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The Science of Pizza: The Molecular Origins of Cheese, Bread, and Digestion Using Interactive Activities for the General Public

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Abstract: We describe a presentation on the science of pizza, which is designed for the general public including children ages 6 and older. The presentation focuses on the science of making and digesting cheese and bread. We highlight 4 major scientific themes: (1) how macromolecules such as carbohydrates and proteins are composed of atoms and small molecules; (2) how macromolecules interact to form networks in bread and cheese; (3) how microbes contribute to the texture of bread; and (4) how enzymes break down macromolecules during digestion. Using live demonstrations and interactive exercises with children in the audience, we provide simple explanations of the scientific principles related to these themes that are essential for understanding how to make pizza, and what happens when we eat it. This general approach can be adapted to a variety of informal and classroom settings focused on sharing the excitement of scientific discovery and understanding with students and the public.

Introduction

This article describes a presentation we developed on the science of pizza that is geared toward nonspecialists and the general public including children ages 6 and older. The presentation is structured around 4 major scientific themes related to the science of making and eating cheese and bread (Table 1): building larger molecules from atoms and small molecules, the formation of networks consisting of larger molecules bonded or linked together, the role of microbes in food texture, and digestion and enzymatic degradation. Since pizza, cheese, and bread are popular foods, this lecture builds on the common experience of individual audience members; moreover, breads and cheeses of various types are present in many cultures, making these topics readily adaptable to diverse audiences. This approach can be used either as a lecture for the general public or as a series of classroom activities for students.

Audience participation is a critical part of our approach and is programmed into the hourlong lecture at 8 to 10 min intervals (Taylor 1988); this pacing is critical for keeping young children engaged in the presentation. We begin by engaging the audience, asking questions such as "Where does cheese come from? Why does bread have holes?" Furthermore, we call for individual volunteers to help with table-top demonstrations and have children from the audience act the behavior of individual molecules during short role-playing segments. To help children identify their role, each child receives 1 of 4 different t-shirts at the beginning of the lecture, which has a unique color and design representing a simple sugar, water molecule, enzyme, or network former (Figure 1A to 1D). Moreover, each person takes part in individual taste experiments. We believe that this interactive format engages people in science; studies have shown that kinesthetic learning is an effective tool for increasing understanding of science and engineering (Felder and Silverman 1988; Gage 1995; Ebert-May and others 1997; Handelsman and others 2004). Furthermore, engaging parents in the learning process of their children helps advance their scientific understanding and affects long-term changes in family learning behavior (Ostlund and others 1985; Gennaro and others 1986). Audience feedback obtained by written questionnaires indicates that we accomplished our goal of generating enthusiasm and discussion about science in an informal setting that extends out into the community (Table 2).

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Sparking Curiosity about a Piece of Pizza

Ask any group of children (or adults) to name a favorite food, and pizza is a likely answer. Pizza's universal appeal, as well as the interesting physical properties and origins of its major ingredients, provides a rich and engaging platform for introducing scientific concepts. Simply looking at a piece of pizza with a high magnification lens raises many interesting questions: Why is melted cheese greasy? Why does the crust have holes? By making these observations, we motivate the audience to ask what gives cheese and

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Table 1–Main questions and related scientific themes.

Theme	Demonstration/audience participation	Main scientific concept
Networks	Formation of alginate gel in calcium chloride solution; children link hands to form a network.	Networks form when molecules link together.
Microbes	Children play the role of yeast cells and cause the network to expand; yeast inflate balloon that is sealed on top of bottle.	Microbes alter the texture of bread.
Digestion	Children act as simple sugars that link together to form chains of complex carbohydrates; "enzymes" come along and break the chains of children apart.	Enzymes break down macromolecules into simple sugars for energy.

