INVITED INSTRUCTIONAL TOOL BRIEF

Chemistry by Design: A 4-Week In-Person and Virtual Activity to Teach Chemistry Through Human-Centered Design

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Abstract

Teaching chemistry through design has been advocated by chemistry education researchers as a pedagogy that can engage students in chemical thinking. This paper presents a 4-week activity to teach chemistry through Human-Centered Design (HCD) for high school students. The paper describes an in-person and online version of the activity including the collaborative learning tasks that a teacher implemented to engage students in human-centered design processes and chemical thinking. In this activity, students will work in groups on a design challenge that engages them in learning about and acquiring relevant chemistry knowledge so they can chemically think and make informed decisions about ideas that can transform into solutions to meet what they identify as people's needs.

Keywords: Human-Centered Design, chemical thinking, collaborative learning

Introduction

Teaching science through design has been widely used by science teachers to create opportunities for all students to learn and implement the common practices of design and science (Puntambekar & Kolodner 2005). Examples of these practices include planning, questioning, observing, experimenting, and testing, employing scientific reasoning, communicating findings, and making evidence-based arguments (Kolodner et al. 2003). Many of these practices align with the science and engineering practices that are listed by the NGSS such as constructing explanations and designing solutions. As students engage in these practices, they experience the applicability of scientific concepts in realistic ways that are relevant to their everyday activities and societies they live in. This can positively impact students' development of 21st century skills such as collaboration and communication, students' interest and awareness in STEM careers, and students' knowledge of the science discipline (Apedoe et al. 2008).

The purpose of this paper is to describe a 4-week activity that was set up to teach chemistry through Human-Centered Design (HCD) for high school students. The paper describes two versions of this activity: an in-person version of the activity that was designed and implemented in 3 actual high school chemistry classrooms in Fall 2019; and an online version of the activity that was designed and implemented in Fall 2020 in 3 virtual high school chemistry classrooms.

What is Human-Centered Design?

Human-Centered Design (HCD) is a problem-solving approach that uses design thinking tools to identify the unmet needs of a population in order to collaboratively and iteratively develop meaningful and innovative solutions (Brown 2008). When students implement HCD, first, they spend time understanding the design challenge through unveiling relevant people's needs and synthesizing design opportunities. Then, students brainstorm ideas and prototype concepts to offer a solution that can address these needs. Finally, students consider ways and strategies that can be used to sustain and evolve the final design in the market. Figure 1 and Figure 2 shows the HCD spaces and processes respectively (Lawrence et al., 2021). It is noteworthy to mention that the HCD approach is non-linear. Each of the listed processes in Figure 2 can be implemented at any time during the problem-solving journey.

This 4-week activity engaged students in learning about and applying the understand, synthesize, and ideate space processes in the context of a collaborative design challenge. Moreover, the design challenge required students to learn about and acquire relevant chemistry knowledge so they can "chemically think" (Sevian & Talanquer 2014) and make informed decisions about ideas that can transform into solutions to meet what they identify as people's needs. During the activity, students worked in the same small groups. The in-person version of the activity took place in a newly designed laboratory setting (see Figure 3) that fostered collaboration within and across the groups. Also, it facilitated access to chemical information, both in the form of the knowledge base of the science as well as results produced by the students through their own experiments. The virtual version of the activity included running synchronous and asynchronous sessions with the groups and the use of a MIRO board as a virtual space that guided the groups as they implemented HCD and documented the outcomes of its processes. A link to a blank template of the board can be found here: https://miro.com/app/board/o9J_lMjEF-4=/

