# UNIT E

# ATOMS, CRYSTALS, AND SNOWFLAKES


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> *"If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis, that all things are made of atoms."*
>
> *–Richard Feynman (1918 - 1998)*

## *0 OBJECTIVES*

1. To investigate what is meant by the atomic hypothesis
2. To consider alternatives to the atomic hypothesis, in the process defining atoms more completely
3. To develop the ability to make *predictions* based upon models, even those in which we don't believe
4. To apply the atomic hypothesis and its alternatives to everyday events in order to determine whether atoms have any effect on our lives
5. To understand how different crystals form, to be able to describe the differences between them, and to be able to relate these differences to the underlying atomic structure
6. To understand why all snowflakes are different and yet the same

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[1] Snowflake picture used without permission from The Snowflake: Winter's Secret Beauty by Libbrecht and Rasmussen.

## 0.1 OVERVIEW

### *Why Study Atoms?*

Atom exist. In the coming weeks you will be debating ideas and theories, using these ideas to make predictions and conducting experiments dealing with atoms. And yet you probably already know that matter is considered to be made up of tiny particles called atoms and therefore may wonder: why are we doing all of this?

The purpose of this unit is *not* to convince you that atoms exist. You already know that. But do you know what it means for atoms to exist? And, if matter were not made of atoms, how would our world be different? It is likely that, having learned somewhere in elementary school about atoms, you were never given the chance to think seriously about the possible alternatives to the atomic hypothesis. But why should you?

One whimsical reason for considering alternatives is described in the cartoon below.

And Hagar is right. If you truly understand an opposing viewpoint, you are more likely to be able to argue against it. Understanding alternatives to the atomic hypothesis will allow you to identify their strengths and weaknesses. But so what? After all, we still believe the "correct" view of atoms, right?

Here's the secret. By understanding where alternative models fail you are actually learning more about where the atomic hypothesis succeeds. In other words, you learn more about atoms by contemplating the alternatives. While this idea may seem radical (after all, in how many of your other classes have you spent time thinking about the "wrong" ideas?), it is the basis of a fascinating theory encompassing mathematics and general science that lies beyond the scope of this class.

This should seem strange and perhaps scary. Don't worry. We won't spend so much time looking at the wrong ideas that we neglect to learn about atoms. But the longer and harder you spend thinking about what seem to be philosophical questions the better you will understand the consequences and ramifications of the atomic hypothesis. There is a concluding sentence to the quote from Richard Feynman given on the title page of this unit. It reads

> *In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied.*

You already know the sentence (atoms exist). Now you will use your imagination and thinking to understand exactly how much information is contained in that one little sentence.

# *1 HOW DO WE DESCRIBE MATTER?*

You will need some of the following equipment for the activities in this section:

- Beakers or styrafoam cups
- Water
- Soap
- Petri dish or other container
- Marbles
- Ground pepper or some other dark spice
- Magnifying Glasses
- String
- Supersaturated salt solution
- Supersaturated sugar solution
- Copper sulfate solution (optional)
- Ring stands (optional)

### 3d Crystal growth setup

Because it takes several days to grow crystals of appreciable size, we will start the process now and return to the crystals in a few days. Your instructor will have supersaturated salt, sugar, and perhaps copper sulfate solutions. To initiate the crystal growth, put the solutions in (different) beakers. Suspend a string from a pencil or ring stand so that it hangs to the bottom of the beaker, lying in the solution. ***Put your name on the beaker so you can identify your crystal at a later date***.

## 1.1 WHAT IS AN ATOM?

So you know atoms exist. Other than the name, however, what do you know about atoms? Do you know how big or small they are? Are they round or triangular? Hard or soft? It s traits like these that define what an atom is. Furthermore, what are the alternatives to atoms? If atoms are the only thing we can think of to comprise matter, why did it take over 2000 years before people finally abandoned the alternative ideas?

### Activity 1.1.1 What are Atoms?

a) Discuss amongst your group what you think is meant by the statement "all matter is made up of atoms." What properties do you think atoms have? Be prepared to present your ideas before the class.

b) Suppose scientists suddenly announce the discovery of a material that is not made of atoms. What properties might it have? How might it differ from substances that are made up of atoms?

c) Imagine you can do any experiment to test for the existence of atoms. What experiment would best provide evidence for the existence of atoms?

d) Suppose you ran your experiment on an object that was *not* made of atoms. What would the result of your experiment be? How would your experiment then disprove the atomic hypothesis that all matter is made of atoms?

## *Do Atoms Matter?*

It is certainly not obvious that atoms exist. As you look around, the table you're working on, the air you're breathing and the coffee you're drinking seem to be continuous. They certainly don't look like they are made up of tiny particles. So whether atoms even play a role in our everyday existence is a very reasonable question. Another aspect of this question is whether our interpretation of the world around us changes if we consciously think of atoms.

Scientific experiments and ideas are presented to the world "ready-made," and so we often don't see the guesswork, stops and starts, and mistakes that led to the tidy conclusion. This is analogous to a novel, where the book you buy likely bears little resemblance to the first rough draft the author wrote. This leads to some misconceptions about science (and writing). We assume that a writer "was born to write" because we do not see the lengthy struggles they have in formulating a coherent book. So to we often think of science as involving complicated, expensive experiments because it is those that are written about in the newspaper.

In fact, most investigations, scientific or otherwise, begin with very simple observations. The purpose of these is not to suddenly understand everything about a phenomenon. Rather, it represents the "playing around" stage where you begin to get comfortable with what you're looking at. In this unit you'll do a lot of "playing around" and might be surprised at what you can understand based on this informal investigation. The first example of this is in the next activity, where you'll contemplate something as simple as soap spreading out on water.

## Activity 1.1.2 Initial Observations

a) Fill a petri dish with water to the very top. Sprinkle pepper or some other spice on the liquid. Add a drop of soap to the liquid. What happens to the pepper?

b) What do you think is happening to the soap that is causing the pepper to act the way it does? Draw a picture indicating what you think is happening.

c) Why doesn't the soap push the pepper all the way to the side of the cup?

d) The fact that a single drop of soap does not spread out to completely cover the surface could be related to the underlying structure of the soap. Assume for the moment that the soap is made of atoms. What might determine how far the soap drop spreads out? Draw a picture indicating what you think the soap atoms on the surface might look like.

e) Assume that the soap is *not* made of atoms. Hypothesize about what might prevent the soap from spreading out to cover the surface. Draw a picture of what you think the soap might look like on the surface.

## *How Big is an Atom?*

In the previous activity you observed that a small drop of soap appeared to spread out on the surface of water. This in itself is not shocking; you're probably familiar with oil spills in which the oil spreads out on the surface of the ocean. It may not have surprised you to see that a small drop was not sufficient to completely cover the top of the water. After all, if we only needed a little bit of soap to clean ourselves in the shower the soap companies would be a lot poorer!

What may be surprising, however, is that such an observation begins to give us clues into the nature of atoms. You may have theorized that the soap spreads out until it makes a layer that is one atom thick. Once it's done so, it cannot spread out any further without separating the atoms. If the soap is made of some gooey substance (not atoms), then maybe some sticky property keeps in from spreading out any further. These are now two competing theories that must be tested against one another before a conclusion can be made about which is correct.

## 1.2 DEVELOPING A TESTING EXPERIMENT

In the previous section we proposed two ideas for why the soap stops spreading. Either the soap could be made from discrete atom or from a sticky but continuous liquid. Is it possible to tell which is correct? To do so we must design a *testing experiment*. A testing experiment is one that is designed to test one theory versus another. What determines whether an experiment is a good testing experiment? Each idea must make a very clear prediction about the result of the experiment. If the observation made does not clearly disagree with at least one of the predictions, then the experiment is not a very good test (or the theories might be too vague). It is in the design of these experiments that creativity really begins to be seen in science. There is not a single good testing experiment, and different people might think up different experiments. Let's see what you come up with!

