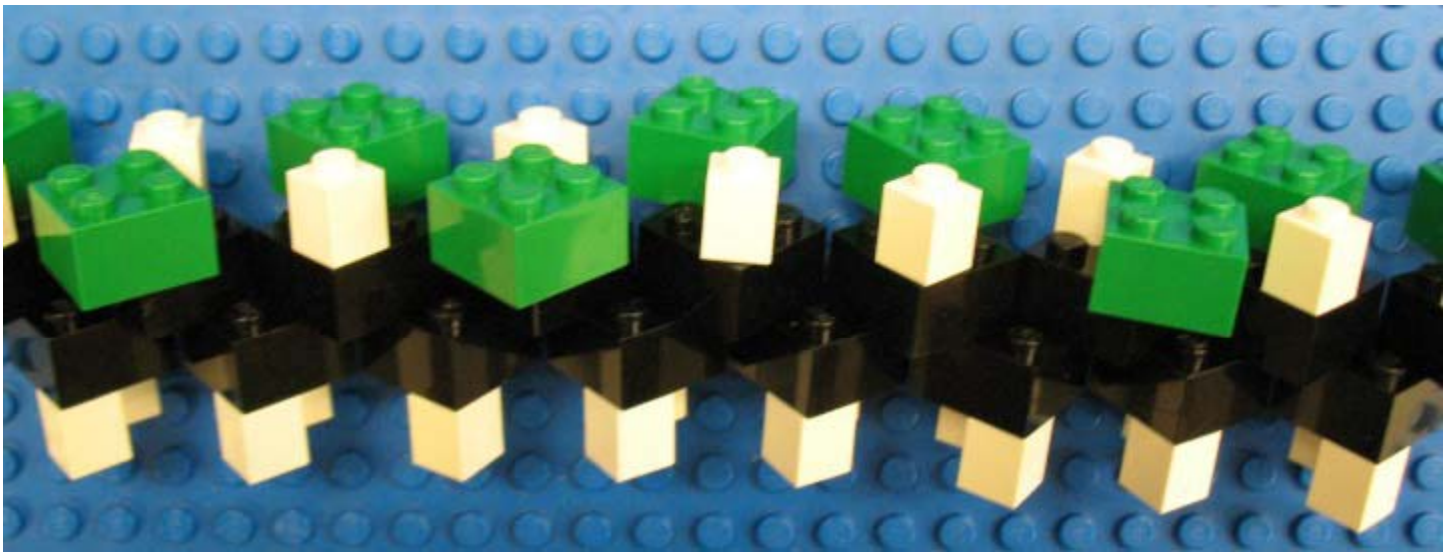
This model requires:
2 black 2x2 bricks
1 green 2x2 brick
3 white 1x1 bricks

Color key:
black = carbon
white = hydrogen
green = chlorine

Building the carbon backbone first might aid in construction.



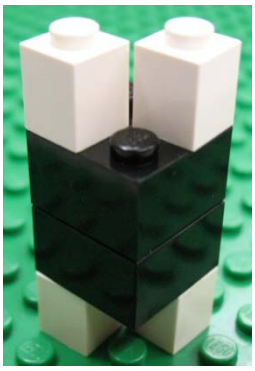
The structure is very similar to high density polyethylene, except one of the two hydrogen atoms on every other carbon atom has been replaced with a larger chlorine atom.



Low Density Polyethylene (LDPE, 4)

Monomer for the addition polymerization:

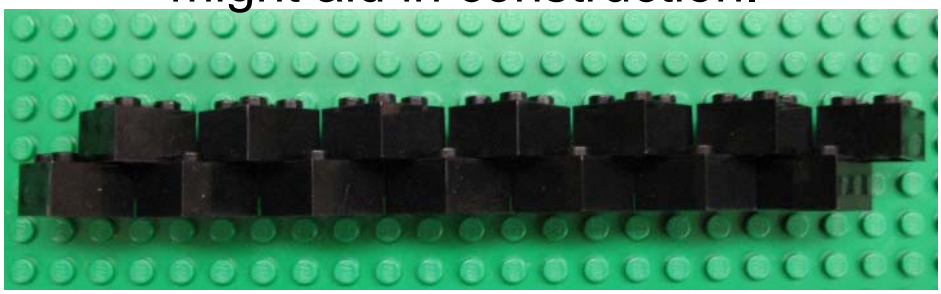
<u>This model requires:</u>
2 black 2x2 bricks
4 white 1x1 bricks



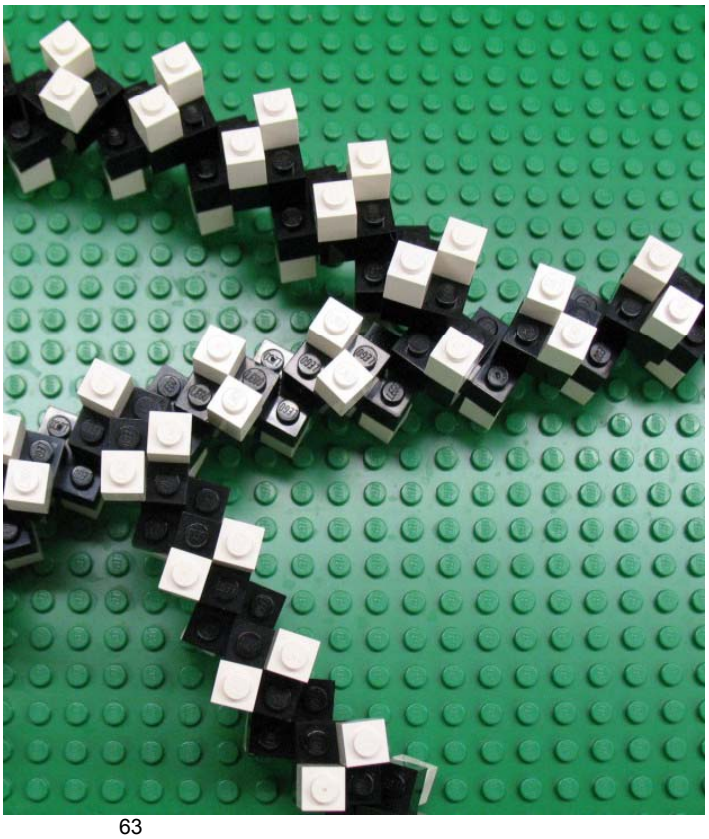
ethylene (ethene)

<u>Color key:</u>
black = carbon
white = hydrogen

Building the carbon backbone first might aid in construction.



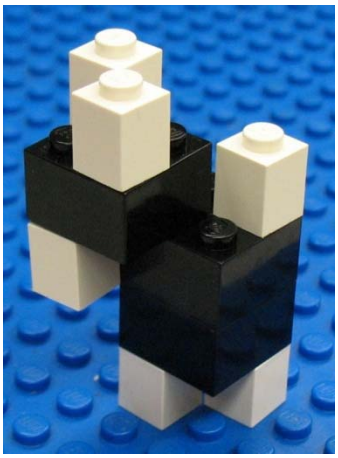
The branching polymer chains pack together loosely, causing the polymer to have a lower density than high density polyethylene.



Polypropylene (PP, 5)

Color key:
black = carbon
white = hydrogen

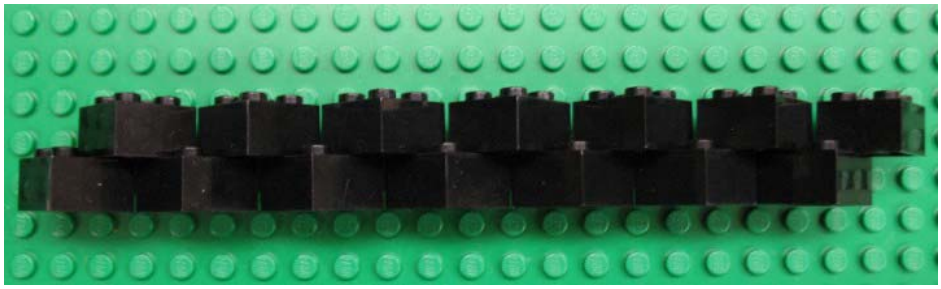
Monomer for the addition polymerization:



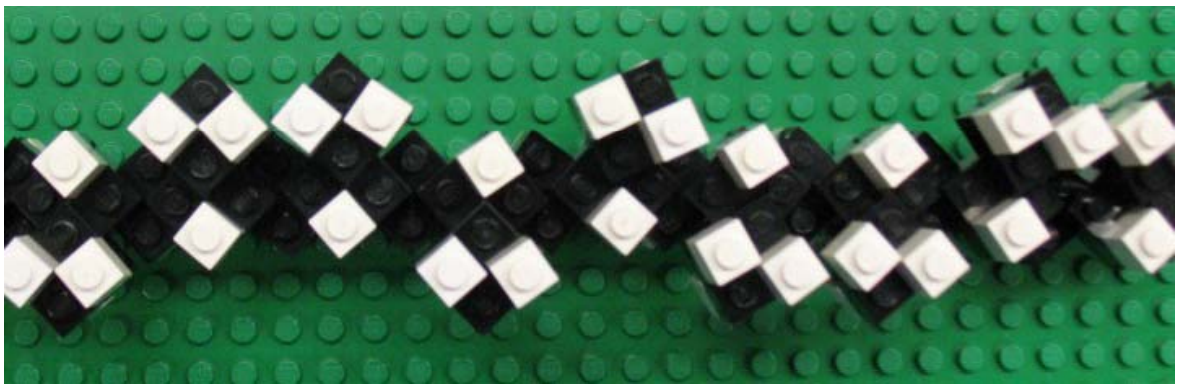
This model requires:
3 black 2x2 bricks
6 white 1x1 bricks

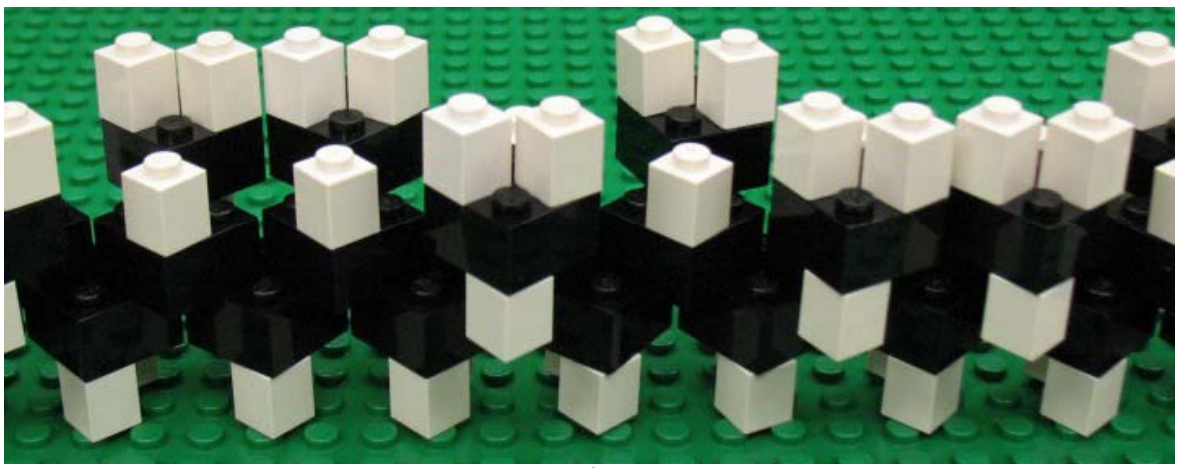
propylene (propene)

Building the carbon backbone first might aid in construction.