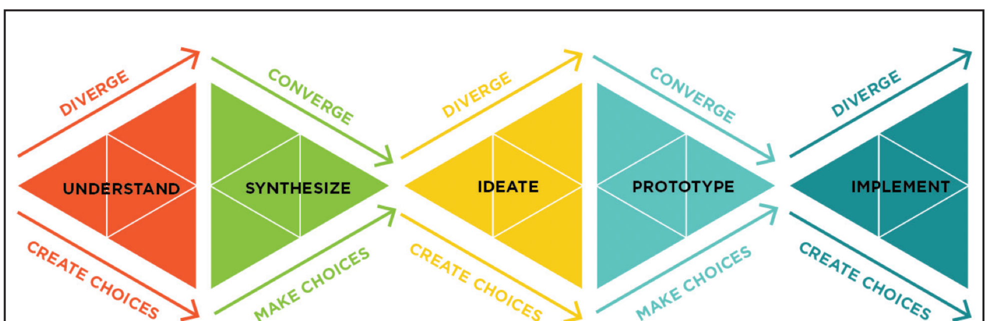

Figure 1. The Human-Centered Design Spaces

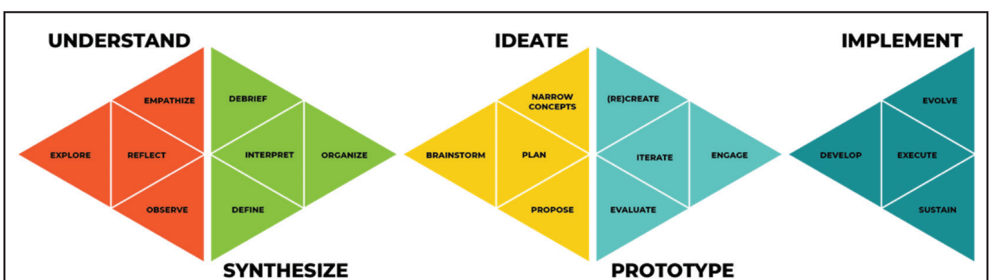

Figure 2. The Human-Centered Design Processes

Figure 3. The newly designed laboratory setting

Connection to the Next Generation Science Standards

This activity is set up to target the following Next Generation Science Standards: HS-PS1-3 Matter and its Interactions, students will plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles; HS-PS2 - 6 Motion and Stability: Forces and Interactions, students will communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials; HS-ETS1-2 Engineering Design, students design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.

Implementing the Activity

In the in-person version of the activity, high school students worked in small groups of four or five students on the following design challenge:

Design a snack that can be consumed by a high school student after an hour of physical activity. For the purpose of this challenge, let us focus on the name and ingredients of the snack.

In the online version of the activity, and to facilitate students' access to people that they can interview, high school students worked in small groups of four or five students on the following design challenge:

Design a nutritional gel that can be consumed by an individual after an hour of early morning workout. For the purpose of this challenge, let us focus on the name and ingredients of the gel.

In the in-person version of the activity, the teacher met with the students every day for 45 minutes over a period of four weeks. During the first two weeks, the teacher introduced students to HCD and engaged them in collaborative learning tasks to understand the design challenge and synthesize design opportunities. During the third week, the teacher engaged students in collaborative learning tasks to acquire the relevant chemistry knowledge. During the last week, the teacher engaged students in collaborative learning tasks to brainstorm and propose ideas and use the chemistry knowledge in making informed decisions about the names and ingredients of a snack that can meet what they identified as a high school student's need after an hour of physical activity.

In the online version of the activity, the teacher met synchronously with the students twice a week for 60 minutes over a period of five weeks. During the first period, the teacher introduced the students to HCD and shared with each group a MIRO board that acted as a virtual joint problem space for the group. The board consisted of templates to assist the groups in collaboratively implementing HCD and documenting the outcomes of its processes. Also, the board had features that assisted the teacher in monitoring students' work and providing feedback and support. Next, during the synchronous sessions of the first two weeks, the teacher introduced the students to the processes of the understand and synthesize spaces and then sent the groups to the breakout rooms to plan their asynchronous work on the challenge and complete the corresponding templates on the MIRO board. During the third and fourth week, the teacher used the synchronous sessions to engage students in the chemistry activities to acquire the relevant chemistry knowledge. During the last week, the teacher used the synchronous sessions to facilitate students' engagement in brainstorming and proposing ideas and using the chemistry knowledge in making informed decisions about the names and ingredients of the gel that can meet what they identified as an individual's need after an hour of early morning exercise.