### Activity 1.2.1 An Experiment to Test Atoms vs. Goo

a) Discuss with your group what experiments might test the two ideas about soap (atoms vs. a continuous sticky substance). Try to generate more than one idea and be prepared to share them with the class. You should describe what the process of the experiment will be (what will you do) and also the results you would measure.

b) Pick one of your experiments and write below what the atoms idea predicts you will observe.

c) Write below what the "goo" idea predicts you will observe in this experiment.

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### *Predicting What you Don't Believe*

It may seem odd to go to the trouble to generate a prediction based upon an idea (goo) that you know to be wrong. In fact, scientists have to do this a lot. Scientific ideas are not fixed in stone; new ideas are always being generated, tested, and discarded. Different scientific groups might disagree on ideas and work very hard to prove the other group wrong. It is important to note that they are not (usually) disagreeing on the experimental details, but rather the interpretation of what happened. Fully understanding the opposing idea is very useful if you're trying to design an experiment to prove it wrong! As Hagar the Horrible said in the cartoon in the introduction, if you understand what the other person is trying to say, you are much less likely to be surprised!

### *Liquid Layers*

For our testing experiment we will add more soap to the top of the water and see what happens when it spreads to cover the entire surface. To see why this might be a good testing experiment, let's work through what each idea will predict will happen.

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## Activity 1.2.2 Liquid Layers: The "goo" Prediction

a) Imagine adding more soap to the top of the water, so much soap that it completely covers the surface and then some. According to the "goo" hypothesis, how would the soap spread out?

b) Draw a picture illustrating what you think the soap/water mixture will look like from the side.

## Activity 1.2.3 Liquid Layers: Atomic Prediction

a) Put some marbles in a petri dish. Draw what they look like from the side when you have just enough to cover the bottom of the dish.

b) Now add 5-10 more marbles and draw what they look like from the side.

c) What does your picture predict you might see as you add soap to the top of water?

d) How does this prediction differ from the one you made above?

**BOXED PREDICTION: What do *you think* you'll see when more soap is added to the water? Why?**

## Activity 1.2.4 Soap and Water

a) Add more soap to the water and look very carefully at it from the side. Do you see anything that resembles your drawing of the marbles? You may find a magnifying glass useful.

b) Take your time and play around with this experiment. You may want to add different kinds of soap, experiment with different ways of adding the soap, or perhaps add drops of water to the surface of the soap. Describe the experiments you do, your observations, and any conclusions.

# 2 *SOLIDS*

You will need some of the following equipment for the activities in this section:

- Newspapers
- Notebook paper
- Protective glasses/goggles and gloves
- Silicon wafers (2 per group)
- Magnifying glass or microscope
- Table salt
- Marbles
- Styrafoam balls (1/2″-2″ in diameter) and toothpicks
- Rock Salt
- Rock Candy
- Razor blades and something to hit them with (wrench, hammer)
- Salt, Sugar, and other crystals grown in section 1

## 2.1 SOLIDS

One of the fascinating properties of matter is its ability to change form as the temperature changes. Why should something solid, like ice, melt just because it gets hot? And what happens when it boils, disappearing from view? One of the difficulties facing ancients pondering matter was the drastically different forms that the phases of matter took. Solid, liquid, gas --- it was hard to imagine all three of these having the same underlying structure. We will tackle each of the phases in turn, beginning with the solid phase. For each phase we will work at developing both an atomic model and also a continuum model. It is only by fully understanding each that we can design and interpret a valid testing experiment.

### Activity 2.1.1 Phases of Matter: Solids

a) Discuss amongst your group how atoms might behave inside a solid. Write your ideas below.

b) In the space below, draw a picture representing your thoughts. Make sure to label the atoms and any other important features.

c) With your group, develop a description for solids that does not depend on atoms. Describe in words what the solid "looks like" inside, and draw a picture that represents your model.

## *Packing of Balls*

It is quite natural to imagine atoms as little balls. In a solid, these balls lie alongside one another. One reason solids are the easiest phase of matter to consider is that we don't typically think of the atoms in a solid moving around a lot. They stay next to their neighbors unless we come along and try and separate them. It is in fact this act of separating atoms, making cracks or *fractures*, that provides a good testing experiment of the atomic hypothesis. But first, as always, a preliminary observation:

## Activity 2.1.2 Preliminary Observations on Fracture

a) Take a piece of newspaper and tear it from top to bottom. Now take one of the two pieces and tear it in half from left side to right. Examine the two tears through a magnifying class. Describe what you observe.

b) With your group develop a theory for why the two tears differ. Describe it below and be prepared to present it to the class.

c) Do you think all pages of newspaper would tear the same way? Why or why not?

d) Do you think all paper would tear this way or can you describe a type of paper that might not?

e) Repeat this experiment with a piece of notebook paper. Do the tears differ significantly?

f) What can you conclude from your experiment on the notebook paper?

### *Underlying Structure and Tearing*

You probably observed small fibers in the newsprint. Tearing along with (parallel to) these fibers produced a different result than tearing across (perpendicular to) the fibers. This difference may not have been as noticeable in notebook paper, where the fibers seem to be distributed more randomly. A key idea is that the small-scale structure of the paper shows itself in the large-scale act of tearing. We sometimes call this a *macroscopic* (large) manifestation of a *microscopic* (small) structure.

Paper fibers, of course, are many times larger than atoms. In order to understand what types of experiments will be good tests of the atomic hypothesis in solids we need to have a clearer idea of how atoms might form solids. This is the purpose of the next few activities.

## Activity 2.1.3 Comparing simple models of matter in one dimension

a) Let's compare a continuum model with an atomistic model for a 1-dimensional string of material. Draw a picture of how you could represent a string as being composed of indivisble atoms.

b) Draw a picture representing the string as being composed of a continuum.

c) Imagine taking a “atom scissors,” so sharp it cuts at the atomic scale, and trying to cut the string. What differences might exist between the continuous string and the string of atoms?

d) Could you cut the continuous string at any location in the string?

e) Could you cut the atomic string at any location? Why or why not?

f) If you kept cutting the string into smaller and smaller pieces, what would the consequence of atoms be?

### *A surprising Consequence of Atoms*

When discussing atoms it is common to hear people cite the second behavior you discussed above: since atoms are indivisible, if you keep cutting something into smaller and smaller pieces, eventually you will end up with 1 atom left and you can't cut that any smaller. Often overlooked, however, is the idea that atoms also imply that substances can only be cut at certain locations, i.e. in between the atoms. Because atoms are so small, we often don't see this in our everyday lives. But that is perhaps also because we don't know what to look for....

## 2.2 FRACTURE IN TWO DIMENSIONS

It is, of course, impossible to fashion a one-dimensional string. For that matter, two-dimensional objects are also only theoretical, as all matter is three-dimensional. You might wonder why we would even consider one- and two-dimensional solids. The reason is simplicity. Thinking about cutting a row of atoms leads to the ideas of indivisibility and special cutting locations. These ideas are much more complicated in two and three dimensions, so it is nice to consider first the simplest case and only then move on to more complicated scenarios.

In the next activity you will extend your ideas on indivisibility and special locations to a two-dimensional lattice. The key question is: if one-dimensional solids can be cut only at specific points, how does this generalize to two-dimensional solids?

### Activity 2.2.1 Comparing models in two dimensions

a) Imagine dropping a plate that is a continuum (i.e. not atoms). What, if anything, governs the directions in which the plate cracks? What, if any, order do you think exists regarding the cracks?

b) Take 25 or so marbles and arrange them in a petri dish so that they form a square. Draw below the arrangement of marbles you have.

c) If this represents a plate that is dropped (and the marbles are all glued together), draw below what types of cracks you would imagine finding.

