CHOCOLATE ACROSS THE CURRICULUM AND OUTREACH

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INTRODUCTION

In standard science, technology, engineering, and mathematics (STEM) curricula, students proceed through courses designed to build knowledge and develop skills in problem-solving and design. Lower-division courses introduce the foundational knowledge and strengthen the problem-solving skills required for success in the upper-division advanced courses. The curriculum culminates in capstone courses that tie the topics together.

A problem with the standard curriculum model is that students tend to compartmentalize their learning. They may not see the interconnection of content and problem-solving skills between separate courses until their final year capstone courses. There is also a tendency to contextualize learning that depends on a particular instructor, one style of nomenclature ("Is the symbol for velocity 'v' or 'u'?") or only in the context of the department offering the course ("I will never use physics …"), which hinders the transfer of learning between courses and topics. Students' inability to "see the big picture" harms their understanding and encourages forgetting the material from last year's classes. Compartmentalization discourages student retention when they focus too much on a course they do not like, even if they like the overall program of study.

Chocolate Across the Curriculum And Outreach (CACAO) addresses this problem by integrating a "big-picture" process that students already have some familiarity with – chocolate production. Content associated with making chocolate is incorporated into courses from each program year. Early courses (for first- and second-year students) provide big-picture concepts such as converting raw agricultural products, qualitative data analysis for different "best" chocolates, equipment descriptions, process flow diagrams, safety, and ethics. Later courses intensify knowledge and experience with each unit operation used in production. Students may voluntarily add a capstone project in which they create a unique chocolate based on their course experiences. Students at any level are encouraged to participate in undergraduate research. Class and research projects range from a few weeks to multiple years. Students use the chocolate process to help understand how each course fits within the curriculum. Figure 1 outlines our curriculum and provides a few example topics from the chocolate-making process.

Year 1 **Introduction**	Chocolate Making, Overall Process, Safety, Supply Chains, Ethics
Year 2 **Mass/Energy**	Process Flow Diagrams, Material and Energy Balances, Safety, Ethics, Qualitative Measures, Waste Management
Year 3 **Unit Operations**	Tempering, Particle Size and Distribution, Safety, Mixing, Standard Operating Procedures, Ethics
Year 4 **Capstone Courses**	Solid-Solid Separations, Maillard Reaction, Safety, Mixing, Economics, Ethics

Figure 1. *Curricular mapping of chocolate making by class year.*

Implementation involves

- enlisting all willing faculty to learn about the process and develop ideas for connecting it to one or more of their classes
- creating a space for students to make chocolate
- creating case studies with learning modules and problem sets appropriate for each course (done by each willing faculty member for their own courses)
- building opportunities for the more interested students to explore an aspect of the process not covered in their classes using undergraduate research/independent study/outreach development projects with a faculty mentor or others within the program (e.g., lab instructor, design instructor, project mentor, classmates, or peer mentorships)

It is very important to enlist the aid of willing faculty members when creating an across-the-curriculum project. Fortunately, this project involves all the current faculty members within our department. Some contribute more, but everyone has been willing to voluntarily incorporate some aspect of the lab within their courses. One reason for our implementation is ABET accreditation and its encouragement of continuous improvement. A second, and stronger reason, is that once faculty experience the lab and the student interest, they want to participate. We believe that the benefit in student enthusiasm and interest outweighs the modest cost in time to create additional or replacement content in our courses

The space for chocolate making requires room for safe storage of the chocolate-making equipment, the ingredients, and the made chocolate. We started in a 300 ft^2 lab and currently use 1,800 ft^2 space. The increase in space became necessary as interest in the lab increased from faculty, students, and campus visitors and tours. The department chose to modernize a teaching lab space to accommodate food safety and higher enrollments. Our space is large enough to fit classes up to 24 or to split larger classes into halves or thirds, though that reduces the time available to each student. A list of equipment is described in a later section. The dedicated space should be large enough for several people to work together or to host a group of visitors. The room must be food-safe, although the essential ingredients are all fine to store in normal indoor conditions or a standard refrigerator for months. Cocoa beans (after fermentation and drying) and cocoa butter are safe to store in airtight (dry) containers for years at room temperature. Chocolate can be stored for up to six months. If stored longer than this, the cocoa butter crystal structure may change, but chocolate can be remelted to return it to the desired crystal structure (tempering).

Any instructor can easily incorporate the case studies into a course with a time commitment ranging from a few hours to several days. Each faculty member typically creates their own learning modules and problem sets for their specific classes, with the possibility of sharing them with others. The modules should be self-contained and may provide a Teaching Assistant or substitute instructor with course material to cover a faculty member's absence. An example is provided later in the Curriculum Integration section – Material Science and Engineering course.

Many opportunities for deeper study and learning happen once students become familiar with the equipment and process. The chocolate lab provides an excellent resource to encourage students to take on research experiences. In our department, the research is student-motivated and is not required. The research can take on many forms, though each requires proper mentoring from a faculty advisor or faculty team. Our department offers students several pathways to participate in undergraduate research, both formal and informal. Formal research can be paid for through a faculty grant, students can apply for a grant through our campus Undergraduate Research Opportunity Program, they can take an independent research or independent study course, or they can fold it into a class project. Informal research happens as students volunteer in the lab as part of the Chocolate Club, where they generate ideas with each other and the faculty as to why the process worked or didn't work the way they wanted. The Club creates opportunities for teamwork-based research in which upper-division and lower-division students work together, a process we refer to as vertical integration within the curriculum. These additional student-student interactions better model real-world teaming and can encourage students to stay in the program as a means of community building. Research projects can range from simple and short-term (e.g., determining the collection efficiency for different winnowing pressure drops) to more complex and long-term (e.g., finding the best roasting profiles in beans from different origins). Our department allows students to choose their own project and faculty mentor, and the faculty member has final say over their involvement and the scope of the research. No one is forced to participate.