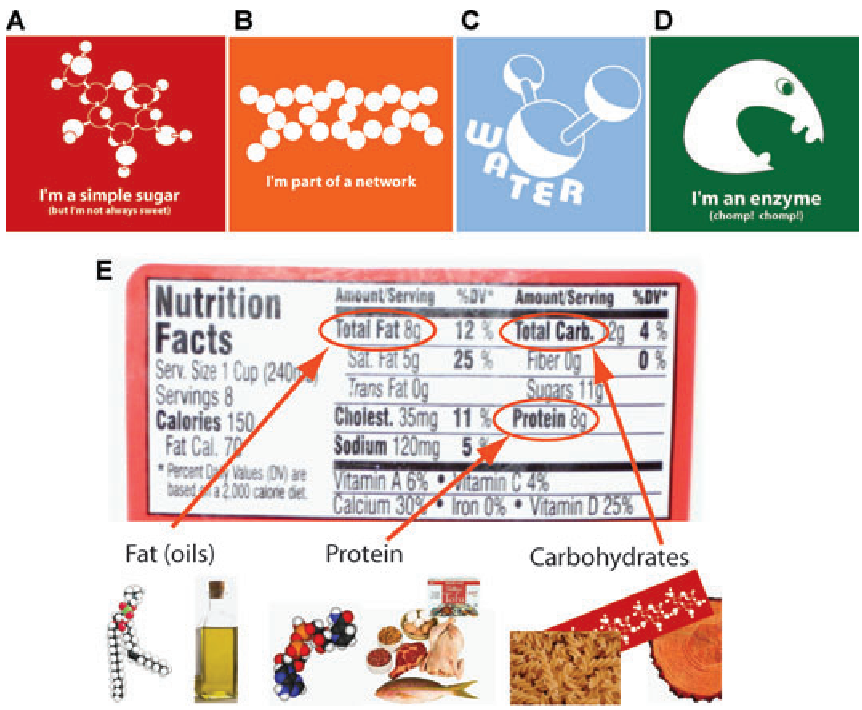

Figure 1–Major players in the science of pizza. To demonstrate the major scientific themes in making cheese and bread, children play the role of individual molecules and act out processes from network formation to enzymatic breakdown. We use the following icons on the childrens' t-shirts as well as throughout the lecture: (A) simple sugars; (B) networks; (C) water; and (D) enzymes. These components are essential for understanding how (E) the major ingredients of milk, as listed on the label of a milk carton, are transformed into cheese.

bread these properties. Moreover, where does pizza come from and how is it made? These questions begin our exploration of the science behind making pizza; this narrative style is an effective way to engage audiences in understanding scientific concepts (Taylor 1988; Kapon and others 2010).

Atoms to Molecules to Macromolecules to Networks

Ultimately all the major ingredients of pizza—tomatoes, cheese, and bread—come from the sun and the soil. Using energy from the sun, plants convert water and carbon dioxide into sugars and longer chained molecules of sugars, producing oxygen in the process. In turn, plants are consumed and digested by humans as well as cows, goats, or sheep, which produce milk. Highlighting the process of photosynthesis shows how small molecules are converted into larger molecules (Figure 2).

Small molecules such as carbon dioxide and water assemble together to build other simple molecules (sugars) that in turn link together to form larger macromolecules (carbohydrates, proteins). Long molecules that consist of many molecules or repeating units are called polymers. Macromolecules or polymers can assemble into even higher order structures or networks. We use a demonstration with beaded necklaces (Demo 1A in Appendix A) as well as with alginate (Demo 1B in Appendix A, Shakhashiri 1983) to illustrate cross-linking and network formation. Since alginate is a negatively charged polymer, it interacts with positively charged atoms or molecules. However, only species with 2 positive charges

Table 2–Summary of audience evaluation. Feedback was obtained through a total of 39 written questionnaires.

Motivation	Question	Participant response
To engage public using interactive activities and live demonstrations.	What did you like about the presentation?	Interactive demonstrations ("Going down to participate;" "The kids demonstrating the ideas;" "Interpretive fun for adults and children") Live demonstrations ("Seeing the milk under the microscope;" "Seeing the acid added to the milk;" "Videos and live action")
To educate the public about scientific concepts in food: (1) foods are composed of smaller constituent parts; (2) microbes play an important role in generating the texture of foods; (3) food consists of macromolecules that are broken down by enzymes during digestion.	What was the coolest thing you learned today?	How cheese is made ("What whey and curds are;" "Adding vinegar/acid to milk makes it clump up, when you squeeze out the whey, you are left with cheese") Role of microbes in food ("Yeast farts out oxygen;" "The holes in swiss cheese come from bacteria!") Role of enzymes in digestion ("Enzymes eat sugar")