### *Fracture Points and Fracture Lines*

As in the one-dimensional solid, a continuum model says *nothing* about how an object will break. There are no restrictions on where the object can break, nor any reason that the cracks will stay in straight lines. This is not implausible; imagine dropping a real plate. The cracks would go in many different directions, resulting in very tiny, irregular pieces.

If, however, we had a plate that was a regular array of indivisible atoms, then we would expect the cracks to stay along well-defined lines. If the atoms were packed in a square, as in the previous activity, these lines would be perpendicular to one another. That is, cracks could go “up-down” or “left-right” but not along a diagonal.

Let’s test these hypotheses with silicon wafers. Silicon is used to make computer chips because it can be grown in a very regular manner. That is, it forms an atomic lattice with very few imperfections. It is also very brittle, so when it breaks watch out!

## Activity 2.2.2 Two dimensional fracture

a) Take a silicon wafer and put it at the edge of a table so that one flat side is perpendicular to the table's edge. Put a book on top of the half that is on the table and push down on the the other half, breaking the crystal. Draw below the pattern of cracks that formed on the half on the table. ***CAUTION: WEAR PROTECTIVE GLASSES AND SAFETY GLOVES WHEN BREAKING THE SALT.***

b) Pick up pieces of the wafer and try and break them. Can you easily break them in any direction?

c) Which directions seem to break easily?

d) Which directions do not break as easily?

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## *A Real-World Indication of Atoms*

Silicon, because it forms such a nice atomic lattice and is so brittle, provides a nice indication of the possibility of atoms existing. The cracks all run in perpendicular directions, and even the cracks that appear to be diagonal in fact can be seen to consist of smaller “left-right” and “up-down” cracks, forming a staircase-like pattern. One could, of course, modify the continuum hypothesis to consist of some solid “goo” that has a direction built in, but it is hard to picture what this would look like.

The flat edge of the silicon wafer, as you might have now inferred, is put there to indicate the directions of one of the lines of atoms. The silicone broke easily because you put the desk edge along the other line of atoms, so your initial crack ran along this line. What happens when you intentionally try to break the silicon in a different direction?

## Activity 2.2.3 Off-axis fracture: Continuum vs. Atoms

a) What does the continuum model predict will happen if you try and crack a plate at different angles? Will the breaking be the same or different? Why?

b) What does the atomic model predict will happen if you try and crack a plate at different angles? Specifically, how would a diagonal crack in your marble model compare with a vertical or horizontal crack?

c) Fully explain why the atomic model predicts two different types of crack patterns.

## Activity 2.2.4 Off-axis fracture: experiment

a) Take a silicon wafer and place it so the flat edge is at an angle (~45 degrees) with respect to the table's edge. BEFORE YOU BREAK IT, predict below what the crack pattern will look like.

b) Now break the wafer and draw below the pattern formed by the cracks. ***CAUTION: WEAR PROTECTIVE GLASSES AND SAFETY GLOVES WHEN BREAKING THE SALT.***

c) What does this experiment imply about the behavior of silicon atoms?

### *Atomic Fracture and Dimensions*

The physics of how something breaks can only be understood at the atomic level. Theories built on continuum ideas do not accurately predict when and where objects break. Fracture is still not a well-understood phenomenon and is an area of active research and debate.

Having explored two different dimensions now (1d and 2d) we can make an interesting observation. The one-dimensional line of atoms broke at specific points. Mathematically, a point has "zero-dimensions" and a line one-dimension. The two-dimensional plane broke along specific lines. So the fracture "surface" always seems to be one dimension lower than the object. This is related to the idea that we measure surface areas in terms of square-feet (or centimeters squared) and volumes in terms of cubic-feet (or centimeters cubed).

## 2.3 CRYSTALS

When the atoms in a solid fall into a regular pattern we say that the object is a *crystal*. The particular pattern is called the crystallographic structure of the solid. So far we have looked at atoms packing into squares. There are many different crystallographic structures, however, that can be made from spheres. When substances pack in different ways the properties also change. In the next activity you will discover a new crystallographic structure and its fracture properties.

### Activity 2.3.1 Packing marbles

a) The ordering of spheres into a square has a name: orthogonal close packing. It is named this because the lines connecting the neighboring atoms are orthogonal (perpendicular) to one another and the spheres are all close (touching). There is another way to pack spheres into a repeating pattern. Play around with the marbles until you have a new type of packing, then draw it below.

b) This packing is called Hexagonal Close Packing (HCP). Why do you think it is named this? (Hint: what does a hexagon look like? Where does the hexagon arise in your packing?)

c) Is this packing more or less dense than orthogonal close packing? That is, are there more or fewer marbles in the same space? Explain.

d) Imagine breaking a plate made from atoms that pack in this manner. Draw below a pattern of fracture lines that might result from this packing.

e) How would the fracture lines differ from those in an orthogonally close-packed lattice?

## 2.4 SOLIDS IN THREE DIMENSIONS

We live in a three-dimensional world. The packing ideas you developed in the last section, however, have consequences for the shape matter takes. Let's see what a three-dimensional packing of atoms would look like and how it would behave.

## Activity 2.4.1 Orthogonal Close Packing in Three Dimensions

a) With the styrafoam balls and toothpicks, arrange the "atoms" in an orthogonal close packing in three dimensions. Draw below what your "solid" looks like.

b) Describe the fracture lines you might expect to find in this three dimensional solid.

c) What general shape would you expect crystals to take if they formed in such a pattern?

## Activity 2.4.2 Hexagonal Close Packing in Three Dimensions

a) With new styrafoam balls and toothpics, start by arranging a number of spheres in a *2-d* Hexagonal close packed array. Draw below what your 2d solid looks like.

b) Keeping with the sprit of hexagonally close packed, where do you think the next layer of balls should be placed? Describe below why you chose this and draw what the crystal looks like.

c) Now use the toothpicks to build your 3d HCP solid. Draw below its overall shape.

d) What fracture lines might you expect to find if your solid shattered? How do they differ from that from the OCP solid?

e) What general shape might you expect crystals forming an HCP lattice to take? How might they differ from that of crystals forming an OCP lattice?

### *Cleavage*

It might not have been too surprising, given our earlier finding on fracture dimension that the atomic hypothesis predicts that three-dimensional solids break along two-dimensional planes. These planes are called *cleavage planes*, and we say the substance *cleaves* when it breaks easily only along these planes. Let's look at some different materials and see which cleave and what we can infer about the underlying atomic structure from the cleavage planes.

## Activity 2.4.3 Three Dimensional Fracture

a) Ordinary salt (NaCl) forms naturally in the ground. It is dug up and sold as "rock salt," so named because it has a lot of dirt in it (so you shouldn't eat it!). Take a piece of rock salt and break it by splitting it with a razor blade. You might want to put the razor blade on the salt and hit it (the blade) gently with a hammer or wrench. Describe below how the rock salt breaks. Include a picture of the salt pieces. ***CAUTION: WEAR PROTECTIVE GLASSES AND SAFETY GLOVES WHEN BREAKING THE SALT.***

b) Now take some of the pieces from the salt you just broke and try to split it into smaller pieces. Can you easily split the salt in any direction you choose? Which directions are easier than others?

c) Examine the salt pieces under a magnifying glass or microscope. How do the cleaved surfaces (the surfaces that just broke) appear?

d) What inferences can you make about how salt atoms pack?

e) Examine some grains of table salt under a magnifying glass. Describe your observations below. Include a picture.

f) How are your observations of table salt consistent with your cleavage experiments? How are they different?