It is noted that most experiments require a sensory or taste evaluation. This requires approval through the University's Institutional Review Board (IRB) for testing with human subjects. Students who want to conduct taste testing experiments receive training and retraining every semester. Faculty oversee every event. All test subjects have their rights explained at every event, including their right to stop participating at any time with no reason or explanation required.

BACKGROUND

CACAO is a department-level initiative to increase student interest in chemical engineering. It provides students with curriculum experiences showing the interconnection between traditional classroom topics and everyday products.

Other schools have also used the transformation of agricultural materials into consumer products to enrich their curriculum (coffee [1-3] and chocolate [4,5]). It is also an outreach tool to explain ideas from chemical engineering in a friendly, exciting manner to general audiences such as visiting high school students and their parents.

In traditional engineering education, students acquire foundational learning of technical principles and design concepts in coursework that is often sequential and isolated from other subjects, related or non-related. The approach can lead to compartmentalized learning and difficulty transitioning knowledge from one course to another. CACAO describes one method to help students decompartmentalize their learning to create interconnected and significant learning experiences for chemical engineering students.

The pedagogical theory of this initiative uses Fink's taxonomy of significant learning,[6] though we realize many other pedagogical theories could also apply such as the spiral curriculum.[7,8] The overall concept is the same – a well-thought-out curriculum can improve learning. Fink's taxonomy contains six elements. The elements and a short description follow:

- **Foundational knowledge** is understanding basic concepts, ideas, and information (e.g., the core lower division courses).
- **Application** applies the foundational knowledge in actual practice. It helps students develop critical and practical thinking skills and fosters creativity.
- **Integration** connects the student's ideas, information, and the learning community with outside people, perspectives, and seemingly unrelated realms of life and learning.
- **The human dimension** helps students learn about themselves and others (e.g., teamwork, outreach, leadership).
- **Caring** about a subject and its learning community helps students develop new feelings, values, and interests.
- **Learning how to learn** helps students increase inquisitiveness and interest in a subject and grow skills in all areas to self-monitor and self-direct personal learning and continued growth.

The six elements are neither linear nor need to be processed in any order. They are interdependent — each learning element connects and interweaves into one or more other elements, leading to more profound and significant experiences for the learner.

The cornerstone of Fink's taxonomy is creating change in the learner. For change to occur, there must be a catalyst for the learner to begin the significant learning process and make connections to lifelong learning. In this project, the catalyst is the chocolate-making process, which provides many ways to engage, not just with chemical engineering but with its rich history: from the Aztecs to the European cocoa houses, the development of solid chocolate, modern-day slavery, and the challenges from climate change.

Chocolate making requires a student to use their knowledge of multiple engineering concepts. The knowledge may come from their classes (e.g., chemistry, physics, math), their lived experiences (e.g., cooking), or professional experiences (e.g., internship or co-op). The *foundational knowledge* provides the background to understanding how and why the various steps are needed. Specific detailed chocolate-making knowledge includes the sequence of the batch unit operations (e.g., as discussed in an introductory or mass balance course), the time and energy needed to perform each step (as discussed in a unit operations course), the requirements from a regulatory and product design perspective, the quantities of each recipe item needed to create the product (from chemistry courses or a mass balance discussion), the how-to information (standard operating procedures) for each unit, as well as how to complete each step safely (throughout their education). One of the first steps in teaching chocolate making is to create a set of standard operating procedures and to make sure they are consistently updated as more experience is gained.

Application of chocolate-making knowledge informs the steps needed, their order of operation, and the time and energy commitment for the entire process. Students may discover efficiencies in running some steps in larger batches than other steps require, finding ways to reduce clean-up time, or sharing work over several days (one batch can require five days to complete, but most of the time is waiting for individual steps to finish). Another application involves the heat transfer needed to roast the beans successfully — the goal is to obtain an interior temperature of 250 °F while limiting the exterior temperature to not more than 280 °F. Many paths and types of equipment can achieve this, but perhaps some are easier or less prone to errors. Application experience is also helpful in troubleshooting issues that can occur within each step.

Integration occurs after students have learned the individual unit operations and seek to find better ways to do their work – less time, better flavor, less waste, less mess, and improved safety. If several students are involved, they form a community of experts who teach and learn from each other. The community helps them see the interdependence of the steps within the process. They may discover that an over-roasted bean can still create good chocolate if you alter the recipe (perhaps add more sugar). The community helps each member to think with a creative, systems approach when developing solutions. Another integration opportunity arises when students become curious about the various beans' origins. They can learn about where and how cocoa beans are grown and processed. Perhaps they will want to learn about the individuals who supply cocoa and the community aspects within the larger chocolate-making world.

Chocolate making requires significant amounts of time to complete. It is much easier to share the work between people over multiple days. Shared work requires good communication between the student makers, verbally or in writing (both are better). Students share this information with other students during the making process, but can they create a systematic method for doing it? *The human dimension* occurs when the team members clearly describe how to share information. They realize that a single leader is unnecessary; they each need to lead at different times and in different ways.