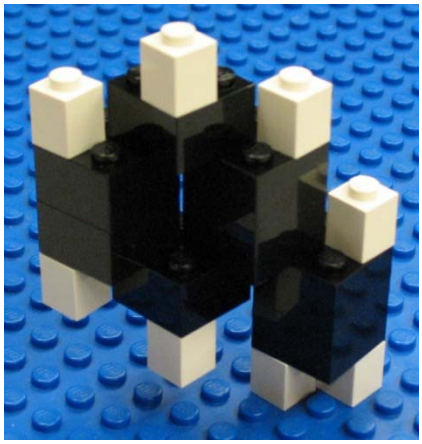
The structure is very similar to high density polyethylene, except one of the two hydrogen atoms on every other carbon atom has been replaced with methyl (CH_3) group.





Polystyrene (PS, 6)

Monomer for the addition polymerization:

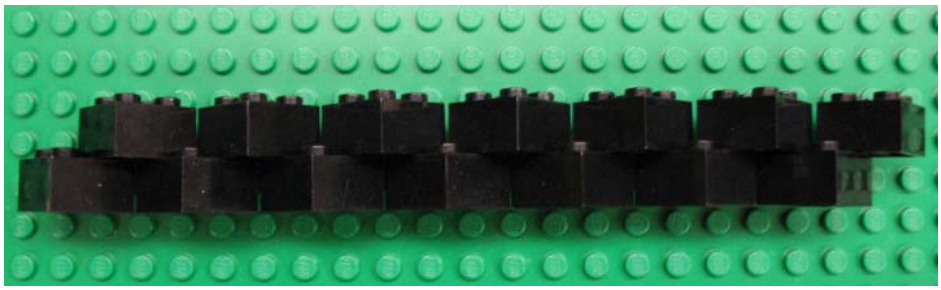


styrene

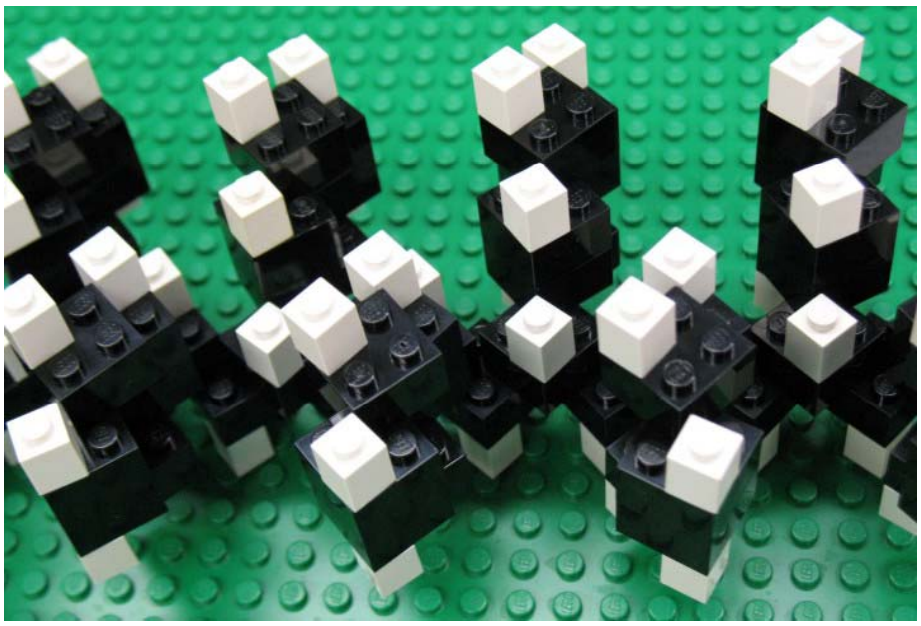
<u>Color key:</u>
black = carbon
white = hydrogen

<u>This model requires:</u>
8 black 2x2 bricks
9 white 1x1 bricks

Building the carbon backbone first might aid in construction.

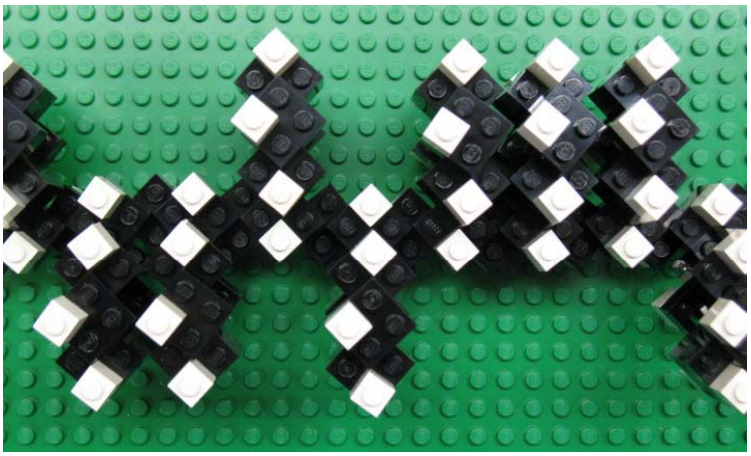


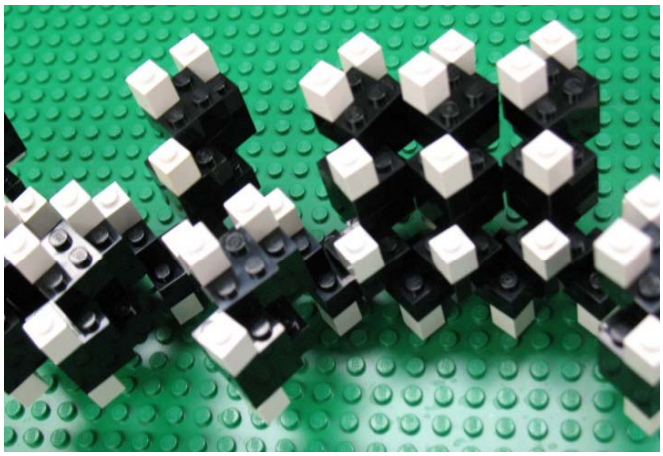
The structure is similar to high density polyethylene, except one of the two hydrogen atoms on every other carbon atom has been replaced with phenyl ($-C_6H_5$) group. These bulky groups reduce the flexibility of the chains and produce a relatively stiff polymer.



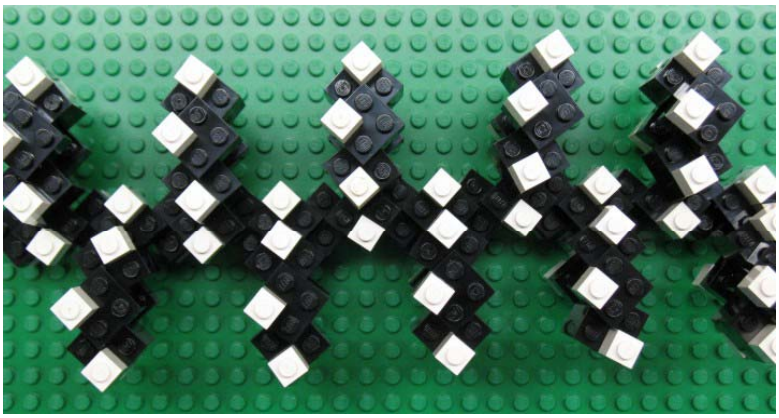
Polystyrene can be produced with varying arrangements of the phenyl groups along their chains.

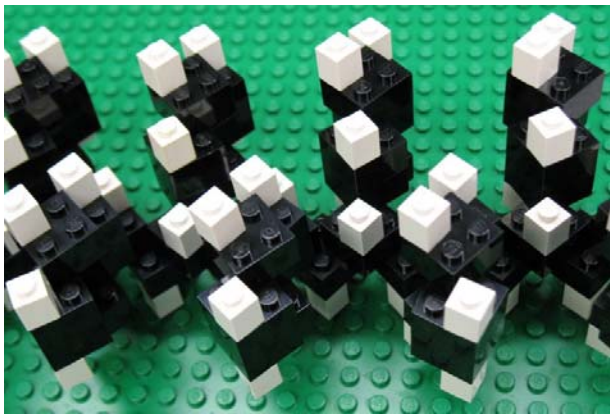
Atactic polystyrene has phenyl groups located randomly on either side of the chain.



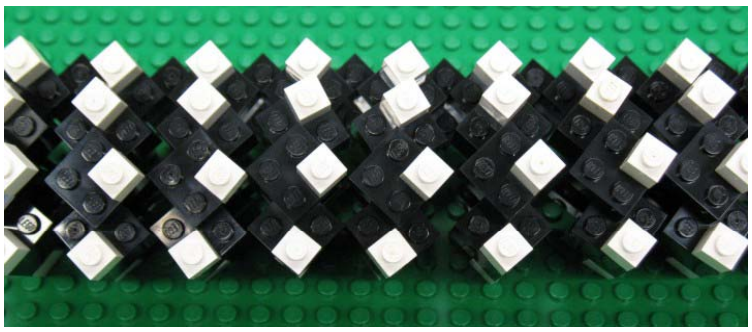


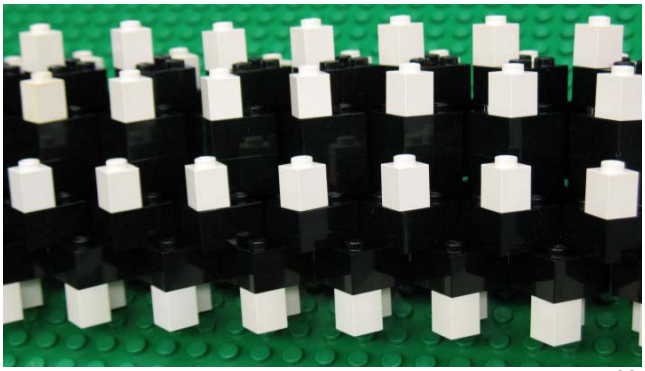
Syndiotactic polystyrene has alternating phenyl groups located on opposite sides of the chain.