During the in-person and the online versions of the activity, the teacher followed the collaborative learning sequence (Shehab et al., 2020) to effectively engage students in collaborative problem solving as they learned about and applied HCD to complete the design challenge. The teacher began each period or synchronous session by clearly stating the task-related objectives and intentionally encouraging students to collaborate. During the period or the synchronous session when students were working in their groups, the teacher visited the groups and implemented dialogic practices to facilitate students' collaboration. For example, the teacher avoided providing the groups with a direct answer to their questions; instead, the teacher invited other group members to provide their answers to the question then challenged their answers by asking "can you explain why you think that?". Also, the teacher continuously instructed the group members of silent groups to communicate with each other to complete the challenge collaboratively.

In both the in-person and the online versions, the activity was centered on a set of collaborative learning tasks that engaged the students in understanding the design challenge, synthesizing design opportunities, acquiring the chemistry knowledge, and brainstorming and proposing ideas and using the chemistry knowledge in making informed decisions about the names and ingredients of the product. These collaborative learning tasks are described below.

Understanding the design challenge

In order to understand the design challenge, the teacher prompted the groups to *explore* the challenge by *establishing a common problem space, reviewing the current landscape or context,* and *documenting assumptions, biases and predictions*. To do so, students discussed their strengths and weaknesses, checked their understanding of the design challenge, researched existing information relevant to the challenge, and explicitly documented their biases and assumptions. In the in-person version of the activity, the teacher required each group to create a Google doc to document their findings as they explored the challenge. In the online version of the activity, the teacher asked the groups to complete the Explore template on their assigned MIRO board. Figure 4 shows the Explore template of the MIRO board:

Next, the teacher prompted the groups to connect with the possible users of the product by conducting observations in relevant locations such as gyms, and by interviewing possible users to learn from them about their needs. The teacher shared with the groups some interview tips (IDEO, 2015) (see Figure 5) that can assist them as they conduct their interviews. During class, and to practice interviewing, the teacher asked the group members to write some interview questions and use them to interview each other. Example questions were "How often do you exercise?", "What kind of food do you consume before and after workouts?", "Think about the last time you worked out, how did you feel after the workout?". The teacher asked each group to conduct 3-5 interviews before the next class.

As groups worked on these tasks, the teacher continuously encouraged the groups to reflect on their performance and identify how new and changing information can inform the overall context and goals of their challenge. For example, after conducting their first few interviews, the teacher began a class session by asking the groups to think about how their documented initial assumptions, biases, and predictions are changing in light of what they are learning from the interviewees.