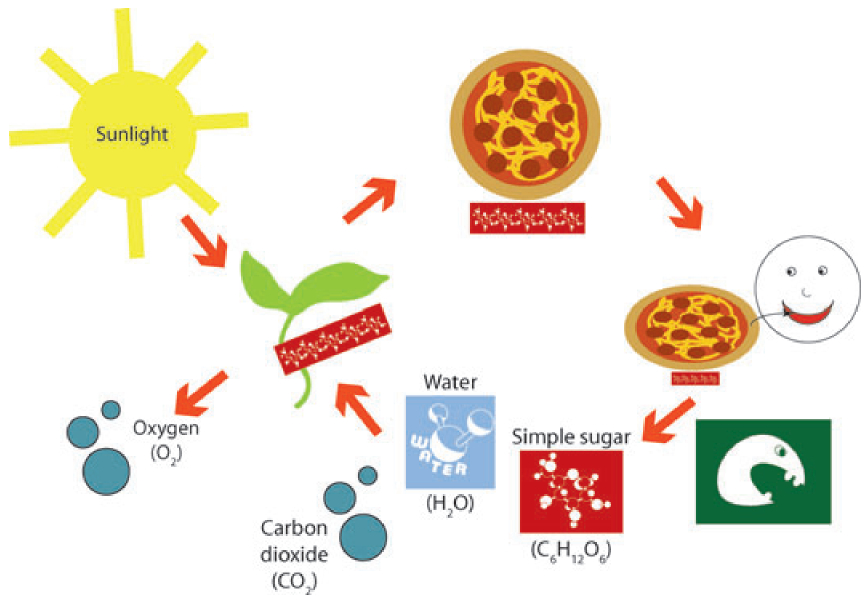

Figure 2–Origins and cycle of pizza. Plants use energy from the sun together with small molecules such as water and carbon dioxide to produce larger molecules that other animals such as cows transform into larger molecules. We transform the raw ingredients of flour, milk, and tomatoes into pizza that we eat. During digestion, enzymes break down larger molecules into smaller molecules including simple sugars that give us energy.

are cross-linkers that can bring together 2 parts of the alginate polymer chain; for example, the divalent cation calcium (Ca^{2+}), which results upon dissociation of calcium chloride ($CaCl_2$), is an effective cross-linker of alginate. This scientific concept of cross-linking and network formation is crucial for understanding how cheese and bread are made.

The Science of Making Cheese

Cheese is central to many cultures around the world, making it an accessible food for engaging people in science. All cheese starts as milk. Studying the label of a milk container reveals that there are many components in milk, including fat, protein, and carbohydrates (Figure 1E). Many common fats are in the form of oil, such as canola or olive oil; proteins are molecules found in high concentrations in food sources such as meat, fish, eggs, nuts, and tofu; carbohydrates are large molecules consisting of simple sugars, which constitute pasta as well as other common plant materials such as wood. Another common word on a package of milk is "pasteurized," a word describing the process whereby milk is heated to a high temperature to kill harmful microbes that might cause illness or spoilage of milk (Figure 3).

A simple way to turn cheese into milk is to add acid, such as vinegar or lemon juice. Vinegar is poured into a beaker of milk, causing the milk to separate into curds, which is the network of coagulated casein particles, which entrap the fat droplets; the remaining liquid is known as whey. Using a strainer, the curds are removed from the whey and drained to remove the excess water. This basic cheese is commonly made in India and is known as paneer. Similar types of fresh or unripened cheeses are found in other cultures.

To understand the mechanism underlying the formation of solid materials in milk, we begin by describing the structure of milk (McGee 1984). Using a microscope to investigate the small-scale structure (Figure 4) of milk reveals that this liquid consists of many small droplets, which are oils (fats) (Figure 5, Demo 2A in Appendix A). Upon adding acid to milk, large aggregates of droplets are observed (Figure 5B). To explain what is happening at the molecular level, we present sketches showing how the fat drops are interspersed among tiny particles consisting of casein (Figure 5C to 5D). The addition of acid lowers the pH and causes the casein particles to aggregate, thereby forming a network in which the fat droplets are trapped. To produce cheese, the water needs to be squeezed out of the network to remove the excess liquid. The 3 basic steps for making cheese are thus: (1) start with milk (blobs of fat and protein in water); (2) add acid (vinegar or lemon juice); (3) squeeze out the water. We then invite about 20 to 30 children from the audience to play the role of macromolecules forming a network and "squeeze" out the water molecules from their midst, thereby demonstrating the process of making cheese (Demo 3 in Appendix A). This style of participation by the children and acting out of basic molecular ideas is popular with the audience.