Cocoa processing provides excellent lessons in the social aspects of engineering, and the role engineers play in *caring* for and supporting society. Students can learn about many issues related to the growing and harvesting of cocoa, such as geographic considerations, the impacts of other countries' governmental policies, and various social traditions embedded within the production of a global commodity. They may discover the intricacies of the global supply chains (e.g., Côte d'Ivoire is the world's largest exporter of cocoa beans at 45%, and Europe is the largest exporter of chocolate at 70%). Students may also want to find new sources of ingredients that meet additional criteria they set, such as using fair trade, direct trade, organic, or personal relationships with local producers. Another example is to find alternative materials so people usually excluded can enjoy chocolate (e.g., diabetic students may want to use sugar with low or zero glycemic index, and vegan students may want milk chocolate with milk made from soy, oat, or coconut).[9]

Chocolate making is a complex, multiple-step process that does not have a single optimum solution. There are several process paths that create very good chocolate, as well as many that lead to mediocre or worse products. Cocoa processing shows systems that depend on each other and how design decisions impact the production process. The goal of enhancing the curriculum with this process is to provide the knowledge, practice, and application of skills that can transfer between courses and throughout their lives. These experiences create a path toward the ideals of *learning how to learn*. It fosters questions, curiosity, critical thinking, and confidence. It can also connect students with the ideals of a liberal arts curriculum – the interconnection between engineering solutions and the world, including issues like safety, ethics, fair labor practices, gender roles, differences between cultures, food and plant sciences, global commodity production, entrepreneurialism, and consumer habits.

IMPLEMENTATION

The CACAO initiative creates multiple opportunities for students to interact with the process, with each other, the university community, and outside groups. This section presents how it has been implemented at our institution.

Implementation Opportunities

Classroom-Specific Knowledge. Faculty create learning modules (lectures, examples, homework data sets, short lab activities) ranging from 10 minutes to 2 hours that apply some aspect of chocolate making to their specific course. The modules use information and data from the lab or industrial-scale chocolate production. Every student in the department learns at least a bit about the process, even if they never get involved with any extracurricular activities. Actual classroom activities are discussed later in this paper. Note that each interested faculty member creates their own activity, often in collaboration with other faculty or a student researcher.

Student Club. Interested students created a "Chocolate Club". The club members work together to learn about, make, and taste chocolates. They often include non-department students in sensory analysis (e.g., taste testing) activities and have created considerable interest in our department across campus and throughout the university system. The club organizes a once-per-semester sale of approximately 25 kg to the university community (under the State of Minnesota Cottage Food Laws). [10]

Outreach. Faculty, staff, and student volunteers lead 5 to 100-minute lab tours to other groups, including campus students, prospective students and their families, campus visitors, local schools from pre-K to high school, community college classes, and University for Seniors. These presentations help introduce and explain chemical engineering to anyone. Most people already have a curiosity about chocolate. Natural curiosity opens the door for conversations and provides the opportunity to explain how the process ties into the education of ChE students.

We have used the production of chocolate to explain chemical engineering to many different groups both on- and off-campus. For example, we have had interest from campus admissions and recruitment offices. They now include the chocolate lab in tours to prospective students and their families. We have given tours to various groups ranging from the President of the University, professional societies, college leaders, student clubs, and other departments. A mobile version of the lab allows us to visit other schools and give demonstrations around the region.

Tours range from a brief discussion of the lab and its teaching goals (5 minutes), modest tours where the entire process is briefly discussed (15 minutes), moderate tours that discuss the collection of materials and equipment use (30 minutes), tours that include all the above and also provide the tour group opportunities to gain some hands-on experience in each step (50 minutes), and events that include all the above and provide time for the group to create their own chocolates with inclusions of their choice (100 minutes).

Undergraduate Research. Projects are designed to fit within an undergraduate student's schedule and can be completed within 10 to 100 hours. Student research projects generally explore one aspect of the chocolate-making process. Examples include outfitting sensors on current equipment, rebuilding/improving equipment, and designing sensory analysis (taste, smell, appearance) experiences to bring qualitative measures into the curriculum. Projects always include a faculty mentor or faculty team, with a strong emphasis on safety. Student research is open-ended in that the student chooses their own topic and mentor, but the research plan and results are reviewed and approved (or not) by the faculty for appropriateness.

Internationalization of the Curriculum. Internationalization emphasizes the relationship between and among nations, people, cultures, institutions, and systems.[11] Cocoa beans are grown in the tropics. Chocolate making usually occurs in the northern temperate zone. Connecting students and chocolate makers with agricultural partners in the tropics creates an opportunity for an international perspective. Commodity supply chains typically extend through multiple countries and regions. We have connected tropical farmers in Trinidad and Tobago with our students with a three-credit study abroad course.[12] Students get first-hand experience on a cocoa farm, and the local farmers include the students with service-learning projects. Students directly experience the differences between countries, transportation, food, culture, history, and the lived experiences of farm workers.

Ethics Discussion. Looking at the variety of practices used worldwide in bean and chocolate production shows considerable challenges to students' value systems (e.g., child labor, slavery, gender roles, racism, agricultural policies) with real-life experiences. Discussions can occur during any event, from the classroom, the lab, or outreach tours. Students learning to make chocolate are naturally curious about the different aspects of the production chain. It also connects required liberal arts course content to their engineering work. Each activity helps students visit, connect, and confirm multiple aspects of Fink's taxonomy. The years-long opportunities allow students from different grade levels — first-year to graduate students — to meet, learn, share, and create.

Chocolate Making

Many materials and processing steps are needed to convert raw agricultural materials into finished products. In our curriculum, we utilize a bench-scale chocolate-making process. Industrial-scale production is much more automated, but both methods use similar steps.[13] This section describes the most common materials and processing steps. Table 1 contains a list of ingredients for the three main types of chocolate (UMD-ChE standard dark, milk, and white). Table 2 describes the US Food and Drug Adminstration's (FDA) definitions of chocolate. If you are concerned about labeling, calling the product "candy" is acceptable. Candy has no legal definition, but its meaning is well understood.