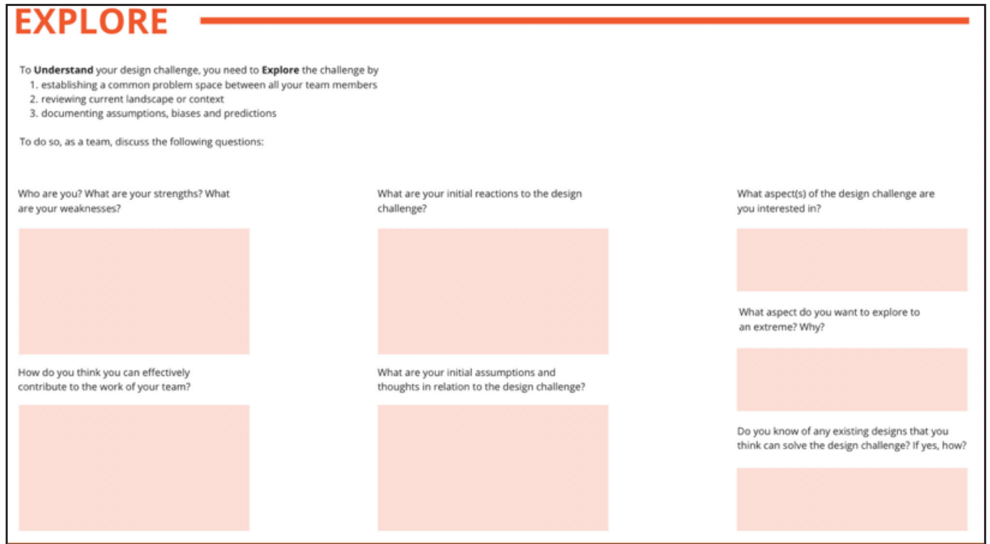

Figure 4. The Explore template

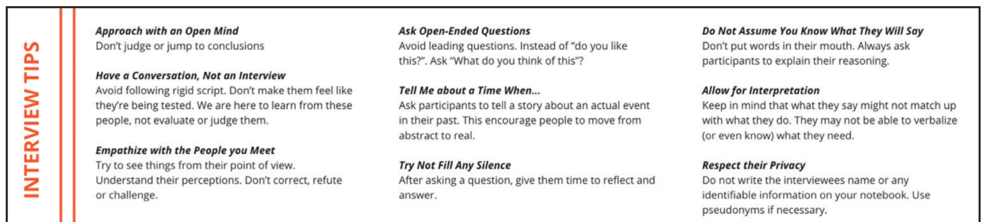

Figure 5. Interview tips

Synthesizing design opportunities

As they conducted their observations and interviews, the teacher asked the groups to implement debrief sessions to document their findings on sticky notes (see Figure 6a). In the online version of the activity, the teacher asked the groups to use the sticky notes on the Debrief template to document their findings from the interviews (no observations were conducted because of the pandemic). Figure 6b shows the Debrief template of the MIRO board. As they documented their findings, the teacher encouraged the groups to filter content for relevance and prioritize information.

After documenting their observations and interviews, the teacher prompted the groups to carefully examine and organize the data by *collapsing content, finding themes,* and *developing insights* (IDEO, 2015). In their groups, students compared and contrasted the information that they have collected from multiple resources. They shuffled the sticky notes to find themes through identifying and examining emerging patterns. Based on these themes, students developed insights about the users and their needs that helped them progress towards identifying design opportunities. For example, one group identified "healthy ingredients" as a theme based on quotes from interviewees that pointed at their preference to consume natural items after a workout. Combined with other themes such as "safety", the group arrived to a design opportunity that they expressed in the form of a How Might We question: "How might we design a nutritional gel that is composed of healthy ingredients that our users feel safe consuming?"

Acquire chemistry knowledge

After performing activities to understand the design challenge and synthesize design opportunities, the teacher asked the groups to interpret their findings by identifying what knowledge they might still need to make progress on their design challenge. Specifically, the teacher urged the groups to consider what chemistry knowledge they might need in order to start thinking about solutions to the design challenge that can be inspired and supported accurately by chemical information. In light of the groups' requests and time and resources constraints, the teacher decided to engage the groups in the following chemistry exercises: introduction to solubility in water, thickeners and emulsifiers, macro and micronutrients, and calorimetry. For each exercise, the teacher required the groups to complete a system framework (see Figure 7). This framework was adapted from (Talanquer 2019). It fostered the