## Activity 2.4.4 Do all solids cleave?

a) Take a piece of rock candy, either store-bought or from the crystals you grew from the super-saturated sugar solution in Section 1. Examine them under a magnifying glass or microscope. Describe their appearance below. Include a drawing.

b) How is their appearance similar to the salt pieces? How is it different?

c) Based upon your observations, predict how the sugar will break when you split it with a razor blade. Fully explain the reasoning behind your prediction.

d) Now split the rock candy with the razor blade. Examine the pieces under a magnifying glass and describe them below.

e) Is sugar similar to salt or different? Explain the similarities and differences and any inferences you can make about the way sugar molecules pack.

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## *Why does a Plate Shatter?*

Earlier we noted that a plate, when dropped, does not appear to break along well-defined lines or planes. *Most* objects that break, glass, metal, wood, etc. do not seem to break along well-defined lines. Does this mean that these substances are not made of atoms? Must we throw out our atomic hypothesis for these materials, or is there a way of reconciling these contradictory ideas?

## Activity 2.4.5 Polycrystals

a) With your group, develop a theory for why a plate might not break along well-defined lines or planes. Be prepared to present your ideas to the entire class.

b) In fact, it is quite difficult to grow a material into a single crystal. In a subsequent section we will look at how crystals form but for now draw below how a substance would look if it was made up of lots of different crystals all oriented in slightly different directions.

c) What parts of this *polycrystal* (literally "many crystals") would be weak? What parts would be strong?

d) How would the polycrystal fracture? Would there be well defined lines throughout the entire substance?

## *Polycrystals*

The fact that most materials are polycrystalline obscures the underlying atomic structure. Note how many of your predictions relied on a perfect ordering of atoms. If this perfect ordering does not exist, then you see complicated results that are difficult to explain. The ability to grow perfect crystals is a fairly modern (last 200 years) achievement. Before this was learned, the only perfect crystals were obtained from minerals and elements growing in the earth. Rock salt, for example, is a polycrystal with well-defined cleavage planes.

## 3 *LIQUIDS AND GASES*

You will need some of the following equipment for the activities in this section:

- Ice
- Scales
- Dry ice
- Balloons
- Sponges
- Rubber Bands
- Motion carts and tracks
- Force sensors
- Rubbing alcohol
- Graduated cylinders
- Sand
- Steel shot or ball bearings

### 3.1 INITIAL OBSERVATIONS OF PHASE CHANGES

The ability of substances to change phases was quite mysterious to the ancients. They new, for example, that steam was related to water and ice, but were unable to explain how. The prevalent theories tended to focus on the use of fire to bring about the phase change, so that steam was somehow "water+fire". It is possible to develop an atomic hypothesis for liquids and gases based, of course, on initial observations!

### Activity 3.1.1 Initial Observations on the Solid-Liquid Transition

a) Weigh a dry beaker and record its weight below. Add 1-2 pieces of ice and record the new weight. What is the weight of the ice? Let the ice melt in the beaker while you answer the next question.

b) Discuss with your group how the mass of the ice will change as it melts to water. Will the weight of the melted water be greater than, less than, or equal to the mass of the ice? Thoroughly explain the reasoning behind your answer. That is, *why* do you think it will be greater/less/equal? Be prepared to discuss your ideas with the class.

c) Wait until the ice has melted and weigh the beaker and water. Compare the weight with that of the ice that you started with.

d) What conclusions can you make from this measurement?

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*Conservation of Matter*

An important observation on phase changes is that the weight does not change. So if we think of water as "ice+fire" we are forced to conclude that "fire" has no weight. This makes raises certain challenges to the idea of fire as matter. If the amount of matter is not changing, though, certain aspects of it certainly are, as the next activity demonstrates.

## Activity 3.1.2 The Solid-Gas Transition: Predictions

a) In a minute you will put a small piece of dry ice into a balloon and tie the balloon. What do you predict will happen to the weight of the system (balloon+contents) as the dry ice turns from solid to gas?

b) *If* we assume that the dry ice is made of atoms, are there more dry ice atoms when it's a solid, liquid, or does the number of atoms stay constant?

c) Now use your answer in question b) to explain your prediction in question a). If you predict the number of atoms to stay the same, what does your prediction in a) imply about the weight of solid atoms compared to gas atoms? If you predict the number of atoms to change, what does this imply about the relative weights?

d) What other changes do you predict you will see in the balloon? Fully explain your prediction, including reasons or attempted explanations for all of your predictions.

## *The Solid-Gas Transition*

It is in fact not obvious what will happen when the dry ice turns into a gas. One might argue that, since none of the dry ice atoms leave the balloon, the weight stays the same. Or, you might think that gas atoms are lighter than solid atoms, in which case you need to think about how the gas atoms might be different than the solid atoms. In particular, you would need to explain the opposite transition (gas to solid) and whether the weight would increase and where the extra weight might come from.

Fortunately, there is a way of avoiding all this work: *making the measurement*! Only if the actual observation indicates these questions are important should we take the time to flesh out our theory. So let's be lazy and do the experiment!

## Activity 3.1.3 The Solid-Gas Transition: Experiment

a) Take a small piece of dry ice. Get an *approximate* measure of its volume by approximating its length, width, and depth. Put the dry ice inside a balloon and tie the balloon. Place the balloon on a scale. Record below your calculations of the dry ice's volume and the initial weight.

b) Does the weight change as the dry ice turns to a gas? (*Note*: balloons feel a buoyant force of about .001 gram for every cubic centimeter. How does this affect your scale's reading?)

c) Record below your observations of the balloon and an estimate of the maximum size the balloon reaches before it breaks.

d) How would a believer in the continuum theory of matter explain what happens to the balloon as the dry ice turns to gas?

e) How would a believer in the atomic hypothesis explain the balloon's behavior?

f) What additional experiment can you propose that might test the continuum vs. atomic theories in gases?

## 3.2 GASES

The dry ice in the previous activity converted directly from the solid phase to a gas phase. This process is called *sublimation*. You may be surprised that we can learn a great deal about the atomic nature of gases by considering the expansion process. There is another reason to study the gases before liquids: they're easier. Once we understand solids and gases --- the phases that surround liquids --- we will be better prepared to understand liquids.

## Activity 3.2.1 Gas Expansion and Pressure

a) Imagine putting the same amount of gas into two containers, one 1ml the other 1000ml. Which container will need to be stronger? Why?

b) Develop in words and pictures a reason for why one container should be stronger than the other. Specifically, what is it about the gas that requires a stronger container?

### *Expansion*

It is probably intuitive that squeezing the same amount of gas into a smaller container requires a stronger container. You may have thought of the gas as being like a sponge, where cramming it down requires some force. The gas, once squeezed down, wants to "spring back" to its original size and, like a spring, pushes harder the more it is compressed. Note that these ideas all involve ideas that center not around atoms but rather continuous elastic things (springs, sponges, etc.). We will use elastic solids (rubber bands, sponges, springs) to form the testing experiments for the gas. If these testing experiments accurately predict how the gas behaves, we still will have no indication of the atomic nature of a gas. It is the deviations from the testing experiment that indicate the potential need for a different picture.

## Activity 3.2.2 Solid expansion

a) Tie one end of a rubber band to the end of a track. Place a force sensor on a card and connect the other end of the rubber band to the force sensor's hook. The idea is to measure, very carefully, how hard the rubber band pulls on the force sensor at different amounts of stretch. *Before you do any measuring*, write down very specific predications. How far do you think you'll be able to stretch the rubber band? Will the rubber band get easier or harder to stretch as it gets longer?

b) Two students make the following measurements of force at different distances:

| Distance Stretched (cm) | Force (N) |
|---|---|
| 5 cm | 10 N |
| 6 cm | 12 N |
| 7 cm | 14 N |
| 8 cm | 15.5 N |
| 9 cm | 16.8 N |

One student argues that the rubber band is getting harder to stretch as it gets longer. What is the basis for this argument?

c) The second student argues that the rubber band is getting easier to stretch as it gets longer. What is the basis for this argument?

d) Which student do you think is correct?

e) Measure this force at 1cm intervals until you max out the force sensor or break the rubber band. Record your data below and use Excel to graph your data.

f) Does your rubber band get easier or harder to stretch as it lengthens?