Figure 3–The technique of pasteurization was invented by the renowned scientist Louis Pasteur (1822 to 1895), a scientist who made many fundamental discoveries in the fields of chemistry and microbiology. Figure from Creative Commons.

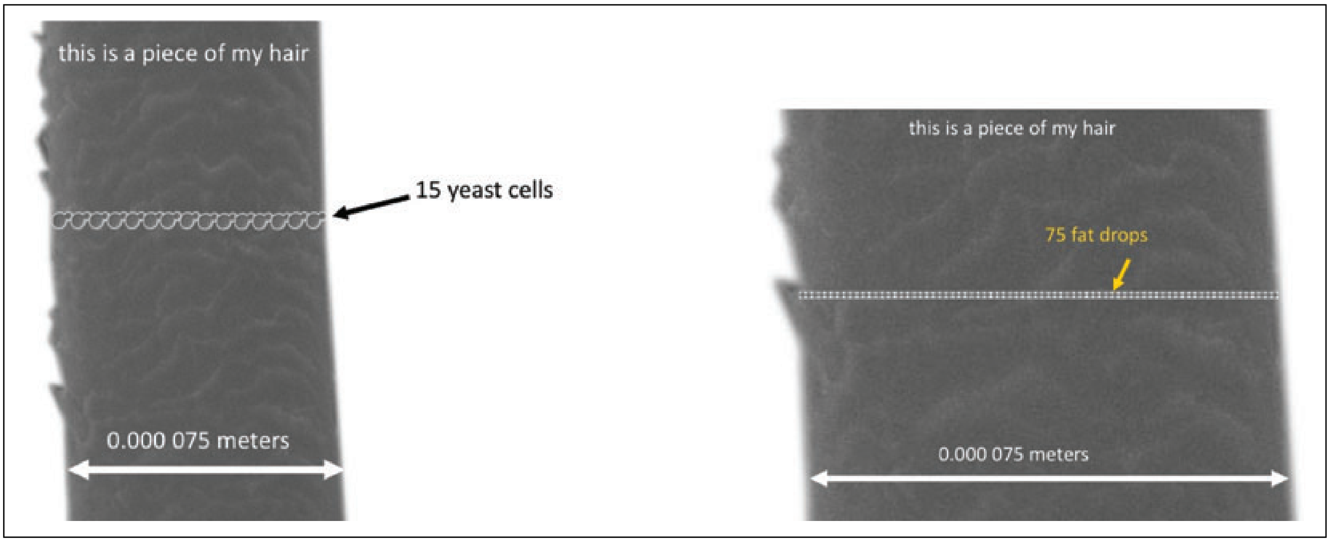

Figure 4–The concept of scale. A major challenge in communicating science to students and the public is to convey a sense of scale. Units such as micrometers or nanometers have little meaning in the context of everyday life. To demonstrate the scale of fat droplets in milk, or the dimensions of a single yeast cell, we compare these objects to the width of a human hair. For example, 15 yeast cells or 75 fat droplets can fit across the width of a single human hair of typical diameter 0.000075 meters. Shown above is a piece of hair imaged by scanning electron microscopy. Brightfield images of yeast cells (left) and fat globules in milk (right) are processed, sized to the same scale as the hair, and superimposed on the image.

