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**Authors**
Rowat, Amy C
Sinha, Naveen N
Sörensen, Pia M
et al.

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# The kitchen as a physics classroom

**Amy C Rowat[1], Naveen N Sinha[2], Pia M Sörensen[2], Otger Campàs[3], Pere Castells[4], Daniel Rosenberg[5], Michael P Brenner[2] and David A Weitz[2]**

[1] Department of Integrative Biology and Physiology, University of California, Los Angeles, CA 90095, USA
[2] School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA
[3] Department of Mechanical Engineering, University of California, Santa Barbara, CA 93106, USA
[4] UB-Bullipèdia Unit/Food and Nutrition Torribera Campus, University of Barcelona, Santa Coloma de Gramenet, 08921, Barcelona, SPAIN
[5] Arts and Sciences Lecture Demonstrations, Harvard University, Cambridge, MA 02138, USA

**Abstract**
Cooking is a tangible, familiar, and delicious tool for teaching physics, which is easy to implement in a university setting. Through our courses at Harvard and UCLA, each year we are engaging hundreds of undergraduate students, primarily non-science majors, in science concepts and the scientific research process. We find that weekly lectures by chefs and professors, paired with edible lab experiments, generate enthusiasm and provide strong motivation for students to learn physics. By the end of the course, students are able to conduct independent scientific research and present their results in a final science fair. Given the considerable broad appeal of food and cooking, the topic could be adapted to other post-secondary as well as secondary-level courses.

## 1. Introduction

A major challenge in teaching physics is to make students see the connection to their everyday lives. In many physics courses, concepts are presented using abstract examples, such as stretching an ideal spring or heating a copper rod. To make the material more relevant, we developed a curriculum that uses examples from cooking to teach physics concepts to undergraduate students. The resulting course, 'Science and Cooking: From Haute Cuisine to Soft Matter Science', fulfils the Science of the Physical Universe requirement as part of the new General Education program at Harvard. Courses that fulfil this requirement are designed for non-science majors and must 'teach central facts and concepts in the physical sciences and engineering, and relate them to issues that students will encounter in their daily lives' [1]. The curriculum was subsequently adapted at UCLA where 'Science and Food: The Physical and Molecular Origins of What We Eat' similarly fulfils the Physical Sciences requirement of the General Education programme.

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Cooking provides a rich set of examples to introduce topics in the physical sciences. Nearly all cooking involves irreversible physical transformations that are intended to improve some combination of the texture, flavour and nutritional content of a food. One especially versatile example is the egg: heating can transform the whites into an opaque gel, whisking can turn the whites into a foam, and blending the yolks with olive oil and lemon juice can produce the stable emulsion known as mayonnaise. However, even a small variation in method or technique can result in cooked eggs that are rubbery, foams that collapse, or emulsions that break. In general, the success or failure of a dish can be explained by a small number of scientific concepts, such as elasticity and diffusion, which are commonly discussed in introductory physics courses.

Cooking also serves as a familiar and tangible example of the scientific method. Each recipe is an experiment; deviating from tradition can result in culinary disaster. Like a scientist, the intrepid cook can explore a range of variations in ingredients and methods through careful experimentation and documentation: systematically varying one parameter of the recipe at a time and observing the outcome. Knowledge of scientific concepts can help to prioritize which of these parameters would be most useful to vary. For example, knowledge of thermal energy diffusion can show how long to cook a molten chocolate cake [2] (figure 1).

In addition to using everyday examples, like an egg, recent developments in high-end restaurants provide new educational opportunities. Over the past several decades there has been a revolution in the kitchens of many restaurants, inspired by methods from scientific laboratories [5–10]. Pioneers such as Ferran Adrià (*el Bulli*) and Heston Blumenthal (*The Fat Duck*) produce striking culinary creations especially suited for teaching science. For example, Joan Roca (*El Celler de Can Roca*) uses precise regulation of temperature [11], enabling unprecedented control over protein denaturation and the final texture of the food. As another example, polymers facilitate the creation of novel food textures; instead of using egg whites or dairy fat to stabilize a foam, only a small amount of the naturally occurring surfactant lecithin can create similar textures of foams that have more pure flavours. These chefs are also famous for their use of liquid nitrogen, rotary evaporation, centrifugation, and other techniques more commonly associated with scientific laboratories.