### *Expansion vs. Compression*

You may have predicted that the rubber bad would elongate in a steady fashion; that it wouldn't get harder or easier to stretch as it gets longer. This is in fact how most courses on springs (or other elastic objects) are taught: by focusing only on small stretches the *linearity* of the spring is shown. (This is also known as Hooke's Law, where the force on a spring is proportional to how much it is stretched.) But real objects *always* eventually break and so, while Hooke's law might apply over a *small* range of stretches, eventually the solid gets harder or easier to stretch.

You may have noticed an important difference between the rubber band and a gas: the rubber band *pulled* back on the force sensor while the gas only *pushed* on the balloon. So, while the rubber band provides insight into continuous elastic behavior, it is not a very good model for a gas. For that we need a testing experiment where the object pushes back on our force sensor.

## Activity 3.2.3 Solids and Compression

a) Put a sponge on the track and use the force sensor (with rubber stopper attachment) to push on the sponge. Measure the force needed to compress the sponge. Measure in 1 cm intervals until you max out your force sensor or cannot push any more. Record your data and a graph of your data below.

b) Does your sponge get easier or harder to compress as it shortens? Explain your reasoning.

c) Which is more like a gas: the sponge or the rubber band? Explain.

### *What are we Looking For?*

Now that you have a testing experiment for the continuous model of gases you can test it! But the experiment is subtle; you have to know what you're looking for if you hope to find it. It is rather obvious that the pressure of the gas will go up when you compress it. In that regard it will look very similar to a sponge. So the test of the continuous model is not simply whether the pressure goes up as the volume goes down, but whether it does so *in the same manner* as the sponge. The more specific you can make your prediction the better your experiment will be at testing the models. The next activity should help you flesh out your prediction to a good level of specificity.

## Activity 3.2.4 Why do rubber bands break?

a) Imagine stretching a rubber band until it breaks. What do you think determines the point at which it breaks? How is that location different from other points in the rubber band?

b) Now take a sponge and push on one end. Explain why the middle of the sponge is also squeezed.

c) You have already modeled atoms as balls and solids as these balls touching one another. If you imagine the gas atoms as balls, are they constantly touching one another? What are they doing?

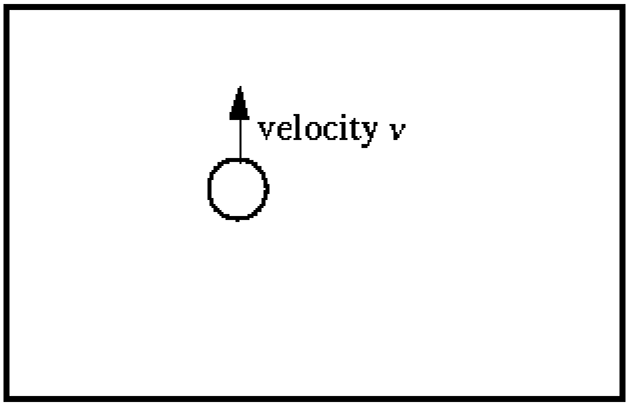
d) If the gas atoms are not constantly touching one another, do you think they exert a force on one another even when they are not touching? Why or why not?

## *Interaction between Gas Atoms*

A key idea in the explanation of elastic solids is that the parts of the sponge or rubber band influence their neighbors. Pushing on the end of the sponge compresses parts that are in the middle. But if we think of a gas a bunch of balls it is hard to imagine how they would do this when they are not in contact. In order to develop a prediction based on atoms, we need to clarify how the atoms interact. For now, let's make the simplest possible assumption --- that the atoms do not affect one another unless they are actually colliding --- and see what the implications are. It is not possible, unfortunately, to conduct a large experiment for the gas atoms as bouncing balls. The best we can do is thought experiments (also called *gedanken* experiments) and computer simulations. This is the purpose of the next activity.

## Activity 3.2.5 Bouncing balls and Pressure

a) Imagine a ball bouncing back and forth in a box, as shown below.



If the box were suddenly made twice as tall, what do you think would happen to the force the ball exerts on the top wall each time it hits? Explain your reasoning.

b) If the box height doubles what happens to the number of times the ball hits in one second? Explain your reasoning.

c) Given your answers in parts a) and b), what happens to the average force on the top wall when the box height doubles?

d) If the box height increases by 10 times, how does the average force change? Is there any limit to this reasoning?

e) Does your logic used in the previous questions require any change in the properties of the ball (that is, does the ball need to speed up or slow down)?

### *Gases as Un-Interacting Balls*

It is important to highlight how the single ball model differs from the continuum picture. Whereas rubber bands and sponges *eventually* stopped showing linear behavior, the bouncing ball seems like it could be linear forever. Even if we extend the volume to 10,000 times the original size, the only consequence is that it takes the ball 10,000 times as long to traverse the container and, therefore, there are 10,000 times fewer collisions per second (and so the average force is 1/10,000). Let's use this finding to make a very specific prediction for how the pressure of a gas depends on its volume. When doing so, make sure to highlight the differences between the atomic and continuum predictions.

## Activity 3.2.6 Predicting Gas Expansion

a) Draw below a prediction of how the gas pressure depends on the volume of its container.

b) Do you predict any significant differences between the gas and the sponge of the previous activity? If not, describe in detail the behaviors that will be similar. If so, how do you think the graph will appear different?

## Activity 3.2.7 Gases as Continuous Things: The Verdict

a) Connect a plastic syringe to a gas pressure sensor. Begin with 4ml of air in the syringe. Pull the syringe out to the maximum of 20ml in 2ml increments. Record your data below and attach a graph.

b) How was the gas similar to the sponge? How was it different?

c) Does your experiment lead you to believe a gas is well-modeled by a sponge or not? Explain.

### *Consequences of the Lone Ball Theory*

It may have surprised you to find out that the model of a single ball produces results similar to your observations of a gas and different from your observations on the sponge. It is important to notice that this behavior doesn't require the ball's velocity to change. Another way of saying this is, if we have lots of balls now in the box, the *average velocity* doesn't need to change in order to decrease the pressure; we just have to increase the box size so the number of times a ball hits the wall (in one second) goes down. While it is difficult to picture this in your head, java applets can help.

## Activity 3.2.8 Elastic Balls and Gases

a) Open the IdealGas java applet (The applet can be found at http://www.phy.ntnu.edu.tw/java/idealGas/idealGas.html). Begin by making the container as wide as possible and record the volume when you have 50 particles with a velocity of 100 and a pressure of 20. (The applet is at http://www.phy.ntnu.edu.tw/java/idealGas/idealGas.html).

b) Change the pressure, decreasing it until the container bar is at the top of the picture. What is the average volume? What happens to the average distance between particles?

c) Play around with this simulation and make a graph of pressure versus volume for at least 10 different pressures. You may also want to change the number of particles and their velocity, *but you should keep these constant for your ten runs.*

d) If the particles had some sort of attraction between one another that got weaker as they moved farther apart, how do you think that would change your graph from part c? Explain, briefly but completely.

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### *Gases as Non-Interacting Balls*

The linear dependence of gas pressure on volume might not surprise you. What might be new, however, is what that tells you about how gas atoms interact. Only if the atoms essentially act like rubber balls can they produce a perfectly inverse relation between pressure and volume.