TABLE 1
UMD-ChE Basic Chocolate Recipes*

Type	Nibs	Butter	Sugar	Powdered Milk
Dark	0.625	0.125	0.25	0
Milk	0.35	0.2	0.3	0.15
White	0	0.34	0.33	0.33

*Data given as weight fractions. "Nibs" are the roasted and crushed dry beans, and "Butter" is additional cocoa butter used to help lower water activity and viscosity during production

TABLE 2
US-FDA[18] Ingredient Requirements by Weight Fraction

FDA Name	Liquor	Solids*	Butter*	Sugar	Milk	Other**
Sweet	> 0.15	0.07	0.07	0.73	0.12	0.01
Semi-sweet	> 0.35	0.17	0.17	0.53	0.12	0.01
White	0	0	0.2	0.67	0.12	0.01
Milk	> 0.10	0.05	0.05	0.77	0.12	0.01
Dark	Not defined by FDA					

*Assumes nibs are equal weights of cocoa butter and solids

**Typical other ingredients include emulsifiers, alkalizers, seasonings, and neutralizers

Raw Materials. Creating chocolate requires a few agricultural products – cocoa beans, sugar, and milk (for white and milk chocolates, not dark chocolates). Other materials can be used to impact flavor or ability to process (e.g., vanilla and lecithin).

Cocoa beans grow on tropical trees (*Theobroma cacao*). Harvest can be year-round but occurs mainly before and after the rainy season. The trees grow pods from their trunk, a style known as cauliflory. The pods contain 40 – 100 beans (which are seeds). A fleshy, sweet fruit pulp surrounds the beans within the pod. Both beans and pulp (called wet beans) are removed from the pod. The pulp is removed during fermentation, typically performed near the point of harvest. Fermentation occurs in the open atmosphere. It begins when local fruit flies deposit yeast (and other organisms) onto the fruit pulp surrounding the beans. The yeast converts the sugars to ethanol (which can be collected as cocoa wine). Open-air fermentation allows bacteria to consume the yeast byproducts from the fruit sugar. The bacteria create heat and a series of organic acids that transform and kill the beans. After fermentation (five to eight days), the now dead beans are open-air dried to reduce moisture from 60 wt% to 5 wt%. The dried beans are sold, usually into international cocoa commodity markets, but other economic models are also possible e.g., co-op and direct trade. The dried beans are the starting point for the chocolate-making process we use in our curriculum. Incoming beans should be inspected for rot and pests.

<u>Cocoa butter</u> is the fat component of the cocoa bean. Dry beans are typically 50 wt% fat that can be extracted from the beans using heat and an oil press or purchased (much easier). It is used in all types of chocolate (see Table 1). Cocoa butter seed crystal (cocoa silk) is a particular form of butter that has been tempered to create a specific crystal structure (type V, see the discussion on tempering).

<u>Sugar</u> is obtained mainly from sugar beets or sugar cane. The beets or cane are processed to remove the sugary juice they contain, which is then processed (evaporation and purification) to recover sugar. Special sugars can be used for people on specific diets. We have used allulose, which has zero glycemic index, to make chocolate for people with diabetes.

<u>Milk</u> must be in a dry, powdered form before use. Many kinds of powdered milk exist, including dairy, oat (good for vegan forms of milk chocolate), goat, soy, coconut, and almond. Milk chocolate is the most common form sold worldwide, accounting for approximately 60% of global sales.[14]

<u>Water</u> must be removed and avoided throughout the chocolate-making process for two reasons: to prevent the growth of microorganisms and to prevent emulsification with the cocoa butter. Dry beans and nibs have very low levels of water, too small to support the growth of microorganisms. If enough water is added such that some water is available for microbial growth, the beans and nibs will quickly begin to degrade and be unusable. This phenomenon is described in the food science literature as "water activity." Water activity is defined as the ratio of the water vapor pressure of the food compared to the vapor pressure of pure distilled water. Values above 0.95 suggest the food will support microorganism growth. Values below 0.85 will inhibit their growth, and such foods are not subject to many FDA regulations for food storage.[15-16] Dry beans and nibs have on average a water activity of around 0.7, while chocolate has a value of approximately 0.3. The second concern with water is that it can emulsify with the fat in the cocoa butter portion of the chocolate. The emulsion increases the mixture viscosity, which can increase energy needs during the refining and conching (mélanger) step and cause difficulty during pouring and molding. Many makers add an emulsifier during the mélanger step to reduce the viscosity of the liquid chocolate. The emulsifier will keep the water activity low and will protect equipment from the damage a water-fat emulsion can create (e.g., motor overload due to the increased viscosity). The most typical emulsifier is soy lecithin, added at 0.1 - 1 wt%. [13] The UMD chocolate lab only uses an emulsifier when humidity may be a concern (e.g., during the summer months).

Bean-to-Bar Process. Chocolate making starts with fermented and dried beans, refined sugar, and dry milk solids or powdered milk; see additional resources.[17] Flavors or additives can be added during refining, after refining, or after tempering. Figure 2 shows a process flow diagram for our bean-to-bar process.

A brief description of each step follows:

<u>Roasting</u> – The dry beans are heated for approximately 15 minutes in a well-mixed manner such that the temperature of the bean exterior reaches 250 – 280 °F. We use a rotary drum roaster in a toaster oven. A lower roast temperature may enhance the fruity/floral flavors of some beans. Warmer roasts may enhance the earthy/nutty flavors of some beans. We use an infrared thermometer to obtain the bean temperature in the roaster. Another control method uses the emitted aroma to know when a roast is done. The aroma starts with a wet, grassy smell, turns drier and more acidic, then ranges into various chocolatey smells (it is done when you get the baking brownies aroma), and then moves into nutty smells before an overdone burning odor.