## 2. Science and cooking course structure

Our aim is to create a physics class for non-scientists, assuming a background of basic high school physics. We seek to engage students in scientific concepts and methods by showing them the science underlying the food of both haute cuisine and everyday cooking. Although several existing courses focus on chemical aspects of food [12, 13], resources that highlight the physics of cooking are sparse [2–4, 14]. Moreover, despite the central importance of soft matter physics in cooking, topics such as gels, foams, and emulsions are rarely taught at an introductory college level. For these reasons, we present here our own curriculum where the physics of soft materials is central. In addition to physics concepts, microbial growth is an excellent example of exponential processes common in physics and is also essential for understanding fundamental culinary processes, such as fermentation; therefore, we additionally include this concept in our curriculum.

### *2.1. Weekly structure of teaching*

To teach this coherent curriculum focusing on soft matter science, we devised a tight pedagogical structure. Each week focuses on a single scientific idea that is essential to numerous culinary examples. This idea is introduced through the ‘Equation of the Week’ (table 1), then elaborated through lectures by professors and chefs, as well as a recipe prepared by the students during their lab section.

(a) **The Equation of the Week summarizes each scientific concept.** To provide a rational framework for understanding the nine concepts we identified as relevant to cooking, we select a single equation for each concept that summarizes the connection between the observable aspects of a food and its microscopic structure. For instance, during the week on thermal energy transfer, the Equation of the Week (table 1, #4, 5) relates the diffusion of thermal energy into a material, *L*, as indicated by the

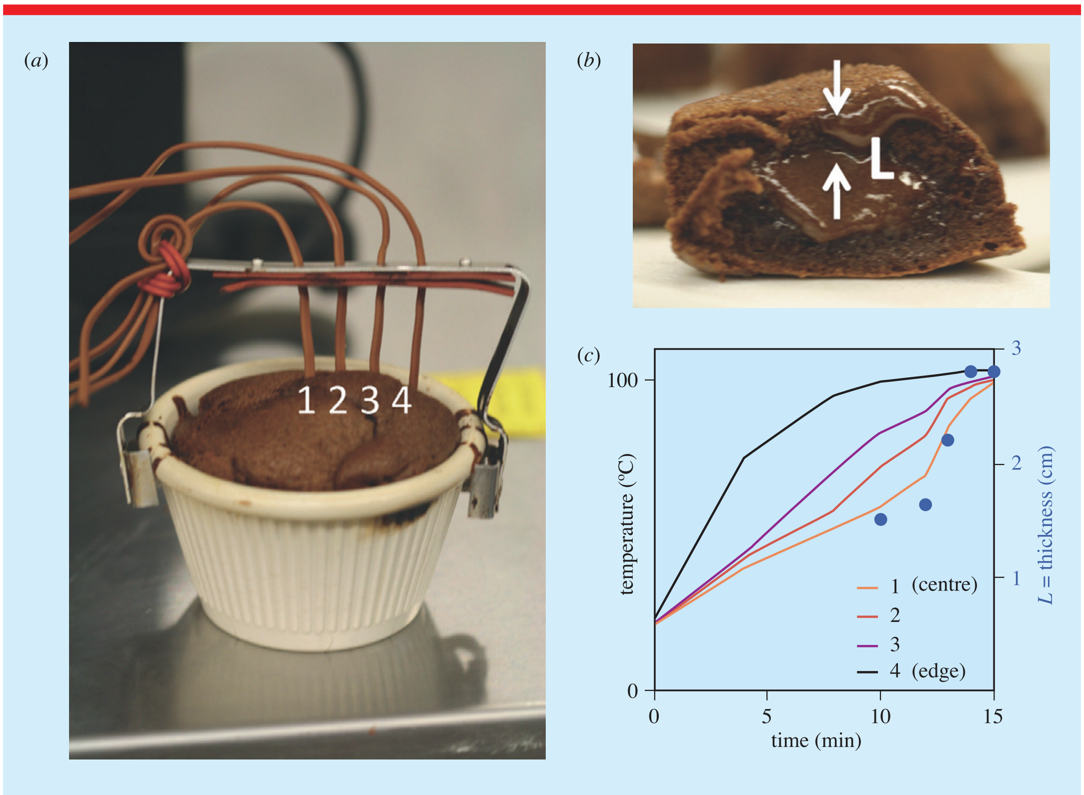


**Figure 1.** Cake as an example to teach thermal energy transfer and elasticity. (*a*) Thermocouples are used to measure the rise in temperature at different points inside a molten chocolate cake as it bakes in an oven. (*b*) The thickness of the solid crust of the cake *L* increases over time. (*c*) Temperature measurements from four thermocouple probes arranged from the centre (1) to the edge (4) of the cake. The blue dots show the thickness of the crust, based on dissections of cakes baked for different times.

solidification of the outer layer of the molten chocolate cake, to the thermal diffusion constant, $D$, and the cooking time, $t$ (figure 1). The time delay before the solidification corresponds to the cake batter reaching the threshold temperature for baking; once this temperature is exceeded, the thickness of the solid layer increases proportionally to the square root of time. While many of the equations we present are exact for ideal systems, food systems are complex; in the case of the cake, water evaporation from the surface, changes in the heat diffusion constant during solidification, and other factors could affect the heat flow. We find that the students appreciate a discussion highlighting the limitations of the equations, and the extent to which they can provide a good approximation.