## 3.3 LIQUIDS

Liquids are perhaps the most difficult phase to understand in terms of atoms. Most people's intuitive picture of a solid as a stack of balls is rather accurate. The picture of a gas as a bunch of balls flying around at random is also rather similar to nature. So what can we make of a liquid? If the atoms are flying around at random, like a gas, why don't they fly apart? If they are in contact, like a solid, how can we pour them? In the next activity, try and articulate not only how you think atoms comprise a liquid, but also how they behave differently than atoms in a solid or gas.

## Activity 3.3.1 Phases of Matter: Liquids

a) Discuss amongst your group how atoms might behave inside a liquid. Write your ideas below.

b) Draw below a picture indicating your thoughts about atoms inside a liquid.

c) Take a plastic syringe and fill it with water. Place your finger over the end of the syringe and try to compress the water. Can you? What inferences can you make about how the atoms in a liquid might be arranged from this observation?

d) Take a beaker of water and pour it into another beaker. What inferences can you make about how the atoms in a liquid might be arranged from this observation? Are these inferences consistent or inconsistent with those from the previous question?

e) With your group, develop a description for liquids that does not depend on atoms. Describe in words what the liquid "looks like" inside, and draw a picture that represents your model.

### *Properties of a Liquid*

We are taught growing up that liquids are "incompressible" and you have now observed this. This would seem to imply that, like a solid, the atoms in a liquid are in constant contact. And yet the fact that liquids pour so easily implies that the atoms are free to move around, like a gas. One of the reasons liquids are so difficult to model is that there isn't an easy, simple model that we can use as a testing experiment. *Our understanding of liquids is* ***far*** *less than our understanding of solids and gases*. A great deal of physics research continues to be done on even the simplest properties of liquids. Nevertheless, we can test some basic ideas of how liquids would behave if they were continuous "goo" or atoms.

## Activity 3.3.2 Liquids and Space

a) Predict the final volume of the solution obtained when you add 5 milliliters of salt to 100 milliliters of water. Fully explain your answer. That is, if you predict a final volume of 105 milliliters, upon what assumptions are you basing your reasoning? If you predict a final volume greater or less than 105 milliliters, explain where this difference is coming from.

b) Measure the mass of 5 ml of salt and 100 ml of water. What do you think the combined mass will be of the two?

c) Now try the experiment. What is the final volume? What is the final mass?

d) There are (at least) two explanations for why the volume is less than 105 milliliters. With your group, develop at least two explanations and be prepared to present them to the class. (NOTE: Saying the salt has dissolved is not a legitimate answer for it doesn't explain why dissolved salt takes up less room than un-dissolved salt).

### *Finding the Holes in water*

Perhaps it was not surprising that the volume of the salt-water mixture was less than 100ml. After all, we see the salt "disappear" as it dissolves. But where does the salt go? It could be that, as it dissolves, the salt takes up less space than it did before, sort of like an empty box can be crushed to take up less space. Or, the salt molecules could be finding space within the water. It is possible to add so much salt that it stops dissolving. At this point we say the water is *saturated* with salt. Let's see if the addition of salt after saturation behaves in the same manner as before.

## Activity 3.3.3 Super-saturated Solutions

a) Based upon your measurement from Activity 3.3.2, make a *prediction graph* of the combined volume of 100 ml of water with successive amounts of salt (5 ml, 10 ml, 15 ml, 20 ml…). Print this out and attach it below. Fully explain your reasoning behind making this prediction.

b) Based upon your measurement from Activity 3.3.2, make a prediction graph of the total mass of combining 100 ml of water with successive amounts of salt. Print this out and attach it below. Fully explain the reasoning behind your prediction.

c) Now add 5 more ml of salt to your water mixture. Stir the solution so the salt dissolves in the water. Record the volume and mass. Add 5 more ml, measure the volume and mass, and continue on. Continue the experiment until you've made at least 5 measurements *after* the salt stops dissolving in the water (you should be able to dissolve about 35 grams of salt in 100 ml of water). Attach graphs of the total volume versus the added volume of salt, the total mass versus the added volume.

d) Were your predictions correct? Explain quantitatively what features of the experiment are consistent with or inconsistent with your experiment.

e) Look carefully at the data points from after the salt stopped dissolving in the water. Is this behavior of the data here different from the data before the salt stops dissolving? Explain what you see and hypothesize about why any difference occurs.

## *Continuum theories of Liquids and Volume Conservation*

Fully saturating the water with salt removes the possibility of additional salt hiding in the holes of the water. But recall that there were two possible explanations for the difference in volume. After all, 10 ml of salt may not really take up a full 10 ml, as there are pockets of air in the salt. The true test comes not when we add a solid to a liquid but when we add another *liquid* to water.

## Activity 3.3.4 Predicting volume conservation and adding liquids

a) Imagine mixing together equal amounts (say 50 milliliters of each) of two liquids. What final volume would be predicted by a person who believes liquids are made of a continuous goo? Why would they make this prediction?

b) Would the atomic hypothesis make the same prediction as the “goo” hypothesis? Why or why not?

c) Add 50 milliliters of sand to 50 milliliters of steel shot or marbles. Shake the final container. What is the final volume?

d) Explain what is happening that results in the final volume being less than 100 milliliters.

**BOXED PREDICTION: What do *you think* the final volume will be when you add 50 milliliters of rubbing alcohol to 50 milliliters of water? Rubbing alcohol is less dense than water.**

## Activity 3.3.5 Volume conservation in liquids: the verdict

a) Add 50 milliliters of rubbing alcohol to 50 milliliters of water. What is the final volume?

b) What do you think is happening that allows the final volume to be less than 100 milliliters?

## *Space within Liquids*

We like to think of matter as having certain properties that don't change. You have already observed that the mass is one such property. When ice melts or dry ice sublimates the mass did not change even though the volume did. But we also like to believe that what we see as a solid (or continuous) *is* continuous. We don't see spaces in water so it's hard to believe that they exist. And yet, the experiments with the sugar and alcohol show that smaller atoms/molecules can find gaps in between the larger particles and so the total amount of space occupied is not a constant.

It is hard to reconcile this observation with any continuous model. After all, by continuous we mean *fills all the space*. The atomic hypothesis, then predicts *lots of empty space in matter*, a prediction that most people tend to ignore. Although it is beyond the scope of this unit, the conception of space and how matter exists in space was a motivating factor in much of the early Greek work on atoms.

## Activity 3.3.6 Inter-atomic forces in Liquids

a) Place a drop of water on the table. Describe its shape and explain why it does not spread out to cover the table.

b) Fill a beaker or cup with water and place a small drop of oil (1-2 cm) on top of the water. *If* the oil is made of atoms, which we've pictured as little balls bouncing around, why does the drop maintain its shape? What does this imply about the atoms?

c) Now place a drop of dishwashing soap (Dawn works nicely) on the oil and describe what you observe.

d) At the beginning of this unit you observed soap to spread out on water and push pepper to the side. But soap does not lie on top of oil, so the same mechanism is probably not present. Knowing what you do about soap (and what we use it for), what do you think the soap is doing to the oil?

e) Describe what the soap must be doing to the oil in terms of the atoms and inter-atomic forces.

## *Liquids and Surface Tension*

We often use the words "surface tension" to talk about liquids. The oil stays together on the water and raindrops are round because of surface tension. Surface tension refers to the forces between the liquid atoms. These forces only arise when the atoms are very close together, so they are not significant in a gas. Other forces tightly bind the atoms in a solid. The inter-atomic forces in a liquid can be disrupted, as you observed when you added soap to the oil. When these forces are disrupted, the coherence of the liquid is lost and the atoms spread out, acting more like a gas than a liquid.