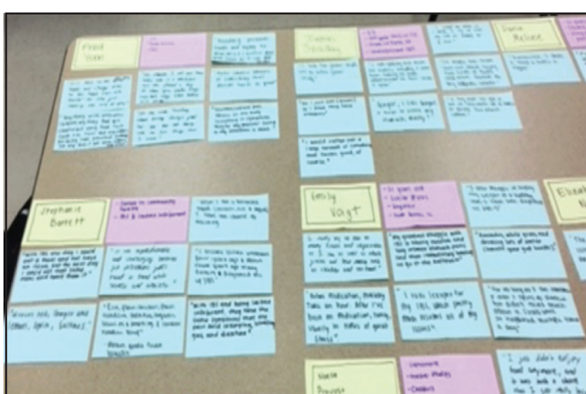

Figure 6a. Actual in-class sticky notes

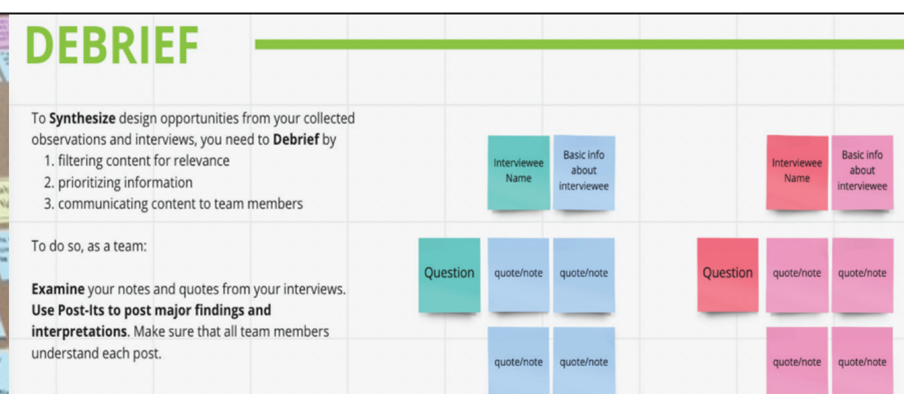

Figure 6b. The Debrief template

System	What Happens?	Under What Conditions?

Models	Components	Properties/Organization	Structure
Macroscopic			
Sub Microscopic			

Interactions	Processes

Figure 7. The System Framework

groups' engagement in chemical thinking at the different levels of representations (macro, micro and symbolic levels). In the in-person exercise, the teacher asked the groups to include these frameworks in their continuous Google doc that is associated with the design challenge. In the online exercise, the teacher asked the groups to import these frameworks into their MIRO boards.

Due to limited access to equipment and materials in virtual settings, the teacher outlined simple exercises that could be further developed into mini research projects by students. Each group had one or two students with skills in experimental design, data analysis, and reporting. During synchronous class time while other group members were together in breakout rooms collaborating via their Miro boards, these lab specialists remained in the main session with the teacher to observe demonstrations, to become familiar with techniques, and to receive special instructions. Since the goal of the overall design challenge was to propose a nutritional gel, students needed to have a basic understanding of water as a solvent and the nature of solution formation.

In the first chemistry exercise, students were challenged to design an experiment to determine the total solubility of salt in water. Although a nutritional gel would not contain a saturated salt solution, students learned that it would be necessary to find out the extent to which their proposed ingredients could dissolve in their serving size of gel. The teacher provided a simple method for determining the solubility of table salt using common kitchen items, and the students were charged with recoding their procedure, observations and data. The students would then fill out a system framework for the experiment including images of the process at the molecular scale that were either drawn or copied and pasted from a molecular simulation program they could access on their laptops.

In the second chemistry exercise, the teacher demonstrated the extreme solubility of glucose and compared it with the formation of a suspension of corn starch that could be used as a thickener for their gel. Students were challenged to design a procedure for testing corn starch and/or other common thickeners to determine an appropriate ratio for their desired gel thickness and to fill out a system framework.

In the third chemistry exercise, students observed that some micronutrients are water soluble and others are fat soluble. Vitamin C readily dissolves in water but vitamin E does not, but vitamin E is soluble in melted coconut oil. Students used information about molecular structures to describe and explain these differences in solubility on a system framework. In addition, students compared the composition of the muscle protein actin and potential food proteins that might supply the amino acids that form it. By finding the percentages of essential amino acids in actin, and the food proteins, ovalbumin, legumin, lactoglobulin, and lectin, students could determine how these macronutrients might be incorporated into their gel.

In the fourth chemistry exercise, the teacher performed a simple calorimetry experiment for students to observe and collect data on the combustion of coconut oil. The wax from an ordinary tealight candle was removed and replaced with semisolid coconut oil. After weighing the modified candle, it was ignited and placed under a small aluminum can with 100 g of water clamped to a stand and a probe that monitored temperature throughout the experiment. Students were challenged to use the mass and temperature data to determine the energy content per gram of coconut oil and compare their experimental result with the accepted nutritional caloric content for fats as well as proteins and carbohydrates. They would then discuss the possible experimental errors that could have contributed to discrepancies between experimental and accepted values.