(b) **Lectures feature both chefs and professors.** Course instructors give science lectures based on the Equation of the Week, which include derivations, worked example problems, and demonstrations. In addition, each week features a culinary lecture by a visiting chef; these lectures complement the corresponding science lectures, to reinforce the science concepts. For example, during the week covering thermal energy transfer, the course staff bakes a cake, plots the rising internal temperature in real-time, and introduces the heat diffusion equation (table 1, #4, 5). The corresponding guest lecture shows how thermal energy transfer is applied to chocolate tempering: chefs provide tangible examples of the scientific concepts; these live demonstrations, often involving food samples, are popular among students.

(c) **Lab sessions involve experiments with food.** Weekly labs give students a hands-on opportunity to explore the current science

**Table 1.** Summary of course: each week students are presented with an Equation of the Week and a recipe, which accompany the science explanations from the course instructors and the demos from the visiting chefs. In the lab, students perform simple experiments and make recipes that illustrate the science concepts.

| Equation | How we introduce the concepts | Recipe and lab instructions |
|---|---|---|
| 1. Energy, temperature, and heating | | |
| $Q = m\, c_p\, \Delta T$ | • Adding cold milk to hot coffee lowers the final temperature.<br>• The relationship between the thermal energy added $Q$ and the change in temperature $T$ for a mass $m$ of food is given by the Equation of the Week, where $c_p$ is the specifc heat capacity of the food. | • **Ricotta cheese.** Prepare cheese by adding acid to milk.<br>• Generate a phase diagram showing the effect of vinegar on the milk.<br>• Calculate the amount of thermal energy needed for the cheese to curdle.<br>• Compare to the thermal energy transferred by the stove. |
| 2. Phases of matter | | |
| $U_{\mathrm{int}} = C\, k_{\mathrm{B}}\, T$ | • The transformations that occur in cooking, such as cooking an egg from a liquid to a solid, can be represented on a phase diagram.<br>• Boundaries of the phase diagram are determined by when the interaction energy, $U$, between molecules in food is equal to the thermal energy, $k_{\mathrm{B}}T$, times a constant, $C$. | • **Ice cream.** Prepare ice cream using a slurry of salt water and ice to cool the base below 0 °C.<br>• Use a phase diagram to explain how the freezing point of water changes with the addition of salt. |
| 3. Elasticity and gels | | |
| $E = \dfrac{k_{\mathrm{B}}T}{l^3}$ | • The texture of foods can be described by their elastic moduli.<br>• A rare steak has a lower elastic modulus than a well-done steak.<br>• The elastic modulus $E$ of a gel depends on the spacing between its crosslinks $l$. | • **Hot and cold tea.** Recreate Heston Blumenthal's recipe by experimenting with the pH and temperature of the gels; measure the elasticity for gels with different acidities.<br>• **Flan.** Compare the elasticity $E$ of flan to the elasticity $E$ of gellan gels at different concentrations. |
| 4. Diffusion | | |
| $L = \sqrt{4Dt}$ | • The rate of many culinary processes, like baking and brining, is limited by diffusion.<br>• The distance $L$ traveled by thermal energy or molecules is proportional to the square root of time $t$. | • **Spherification.** Solid shells form around liquid droplets as a solution of alginate polymers are crosslinked by calcium ions.<br>• Measure the thickness of the solid shell $L$ as a function of time $t$, in order to calculate the diffusion rate for calcium ions $D_{Ca^{2+}}$. |
| 5. Thermal energy transfer | | |
| $T(t) = (T_{\mathrm{in}} - T_{\mathrm{out}})\, e^{\frac{-t}{\tau_0}} + T_{\mathrm{out}};\ \tau_0 = \dfrac{L_0^2}{4D}$ | • Manipulating the temperature of food is central to many cooking processes, from baking a cake to making ice cream.<br>• Thermal energy can flow by diffusion.<br>• The temperature of a food over time $T(t)$ depends on its starting temperature $T_{\mathrm{in}}$, the external temperature $T_{\mathrm{out}}$, and the size of the food $L$. | • **Molten chocolate cake.** Use thermocouples to measure the temperature at multiple points within a cake as it bakes.<br>• As the cake bakes, the exterior sets into a solid, but the interior remains liquid; by measuring the thickness $L$ of the solid layer over time, measure the thermal diffusive constant of cake batter. |