<u>Bean Breaking or Grinding</u> – The shells are removed from the bean meat (nibs), reducing the size of the roasted beans to an effective diameter of approximately 1/8-inch, irregular shapes. The product will be a mixture of 75 wt% nibs (the roasted meat of the bean) and 25 wt% crushed shells. Many small-scale artisanal chocolate makers use the Champion Juicer® (a hammer mill).

<u>Winnowing</u> – The mixture of nibs and shells is separated using a cross or counterflow air stream. Shells are less dense and have a larger surface area/mass ratio than nibs. Shells are easier to fluidize, making winnowing a good separation choice. The shells are removed because they can give the final product a course, grainy texture and generate an off-flavor. Note that complete separation is unnecessary. The US FDA allows up to 1.75 wt% shells in US chocolate.[18]

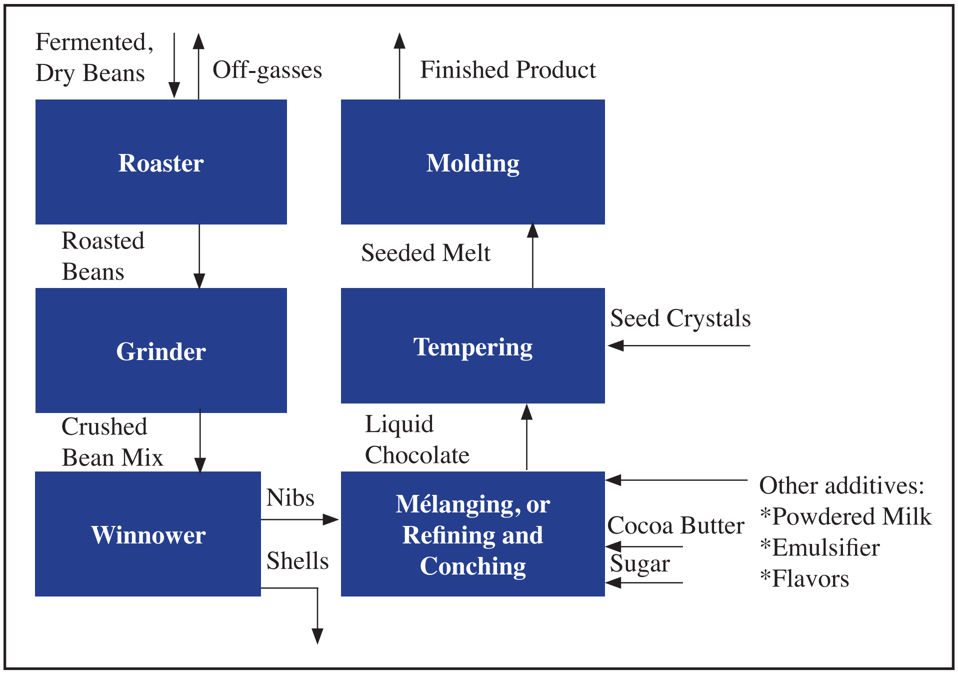

Figure 2. *The bench-scale chocolate-making process.*

Liquor (optional) – The winnowed nibs transform into cocoa liquor by additional particle size reduction. The fine grinding creates heat that melts the fat (cocoa butter) within the beans. This step can be messy and reduces the final yield of chocolate. The UMD chocolate lab does not use this step; the particle size reduction occurs in the refining step.

Refining and Conching – These steps combine the materials needed to make the chocolate – nibs, additional cocoa butter, sugar, dry powdered milk (if desired), and additional flavorings such as vanilla (raw, dry powder, or oil-based extracts only, not alcohol-water based). Refining reduces the particle size of nibs. Conching coats the small particulates with cocoa butter. The equipment, called a mélanger, combines both steps in a single process. It is a set of stone rollers riding over a stone plate (edge runner). As the stones run over the materials, they break into smaller particles. The desired average particle size of chocolate is on the order of 25 microns (ranging from submicron to 50 microns). People can detect particles of approximately 50 microns or larger with their mouths. Thus, this size range is detected as smooth and creates one of the critical properties of chocolate called "mouth feel." Particle size and distribution can be quickly and easily measured using a grindometer (see equipment section) or by tasting.

Tempering – Cocoa butter has six crystal structures.[19] The type V structure is associated with the most desired properties of good chocolate – consistent color, shiny appearance, smooth mouthfeel, strength (snaps when you break it), and resistance to melting in your hand. Type V crystals form below 92 °F (37 °C), Type IV crystals form below 88 °F, and the other crystals form at lower temperatures. Type VI crystals form over time (about six months if starting from type V crystals) and cannot be created directly from liquid chocolate. Liquid chocolate, left to cool on its own, usually forms a mixture of many crystal types. Heat treatments can make chocolate with the desired type V crystals. Two standard bench-scale methods for heat treatment are

- temperature-controlled cooling of the chocolate to below 85 °F, then reheating it to between 88 and 92 °F (so all except the type V crystals melt)
- seeding chocolate at 93 – 98 °F (our lab-based observation in up to five-pound batches) with 10 grams of preformed type V crystals (also called cocoa silk) or with a properly tempered chocolate

Application and Molding – Tempered liquid chocolate is then ready for dipping, spraying, or molding using any food-safe candy or chocolate mold. Molds are readily available from candy suppliers and can often be found second-hand. Molds must be cleaned after every use and retired once scratched, broken, or have permanent stains. The chocolate is demolded as soon as it has finished solidifying, typically taking one hour at room temperature (70 °F). Refrigeration reduces the time to about fifteen minutes.