## *4 CRYSTALS AND SNOWFLAKES*

You will need some of the following equipment for the activities in this section:

- 1 20-oz plastic coke bottle
- 3 large-diameter styrofoam cups
- small kitchen sponge (½ inches thick)
- short length of nylon fishing line (thinner the better)
- a strong sewing needle
- 4 straight pins
- paper clips
- paper towels
- Graph paper (¼ inch sidelength)
- Hexagonal graph paper (¼ inch sidelength)
- Diffusion Limited Aggregation software (freely available)

### 4.1 CYRSTALS AND SNOWFLAKES

In Section 2, when discussing solids, you developed many ideas about how atoms pack to form crystals. You investigated two different crystal types (orthogonal close packing and hexagonal close packing) and the differeent characteristics they would have. Your instructor may have had sample s of crystals formed from a HCP structure and showed you how the cyrstals form parallelograms, not rectangles, since the atomic planes can't grow at right angles to each other.

So what causes a snowflake to grow as it does? You may already know that all snowflakes have six sides (and no two are alike!). Does this mean that water packes in a hexagonal manner? Is anything else required to get the particular beauty of a snowflake?

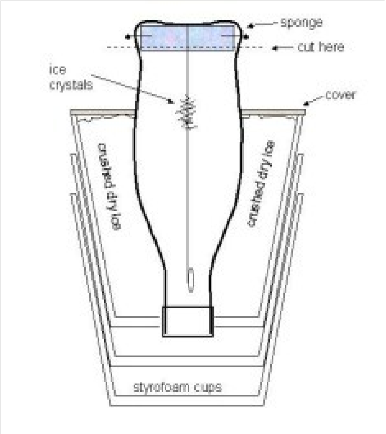
Before we begin to investigate how a snowflake might form, let's start growing our own snowflakes. They'll take about 30 minutes to grow, so we can work on other activities while they develop. The instructions for this next activity were taken from the SnowCrystals.com (http://www.its.caltech.edu/~atomic/snowcrystals/project/project.htm)

## 3d Crystal growth setup

Step 1. After rinsing out the Coke bottle, use a sharp knife to cut the bottle in two, about 1/2 inch above the bottom, as shown in the figure. Poke a hole in the center of the bottle bottom using the sewing needle, and also poke four holes in the side of the bottle bottom. Make a small round sponge to fit inside the bottle bottom, and hold the sponge in place by putting the four straight pins into the side holes you made (see figure).

Step 2. Thread the fishing line into the sewing needle, and push the needle through the hole in the bottle bottom, and through the sponge. Attach the fishing line to the bottle bottom with a piece of tape, and tie a knot in the other end to hold the paper clip. When the Coke bottle is inverted and reassembled, the string should swing freely inside the bottle, as shown in the figure.

Step 3. Place the inverted Coke bottle inside the three styrofoam cups, as shown, so that the bottom of the Coke label is at the same height as the top of the cups (see figure). There should be about one inch of clear space between the sides of the Coke bottle and the top edge of the styrofoam cups.



Step 4. Pull the top off the chamber (bottle bottom + sponge), wet the sponge with tap water, and replace.

Step 5. Put the dry ice inside two plastic grocery bags, and pound on it with a hammer (or other blunt object) to crush the dry ice. This works best on a hard surface, like concrete or asphalt. Dry ice is much softer than water ice, and it crushes very easily. Put the crushed dry ice back into its styrofoam cooler, and use a spoon to transfer some into the styrofoam cups around your chamber (see the figure). Fill the cups to the top, and cover with a piece of cardboard cut to shape, or with some paper towel strips. It's also a good idea to wrap some paper towels around the top of the styrofoam cups, to keep them from "sweating.". Be sure to add as much dry ice as you can to the cups, and add more dry ice every so often. If the experiment doesn't work, it's probably because the dry ice level is too low.

## Activity 4.1.1 Why do crystals grow?

a) Recall the first activity of this unit: growing salt and sugar crystals on string. In that activity you suspended the string in water that had lots of sugar and salt dissolved in it. Why do you think crystals grew on the string?

b) If a small crystal had already started growing on the string, what do you think happened that enabled it to grow? (Hint: What were the sugar/salt atoms doing in the liquid? Were they at rest?)

c) Imagine a small crystal on the string (small to us but many hundreds of atoms large). What do you think determines where the crystal grows next?

d) Imagine a believer in "goo". How might they predict the prediction to grow? How might this differ from an atomic explanation?

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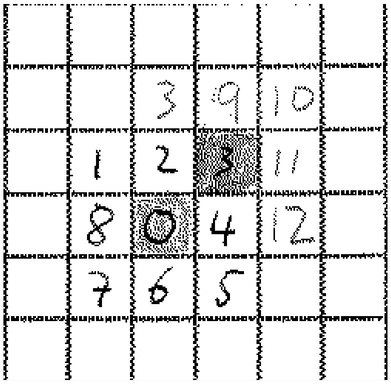
## *Atomic Aggregation*

Your group may have decided that the salt/sugar molecules were not at rest in the water, but rather moved around at random. If they happened to hit the growing crystal, maybe the stuck to it. In this way the crystal could slowly grow as it ads more and more atoms. Exactly where the grows depends on where the next atom sticks; this probably happens at random. We say that the atoms have formed an *aggregate* (something made up of a collection of particles). The process by which the crystal grows is *aggregation*. It is not unreasonable to think that the underlying atomic packing influences the shape of the aggregate. Let's see what shape crystal results from random aggregation on a square and hexagonal lattice.

## Activity 4.1.2 Random Aggregation on Lattices

a) Predict the shape that a 2-dimensional crystal formed by random aggregation of particles that pack in an orthogonal close packing lattice form. Will it be a square? A cross?

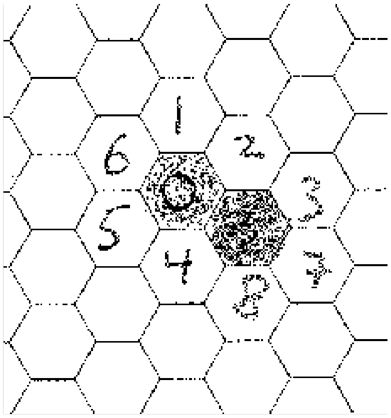
b) We wlll “grow” our aggregates on graph paper. On the next page is a piece of graph paper. The central box is shaded to represent the seed atom. We'll number this site “0” and the 8 squares that touch it 1-8. Each of the numbered sites represents a *potential* location for growth. To randomly choose exatly which location (between 1 and 8) grows we'll use excel. Type the following equation directly into cell B1 (start with the equal sign): **=1+int(rand()*A1)**. Now enter the number 8 into cell A1. Note that B1 now shows a number between 1 and 8. If you hit “recalculate” (F9 on some version) it will choose a new random number between 1 and 8. Shade in pencil the square chosen by Excel. In the example picture below site 3 was chosen. Note that any square touching the chosen site is now a new potential for growth. Number these sites *starting with the number chosen by Excel*. You now have a new number of possible sites (either 10 or 12 depending on whether a corner or middle site was selected). Enter this new number into cell A1, hit recalculate, and thus generate a new growth site. Continue until your cyrstal has reached a good size (~100 sites). What shape is it?