Brainstorm and propose ideas to solve the problem

After performing all chemistry exercises, the teacher engaged the groups in a brainstorming session and prompted them to come up with ideas that they think will solve the design challenge. To facilitate the groups participation in brainstorming, the teacher shared some tips and guidelines for a successful and fruitful brainstorming. These included deferring judgments, encouraging wild ideas, building on the ideas of others, and generating as many ideas as they can (IDEO 2015). Next, the teacher asked the groups to use their knowledge about their target users and the chemistry knowledge acquired during the exercises to make informed decisions and select the names and ingredients of their product. To facilitate the groups' decision-making process, the teacher requested each group to complete the table shown in Figure 8.

In the online activity, the teacher demonstrated how the groups can import this table to the board and then use the "connection line" command in MIRO to show how their findings from the interviews and what they learned from the chemistry exercises is supporting certain ideas

Copy few sentences from each of the System Framework document and paste them in this table

Activity Title	Summary of what we learned	How might we use this to think about our product?
Introduction to Solubility in Water		
Thickeners and Emulsifiers		
Macro and Micronutrients		
Calorimetry		

Figure 8. Facilitating the groups' decision-making process

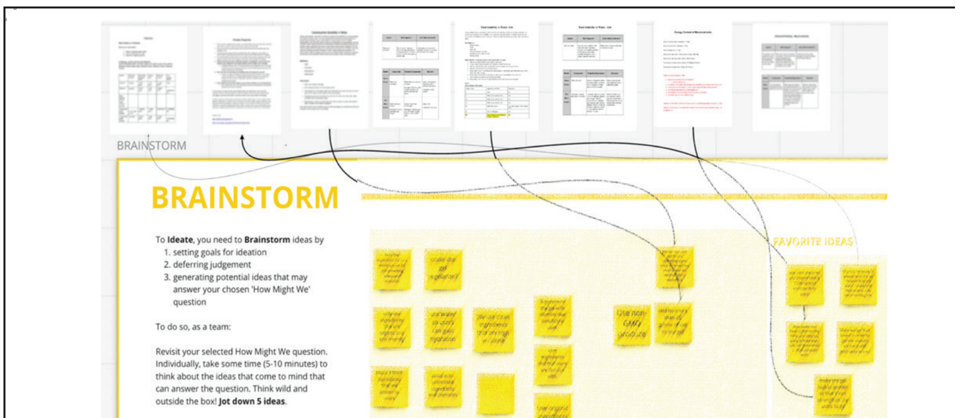

Figure 9. Connecting the chemistry knowledge to brainstorming ideas

on the Brainstorm Template of the Miro Board. Figure 9 is one group's board showing connection between each of the System Framework documents and the ideas that the students generated during the brainstorming session. Following the brainstorming session, the teacher engaged the groups in a proposing session where each group was invited to present their work on the design challenge.

Assessment

During both the in-person and the online versions of the activity, the teacher implemented a variety of tools to assess students' performance and provide appropriate feedback during the collaborative tasks. For example, before writing their interview questions, the teacher shared with the groups the Interview Quality Checklist (see Figure 10) that was later used to provide the groups with feedback on their interview questions. In addition, before generating their How Might We questions, the teacher shared with the groups the HMW Quality Checklist (see Figure 11) that was later used to provide the groups with feedback on their How Might We questions. In some classes and to encourage whole-class discussions, instead of providing written feedback, the teacher invited the groups to briefly present their interview questions or How Might We questions and used the checklists to provide the groups with verbal feedback.

At the beginning of the design challenge, the teacher shared a rubric with the groups that describes what they need to include in their final presentations during the proposing session where each group will be invited to present their work on the design challenge. The rubric is shown in Figure 12. The system frameworks and other evidence of chemical thinking were assessed formatively through providing feedback in order for students to produce more complete and accurate representations of chemical information that could be used in support of their proposed products.