Aging – Experience recommends that chocolate age one to two days after it is removed from the mold for the flavor to become consistent. There is no harm if it is eaten as soon as it is removed from the mold. It may be a good qualitative experiment to investigate this claim. Chocolate has a shelf life of approximately six months, depending on the storage environment.[20] After six months, the crystal structure of the cocoa butter may convert into a type VI crystal, increasing compressive strength, melting temperature, and alteration of color and texture.

Waste – The primary wastes include the shells and cleaning water. Possible fates for the shells include standard solid waste disposal, compost, mulch, or as the base for brewing cocoa tea (one spoonful per cup, steep in hot water for five minutes, sweeten to taste). Clean all equipment and lab areas with fresh hot, soapy water except the mélanger stones, which use fresh hot water only. Disposal of wastewater uses the standard sink drain with screening for large particulates. Chocolate and cocoa butter do not generally suffer from microbial degradation or contamination due to their low water activity. Hot soapy water has proven to be an adequate cleaning process in our lab. Note that one of the major pathways for chocolate contamination is from using contaminated water during the cleaning steps.

Safety – Chocolate making requires formal departmental lab safety training. Additionally, the lab uses the Minnesota Department of Health Food Code [21] for food-specific student training and workspace care. The lab adheres to University of Minnesota (IRB) guidelines when performing taste testing using human subjects. The most likely, though uncommon, source of microbial contamination originates on the surface of dry, fermented cocoa beans. The bean handler must take appropriate safety steps to reduce the possibility of exposure. The steps include wearing gloves when handling the dry beans and washing their hands/arms after completing their tasks. While the beans could be tested for microorganisms, it is easier to simply assume they are contaminated and to take proper precautions. Lab workers and visitors should be informed that the dry, pre-roasted beans should not be directly eaten. Roasting kills any surface organisms.

Equipment. A brief overview of our equipment choices is provided. If you want more details on what equipment to choose for your setup, explore the discussion supplied at the "Chocolate Alchemy" website.[29]

Roaster – We repurposed a toaster oven with a rotary drum roaster made for roasting coffee beans. Coffee roasts at a much higher temperature, so we overload the drum to keep the temperature lower. The batch size is three pounds. Cleaning requires one to two minutes.

Bean Breaker or Grinder – A hammer mill reduces the particle size of the roasted beans. We use the Champion Juicer, as do most small-scale chocolate makers in our area. This step is essential for removing the shells from the bean meat (nibs). In approximately ten minutes, it can reduce three pounds of roasted beans to nibs (1/8 – 1/4-inch pieces) and shells. Cleaning requires five to ten minutes.

Winnower with Vacuum – We set up a counter-current air flow (up) and the nib/shell mix (down) from the grinder. The up-flowing air carries the shells (unwanted) away from the nibs (desired). Removing most of the shells is essential, but complete separation is unnecessary. This step is combined with bean breaking by feeding the output from the grinder to the input of the winnower. The airflow is created using a HEPA-filtered shop vacuum. Cleaning requires five to ten minutes.

Mélanger – An edge runner device with stone wheels running over a stone base is used for refining (particle size reduction) and conching. Refining reduces the particle size of the cocoa solids (nibs). Conching is the shear-induced mixing for contacting the cocoa solids, butter, and sugar to create a uniform composite mixture. A typical batch ranges from one to five pounds. This device requires 48 to 72 hours to create a smooth chocolate. Charging the materials takes ten to fifty minutes (temperature dependent). Cleaning requires fifteen minutes and uses hot water and gentle scrubbing. The water should be drained to the sewer and not reused.

Applications and Molds – The liquid chocolate can be used to enrobe many other substances (e.g., strawberries, marshmallows, and pretzels). It can also be poured into custom molds to create individual candies ranging from 1 to 100 grams. Tempered liquid chocolate is poured into the mold cavities and then allowed to solidify. Some locations may need to place the molded chocolate into a cooled area to solidify. Other places are sufficiently cool (low 70s°F), so additional cooling is unnecessary. Tempering troubles may occur if the molding area is warm (above 78°F) or has high humidity.

Measurements – A *grindometer* is a simple hand tool (Figure 3) used to measure particle size and distribution of a solid-liquid suspension, such as chocolate, inks, or paints. It is made of hardened steel and has a channel of varying depth machined into it. The grindometer includes a graduated set of depth marks on the block near the channel. The depth decreases linearly, starting at 100 microns, until it is smooth with the block surface. An aliquot of the suspension is dropped into the channel's deepest portion and then scraped using a flat blade towards the shallow end. The suspension fills the groove when the particle sizes are smaller than the depth and are scraped clear at shallower depths. The average size and distribution can be observed from where the fill becomes partial. At 50% full (shown with arrows in the figure), you find the average size. The 90% and 10% settings (shown with bars in the figure) provide a good estimate of the distribution. Note that streaks are caused by single particles larger than the groove depth.