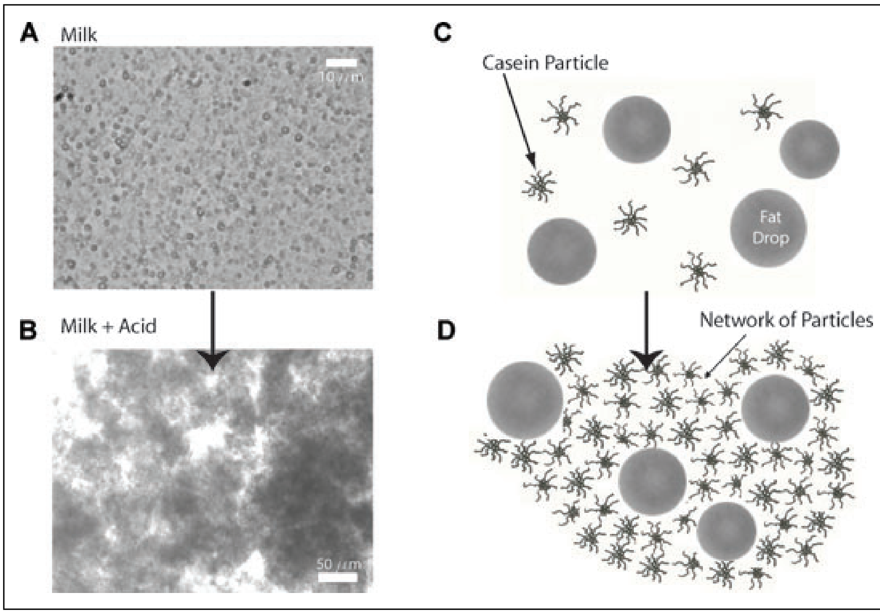

Figure 5–How milk turns into cheese. (A) Milk viewed with a light microscope reveals tiny fat droplets. (B) Upon adding acid in the form of vinegar, these droplets are observed to coagulate. (C) At the molecular level, this schematic illustration shows that milk consists of fat droplets and protein (casein) particles. (D) Upon addition of acid, the casein particles stick together forming a network in which the fat droplets are trapped. The coagulation of milk upon decrease in pH demonstrates a simple way to make cheese from milk.

Developing the texture and flavor in more complex types of cheese relies on enzymes to induce formation of the curds, and microbes that help to lower the pH and create distinct flavors. While paneer is one of the simplest cheeses to make, it is also relatively straightforward to make mozzarella cheese using enzymes (Appendix B).

The Science of Making Bread

Central to daily life, bread is found in different forms in cultures around the world ranging from bagels to rye bread to pizza dough. All bread products derive from flour, making the label of a bag of flour a natural starting point for a discussion of bread. Investigating the label reveals that carbohydrates and proteins are major ingredients in flour. We reintroduce these words that were first discussed in the context of milk.

We describe a simple way to make bread from flour, by adding water. A mixture of flour and water is easy to prepare in the classroom, or at the individual level with students. Baking this flour–water mixture yields a flatbread that is very dense and has no holes. We image the "flatbread" by electron microscopy, which reveals a dense aggregate of starch granules (Figure 6A); in between the starch granules is a protein network of gluten proteins, which is schematically illustrated in Figure 6C. Clearly, pizza dough has holes and a lighter texture.

To demonstrate how we can form holes in bread, we introduce yeast, which is a microbe that produces gas (Figure 4). The yeast cells consume sugar and produce carbon dioxide: filling a bottle with yeast and sealing the top with a balloon shows that the balloon inflates over time as the yeast cells produce gas (Demo 4A in Appendix A). Using children from the audience, we

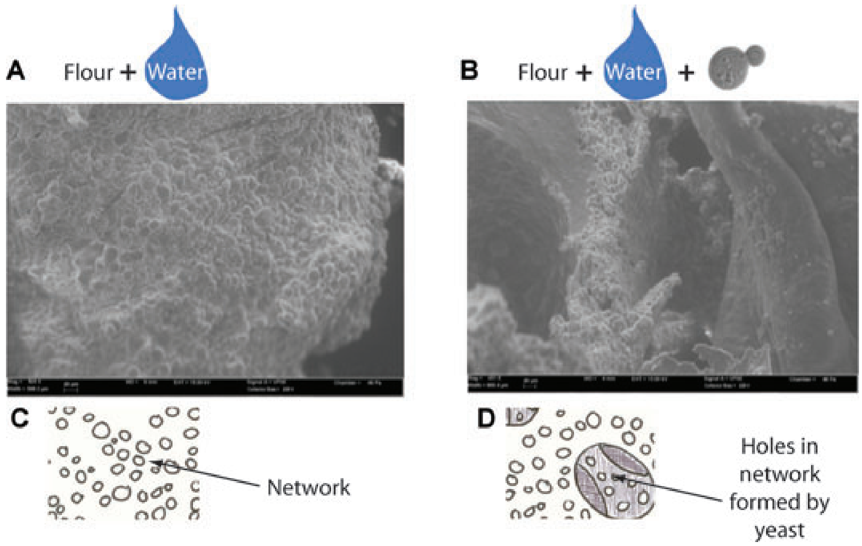

Figure 6–Yeast cells alter the texture of bread. (A) Mixing together flour and water produces a basic bread that remains flat when baked. Imaging by electron microscopy reveals aggregates of starch granules. (B) Adding yeast to this mixture yields a bread with bubble and holes, as yeast eat simple sugars and in turn produce gas. (C) Schematic illustration showing the starch granules in a network of flour proteins, which consists largely of gluten proteins. (D) Yeast form holes in the network, giving bread a lighter, airy texture.