Evaluation

The purpose of this activity was to engage high school students in human-centered design processes and chemical thinking. Examining the content of the students' Google docs, MIRO boards, and presentations indicated that the students were able to successfully apply HCD practices, such as interviewing, and engage in chemical thinking to make informed decisions about ideas that can transform into design solutions that meet people's needs. For example, during their final presentations, most of the groups were able to identify an unmet need of certain interviewees and came up with ideas to fulfill that need. In their presentation, one group stated, "it seems that our interviewees do not feel like eating after a workout, but are often thirsty, so making our snack a smoothie can more likely give them what they want". Moreover, groups were able to use the chemistry knowledge acquired during the chemistry exercises to make informed decisions and select the names and ingredients of their product. For example, after comparing the composition of the muscle protein actin and potential food proteins that might supply the amino acids that form it, one group concluded that "if we want our snack to help build and regrow muscles stronger and bigger, we should use ovalbumin – protein found in eggs – as it has the closest essential amino acid composition to actin, the muscle protein".

In addition to examining the content of the students' Google docs, MIRO boards, and presentations, students were asked to complete an evaluation form at the end of the activity. The form included questions such as, what was your experience in Human- Centered Design before participating in the design challenge? By participating in this design challenge, what did you learn about the role of HCD in completing design challenges? Do you think you were engaged in chemical thinking as you completed the challenge? How? How did participating in this design challenge influence your views of chemistry? Students' responses indicated that most of them did not have experience with HCD prior to the activity; nevertheless, they came to appreciate the role of HCD in structuring the problem-solving process and empathizing with the users. For example, one student wrote "I realized how important it is to get feedback from the consumers, you need other people's opinions to be able to make a product that they will respond positively to". Moreover, students thought that they were engaged in chemical thinking and their views of chemistry were positively influenced. For example, one student mentioned "during the snack design, we focused on what specific ingredients can do for our health by looking at what micro and macro-nutrients were in the ingredients." Another student mentioned "before the activity, I did not think of chemistry as being part of the process in designing a snack, I always viewed it as something not connected to everyday life but now, I realize that chemistry is used in about everything". Considering the students' learnings, future iterations of this activity must include more time for the teacher to help the students engage in chemical thinking more deeply and effectively. During this time, the teacher can examine the quality of the connections that students make between the chemistry concepts and mechanisms and their design decisions.

Following this activity, the teacher also followed the in-person version of the activity by another 4-week activity where students worked on redesigning the water

CRITERIA	Do you think your interview questions meet this criterion?	How?	Instructor's Feedback
There are 3-5 questions, including probing questions where necessary.			
Interview questions follow a logical sequence			
All questions are relevant; there are no inappropriate or off-topic questions.			
All questions are open-ended; there are no leading questions.			

Figure 10. The Interview Quality Checklist

CRITERIA	Do you think your HMW meets this criterion?	How?	Instructor's Feedback
Starts with "How Might We"			
Is inspired by one of the developed insights			
Frames the challenge but does not imply only one solution			
Can be answered by at least 5 different unique, but specific ways			

Figure 11. The HMW quality checklist

quality report that is usually published by the local water institution. Given students' experience with implementing HCD, it was easier for them to implement the processes to understand the design challenge and synthesize design opportunities; thus, more time was devoted to acquiring the relevant chemistry knowledge, ideating, and running one cycle of prototyping. Future work must explore the potential of transforming this follow-up in person activity into an online activity. Moreover, future work must integrate more assessment tools that capture the impact of such activities on students' awareness and interest in STEM careers