(*Continued*)

**Table 1.** (*Continued*)

| Equation | How we introduce the concepts | Recipe and lab instructions |
|---|---|---|
| 6. Viscosity and polymers | | |
| $\eta = E\,\tau_{\mathrm{flow}}$ | • Tuning the consistency and mouthfeel of foods is central to cooking.<br>• How easily a liquid flows is quantified by the viscosity $\eta$.<br>• At a microscopic level this depends on the time scale for molecules to move past each other $\tau_{\mathrm{flow}}$.<br>• The viscosity $\eta$ depends on both $\tau_{\mathrm{flow}}$ and the elasticity $E$.<br>• Foods that are viscous over long time scales can appear highly elastic on short time scales. | • **Milkshakes.** Many commercial foods contain xanthan gum as a thickening agent; this microbial byproduct is so effective since the molecules are unusually long.<br>• Vary the amount of xanthan gum in a recipe to match the viscosity of a milkshake, enabling the same consistency with far less fat. |
| 7. Emulsions and foams | | |
| $E = \frac{\sigma}{R}\left(\phi - \phi_c\right)$ | • Emulsions appear in the kitchen in many forms, ranging from sauces to whipped cream.<br>• Adding bubbles or droplets increases the volume fraction $\phi$.<br>• At low volume fractions the bubbles or droplets thicken the liquid.<br>• Above a critical value $\phi_c$, an elastic solid is formed with elasticity $E$. | • **Mayonnaise.** Prepare then observe mayonnaise under a microscope to determine the average radius $R$ of the oil droplets.<br>• **Lime foam.** Prepare a foam of lime juice and measure the size $R$ of the air bubbles with the microscope.<br>• Explain how the elastic moduli $E$ of these foods are related to the radii $R$ of the droplets or bubbles in the dispersed phase. |
| 8. Microbes | | |
| $N(t) = N_0 e^{k\,t}$; $k = \ln 2/\tau_2$ | • Microbes play a profound role in cuisine; they can improve taste and texture, but can also cause illness.<br>• A population of microbes can grow at an exponential rate, whereby the rate of change is proportional to the present quantity. | • **Final projects** |

*Note*: $Q$ = thermal energy transferred, $m$ = mass, $c_p$ = specific heat capacity, $\Delta T$ = change in temperature, $U_{\mathrm{int}}$ = molecular interaction energy, $k_{\mathrm{B}}$ = Boltzmann constant, $C$ = empirical constant, $T$ = temperature, $E$ = elasticity, $l$ = crosslink spacing, $L$ = distance of diffusion, $D$ = diffusion constant, $t$ = time elapsed, $T_{\mathrm{in}}$ = initial temperature inside food, $T_{\mathrm{out}}$ = temperature at outside boundary of food, $\tau_0$ = heating time constant, $L_0$ = distance to centre of food, $\eta$ = viscosity, $\tau_{\mathrm{flow}}$ = time scale for material to flow, $\sigma$ = surface tension, $R$ = radius of droplets or bubbles, $\phi$ = volume fraction, $\phi_c$ = critical volume fraction, $N$ = number of microbes in the population, $N_0$ = initial count of microbes, $k$ = microbial growth constant and $\tau_2$ = microbial doubling time.

concept and apply the Equation of the Week. Lab sessions are designed to last a total of two hours, with the first thirty minutes devoted to a review of the lectures and guided problem solving. In conducting their laboratory investigations, students work in groups of three to collect data, record observations, as well as analyze and eat their results. Such tactile lab exercises are an ideal way to engage students who may have diverse learning styles [15]. Moreover, inquiry-based approaches to lab instruction are effective methods to foster conceptual understanding and scientific reasoning [16]. The labs also guide students on how to vary a single parameter in an experiment, in order to obtain a deeper understanding of the relevant science; this further prepares the students to conduct their independent research projects at the end of the course. Throughout the lab sessions, we closely follow guidelines on food safety recommendations and best practices as provided by our institutional Departments of Environmental Health and Safety. This includes using proper food handling and storage procedures, as well as washing and sanitizing protocols. We also ensure student safety by providing a tutorial before lab sessions begin, which covers safe knife handling practices as well as how to safely handle hot pots and ovens. As in all laboratory exercises, students are required to wear close-toed shoes and long trousers and tie up long hair. Furthermore, we advise students that foods prepared in lab sessions may contain allergens; consuming them is completely optional.