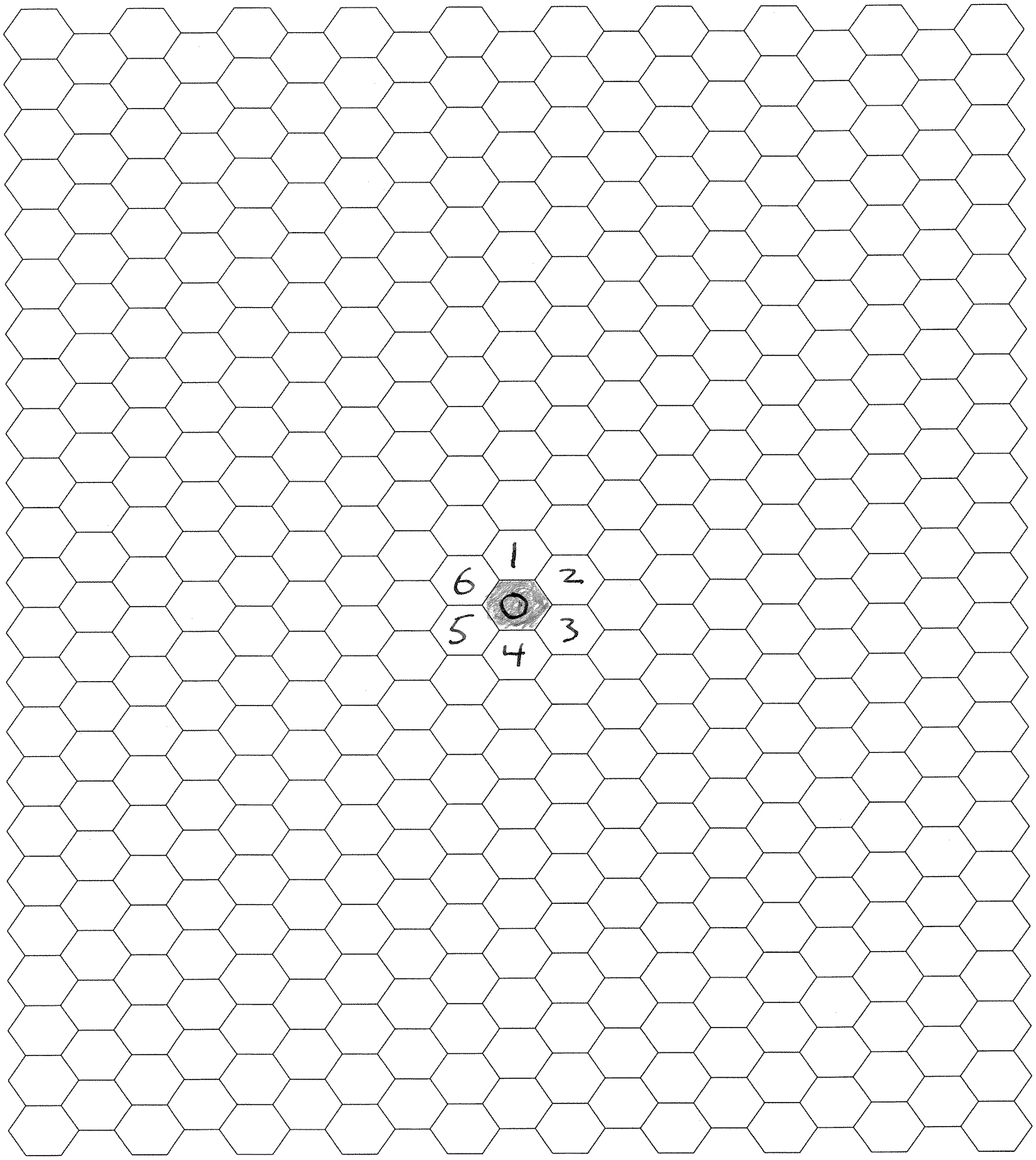
1 2 3
8 0 4
7 6 5

c) Predict the shape hat a 2-dimensional crystal formed by random aggregation of particles that pack in an hexagonal close packing lattice form.

d) Repeat the process on hexagonal graph paper (see following page). In this case, note that there are only 6 potential growth sites. A sample is shown below in which site 3 was the first selected site for growth. Continue until your cyrstal has reached a good size (~100 sites). What shape is it? Does it look much like a snowflake?



e) Why do you think this method fails at generating snowflakes? What do you think is going on in snowflake growth that this process fails to capture?


1
2
3
4
5
6
0

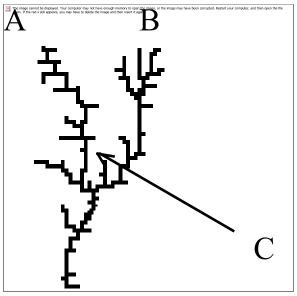
### *Diffusion Limited Aggregation*

The "crystals" you developed on the lattices probably did not look much like a snowflake. You may have realized that this is because, in your method, all sites eventually attract a new atom. You don't find many spikes in your crystals, and end up with an amorphous blob. It is possible, however, that some sort of shielding is at work, where long branches prevent atoms from reaching the inner core. This idea is developed in the next activity, which uses a software program to model diffusion limited aggregation.

## Activity 4.1.3 Diffusion Limited Aggregation (DLA)

a) Open the *DLA* software and grow a 2-d crystal. (Instructions will vary depending upon exactly which program is used.) Play around with it a bit and describe below what is happening.

b) Below is a pattern that has just split into two branches. When new particles are introduced, are they more likely to hit one of the two branches (labeled "A" and "B") or find there way between the branches (labeled "C")?



c) Based on your answer to part b, once branches form, will they tend to grow or will the gaps between the branches fill in? Explain why a uniform, circular pattern will usually not form.

d) If the DLA software allows, grow more crystals. Grow 2-d and 3-d crystals and use different rules for how the atoms stick. Summarize your playing below. You should be able to do 5-10 different conditions with noticeably different crystals.

### *Why are Snowflakes Branched?*

The ideas behind diffusion limited aggregation can explain why snowflakes grow such ornate, branched patterns. Larger branches screen the smaller ones, preventing water molecules from reaching the smaller branches. Thus, bigger branches get bigger, smaller branches don't ever grow. Combining this idea with an underlying hexagonal packing produces crystals that are branched and also six-sided.

At the beginning of this section you set up an experiment to grow your own snowflakes. Let's see how they turned out.

## Activity 4.1.4 Different temperatures, different snowflakes

a) Look closely at the string in your snowflake experiment. Describe what you see. You should be able to see at least two different types of crystals. Describe them. Do different types of crystals prefer different locations on the string?

b) Look at the structures using a magnifying glass or stereoscope. Do you see anything that indicates an underlying six-sided symmetry? (Hint: what angle did you find to arise in hexagonal close packing?) Carefully draw below a picture of what you see.

c) Explain why the structures you observe indicate a deficiency in the goo hypothesis. (Why is such a structure unlikely to appear from a goo theory?)

## *Atoms in Our Everyday Life*

The beautiful and complex shape of snowflakes is compelling evidence for the existence of atoms. Note that this can only be understood when we first predicted what would result from a continuum model for matter. The existence of atoms doesn't' just explain the branched structure, it *predicts it* as well. Review the activities on Diffusion Limited Aggregation this point is still unclear. Similarly, many of the phenomena you have looked at in this unit not only can be explained by an atomic hypothesis, but they also rule out alternative continuum or goo hypotheses. To see this, however, requires a good understanding of what a continuum theory predicts. The power of a scientific idea is not just in its ability to explain, but also to make accurate predictions.

When you started this unit a few weeks ago you already believed in atoms. This did not stop you from sometimes thinking of matter as continuous, however, and it is only by carefully considering the alternate ideas that you became aware of some of the subtle manifestations of atoms. Everyday phenomena --- from the salt on your table to the ability of soap to clean your plates --- are difficult to explain from a continuum point of view *if you understand the continuum point of view*. Now it is your turn to find testing experiments. As you look around the world, ask yourself: "How would I explain this phenomenon? Can a continuous goo explain what I see? How would an atomic hypothesis apply here?" With the right application of imagination, creativity and thinking, Feynman's quote found at the beginning of this unit is justified: *In that one sentence [matter is made of atoms] you will see, there is an enormous amount of information about the world.*

## 5 *PROJECTS*