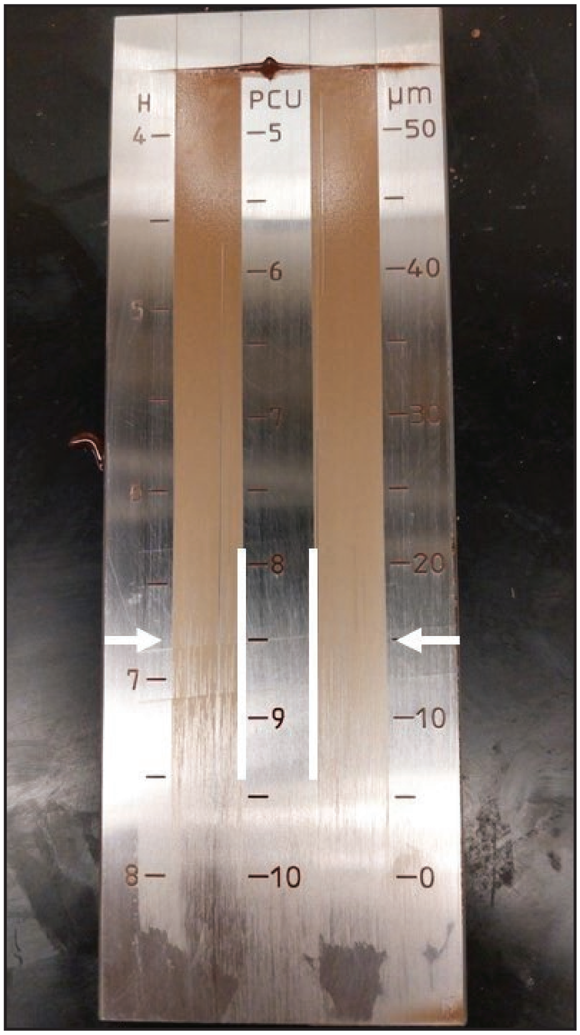

Figure 3. *Photo of a grindometer.* [22]

Irregularities appear when the depth of the groove matches the largest particles within the suspension. The advantages of this method are that it uses a small sample and gives a rapid indication of the high end of the particle size distribution, allowing direct observation of the production process. A disadvantage is that it is not easily adapted to continuous measurements.

Other tools may be used, especially if automated measurement is desired. An *infrared thermometer* is a simple hand tool for measuring the average temperature of the surface of a material. The tool is non-invasive, reducing opportunities for accidental contamination.

Cleaning and Safety – Cleaning is done with warm water (mélanger stones) and warm soapy water (everything else). Students require standard food safety personal protective equipment – training, gloves, hair nets, and safety glasses.

CURRICULUM INTEGRATION

Creating chocolate involves processes typically discussed throughout a chemical engineering curriculum (Table 3). Classroom integration is dependent on each faculty member. Not every class includes modules every semester. Not every faculty member uses the lab in every course or every semester. The following is a list of activities by course:

Introduction to Chemical Engineering is a first-year course. It is often the first opportunity to show students what chemical engineering is and what it is not. A one-day case study can show students an overview of the bean-to-bar process. We let students participate in the molding process using premade tempered chocolate and molds. The case study also includes a discussion on the ethics behind fair trade, direct trade, and labor markets in bean-source countries and a discussion of FDA definitions of the various types of chocolate (see Table 2).

Material and Energy Balances is a sophomore-level course. It focuses on problem-solving and methodologies in chemical engineering. A case study describes the process flow diagram focused on the mass balance aspects – determining the agricultural feedstocks' total raw materials, products, and waste materials.

Factorial Design of Experiments focuses on statistical methods to design experiments and analyze data from them. A case study on creating the 'best' chocolate introduces the concept of combining quantitative and qualitative information, exploring outcomes when there are many variables, and using both qualitative and quantitative data in decision-making. The qualitative measurement of chocolate is often called sensory analysis; see additional resources.[23] It is interesting to note that the local environment of the sensory analysis can impact results.[24]

Heat, Mass, and Momentum Transfer courses focus on using conservation equations to model systems. One case study explores modeling heat transfer within a single cocoa bean during roasting. Students are asked to make appropriate assumptions (sphere or cylinder?) and justify their choices. Another project involves designing an experiment to measure the temperature profile in a heated bean. The momentum transfer (also called fluid mechanics) case study explores the non-Newtonian fluid behavior of chocolate[4] or the impact of particle size distribution.[25] Rheological measurements of the chocolate melt explore the various factors, such as temperature, composition, and particle size and distribution, impacting the melted chocolate's viscosity. Viscosity is essential for determining the pourability, moldability, and time before solidification. A mass transfer case study looks at the effect of timing on flavor by varying additions during the mélange or before molding.

TABLE 3
Curricular Mapping of the Unit Operations in Chocolate Making by Process Steps

Chocolate Making Unit Operations*	Curriculum Topics
Roast	Thermodynamics, Heat Transfer, Process Control
Grind	Mass Balances, Particle Technology
Winnow	Separations, Fluid Mechanics, Particle Technology
Refine	Fluid Mechanics (rheology), Separations, Particle Technology, Design
Conch	Fluid Mechanics (mixing), Design, Mass Transfer
Temper	Material Science, Heat Transfer
Applications	Design, Mass Balance, Introduction (Creativity), Design of Experiments

* Each unit operation should also include appropriate safety information and process control considerations.

Material Science and Engineering discusses the properties and uses of common metal, ceramic, and polymer substances. The chocolate module focuses on the heat treatment or tempering of chocolate, which is like tempering steel but can be done by students at their desks. Tempering is essential to give chocolate desirable final properties – color, sheen, brittleness, and smooth texture. Cocoa butter has six crystal structures, with type V crystals being the desired form. Student teams use different tempering techniques, and then all groups' results are compared using a variety of observations.

> Example Classroom Module – We do a 30-minute lab within the material science and engineering course focusing on tempering outcomes for various tempering methods. Methods include no treatment, adding type V seed crystals at various concentrations and temperatures, following a scripted heat-cool-reheat format, or holding liquid chocolate at a certain temperature for a set time. Student teams chose a few methods to try. Students revisit the lab the next day to observe and assess each method's chocolate for surface appearance, flexural strength, taste, and mouthfeel. The homework assignment allows students to share their observations between groups to analyze the results statistically.