demonstrate how a network can expand when yeast in the network produce gas (Demo 4B in Appendix A). We show that the equivalent flour–water mixture rises due to the activity of yeast in the dough. Comparing the electron micrograph shows there are large holes in the bread's protein network structure (Figure 6B to 6D). These demonstrations on the science of bread build upon the theme of creating networks of macromolecules and show the role of microbes (yeast cells) in developing the texture of bread.

Digestion

With the knowledge of how to make cheese and bread, the next natural step is to assemble and eat pizza. Upon eating pizza, it must be digested to break down carbohydrate and protein macromolecules into smaller components, such as simple sugars and amino acids—the building blocks of food—that can be used for energy. Revisiting the theme of building small molecules into longer chains of molecules, we show how simple sugars link together to form long molecules or complex carbohydrates. These long molecules can be broken down into small molecules again with the help of special protein molecules, called enzymes. A common enzyme that may be familiar is lactase; people lacking this enzyme cannot digest milk, since they are unable to break down the milk sugar, lactose.

To visualize the activity of enzymes, we invite children from the audience to the front of the room to play the role of simple sugars and enzymes: simple sugars link hands to form long chains of complex carbohydrates; then enzymes act as scissors, breaking the long chains into smaller pieces, and eventually into individual sugar molecules. This activity can also be expanded to include a description of the enzymatic breakdown of proteins into their amino acid building blocks.

Explaining the mechanism of digestion completes knowledge of the "pizza" cycle: plants use sun to build complex macromolecules out of simple molecules; we use these materials to make pizza; after eating the pizza, enzymes break down the macromolecules into simple molecules such as sugars, as well as by-products including water and carbon dioxide that we breathe back into the atmosphere.

Adaptation to the Classroom and National Science Education Standards

To inspire discussions of science within families, as well as incite curiosity about the natural world, we strive to make the material accessible to children in kindergarten, yet also interesting for older children and adults. Therefore, we believe the material can be used in elementary, middle, and high school classrooms to teach important concepts in scientific inquiry and the physical sciences that meet the National Science Education Standards, as presented in Table 3. The activities described above can be adapted as a 1-h lesson plan (Table 4) or used in a modular fashion in the classroom.

Conclusion

This presentation on the science of pizza employs many techniques known to be effective for science education (Felder and Silverman 1988; Gage 1995; Ebert-May and others 1997; Handelsman and others 2004): we present scientific concepts in the context of a familiar food, pizza, that many people know and love; we use interactive demonstrations where children act out the role of molecules. At the end of the lecture, a professional pizza maker twirls pizza dough, and we even serve pizza so that everyone can experience the food they just learned about. Based on audience feedback, the presentation generates excitement and curiosity to continue asking questions about science in everyday life.

Note 1. Powerpoint slides and templates for labels and t-shirts are freely available upon request.

Note 2. An excellent online resource for exploring the science of pizza, which was created by Purdue Univ., is provided at: http://pizza.accessexcellence.org/pizza/.

Appendix A: Demonstrations

We use cameras to project demonstrations at the front of the auditorium onto a large screen. Using these methods, we have presented to audiences of up to 500 people.

Demo 1A—demonstrating cross-linking using beaded necklaces

We use beaded necklaces to explain the principle of cross-linking polymeric chains. The necklaces lie on the floor. Three

Table 3–Mapping lecture components to National Science Education Standards.