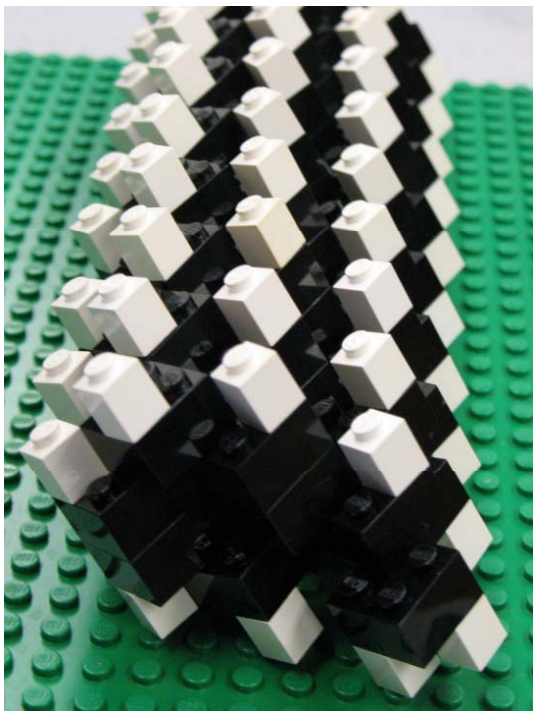




Isotactic polystyrene has all phenyl groups located on the same side of the chain.



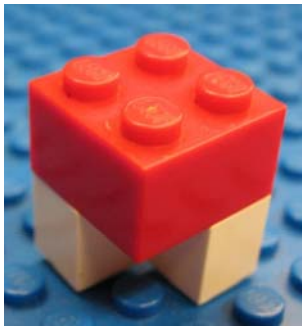




Polydimethylsiloxane

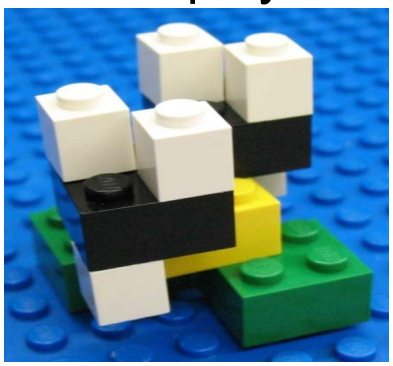
Monomers for the condensation polymerization:

Color key:
yellow = silicon
black = carbon
white = hydrogen
red = oxygen
green = chlorine



water

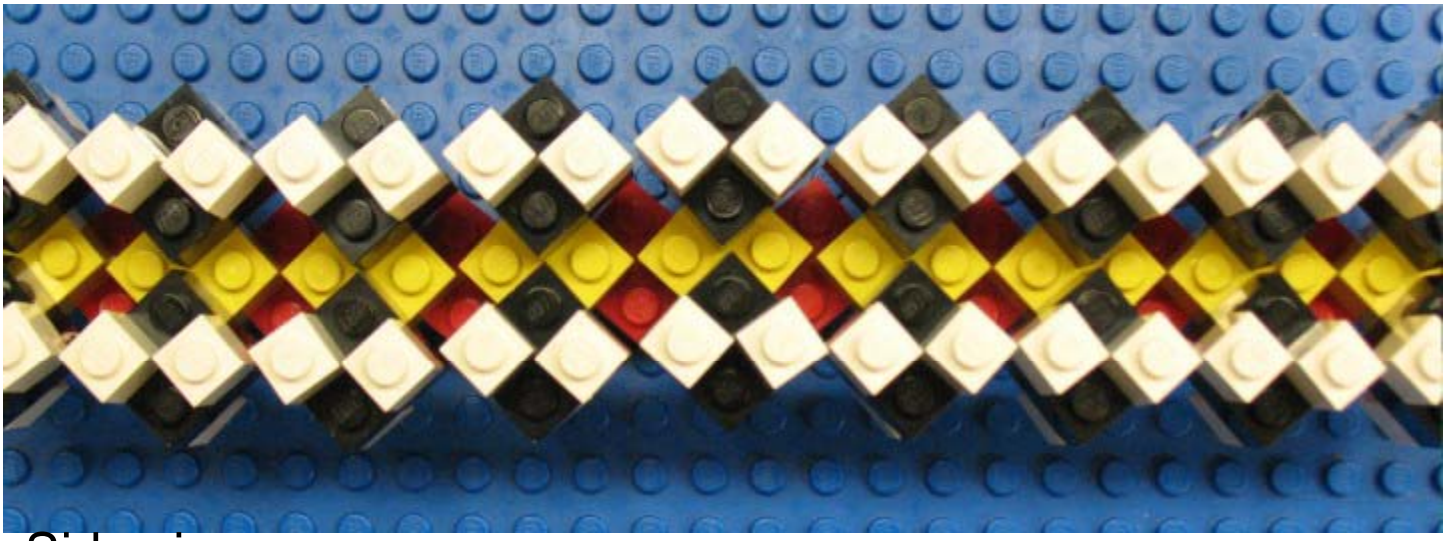
This model requires:
1 red 2x2 brick
2 white 1x1 bricks



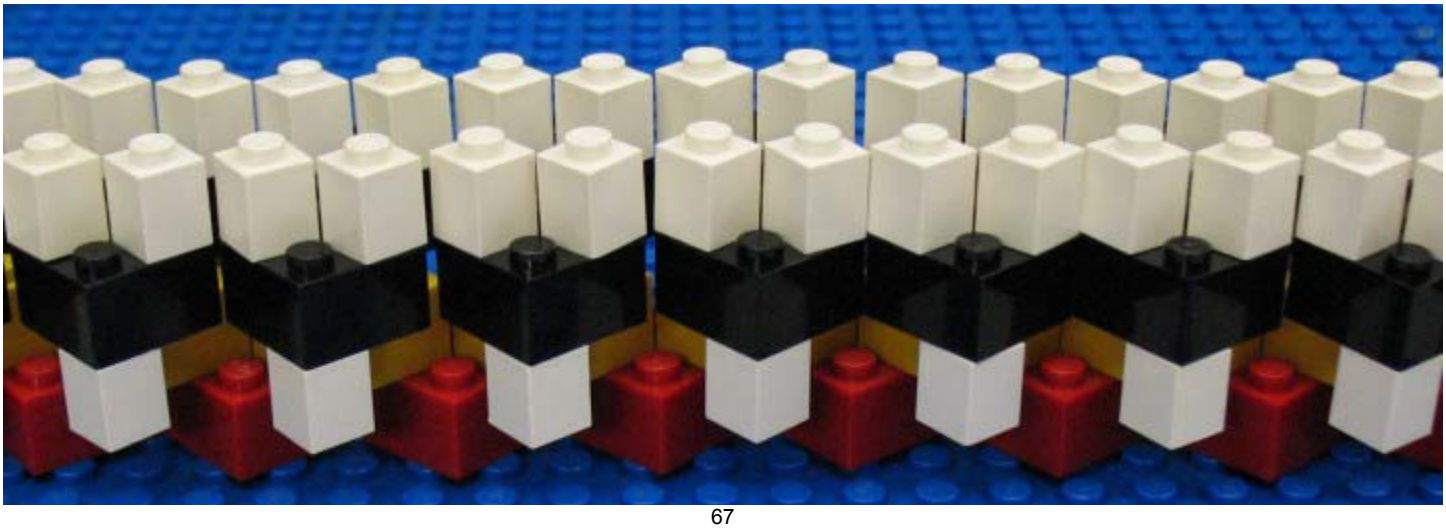
dichlorodimethylsilane

This model requires:
2 green 2x2 bricks
1 yellow 2x2 brick
2 black 2X2 bricks
6 white 1x1 bricks