The Unit Operations Laboratory allows students to learn about various unit operations. The chocolate lab uses several unit operations that students can explore. Experiments include creating a standard operating procedure, equipment optimization, developing new/improved methods, expanding/refining measurement techniques, and developing qualitative measurements such as taste testing.

Separation Engineering explores the various methods used to separate mixtures of substances. The case study explores the separation of cocoa nibs from shells using density and shape differences of the particulates – winnowing by cross-current or counter-current air-solid streams and measuring separation efficiencies as a function of air flow rate, pressure gradient, and ground bean (nibs and shells) flow rate.

Reaction Engineering focuses on the preliminary design of chemical reactors as a unit operation. A case study introduces the Maillard reaction (non-enzymatic browning), which describes the reactions occurring during baking and cooking.[26] The roasting of dried cocoa beans removes bitterness and develops the chocolate flavor. The bean gets mellower when some acids, such as lactic, acetic, and ethanoic acid, evaporate.[27]

Capstone Design (senior level) is an open-ended course where student teams create, design, improve, or repurpose a process. Part of the coursework may involve exploring how to produce new materials, exploit alternate methods, develop new products, or use new or revised systems to generate a product. Students typically perform a preliminary estimate of the market and economics of the process, propose their ideas, and determine the usefulness of the changes. Chocolate making could be an initial study or a semester-long project, depending on how the course is taught. Student teams may explore bean-to-bar or farm-to-bar product creation, development, waste utilization,[28] and marketing of niche chocolate products. Our department allows students to choose their own projects, and the instructor mentors each group. The chocolate process is one possibility, but not all students choose to work on this topic.

Study Abroad, Chocolate in Trinidad is a three-credit freshman-level alternative for the introduction to chemical engineering course. The international course takes place over winter break in Trinidad and Tobago, a Caribbean nation. The course explores the front side of the chocolate supply chain. We work with a cocoa farmer [12] to learn what occurs before the dry beans reach the market, an essential aspect for any industry that relies on commodity materials. Students engage with the farmer to learn about the agricultural side of cocoa beans – planting, pruning, harvesting, fermenting, and drying the beans. We also engage in service-learning projects with the local farmers and their community – building or fixing farm-based infrastructure. Students in the course experience all the steps in making chocolate from farm to bar. They also learn cultural aspects of cocoa bean production, such as history, technology, and anthropology.

In addition to class-based modules, our department uses the chocolate lab to include more educational concepts in an across-the-curriculum format: process safety, food safety, supply chain logistics, legal definitions, and regulation of chocolate in the US and other countries (an excellent topic for internationalizing a subject).

ASSESSMENT

COCOA has become an exciting, practical, and much-discussed part of our department's student experience. While it is difficult to quantify or assess the impact of enthusiasm on student learning, several observations address our pedagogical questions. Assessment of the initiative considers student demographics, statistical analysis of GPA, course and program outcomes, and anecdotal evidence on student impacts.

Are students performing better? Comparisons (three years of data) between students that are heavily involved (volunteer 2+ hours/wk), modestly involved (1-6 hours/month), and uninvolved (class work only) showed no differences in individual course grades, semester grades, or overall GPA. These observations indicate that voluntary participation in the lab does not harm student performance.

Has it succeeded at decompartmentalizing the curriculum? There are no data to suggest a change other than increased student awareness – likely due to discussions among faculty, staff, and students.

Is there an impact on student diversity? An important goal of the department is to attract and retain a diverse student population. The most heavily involved students (around 15 per semester out of 150) are more diverse than the department average. This group is 50% women versus 30% overall in the department. Also, the involved students who identify as minorities make up 33% of the involved students versus 15% overall within the department. Is this meaningful? This observation could be due to many aspects of the lab, such as the learning community, the relationships between the faculty and staff that oversee the lab, and the involved students. Alternatively, it could be an artifact of the students who first got involved and attracted others like themselves. More time (longer-term data) is needed to understand the trends better.

A spring semester (2023) survey was sent to all 150 registered ChE students with 21 responses. The survey topics and replies show:

- **First encounter**. About three-quarters of the students report learning about the lab before admission to campus or during first-year orientation. The remainder first learned about the lab due to a class project or during a lab outreach event.
- **Visit frequency.** Ninety percent of students report visiting the lab at least once per semester, and almost half visit it weekly during a semester (but not every semester).
- **Visit purpose.** The most common responses suggest students visit the lab to experience chocolate (tasting, purchasing, making), learn about the process for class projects, and learn about the study abroad course (Chocolate in Trinidad).
- **Educational aspects.** More than half of students said the lab provided them with hands-on engineering experience, teamwork opportunities, and an understanding of the unit operations within the ChE curriculum. Other popular responses include improved time management, practical problem-solving, a global perspective of engineering, experimental design protocols, and an appreciation for curriculum design.
- **Overall utility.** Ninety percent expressed a positive experience with the lab.

Anecdotal evidence. Due to student demand, the lab remained open and functional during the COVID shutdown. Several students expressed that the lab is why they chose to attend our campus.

CONCLUSION

Our experience with the lab suggests it increases student interest and retention in ChE as a major, creates new pathways for student learning, and encourages community relationships between grade-levels, departments, and regional educators (pre-K to high school). The lab provides an easy way to explain chemical engineering to many audiences. Prospective students and their parents/guardians consider it the high point of their campus tour. Administrators, including the past University President, have visited the lab and been highly encouraging about its creation and expansion. The UMD-ChE program's Industrial Advisory Board wholeheartedly expresses approval for the lab and its pedagogical goals (and wishes it had existed when they were students).

Additional resources are included for more information on making artisanal scale chocolate and sourcing fair and ethical beans.[5, 17, 23, 29 – 36]

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