Using both theoretical and practical approaches to teaching physics, we aim to ensure that students gain experience with the scientific concepts from multiple perspectives. In addition, we pursue an iterative approach, framing new material in the context of what was previously presented. For example, during the week on gelation, previous concepts reappear, such as elasticity and diffusion, as shown in table 1. According to feedback from the teaching staff, many students found this approach helpful for preparing for the exams.

## 3. Examples of topics

To illustrate the course contents in more detail, we present two representative examples of topics: elasticity and thermal energy transfer. For each topic, we discuss how we introduce the subject, an example homework problem, the weekly lab activity, as well as the limitations of the Equation of the Week. We present similar information about all the topics in table 1.

### *3.1. Elasticity*

Gels are ubiquitous in cuisine: from simple, single-component gels such as jelly (jello), made of gelatin, to the complex networks of molecules in meat. The mechanical properties of gels are essential for food texture, and also provide a simple way to understand elasticity. While we eat a wide range of gels, they all consist of food polymers that form an interconnected network in a matrix of water. In fact, most simple gels consist largely of water, as they typically contain less than a few percentages by mass of polymer. Even meat consists largely of water, typically over 65% [18]. But despite their high water content, both simple and complex gels exhibit the behavior of solid materials and can be characterized by an elastic modulus.

**In the classroom.** We begin our discussion of elasticity by demonstrating how to measure the elastic modulus of a raw steak, simply by measuring the amount of deformation that occurs in response to a 100 g weight placed on the steak. We then explain how to calculate the elastic modulus of the steak using the Equation of the Week: $F = E\ A\ (\Delta L/L)$; to develop an intuition for this expression, we explore how the variables change dependent on each other. We then heat up a frying pan on a hot plate and fry the steak for several minutes; subsequent measurements of the elastic modulus reveal that steak becomes more resistant to deformation after cooking.

To explain these observations at the molecular level, we consider the elastic modulus of a network of proteins that can be simply described as $E = k_B T/l^3$, where $l$ is the mesh size or distance between crosslinks, and $k_B T$ is the interaction energy of the crosslinks. An increased elastic modulus reflects a decrease in the mesh size of the network, which is consistent with the loss of water during cooking and other molecular-level changes (such as protein denaturation and coagulation) that may occur in response to increased temperature. To demonstrate the concept of elasticity in a completely different type of food, the visiting chef demonstrates chocolate making, and the discussion turns to yield stress and other elastic behaviors.

**Homework problem.** *Elasticity of a steak.* Elasticity is one way to quantify the doneness of a steak. In class, we measured the elastic modulus of a medium rare steak as 53 kPa. If you put a 1 kg weight on top of a 4 cm cube of steak, similar to figure 2, how much would it compress?

**Lab.** *Hot and cold tea.* Many types of foods contain naturally derived polymers, such as agar and carrageen; such hydrocolloids have recently

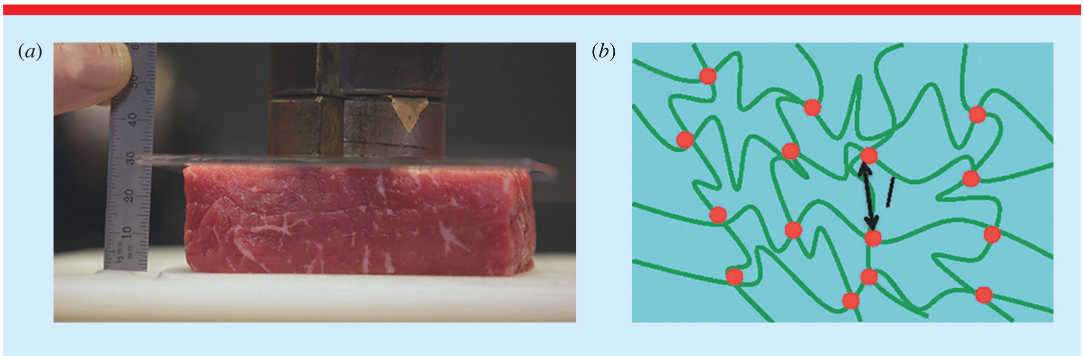


**Figure 2.** Elasticity of steak. (*a*) Measuring the elastic modulus, $E$, of a piece of steak by measuring the change in height when compressed by a weight on the top surface. (*b*) Simplified physical model for the microscopic structure of a steak. The steak can be viewed as a gel with a crosslink spacing $l$. During cooking, the spacing between crosslinks decreases and the elastic modulus of the steak increases.

emerged as popular ingredients among chefs who use them to create gels with different textures. One famous example is 'hot and cold tea' by chef Heston Blumenthal, in which a cup of tea is served with one side being hot and the other cold; each side is a weak gel, which keeps them separate. In the lab, students recreate a version of this recipe by experimenting with the elastic moduli of gels created by the polymer, gellan. This dish is made possible by the unique pH- and temperature-dependence of gellan molecules: when heated in an acidic solution they form a viscous liquid; this is the 'hot' half of the beverage. The other side of the beverage is less acidic, and thus a liquid with the same viscosity at a much lower temperature; this is the 'cold' half of the recipe. Students discuss how the elasticity and viscosity of each side of the drink relates to the microscopic structure of the polymers.