Top view



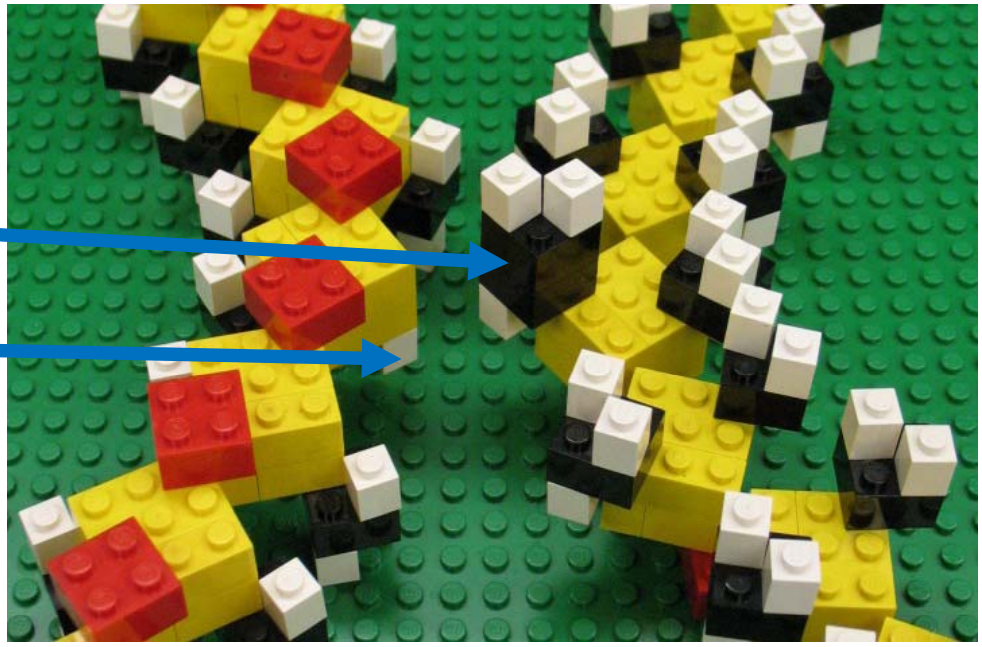
Side view



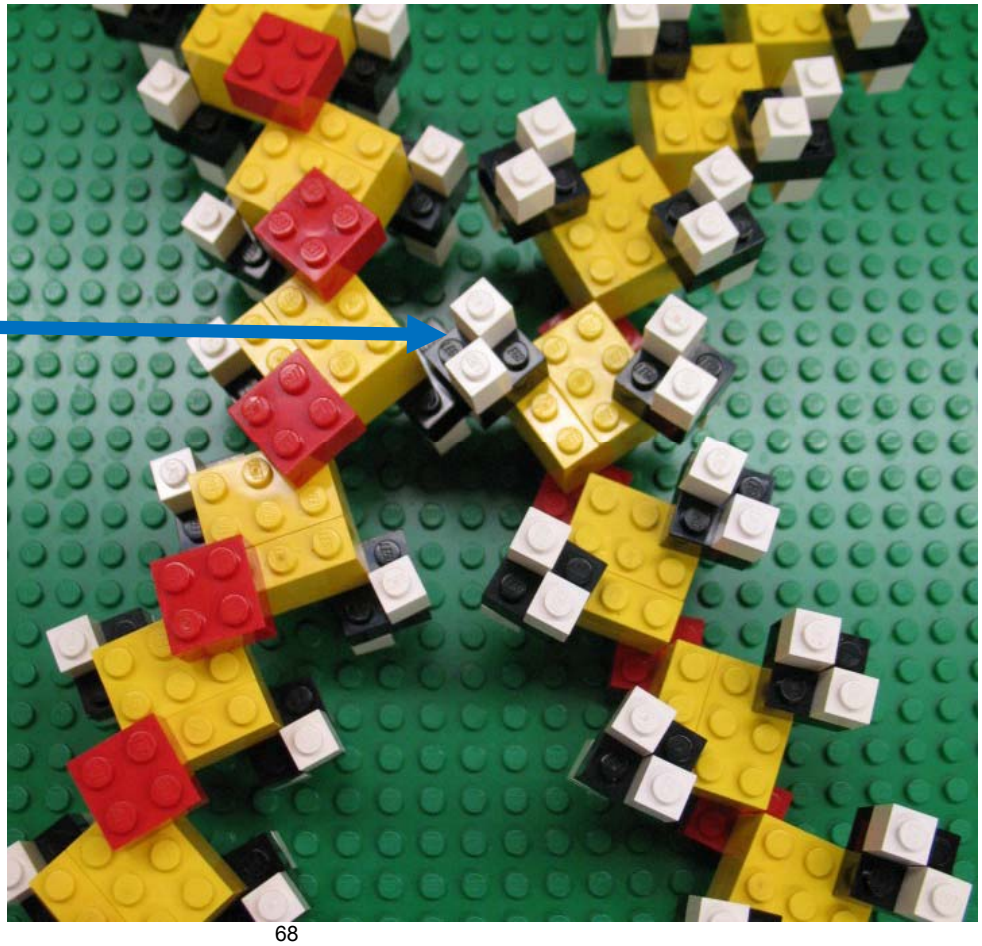
Polydimethylsiloxane crosslinking via a hydrosilation reaction

The large yellow silicon atoms can be made by placing a 1x3 brick and a 2x3 brick over 1x3 brick and another 2x3 brick.

Before crosslinking, oligomers contain vinyl groups and silane groups. (Note the chains are shown in opposite orientations.)



A hydrosilation reaction crosslinks the oligomers together.

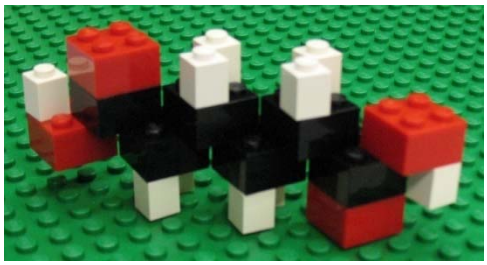


Nylon-6,6

Monomers for the condensation polymerization:

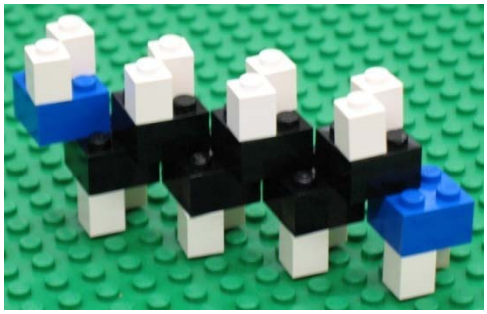
<u>Color key:</u>
black = carbon
white = hydrogen
red = oxygen
blue = nitrogen

<u>This model requires:</u>
6 black 2x2 bricks 4
4 red 2x2 bricks
10 white 1x1 bricks

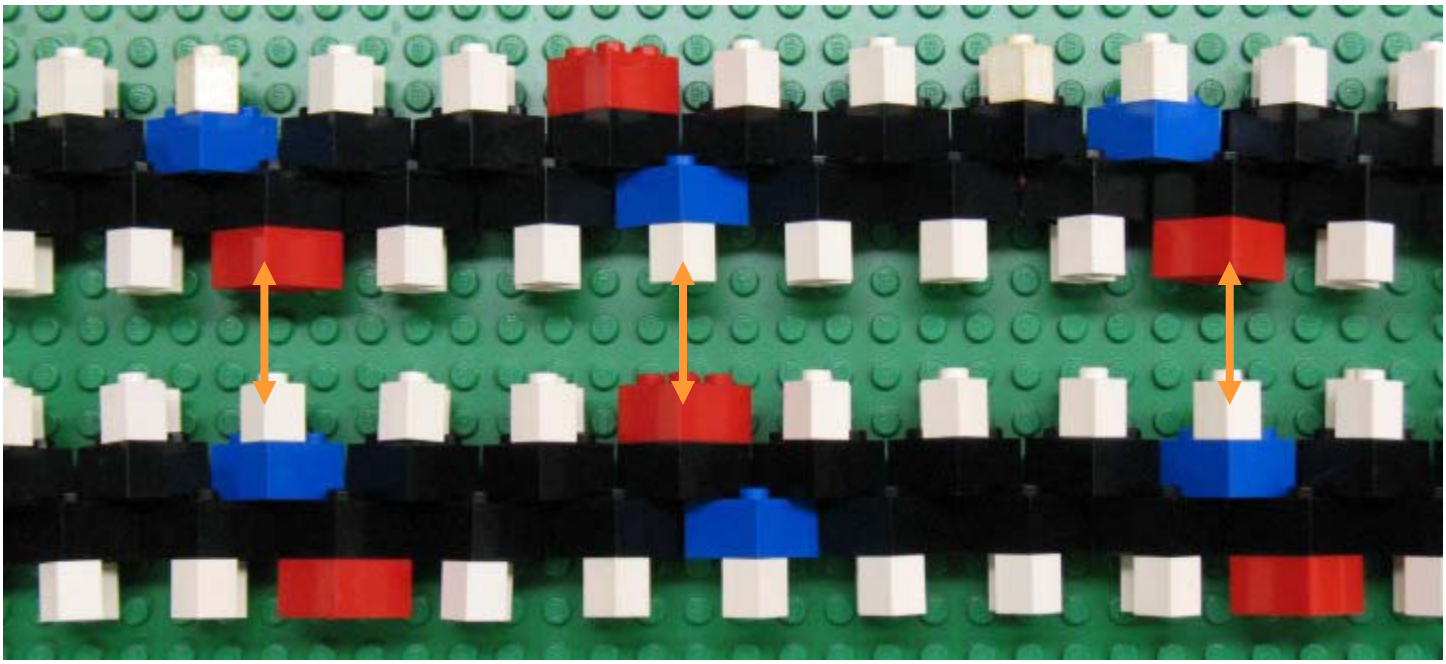


hexanedioic acid

<u>This model requires:</u>
6 black 2x2 bricks
2 blue 2x2 bricks
16 white 1x1 bricks



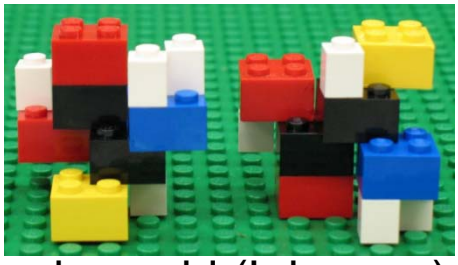
1,6-diaminohexane



Hydrogen bonding (orange arrows) between oxygen atoms on one polymer strand and hydrogen atoms attached to nitrogen atoms on an adjacent polymer strand help to give nylon its strength.

Polypeptide (protein)

Monomer for the condensation polymerization:

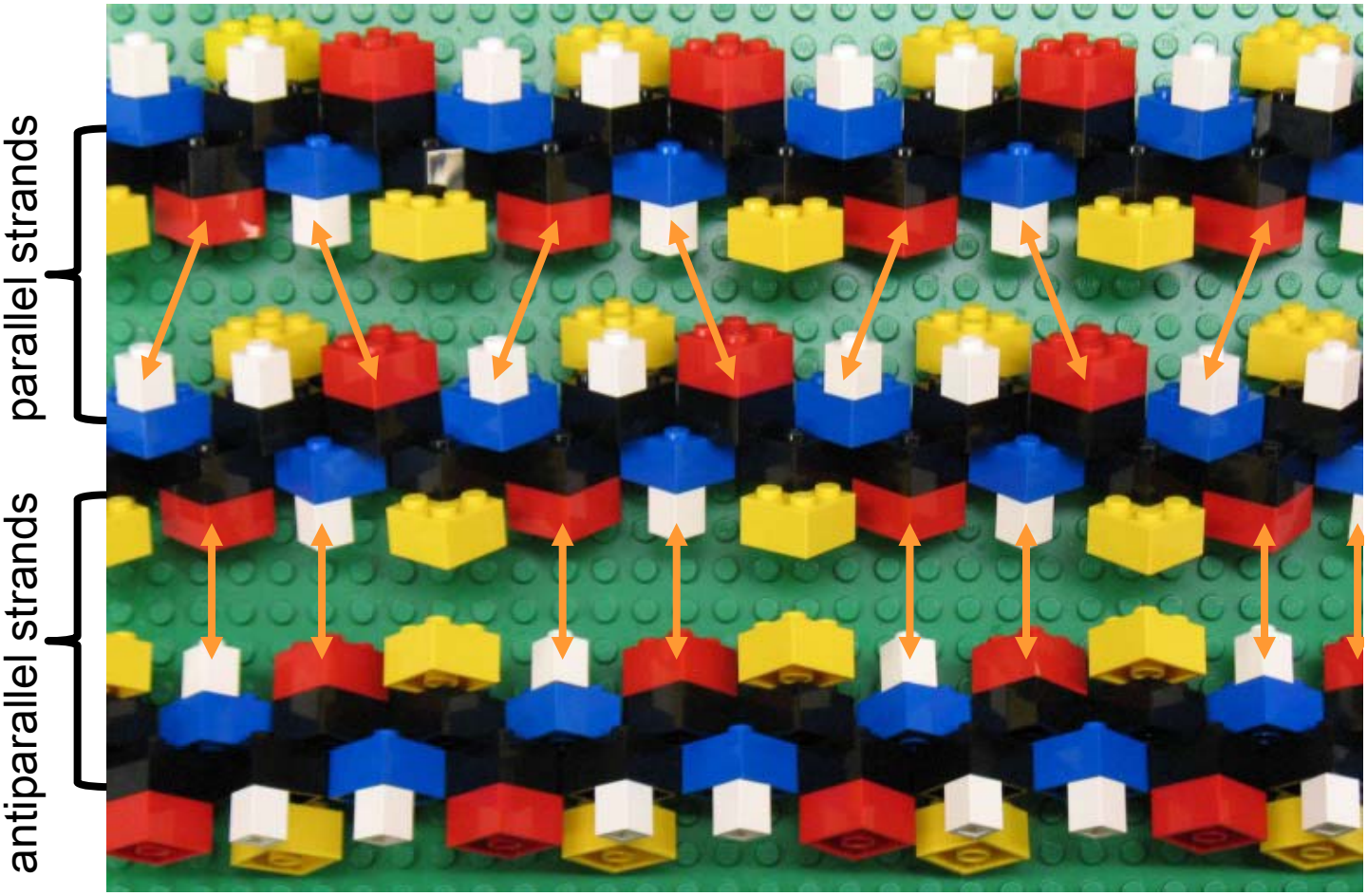


amino acid (L isomer)

Color key:
black = carbon
white = hydrogen
red = oxygen
blue = nitrogen
yellow = assorted functional groups

This model requires:
35 white 1x1 bricks
22 red 2x2 bricks
23 blue 2x2 bricks
46 black 2x2 bricks
25 yellow 2x2 bricks

Hydrogen bonds (orange arrows) can form between oxygen atoms on one polymer strand and hydrogen atoms attached to nitrogen atoms on an adjacent polymer strand.



