The Science of Chocolate: Interactive Activities on Phase Transitions, Emulsification, and Nucleation

Amy C. Rowat*
Department of Physics and School of Engineering & Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, United States
*rowat@seas.harvard.edu

Kathryn A. Hollar and Howard A. Stone†
School of Engineering & Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, United States

Daniel Rosenberg
Faculty of Arts & Sciences Lecture Demonstrations, Harvard University, Cambridge, Massachusetts 02138, United States
†Current address: Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, New Jersey 08544, United States

Here we describe a presentation we developed on the science of chocolate for the general public, including children ages 6 and up. Chocolate is a complex material, yet nonetheless demonstrates basic scientific concepts that we guide the participants to understand through a series of inquiries and simplified explanations. We structure the 1-h presentation around three simple questions related to observable properties of chocolate (Table 1). To answer these questions, we provide each audience member with a tasting packet (Figure 1) and guide them through a series of taste experiments. This format is a highly effective way to engage people in science, as each person takes part in individual taste experiments *(1−4)*; indeed, audience feedback indicates that we accomplished our goal of generating enthusiasm and discussion about science. Each child receives one of three different T-shirts, identifying them each as one of the major chemical components of chocolate.[1] To explain scientific concepts, we use basic chemical experiments as well as interactive demonstrations with children playing the parts of molecules. The material that we describe can be adapted as a lecture for families and the general public or in the classroom. Because chocolate is a popular subject for science education *(5)*, general science journals *(6, 7)*, as well as active scientific research *(8−14)*, there is a wide variety of resources that can be used to complement and supplement the material we present here.

The Origins of Chocolate

We motivate the questions framing our presentation with the challenge of how to make a good chocolate bar. The consumption of chocolate dates back to ancient Aztec and Mayan civilizations. Since the industrial revolution, many people have tackled the problem of how to produce good chocolate. As a result, many famous chocolatiers have pioneered processes critical to manufacturing a successful chocolate bar including Cadbury, Hershey, Lindt, and Nestlé. All of these chocolatiers asked the same question inspiring this lesson: how to make the perfect chocolate bar?

To address the question of how to make good chocolate and motivate our scientific themes, we begin by explaining the ingredients in a typical chocolate bar (Figure 2A). We identify the major components listed on the label: cocoa beans or mass, cocoa butter, and soy lecithin (an emulsifier) (Figure 2B−D). Each member of the audience is then prompted to taste a pure cocoa bean: because to most participants the bean tastes sour, bitter, and "disgusting", this observation prompts the question of how these beans are transformed into a delicious chocolate bar.

The path to tasty chocolate begins with the cocoa tree that bears fruit in the form of giant cocoa pods *(14, 15)*. These pods contain white pulp in which the cocoa beans are embedded, and are akin to familiar fruits such as peaches or plums with pits or apples with bitter seeds. The pods are harvested, split open, and the pulp becomes a food source for natural yeast and bacteria. Over the course of several days, the pulp is digested; this fermentation process is also essential to develop the flavor profile of chocolate, as chemical reactions initiated by the microbes help to make the beans taste less bitter. The beans are then picked out of the pod and dried. The next step of roasting the beans is also important for developing the characteristic flavor of chocolate *(5)*. Thereafter, the beans are crushed into small pieces or pressed to extract the cocoa butter fat from the cocoa solids. This process of extraction is similar to how olive oil is pressed from olives, or juice is extracted from fruits like apples or oranges. In this way, the two main ingredients of chocolate, cocoa solids and cocoa butter, are generated.