Science content standard	Lecture activity	Grades K to 4 teachers can:	Grades 5 to 8 teachers can:	Grades 9 to 12 teachers can:
A: Understanding scientific inquiry	Observe the appearance, taste, and texture of pizza, bread, and cheese.	Ask students to make observations about the texture of cheese and bread and formulate questions about their observations: Why does bread have holes? Why is some cheese soft and other cheese hard? How are bread and cheese made?	Ask students to make observations about the texture of cheese and bread and formulate questions about their observations: Why does bread have holes? Why is some cheese soft and other cheese hard? How are bread and cheese made?	Ask students to make observations about the texture of cheese and bread and formulate questions about their observations: Why does bread have holes? Why is some cheese soft and other cheese hard? How are bread and cheese made? What are the molecular origins of these properties?
B: Physical science standards	Discuss how the properties of materials depend on chemical composition motivated by the question "Why is milk liquid and cheese solid?"	Observe that milk is liquid and cheese is solid; properties of materials.	Observe the shape, color, and texture of milk versus cheese; milk is liquid and cheese is solid; properties and changes of properties in matter.	Observe the shape, color, and texture of milk versus cheese; molecular mechanism of forming a gel (cheese) from a liquid; structure and properties of matter.
E: Science and technology	Discuss technologies that have been developed to process milk and flour into cheese and bread.	Distinguish between natural and synthetic materials; the cheese we eat is made from milk.	Discuss technological design and innovations for production of bread and cheese.	Discuss technological design and innovations for production of bread and cheese.
G: History and nature of science	Profile food scientists, explore how they advanced food technology for cheese and bread production; profile men and women microbiologists who contribute to understanding microbes.	Discuss science as a human endeavor.	Discuss science as a human endeavor; history of science.	Discuss science as a human endeavor; history of science.

Table 4–Proposed timeline for implementing the lecture in a elementary school classroom.

Time	Preparation
One mo before	Order alginate and salt (Demo 1B) Optional—order cheese-making kit
One wk before	Order alginate and salt (Demo 1B) Obtain beaded necklace (Demo 1A) Obtain glitter or confetti (Demo 3) Make signs that children can wear: Demo 3 → 2:1 water molecules to network-makers Demo 4 → 3:1 network-makers to yeast cells Demo 5 → 5:1 simple sugars to enzymes Locate bottle and balloon (Demo 4A)
One d before	Order alginate and salt (Demo 1B) Buy: vinegar, milk (Demo 2B); sugar, 1 package dry yeast (Demo 4A) Prepare alginate and salt solutions (Demo 1B) Dilute milk (Demo 2A) Prepare glass dishes or slides and microscope or projection apparatus (Demo 2A) Optional: buy flour to make bread
Day of lecture	Set up bottle containing yeast topped with balloon (Demo 4A)

All demos are provided in the Appendix A.

presenters pick up the chains with only one hand, illustrating the null effect of NaCl on an alginate solution. To demonstrate how $CaCl_2$ cross-links alginate polymers, the presenters pick up the chains with both hands, and form an entangled network.

Demo 1B—alginate cross-linking

Two children help by squirting alginate solution into large beakers of either $CaCl_2$ or NaCl solutions (Shakhashiri 1983). While there is no effect in the NaCl solution, the $CaCl_2$ cross-links the alginate to form long gel "worms" that can be removed by scooping up from the water beaker by hand.

Demo 2A—microscopic structure of milk

Clean a glass microscope slide by wiping with microfiber glass cleaning cloth. Prepare a parafilm "well:" with a sharp 8-mm dia cork boring tool, punch out holes in backed parafilm, leaving room between to cut a 20 × 30 mm rectangle around the hole. Place the parafilm with the backing on top in the center of the microscope slide, matching the aspect ratio; gently press on the backing to adhere so the parafilm lies flat and unwrinkled on the glass. To aid the sealing, use a cylinder (cork borer) to press the film to the glass, rolling carefully with even pressure to prevent distortion of the film. Remove the backing.

Modify the well by cutting a 2 to 3 mm wide channel into the short side of the parafilm: press down twice with a new, single edge razor and peel out the segment. To prepare the milk solution, start with 1 mL half-&-half cream in a small cup. Use a small plastic pipette to add one drop of cream to 1 mL of distilled water in a small centrifuge vial, and mix by aspiration. Place one drop of this solution in the center of the well slide: aim for a small drop that bridges the gap between slide and cover glass but does not touch the sides of the well, as there will be no possibility of flow. Carefully place a 22 × 22 mm cover glass on top of the drop so that it covers 3 to 4 mm of the channel.