NOTE: Hydrogens connected to the nitrogens on the bottom reversed strand have been moved to the front for ease of viewing.

Cellulose

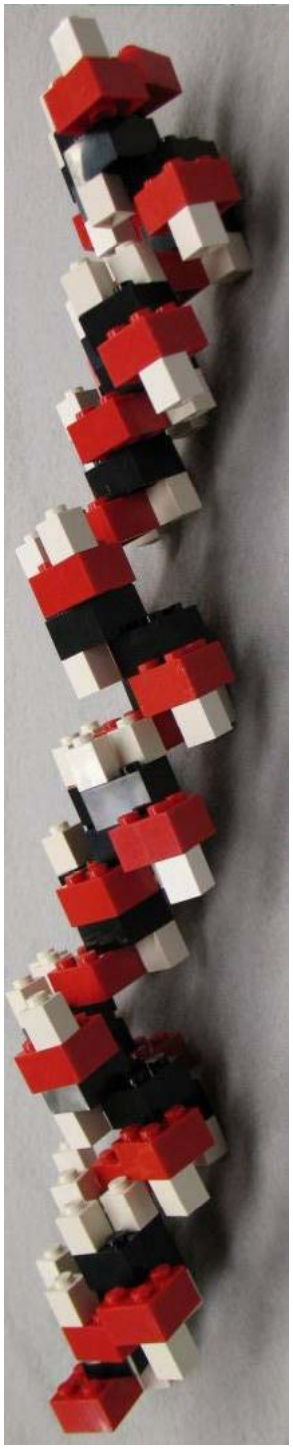
(monomers not shown)

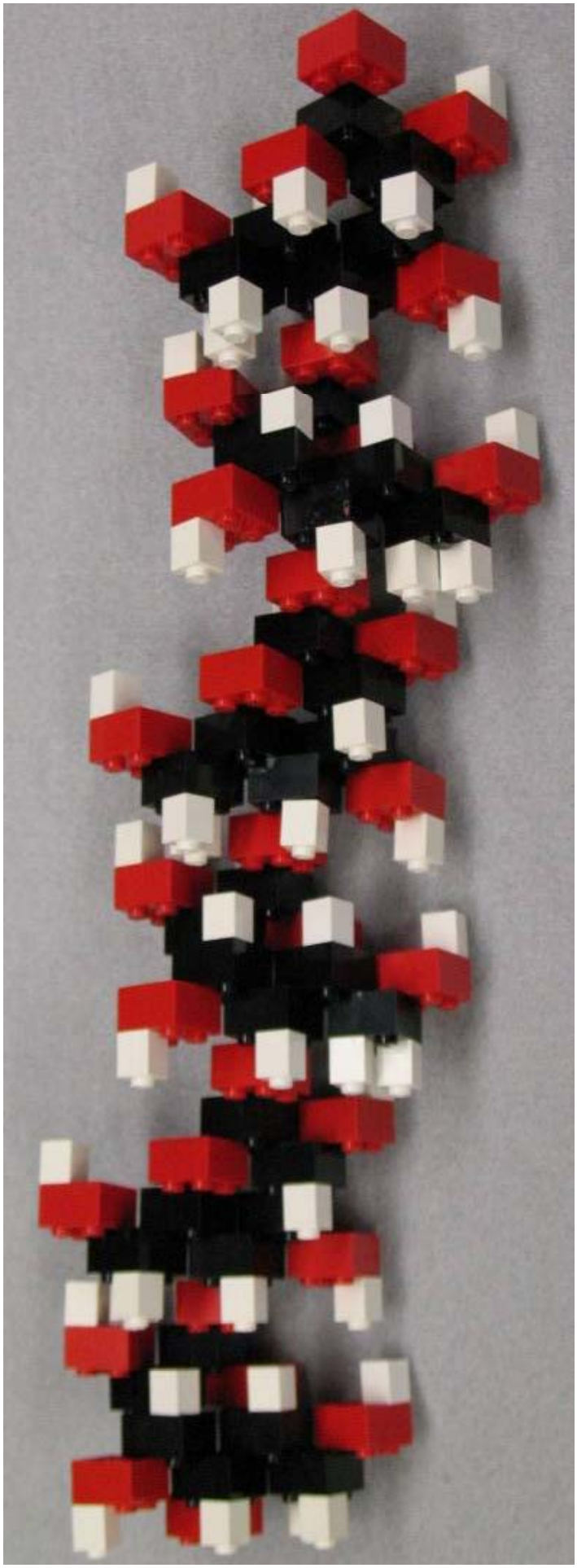
Color key:

black = carbon

white = hydrogen

red = oxygen





This model requires:

34 black 2x2 bricks

31 red 2x2 bricks

45 white 1x1 bricks

NanoKid™ Building Steps

NanoKids™ are people-shaped molecules developed at Rice University.