Questions about Chocolate

We address specific questions about the physical properties of chocolate by guiding the audience through a series of three additional taste experiments (Figure 1, Table 1). Taste experiments require that each audience member is engaged in making observations about chocolate: What does it look like: glossy or dull? What does it feel like: smooth or soft or crumbly? What does it taste like: bitter or sweet? Details about the demonstrations,

10.1021/ed100503p Published on Web 10/27/2010

Table 1. Main Questions and Related Scientific Themes

Motivating Question	Taste Experiment	Specific Question	Result	Answer	Main Scientific Themes
Why does chocolate usually melt in my mouth, not in my hand?	Dark chocolate versus milk chocolate chips	Which chocolate melts first in your mouth?	Milk chocolate melts at a lower temperature than dark chocolate	Melting temperature depends on material composition and on the shape of fat molecules; cocoa butter melts at around your body temperature	Phases of matter, phase transitions, lipid composition
Why does chocolate feel smooth?	European-style chocolate versus Mexican-style chocolate	How do the chocolates feel different in your mouth?	One chocolate feels rough or bumpy compared to the other	Texture depends on particles size; amphiphilic molecules or emulsifiers also help make chocolate feel smooth	Hydrophobic, hydrophilic, emulsification
Why does chocolate snap when you break it and have sheen?	Tempered versus untempered chocolate	How do the appearance and texture of the chocolates differ?	Tempered chocolate has sheen and snaps when broken; the untempered chocolate looks spotty or moldy, and crumbles	Cocoa butter molecules need to pack in the right way	Phase transitions, crystallization, nucleation

Figure 1. Tasting experiment packet and contents: (A) The envelope distributed to each audience member. (B) The envelope contains small plastic bags for each of the following taste experiments: (i) a raw cocoa bean; (ii) a piece of dark and milk chocolate; (iii) two pieces of chocolate with different texture, one smooth and the other grainy; (iv) a piece of chocolate that has been "untempered" and a tempered control sample.

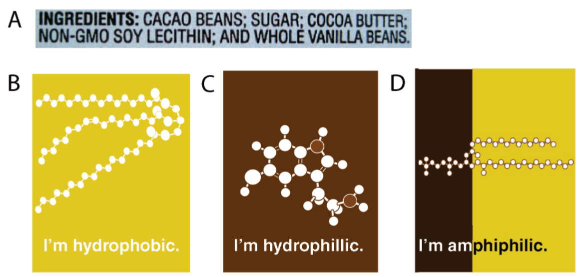

Figure 2. Major ingredients in chocolate. (A) Label of a chocolate bar illustrates the major ingredients in chocolate: cacao bean (or cocoa mass), sugar, cocoa butter, and soy lecithin. For the purposes of the lecture, we focus on the cocoa beans, cocoa butter, and soy lecithin (emulsifier), each of which are represented by the following icons on the children's" T-shirts and throughout the lecture: (B) Cocoa butter is represented as a triglyceride molecule, a component of cocoa butter that is largely hydrophobic. (C) Cocoa mass is represented as a serotonin molecule, a component of cocoa that is largely hydrophilic. (D) Amphiphilic molecule or emulsifier is represented as lecithin, an amphiphilic compound that is naturally found in the cocoa bean and is also added when producing chocolate.

experiments, and simulations are provided in the supporting information.

Why Does Chocolate Melt in Your Mouth and Not in Your Hand?

We begin by sampling small pieces of dark and milk chocolate, each of which melts at a different temperature. We instruct each person to simultaneously place the milk chocolate on the left side of their tongue and the dark chocolate on the right side and observe which chocolate melts first. We use a show of hands to record the results of this "experiment", making it clear that the milk chocolate melts first.

To explain why different types of chocolate melt at different temperatures, we introduce the concept of phases: materials exist in different states, such as solid and liquid. Because chocolate is a