**Limitations.** While these simple equations can be used to understand the elastic and viscous responses of food materials, and how they vary for networks of crosslinked molecules, we emphasize that mechanical behavior as well as the microstructure of food materials is complex. For example, many food materials exhibit a response to deformation that depends on time. Understanding how liquids flow is presented in a subsequent lesson (table 1, #6). Moreover, the molecular-level structure of foods may change during cooking processes; for example, as a steak cooks, its water content decreases, proteins denature, and may coagulate. While the molecular mechanism underlying the increase in elastic modulus upon cooking a steak is complex, this simple model nonetheless provides a conceptual and quantitative framework for understanding elasticity.

### *3.2. Thermal energy transfer*

The transfer of thermal energy is essential in many forms of food preparation from baking to roasting to making ice cream. In the previous week, we introduced diffusion, which limits the rate of many culinary processes, such as cooking and brining. The distance $L$ travelled by thermal energy or molecules is proportional to the square root of time $t$: $L = \sqrt{4Dt}$. Here we show how thermal energy can flow by diffusion. The rate of thermal energy transfer depends on the temperature difference between the food $T_{\mathrm{in}}$ and its surroundings $T_{\mathrm{out}}$. The temperature within the food over time $T(t)$ is also related to a time constant $\tau_0$, which depends on its size $L$ and thermal diffusion constant $D$: $T(t) = (T_{\mathrm{in}} - T_{\mathrm{out}})\,\mathrm{e}^{-t/\tau_0} + T_{\mathrm{out}}$; $\tau_0 = \dfrac{L_0^2}{4D}$.

**In the classroom.** We present the concept of thermal energy transfer in the context of familiar concepts in cooking. For example, we ask how long it takes to roast a turkey, and then calculate the time required for the interior of the bird to reach a temperature of 75 °C (165 F), which is safe for eating. To illustrate the predictive power of this simple model and equation, we then compare our prediction with recipes. To facilitate a live demonstration of thermal energy transfer, we bring a toaster oven into the classroom and baked

**Table 2.** Sample exam problems: chocolate chip cookies.

| Topic | Question |
|---|---|
| Elasticity | In an effort to bake chocolate chip cookies of uniform thickness, you decide to use your coffee cup to press the dough. Suppose the cup weighs 100 g. You notice that if you shape the dough initially into a cube 3 cm × 3 cm × 3 cm and put the cup on it, the dough compresses to three quarters of its original height. What is the elastic modulus of the cookie dough? |
| Gels | From your calculation of elastic modulus in the previous problem, calculate the distance between crosslinks in the gluten network in the cookie dough, which is the primary determinant of the elastic modulus. Assume the other ingredients do not contribute to the elastic modulus. |
| Thermal energy transfer | You place the cookies on a pan and bake them in the oven at 179 °C (375 F) for 10 minutes. Approximate the dough as a sphere of radius 2 cm and assume that it does not change shape while baking. Also, assume that heat is supplied from all directions. What temperature does the centre of each cookie reach? |

a cheesecake with thermocouples inserted into its core, measuring the temperature increase in real time. Complementing the scientific introduction of diffusion, the visiting chef demonstrates a culinary technique called spherification: droplets of liquid containing the polymer, alginate, which can be crosslinked by ions, are dispersed into a calcium solution; the subsequent gelation of the alginate is limited by the diffusion of ions into the droplet.

**Homework problem.** *Cooking salmon*. How long should we cook a 5 cm (2″) thick salmon steak to reach its ideal temperature of 57 °C (135 F)? Assume the raw salmon has an initial temperature of −1 °C (30 F) and a preheated oven is set to 177 °C (350 F). Note: the diffusion constant of fish is about $10^{-3}$ cm$^2$ s$^{-1}$.

**Lab.** *Molten Chocolate Cake*. In this lab, students use thermocouples to measure the temperature at multiple points within a cake as it bakes. Over the course of about seven minutes, the exterior of the cake sets into a solid, leaving the molten interior (figure 1). By plotting the thickness $L$ of the solid layer over time, students measure the thermal diffusion constant, $D$, of the cake batter, which is nearly the same as water.