Step 4

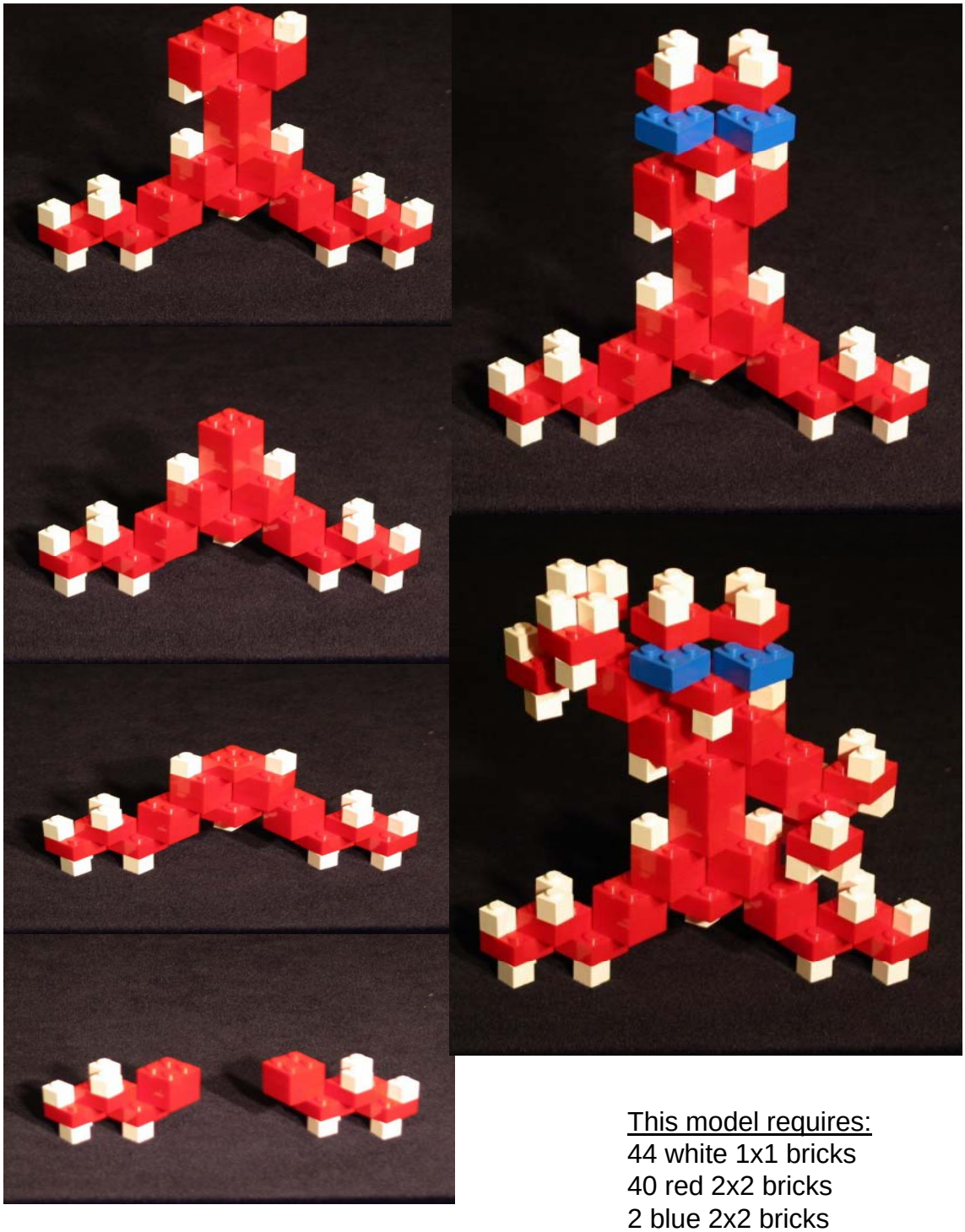
Step 5

Step 3

Step 2

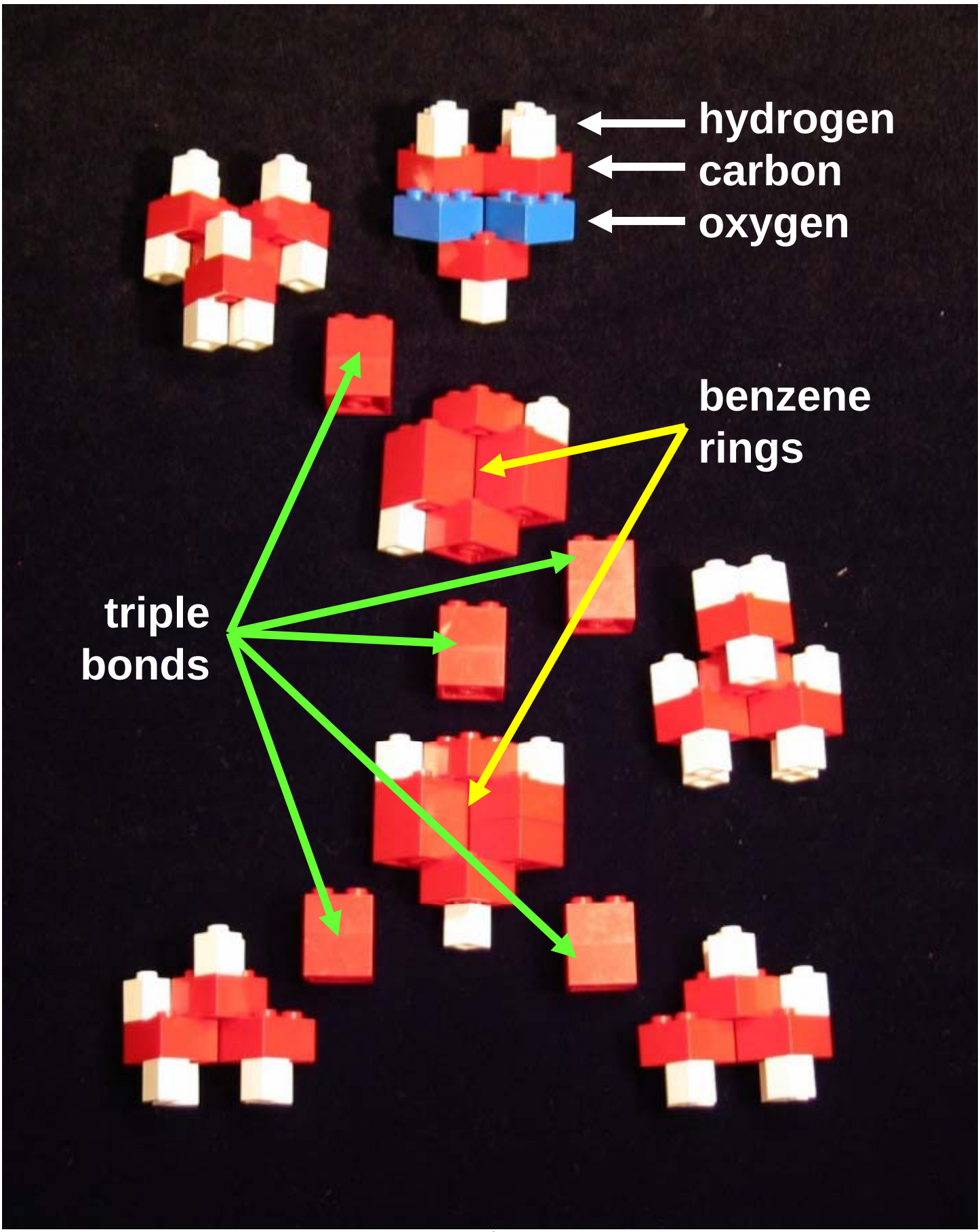
Step 6

Step 1



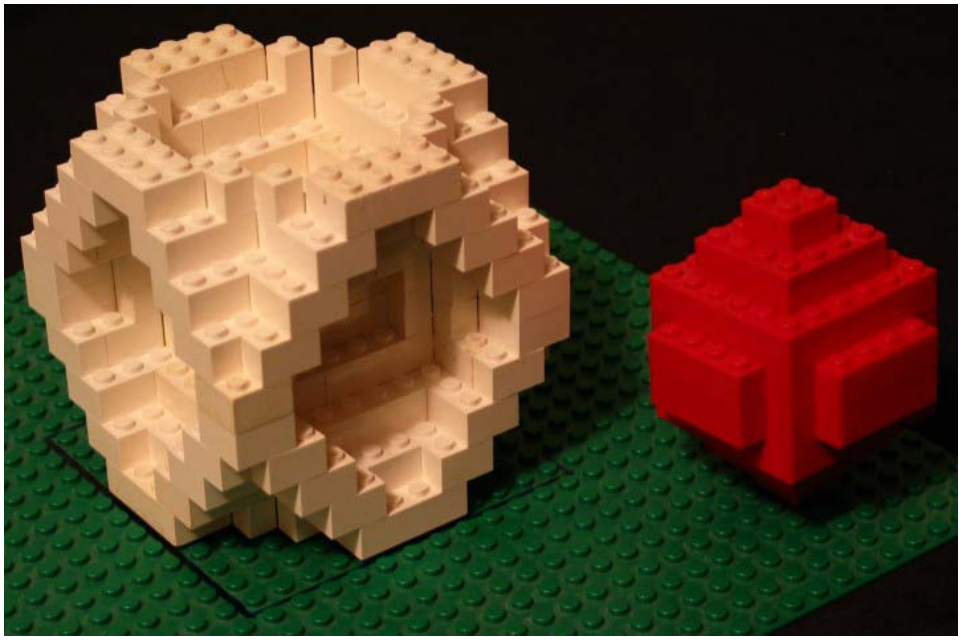
This model requires:
44 white 1x1 bricks
40 red 2x2 bricks
2 blue 2x2 bricks

NanoKid™ Parts



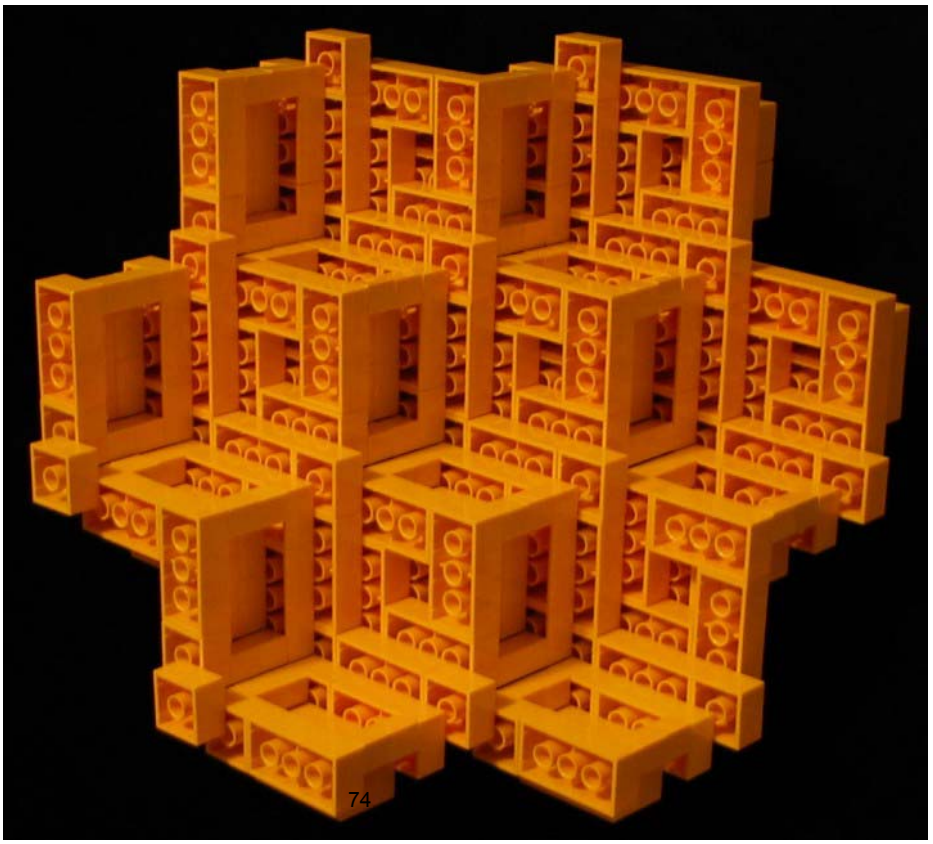
Face-Centered Cubic Inverse Opal (separated spheres)