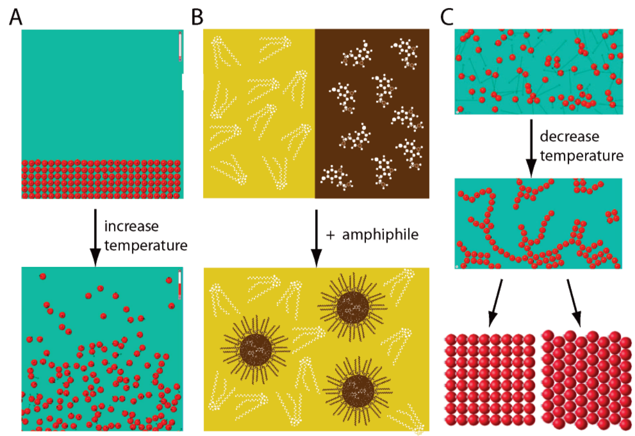

Figure 3. Main scientific themes in chocolate. (A) Phase transitions: why does chocolate melt in your mouth? We use a computer simulation to illustrate the behavior of molecules as the temperature increases and the phase transitions from solid to liquid to gas or vapor. We also melt ice in a hot pan to show the transition from solid to liquid to vapor. (B) Emulsification: why does chocolate feel smooth? We show how an amphiphilic molecule like detergent can help water and oil to mix. (C) Nucleation and crystal formation: why does chocolate have sheen and snap when you break it? We explain how molecules can pack together in different ways when cooled. We then show crystal formation with the computer simulation and also nucleation of ice and salt crystals with live demonstrations.

complex material, we begin with a demonstration of water. As evidenced by the melting of ice into liquid and subsequent evaporation to vapor, water exists in different forms: solid, liquid, and vapor (Demo 1). To understand what happens as a material melts, we explain that materials consist of molecules that are built up from individual atoms. We illustrate the concept of how temperature can affect molecular motion using a computer simulation: (i) at a low temperature, atoms are in a solid or crystalline ordered state and make only small vibratory movements about a fixed position on a grid; (ii) at higher temperatures, atoms move freely past each other, characteristic of a liquid; and (iii) as a gas at even higher temperatures, atoms move wildly about within their confined space (Figure 3A). With this computer simulation fresh in everyone's minds, we invite a group of children to the front of the room, have them stand on marked locations on a regular lattice, and then act out "molecular movements". As the temperature is raised, as indicated by a giant thermometer projected on the screen, children in a solid state vibrate while standing on fixed grid points, then walk around past each other as a liquid, and finally turn into a gas and flee back to their seats.

To understand how chocolate melts, we consider the major fat in chocolate, cocoa butter. This fat is similar to butter or other common fats found in the kitchen, such as olive oil, butter, and lard. However, we demonstrate that, while olive oil is a liquid at room temperature, cocoa butter is a solid (Demo 2). We explain why some fats are liquid while others are solid at the same temperature by introducing the molecular structures of fat molecules. The majority of fats in butter has straight chains (saturated fatty acids) and can thus pack closely together; these types of fats typically melt at higher temperatures ($T > T_{room}$). In contrast, olive oil consists largely of molecules (unsaturated fatty acids) that have a kink in them; they cannot pack as closely together and exist in a liquid phase at lower temperatures, melting at $T < T_{room}$.

Table 2. Guide to Hydrophilic, Hydrophobic, and Amphiphilic

Greek Word Root	Meaning	Common words
Hydro-	Water	Hydrofoil, fire hydrant, hydroponic, hydroelectricity
-Phobic	Fear	Arachnophobic, claustrophobic
Amphi-	Both	Amphibian, amphitheater
-Philic	Love	Philadelphia, philanthropy, chocophile

Using children from the audience, we demonstrate how the different molecular structures of saturated and unsaturated fats result in different melting temperatures (Demo 3). The children who are "saturated" fats stand up straight and gather close together; the "unsaturated" fats adopt a kinked shape by bending at the waist, and thus cannot stand as close to each other. As the temperature is increased, we instruct the children to act out how the "unsaturated fats" melt at a lower temperature than the "saturated fats", which demonstrates how molecular architecture affects the material's melting transition temperature. Interestingly, the cocoa butter fat in chocolate has a melting transition temperature of around 97 °F, close to body temperature. Thus, at temperatures below 97 °F, chocolate is a solid; because hand temperature is measured to be 80−90 °F, this explains why chocolate is typically solid in your hand. However, at 97 °F or above, cocoa butter exists in a liquid phase. This demonstration of how the molecular composition determines the melting transition temperature illustrates why chocolate typically melts in your mouth, not in your hand.