To image, we used a microscope (Olympus CH-2), 100× objective (Olympus E A100, NA 1.25 oil), relay lens (Diagnostic Instruments HR055-CMT, 0.55×), camera (Costar Imaging SI-C400N), camera output S-Video to digital video scaler Extron DVS204 with VGA output (15 pin) to video projector. Focus on the cover glass and just under with the 40× air objective to locate the drop and get the lighting and camera right. Place a drop of scope oil on the focal spot and swing in the 100× oil objective. With the coarse focus knob, bring the lens down to the drop and slide; using the fine focus bring the micelles into focus. The fat globules stick to the glass, so continue to focus down a short way into the volume to see the Brownian motion of the micelles. Be careful focusing at higher magnifications, as the well can be deep enough for the objective to hit the cover glass with sample still in focus. To curdle the milk, place a single drop of vinegar on the slide at the inlet; it will be pulled in to mix with the milk.

Alternatively, the milk samples can be placed in a transparent, shallow dish, such as a glass or plastic petri dish, and displayed onto a screen using an overhead projector. Separation of curds and whey can be observed upon adding acid to the dish.

Demo 2B—milk particles coagulate upon addition of acid

Approximately 30 to 45 mL (2 to 3 tablespoons) of white vinegar is added to 70 mL (1/4 cup) milk. To image, we follow the same procedure as described above.

Demo 3—simple steps for making cheese

To demonstrate the basic steps to make cheese, we use 20 children to play the role of network makers, while 40 children are water molecules. In an audience with children of mixed ages, this demonstration is effective when the smaller children are the water molecules. A presenter sprinkles acid (glitter or confetti) onto the children, and the network makers hold hands to form an interconnected mass. We then instruct the network to squeeze as close together as possible, thereby expelling the water from their midst.

Demo 4A—yeast cells produce gas

Simple table sugar (30 mL or 2 tablespoons) is dissolved in 250 mL or 1 cup of warm water. The solution is placed in a bottle and 1 package of dry yeast is added. A balloon is placed tightly around the mouth of the bottle. The bottle is placed in a warm place, and the balloon gradually inflates as the yeast cells produce gas. Recipe adapted from: http://www.exploratorium.edu/cooking/bread/activity-yeast.html.

Demo 4B—yeast alters the texture of bread

We call on 30 network formers to create a network by holding hands. Within the network, we place 10 children representing yeast cells. As the yeast cells blow bubbles, the children forming the network move farther apart from each other while still holding hands. Yeast producing gas can be represented by blowing soap bubbles, or simply by holding a sign indicating the child is a yeast cell.

Demo 5—digestion: enzymes break down large macromolecules into simple molecules

About 50 children play the role of simple sugars; they link hands to form long chains representing complex carbohydrates. Another 10 children acting as enzymes come up and with a scissor-like motion, cut links between simple sugars. Simple sugars sit down as they are cut from chain. To demonstrate the digestion of proteins into simpler amino acid components, t-shirts may be printed with amino acids on the backside.

Appendix B: Materials and Methods

Networks

Salts are obtained from Sigma-Aldrich. Sodium alginate is dissolved in water to a concentration of 20 mg/mL and placed in a squirt bottle. We prepare solutions of 0.5 M $CaCl_2$ and NaCl in large glass beakers. To demonstrate the effect of different salts on cross-linking, we squeeze the alginate solution into the beakers (Shakhashiri 1983). Alternatively, the experiment can be performed by placing the salt solutions in shallow, transparent dishes such as petri dishes, set on an overhead projector to display on a screen. We add a fluorescent dye or food coloring to the alginate solution and pipette the alginate into the salt solutions.

Cheese

We use whole milk and white vinegar from the grocery store to make simple cheese. To make mozzarella cheese, we use a home cheese-making kit available from New England Cheese Making Supply Company (Ashfield, Mass., USA). The rennet enzymes can also be purchased separately.

Bread

An equal volume of water is added to all-purpose flour and stirred to mix. The mixture is spread onto a baking sheet and baked at 400 °F for 10 to 15 min or until slightly browned. The resulting flatbread can be sliced into thin sections and imaged by light microscopy. To make leavened bread, we use a standard recipe for yeasted bread using a 750 mL (3 cups) flour, 1.25 mL (1/4 teaspoon) yeast, and 400 mL (1.6 cups) water.

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