Inverse opal unit cell

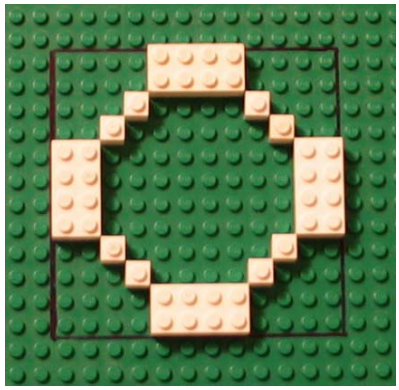


Full sphere

(111) interlayer structure



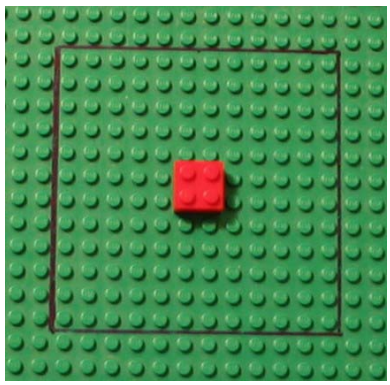
Opal layers

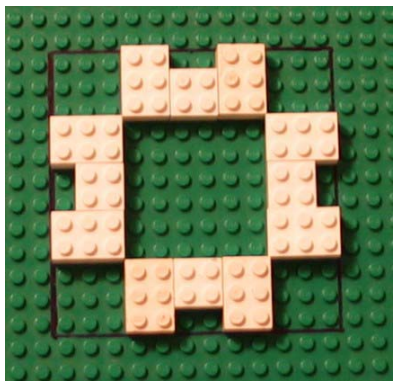


Layers 1, 10

Sphere layers

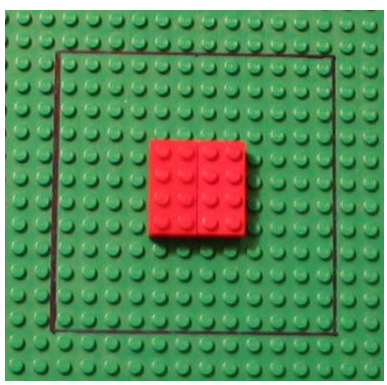
Layers 1, 8

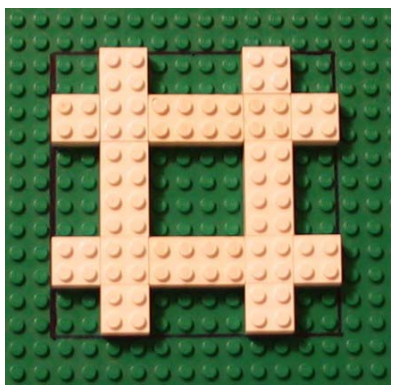




Layer 2, 9

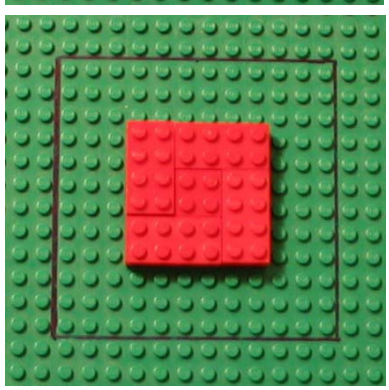
Layers 2, 7

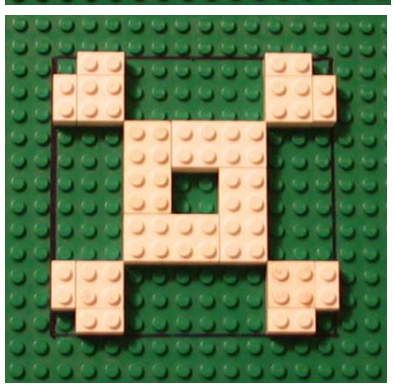




Layer 3, 8

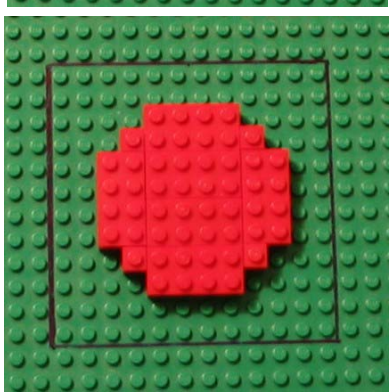
Layers 3, 6

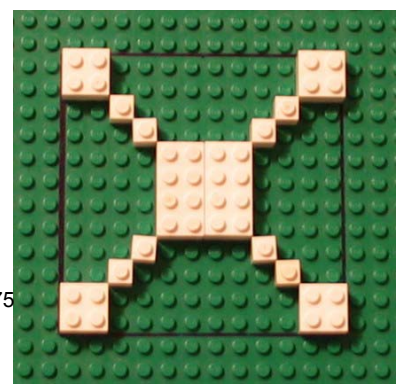




Layer 4, 7

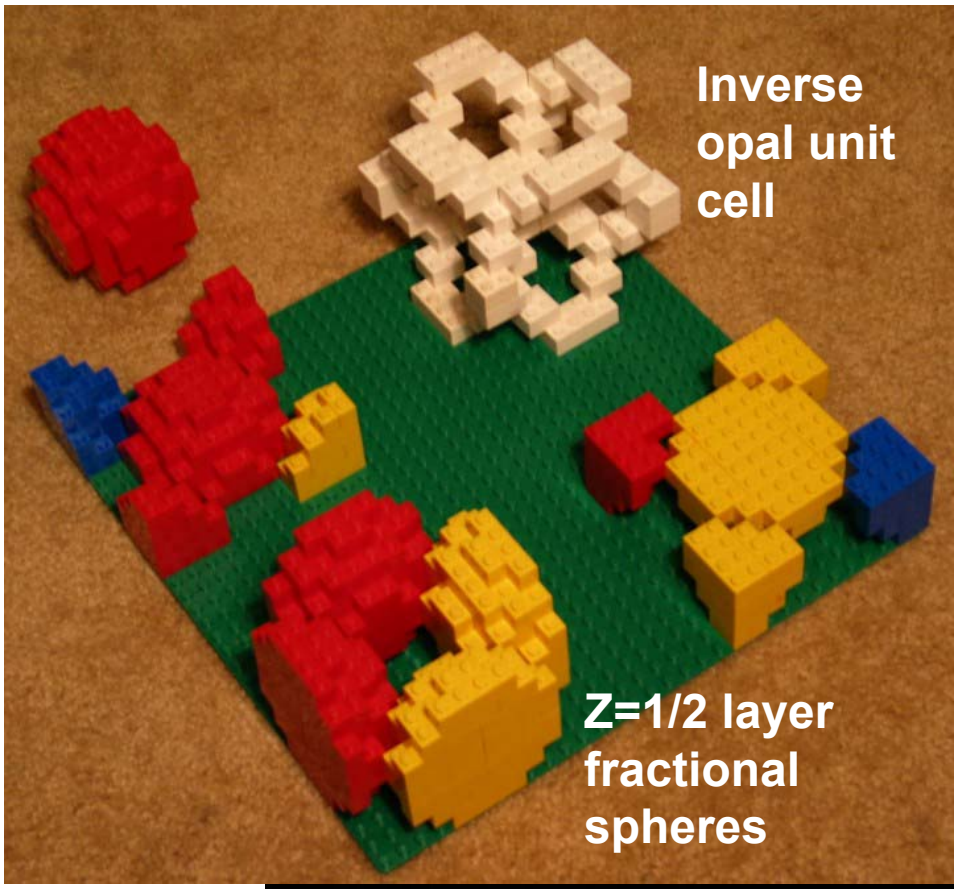
Layers 4, 5

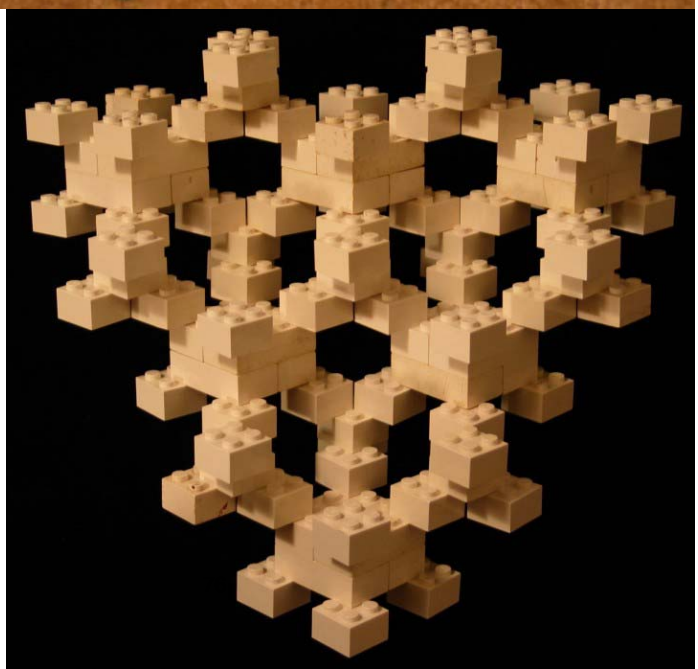




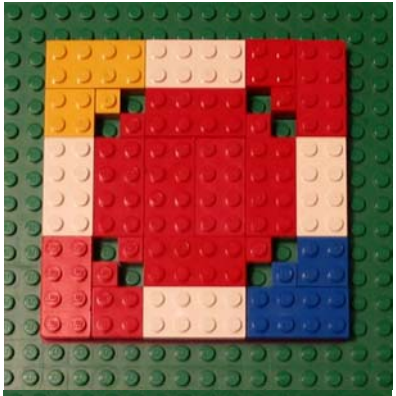
Layer 5, 6

Face-Centered Cubic Inverse Opal (touching spheres)