Why Does Chocolate Feel Smooth in Your Mouth?

Next we focus on texture. Audience members compare the taste of two chocolates with different textures (European-style versus Mexican-style), and we ask them to pay special attention to how the chocolate feels on their tongue. The audience observes one of the chocolates feels "rough", "bumpy", or "grainy". What makes chocolate feel smooth in your mouth? One guess is that the size of particles present in the chocolate determines the texture of chocolate. For example, sugar is milled to different sizes, which results in a variety of sugar types ranging from rock candy to table sugar to powdered sugar.[2] The cocoa beans are also ground into particles whose size can vary.

In addition to particle size, the chemical composition is also important for chocolate's texture. As introduced when we examined the chocolate label, cocoa particles coexist in a chocolate bar together with the cocoa butter. But a simple demonstration shows that cocoa powder does not disperse in oil, but can be suspended in water (Demo 4A), which is a concept familiar to anyone who has made chocolate milk. Thus, we introduce the concept of materials that are hydrophobic (dislikes water) versus hydrophilic (likes water) (Table 2). The cocoa mass in chocolate is hydrophilic, whereas the hydrophobic cocoa butter fat molecules are composed mainly of carbon and hydrogen and do not readily interact with water.

By shaking a flask containing water and oil and observing the immediate phase separation (Demo 4B), we clearly demonstrate that hydrophobic and hydrophilic materials do not mix well. We then show how water and oil mix simply by adding a detergent (an amphiphilic molecule) that likes both water and oil (Table 2). Such a mixture is called an emulsion and the detergent is an emulsifier. Many people are familiar with emulsifiers in salad dressings such as egg or mustard that are added to form a stable emulsion of oil and vinegar. An "emulsifier" that is commonly added to chocolate is soy lecithin (Figures 2A, 3B), that promotes mixing of cocoa solids and cocoa butter: these amphiphilic molecules coat the hydrophilic cocoa solids with a hydrophobic layer, thereby helping to maintain a stable chocolate, and making the chocolate feel smooth in your mouth. With this approach, we explain and illustrate the chemical concepts of hydrophobic, hydrophilic, and amphiphilic.

Why Does Chocolate Look Glossy and Snap When You Break It?

Finally, we compare chocolate that has been properly versus poorly stored. Storage at the wrong temperature, for example, in a hot car or in a pocket, typically results in chocolate with a surface that appears "moldy", and with a crumbly texture. To understand the surface appearance and mechanical properties of chocolate, we consider the formation of solid materials from liquids. Solidification occurs upon a decrease in temperature, as molecules move more slowly and form ordered clusters as they cool (Computer Simulation, Figure 3C). Clumps of ordered, repeating structures are small crystals in a solid phase. To describe crystal formation, we perform two demonstrations (Demo 5A,B), which illustrate the formation of solid crystals from a liquid. We explain that molecules in crystalline structures can pack together in slightly different ways. An excellent analogy is how you pack balls or holiday decorations in a box: round objects can pack into the same box in slightly different ways (Figure 3C). Similarly, a fixed number of coins can be arranged in different patterns to fit into the same area. Importantly, the resulting crystalline form affects the material's mechanical properties.

In chocolate, fat molecules can crystallize into six different forms when chocolate cools and solidifies *(5, 14)*. Only two of these crystal forms result in chocolate that is smooth, glossy, and has a desirable texture, whereas the other forms yield poor quality chocolate. The way the cocoa butter molecules pack together is thus critical for the final texture, appearance, and shelf life of chocolate. Chocolatiers control the size and type of crystals that form by gently heating and cooling the chocolate while it solidifies in a process called "tempering". This process promotes the formation of seed crystals of the right type and homogeneous size and results in chocolate that looks glossy and snaps when you break it. When chocolate is stored improperly, the desirable type of crystals melt and resolidify into forms that yield chocolate that no longer has sheen, and crumbles when broken.