**Limitations.** Here we consider only the time-dependent temperature based on diffusion. We neglect other forms of heat flow, such as convection. Yet since diffusive transfer of thermal energy dominates the internal rise of temperature, we find this simple model makes accurate predictions about cooking times. At least one student was convinced in the predictive power of this equation, applying it to estimate the cooking time of her family's Thanksgiving turkey.

## 4. Assessment of student learning

To assess the extent to which students understand the scientific concepts and methods, we used three main approaches.

(a) **Written problem sets.** A weekly problem set, with about five to seven questions, asks qualitative questions about the current concept and quantitative questions about how to apply the Equation of the Week to culinary examples.

(b) **Lab worksheets.** To guide students in their observations and analysis of data, the lab exercises are accompanied by a brief lab worksheet.

(c) **Written exams.** A two-hour midterm exam and a three-hour final exam test the abilities of students to integrate scientific concepts from multiple weeks and to solve quantitative, multi-part problems. Table 2 provides a representative example of a series of questions that involve chocolate chip cookies, similar to what could appear on a final exam.

(d) **Final independent research projects.** The last four weeks of the course are devoted to students working on independent research projects.

## 5. Final projects

The final projects are one of the most challenging and rewarding aspects of the course for the students. Although we provide them with a list of possible topics, many of them choose instead to draw on inspiration from the visiting chefs as well as from their own experiences with food to develop their own topics, thus bringing personal creativity and passion to their research. We encourage students to continue refining their ideas in discussion with the chefs and the course staff at all stages of the research process, from brainstorming to data interpretation. We are thus able to create an environment where students are actively engaged to learn the scientific method, while also allowing them creative freedom. The main criteria of the projects is to address a scientific question related to cooking, then to generate and analyze at least one plot of data that captures the core findings. Specifically we provide three main criteria.

(a) Describe motivations for the project and the main scientific issue being addressed.
(b) Describe the experiments and measurements used to answer the scientific question.
(c) Describe the results, including at least one graph, such as the effect of varying the ratios of ingredients in a recipe.

In conducting their final projects, we require students to become scientists and practise their scientific skills. Students work either alone, or collaboratively in groups of two to three. They keep a lab notebook and submit weekly updates to their Teaching Fellow. They also have a small budget to order any supplies they need. At a final science fair, each group presents their research and submits a final written report. Students submit a summary of their work, similar to an extended abstract. In describing several weeks of research in a space-limited format, students are required to practice good skills in science communication, such as choosing which data to present and making their material relevant to their audience [17]. Some examples of final projects from the last three years of the course are given in the appendix (figures A.1 and A.2)

## 6. Conclusions

Our experience with these courses bridging physics with food and cooking demonstrates the potential impact of using examples from the culinary world to teach scientific concepts and methods. Our approach is similar to other conceptual physics courses, such as Hewitt's, which also present simple physical laws through practical examples with numerous simplifications, such as neglecting air resistance or other non-linear effects. In contrast to traditional approaches, such as beams to illustrate stretching and compression, our approach utilizes tangible examples, such as jelly (jello), that students have experience with in their everyday lives. Another advantage of teaching science and cooking is that it is relatively easy for students to ask questions about why cooking protocols behave as they do. For example, why does toast burn so suddenly? Why add baking powder to chocolate chip cookie dough? Although the examples and answers may be less straightforward than traditional conceptual physics courses, the students have the opportunity to let their own curiosity to guide them to learn about the true nature of science.

The final projects demonstrate the success of this inquiry-based approach in training students to be scientists within an undergraduate course: even non-science majors are able to successfully formulate scientific questions, develop new experimental methods, and analyze and interpret data within a theoretical framework. We also heard several examples of students applying scientific concepts in their daily lives, including how to minimize cooking time by calculating the optimal shape of pasta or the location to place a hot dog in a microwave.

Although we conducted the courses at major research institutions with well-known chefs, the same approach could be implemented elsewhere. The lab component could be adapted for any large kitchen, such as a school cafeteria, or as practical homework assignments for the students to complete in their own kitchens. Local chefs have a wealth of knowledge about cooking techniques and can serve as mentors for student research projects; we have discovered that chefs are enthusiastic to share their culinary experience with students, and to learn more about the science behind their cuisine. Moreover, utilizing local facilities and culinary talent can more deeply show the connection to the students' everyday lives.