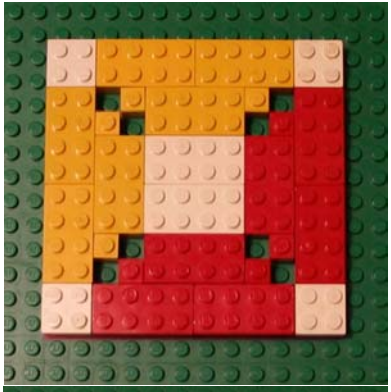




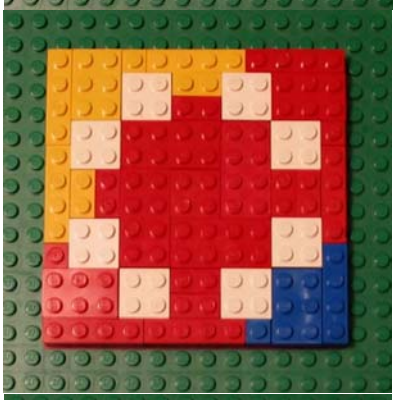
Layer 1



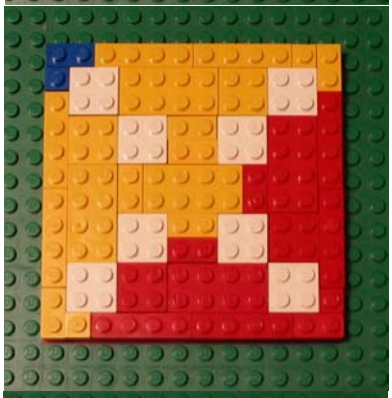
Layer 6



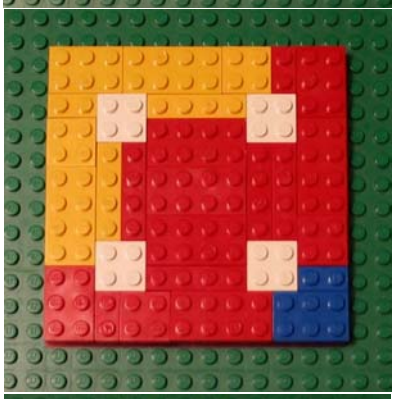
Layer 2



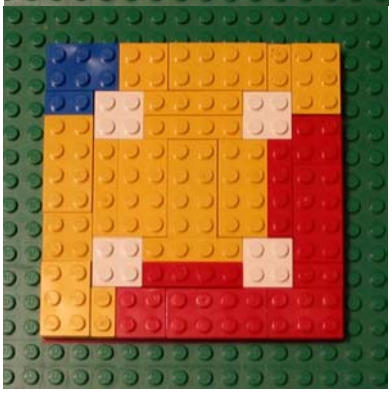
Layer 7



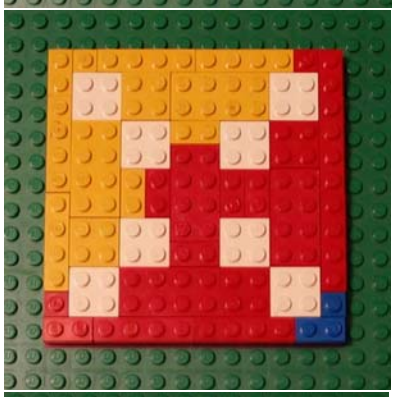
Layer 3



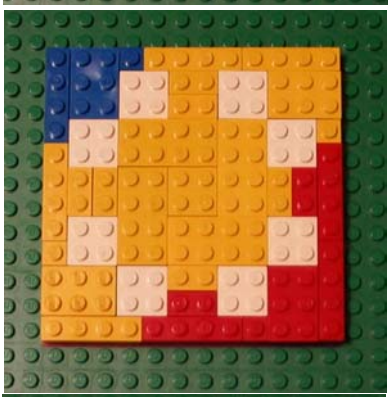
Layer 8



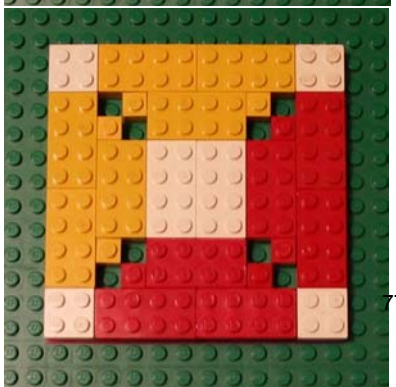
Layer 4



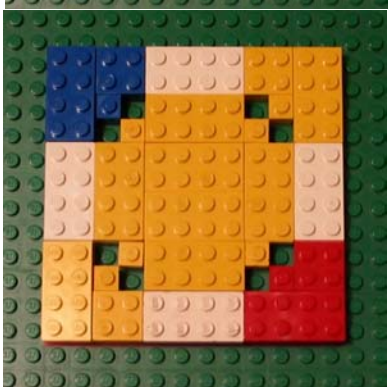
Layer 9



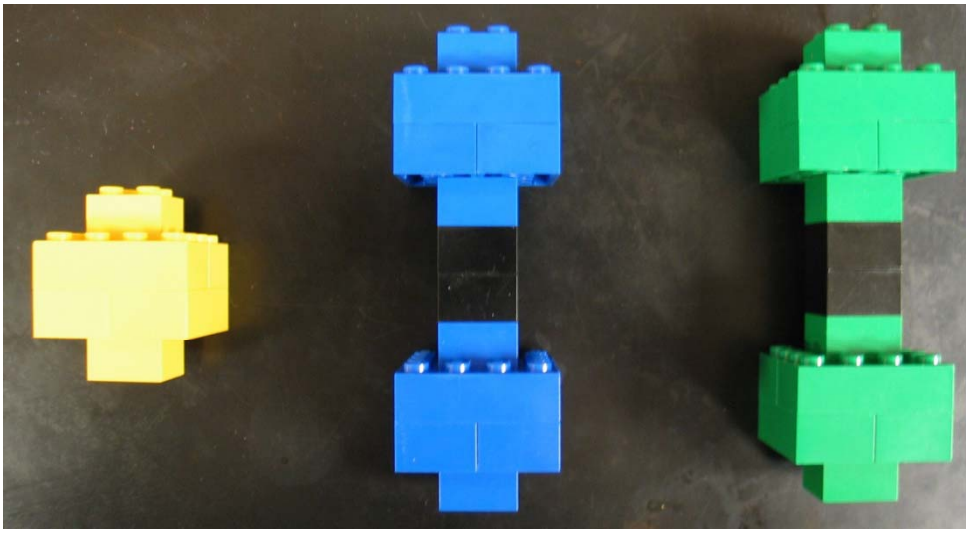
Layer 5



Layer 10



Atomic Orbitals

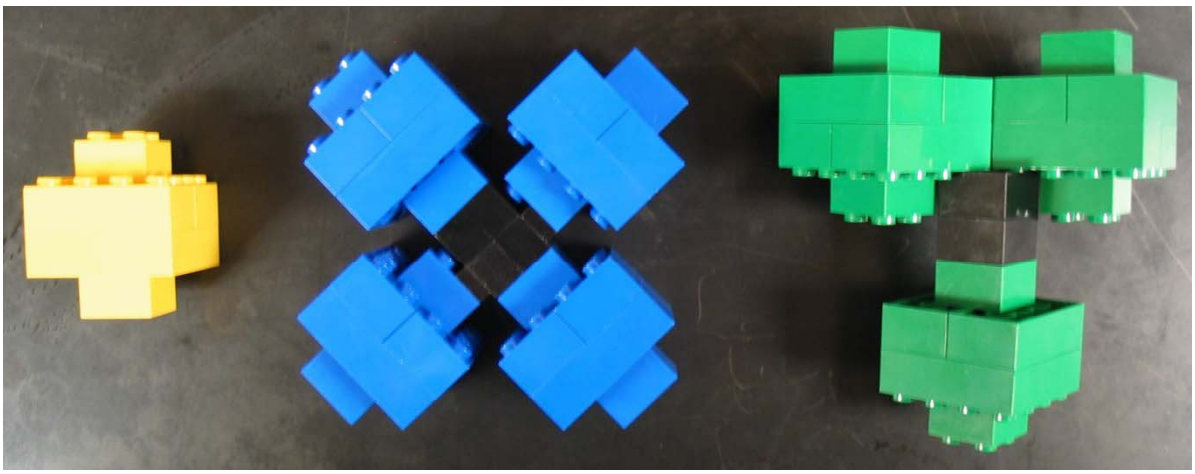


s orbital + p orbital = sp orbital

This model requires:
4 yellow 2x4 bricks
2 yellow 2x2 bricks

This model requires:
8 blue 2x4 bricks
4 blue 2x2 bricks
2 black 2x2 bricks

This model requires:
8 green 2x4 bricks
4 green 2x2 bricks
2 black 2x2 bricks



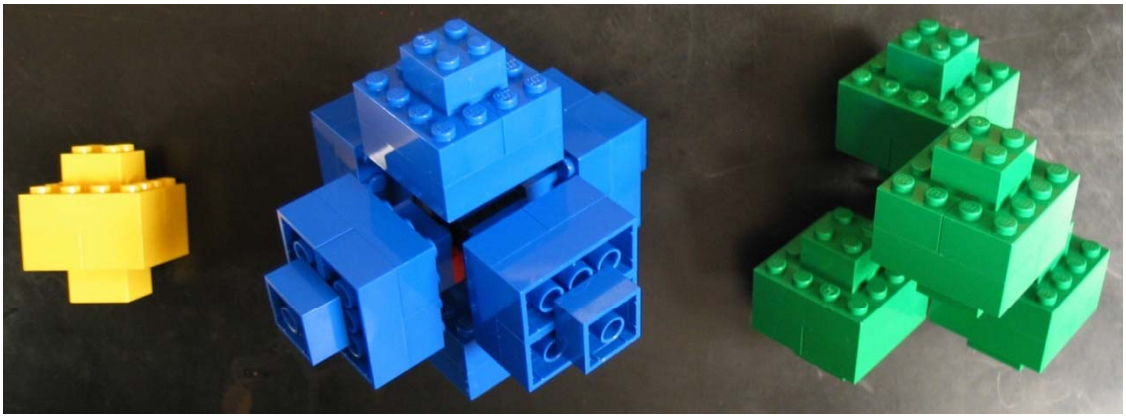
s orbital + two p orbitals = sp^2 orbital

This model requires:
4 yellow 2x4 bricks
2 yellow 2x2 bricks

This model requires:
16 blue 2x4 bricks
8 blue 2x2 bricks
2 black 2x2 technic bricks
2 black 1x2 plates w/ 1 knob

This model requires:
12 green 2x4 bricks
6 green 2x2 bricks
2 black 2x2 bricks

Atomic Orbitals

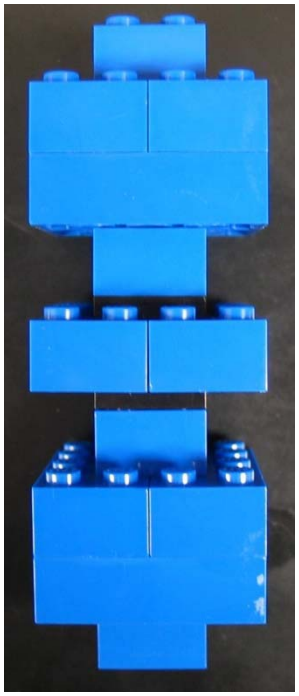


s orbital + three p orbitals = sp^3 orbital

<u>This model requires:</u>
4 yellow 2x4 bricks
2 yellow 2x2 bricks

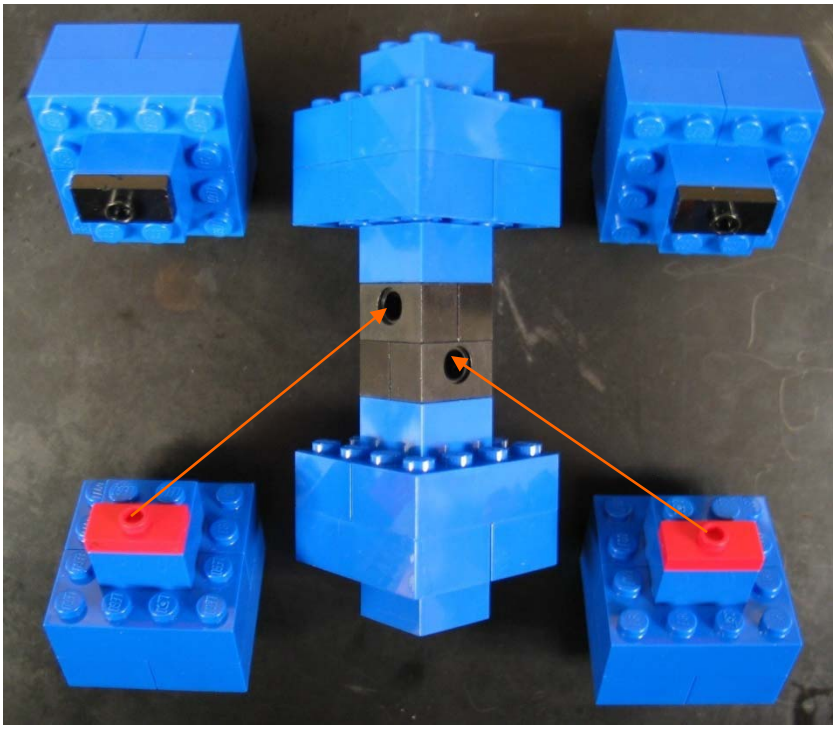
<u>This model requires:</u>
24 blue 2x4 bricks
12 blue 2x2 bricks
4 black 2x2 technic bricks
4 black 1x2 plates w/ 1 knob

<u>This model requires:</u>
16 green 2x4 bricks
8 green 2x2 bricks
2 black 2x2 bricks



d_{z^2} orbital

<u>This model requires:</u>
10 blue 2x4 bricks
4 blue 2x2 bricks
2 black 2x2 plates



"three p orbitals" model
(taken apart for clarity)
same concept used for "two p orbitals" model