Suggestions for Engaging the Audience

We find that the taste experiments are highly effective for engaging each individual audience member, as they are asked to become a scientist, ask their own questions, make observations about the appearance, texture, and feel of their chocolate samples, and to follow the explanations. This approach is a highly effective way to foster conceptual learning and scientific reasoning *(1, 15)*. We also encourage audience participation throughout the presentation at 8–10 min intervals; this pacing is critical for keeping young children engaged in the presentation. We begin by engaging the audience, asking questions such as What is your favorite chocolate? Where do cocoa beans grow? What did you

Table 3. Mapping Lecture Components to National Science Education Standards

Standard	Lecture Activity	Grades K–4 Teachers	Grades 5–8 Teachers	Grades 9–12 Teachers
A: Understanding Scientific Inquiry	Taste experiments and visual observations about the appearance, taste, and texture of cacao beans and different chocolates.	Ask students to make observations about the material properties of chocolate and formulate questions about their observations: Why is some chocolate soft? Why does some chocolate look white?	Ask students to make observations about the material properties of chocolate and formulate questions about their observations: Why is some chocolate soft? Why does some chocolate look white?	Ask students to make observations about the material properties of chocolate and formulate questions about their observations: Why is some chocolate soft? Why does some chocolate look white?
B: Physical Science	The question "Why does chocolate melt in my mouth but not in my hand?" motivates an understanding of how the properties of chocolate change with temperature as well as the different states of matter: solid, liquid, and gas.	Discuss the properties of objects and materials; students observe that chocolate can exist in liquid or solid state.	Discuss the properties and changes of properties in matter; students observe the shape, color, and texture of chocolate; chocolate can exist in liquid or solid state.	Discuss the structure and properties of matter; shape, color, and texture of chocolate; structure of fat molecules determines melting point of different fats as well as chocolate. Nucleation and crystallization helps to explain chocolate's texture and appearance.
E: Science and Technology	Technologies are developed and applied to process cocoa beans and produce chocolate bars.	Introduce natural and synthetic materials; the chocolate we eat is processed in a factory.	Introduce technological design and innovations for manufacturing chocolate.	Introduce technological design and innovations for manufacturing chocolate.
G: History and Nature of Science	Men and women scientists have contributed to knowledge of hydrophobic or hydrophilic materials, while chocolatiers have advanced chocolate-making technology.	Present science as a human endeavor.	Present science as a human endeavor; history of science.	Present science as a human endeavor; history of science.

notice about the chocolate you just ate? Furthermore, we call for individual volunteers to help with tabletop demonstrations and have children from the audience act out the role of individual molecules. Each child wears a T-shirt and plays the role of a hydrophilic, hydrophobic, or amphiphilic molecule during our interactive demonstrations (Figure 2). The images and colors of the T-shirts are coordinated with the presentation slides.

Another effective way to engage the audience is by presenting chocolate in the context of familiar local culture and history. For example, in a lecture at Harvard University, we describe how one of the first successful chocolate mills in the United States was co-established by Harvard graduate, James Baker, in the mid-1700s in nearby Dorchester, MA. We also collaborate with local chocolate company, Taza Chocolate, who provides invaluable knowledge and expertise, as well as chocolate. At a lecture held in Albuquerque, NM, we discuss the discovery of theobromine in ceramic vessels of the ancient Pueblo peoples *(8)*.

Adaptation to 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. These activities can be adapted as a 1-h lesson plan or used in a modular fashion in the classroom.[3]

Conclusion

Our interactive presentation on the science of chocolate employs many techniques known to be effective for science education *(1−4)*. We present scientific concepts in the context of a familiar material, chocolate, that everyone knows and loves; we engage each individual in tasting experiments whereby they make their own observations and ask questions; and we use demonstrations where children act out physical responses displayed by molecules. Comment cards that attendees complete at the end of the lecture indicate that we accomplish our goals of inspiring discussions of science among families and of generating excitement and curiosity to continue asking questions about science in everyday life.