CRITERIA	APPROACHING EXPECTATIONS	MEETING EXPECTATIONS	EXCEEDING EXPECTATIONS	CHECKLIST
Context	Designers inadequately describe context for the proposed solution they present that only somewhat addresses the human-centered angle and background information about the problem.	Designers clearly describe the context for the proposed solution including the human-centered angle and background information.	Designers thoroughly describe the context for the proposed solution and provide a deep understanding of the problem, demonstrating that they explored the human-centered angle as well as multiple other angles to understand the context.	· **context for the proposed solution** · **deep understanding of the problem** · **human-centered angle** · **multiple other angles**
Identified Need	Designers inadequately describe the need for this proposed solution and/or only allude to the context. Suggesting that the design may only partially address the human-centered element, or may be an idea that was not developed from a different user's perspective.	Designers clearly describe the need for this proposed solution and how it was created from someone else's perspective, building on the context and addressing the human-centered element.	Designers thoroughly describe the identified need by building on the context and exploring the need from a variety of perspectives.	· **identified need** · **building on the context** · **exploring the need from a variety of perspectives**
Ideation Processes	Designers inadequately describe their ideation process by addressing only some elements of it fully or by providing only partial explanations of how their brainstorming, convergence toward viable ideas, and learning of chemistry led them to select one idea and plan for it.	Designers clearly describe the ideation process they went through to get to the ideas they are presenting including an overview of their brainstorming, convergence toward viable ideas, and learning of chemistry led them to select one idea and plan for it.	Designers thoroughly describe their ideation process from brainstorming to making a decision on one idea. Each step of the process includes specific examples to demonstrate how they arrived at their proposed idea by using what they learned about the chemistry of water.	· **ideation process from brainstorming to making a decision on one idea** · **specific examples to demonstrate how you arrived at the proposed idea** · **what you learned about the chemistry of water**
The Ingredients of the Gel	Designers inadequately describe the ingredients of the gel and how it addresses the context by only making general connections between the context and the content or by failing to show how their gel ingredients were informed by the human-centered angle and chemical thinking.	Designers clearly describe the ingredients of the gel and how it addresses the context and identified need and justify fully how the gel ingredients were informed by the human-centered angle and chemical thinking.	Designers thoroughly describe the ingredients of the gel and how it addresses the context and identified need by highlighting the trade-offs and affordances that their ingredients have from the human-centered angle and a chemical thinking perspective.	· **how it addresses the context and identified need** · **trade-offs and affordances that these ingredients have** · **human-centered angle and a chemical thinking perspective**
Next Steps	Designers inadequately describe their next steps by including only some discussion on whether there will be additional tests or by providing only a general plan for implementation.	Designers clearly describe next steps in the design process such as expanding testing of the prototype with users or how they will implement the solution.	Designers thoroughly describe a complete plan for next steps including specific tests they want to run, stakeholders they need to get feedback from, and plans for implementation.	· **complete plan for next steps** · **specific tests you want to run** · **stakeholders you need to get feedback from** · **plans for implementation**
Presentation Organization	Designers inadequately organize their presentation in a logical manner that also may lack a narrative style. The presentation uses visuals or other modes that are sometimes effective. Some aspects of the presentation narrative may be uneven or seem disjointed.	Designers clearly organize their narrative presentation in a logical manner that makes effective use of the platform (e.g. Power Point, Prezi, etc.) and integrates visuals (or other modes) as necessary to convey ideas.	Designers thoroughly organize their narrative to seamlessly flow throughout in a logical and creative manner. The visual presentation (and other modes) enhances the verbal/non-verbal communication.	· **organize narrative to seamlessly flow** · **logical and creative manner** · **visual presentation (and other modes) enhances the verbal/non-verbal communication**
Presentation Skills	Designers inadequately communicate their ideas to an audience, and there may be a mismatch between verbal and non-verbal communication.	Designers clearly communicate ideas to an audience through their verbal and non-verbal communications including effective voice control, eye contact, and gestures.	Designers thoroughly communicate ideas and make connections with the audience through their exceptional use of verbal and non-verbal presentation skills.	· **communicate ideas** · **make connections with the audience** · **verbal and non-verbal presentation skills**

Figure 12. Final presentations rubric

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David Bergandine taught for 37 years at University Laboratory High School with a focus on state-of-the-art research at University of Illinois at Urbana-Champaign for improving and advancing chemical education. Collaborations included: testing interactive video lessons; piloting curriculum units; creating a computational chemistry website for high schools; developing, testing, publishing, and teaching laboratory activities that featured tools, techniques, and materials in the areas of food science, polymers, superconductivity, materials science, nanotechnology, biophysics, robotics, and human-centered design. Decades of engagement leadership involved hundreds of high school students volunteering in dozens of elementary and middle school classrooms across the community that continues into post-retirement.