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## Appendix A. Examples of student final projects

### *A.1. Spherification*

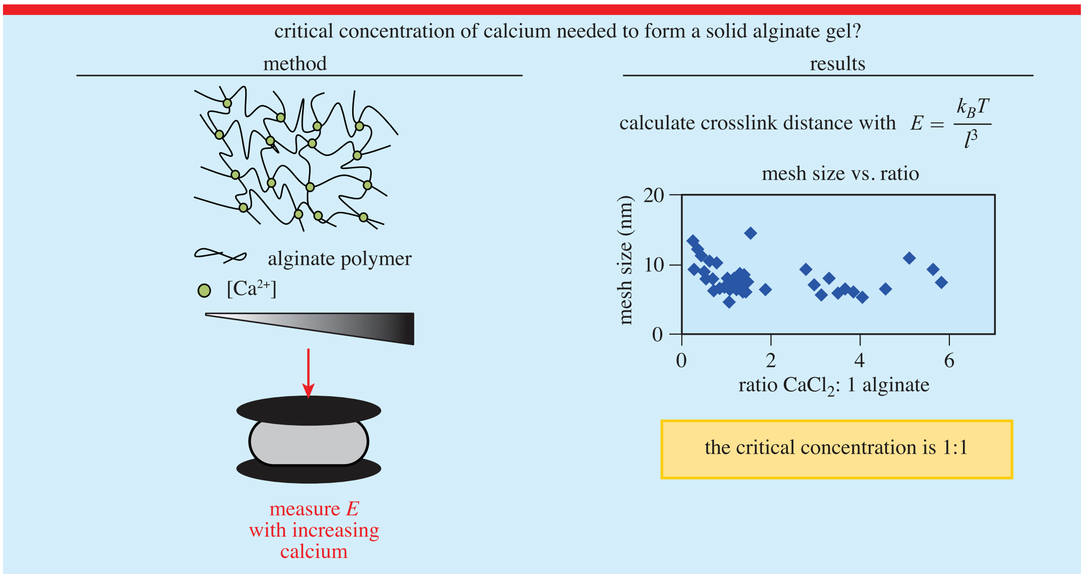


**Figure A1.** Spherification: inspired by the visiting chefs who demonstrated the culinary technique known as spherification, a team of students sought to find the critical concentration of calcium required for gelation of an alginate polymer solution. After testing over 60 samples, they discovered that above a molar concentration of one calcium ion per one alginate molecule, the elasticity of the polymer gel, and therefore the mesh spacing, reached a plateau; this concentration corresponds to the minimum amount of calcium specified in recipes.

### *A.2. Heat resistant chocolate*

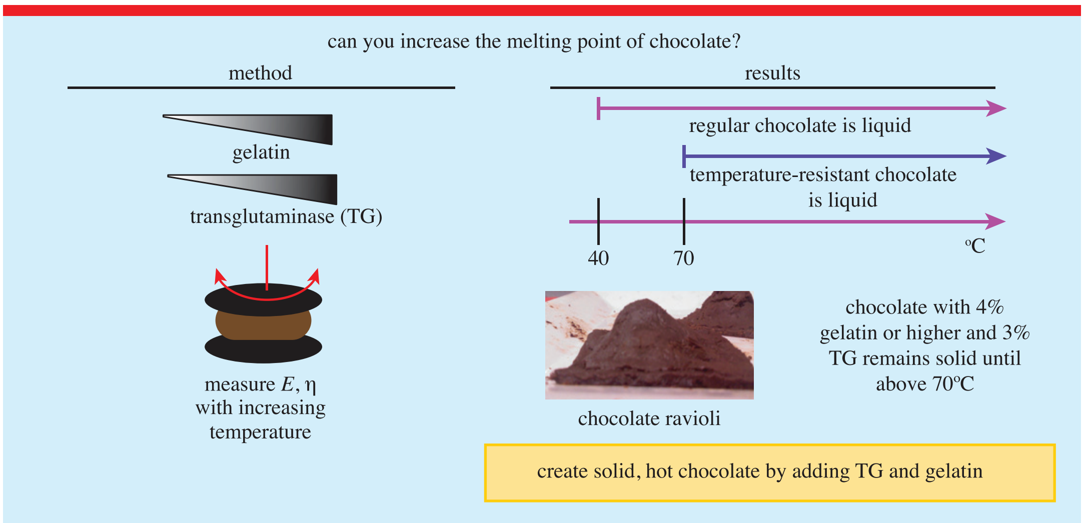


**Figure A2.** Temperature-resistant chocolate. Motivated by chef Wylie Dufresne's lecture, students used the enzyme transglutaminase to create a chocolate composite that retained its solid characteristics even above the normal melting point for dark chocolate. By exploring a range of enzyme and gelatin concentrations, and measuring the elastic and viscous properties of the final product, the team constructed a phase diagram of chocolate textures.

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