Acknowledgment

We gratefully acknowledge the support of the Harvard School of Engineering and Applied Sciences (SEAS), the Faculty of Arts and Sciences (FAS), the Provost's Office, the Materials Research and Science Engineering Center (MRSEC), the Microbial Sciences Initiative (MSI), the Nanoscale Science and Engineering Center (NSEC), the School of Engineering and Applied Sciences (SEAS), the Center for Nanoscale Systems (CNS), as well as the staff at the Harvard Science Center. Dissemination of the chocolate lecture was also supported by the Partnership for Research and Education in Materials between the University of New Mexico and the Harvard MRSEC. We are also grateful to Ellen Hodges for her help with scanning electron microscopy, as well as Naveen Sinha, Jeremy Agresti, Christian Holtze, Alex Fiorentino, Taza Chocolate, and Unilever for their generous contributions. The NSEC, MRSEC, and PREM are funded by the National Science Foundation under the grants PHY-0646094, DMR-0820484, and DMR-0611616.

Notes

1. We use T-shirts to identify the children as molecules in chocolate as they perform interactive demonstrations. Lower cost alternatives include stickers, or simply sheets of paper taped to clothing.
2. Whereas the typical particle size in European chocolate (e.g., Lindt) is ~20 μm, Mexican chocolate is not milled as finely, yielding a larger particle size. In addition, Mexican chocolate contains sugar crystals as well as cinnamon that may also contribute to its texture.
3. PowerPoint slides and templates for labels and T-shirts are freely available upon request.

Literature Cited

1. Handelsman, J.; Ebert-May, D.; Beichner, R.; Bruns, P.; Chang, A.; DeHaan, R.; Gentile, J.; Lauffer, S.; Stewart, J.; Tilghman, S. M.; Wood, W. B. *Science* **2004**, *304*, 521–522.
2. Ebert-May, D.; Brewer, C.; Allred, S. *Bioscience* **1997**, *47*, 601–607.
3. Gage, R. *English Journal*, December**1995**, 52−55.
4. Felder, R. M.; Silverman, L. K. *Eng. Educ.* **1988**, *78*, 674–681.
5. Tannenbaum, G. *J. Chem. Educ.* **2004**, *81*, 1131–1135. Amey, J. R.; Fletcher, M. D.; Fletcher, R. V.; Jones, A.; Roberts, E. W.; Roberts, I. O. *J. Chem. Educ.* **2008**, *85*, 1361–1364.
6. Windhab, E. J. *Physics Today*, June **2006**, 82−83.
7. Fryer, P.; Pinschower, K. *MRS Bulletin*, December **2000**, 25−29.
8. Crown, P. L.; Hurst, W. J. *Proc. Natl. Acad. Sci. U.S.A.* **2009**, *106*, 2110–2113.
9. Afoakwa, E. O.; Paterson, A.; Fowler, M. *Trends Food Sc. Technol.* **2007**, *18*, 290–298.
10. Afoakwa, E. O.; Paterson, A.; Fowler, M.; Vieira, J. *Eur. Food. Res. Technol.* **2008**, *227*, 1215–1223.
11. Peschar, R.; Pop, M. M.; De Ridder, D. J. A.; van Mechelen, J. B.; Driessen, R. A. J.; Schenk, H. *J. Phys. Chem. B* **2004**, *108*, 15450–15453.
12. Mayama, H. *Soft Matter* **2009**, *5*, 856–859.
13. Rousseau, D.; Smith, P. *Soft Matter* **2008**, *4*, 1706–1712.
14. Beckett, S. T. *The Science of Chocolate*, 2nd ed.; Royal Society of Chemistry: Cambridge, 2008.
15. Young, A. M. *The Chocolate Tree: A Natural History of Cacao*, 2nd ed.; University Press of Florida: Gainesville, FL, 2007.

Supporting Information Available

Details about the demonstrations, experiments, and simulations. This material is available via the Internet at http://pubs.acs.org.