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Development of a Pre-College Curriculum for Nuclear Science and Engineering (Fundamental)

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Abstract

The intent of the Nuclear Waste Policy Act of 1982 was to establish a waste stream for spent nuclear fuel (SNF) from operating reactors. To date, all efforts by the U.S. Department of Energy (DOE) to establish a permanent repository for commercial SNF have been unsuccessful. In recent years, the DOE has focused on developing a consent-based siting process for a federal consolidated interim storage facility as a mechanism to meet its obligation to dispose of spent nuclear fuel.

With support from DOE, a group of researchers at Rensselaer Polytechnic Institute (RPI) has developed and deployed a series of nuclear science and engineering (NSE) learning modules to facilitate dialogues about SNF disposal. These learning modules are based on a previously developed novel scientific framework, Small-To-Big Physics (S2BP) [1], to enable students to acquire sufficient knowledge of NSE concepts to have informed dialogues regarding the interdependency of technical and social factors of nuclear technology. These learning modules use tactile methods to establish a baseline of NSE prior knowledge, that can be later converted to understanding through guided dialogue, without reliance on math or complex scientific theory.

In summer 2024, twenty-four junior and senior high school students from the United States and Australia attended the RPI Pre-freshman and Cooperative Education (PREFACE) program, a two-week in-residence Science, Technology, Engineering, and Math (STEM) camp on the RPI campus in Troy, NY. Participants engaged with just over ten hours of S2BP-related learning module content in preparation for approximately seven hours of facilitated dialogue culminating in student presentations regarding sociotechnical considerations related to SNF. The goals of this interdisciplinary summer experience were to 1) assess the general knowledge of and exposure to NSE concepts at the junior and senior level, 2) analyze the effectiveness of various NSE learning modules, and 3) evaluate the impact of NSE education on the support or opposition to incorporating a hypothetical CISF in participant communities. While this paper is focused on pedagogy for NSE education for students nearing the end of their secondary education, the learning modules and frameworks introduced and analyzed here offer arguments for fundamental shifts towards a more tactile, dialogic, and experiential approach to STEM education that could be adapted for diverse age groups, learning environments, educational levels, subject matters, and objectives.

Introduction

The Nuclear Waste Policy Act of 1982 has produced multiple efforts to create a permanent storage facility for non-military nuclear waste in the U.S. Ongoing concerns about the dangers of nuclear energy-related accidents, uncontrolled costs associated with nuclear power plant construction and operations, and successful efforts by state and Tribal governments to block final dispensation of nuclear waste has motivated the DOE to pursue a collaborative-based siting (CBS) process. This in-development CBS approach could prove to be a significant departure from the legacy of non-consent between communities, government entities, and companies when developing and deploying nuclear technology and infrastructure. Development of a CBS process for nuclear technology, however, is challenged by concerns related to national security, issues of non-proliferation, and ongoing debates over diversity, equity, and inclusion (DEI), environmental justice, naming conventions and related frameworks. Given historical opposition to nuclear waste consolidation, improving public literacy and building conditions that are more worthy of trust will remove barriers to advancing the federal government's nuclear waste management goals, regardless of the specific method used to achieve these goals.

In support of CBS process development, and the broader goal of building what we call "nuclear systems literacies," learning modules were developed and tested in the RPI Pre-freshman and

Cooperative Education (PREFACE) program, a "pipeline initiative" geared towards students that have been historically underrepresented in Science, Technology, Engineering, and Math (STEM) fields, though open to any interested student. In 2024, 24 high school students from various U.S. states and Australia came to the RPI campus in Troy, New York, for this intensive two-week program.

The learning modules at the heart of the program were created using an Empirical Cognitive Model (ECM) [1] that relates sensory perception with principles of development of complex schemata and embodied cognition. A detailed description of one of the learning module applications (nuclear structure and forces using BBs and magnets) is described below to illustrate the ECM principles.

The goals of our learning modules, overall pedagogical approach, and survey-based evaluation of the PREFACE program were threefold: 1) assess the general knowledge of and exposure to nuclear science and engineering (NSE) concepts at the junior and senior level, 2) analyze the effectiveness of multiple NSE learning modules, and 3) evaluate the impact of this NSE education on the support or opposition to incorporating a hypothetical CISF in participant communities.

PREFACE students filled out a total of six surveys before, during, and after the learning modules to measure the receptivity of students to different types of nuclear infrastructure in their communities and showed an increase in support, and reduced opposition, for both a stand-alone nuclear waste facility and a nuclear waste facility co-located with a knowledge creation center. Future work will focus on the development of additional learning modules, activities, and applications to other complex topics – such as the role of Artificial Intelligence in society – requiring a fast-paced learning environment for the cultivation of literacies that enable meaningful participation in technological and infrastructural decision-making.

Background

Beyond the specific application of improving processes for siting a CISF for spent nuclear fuel, integration of NSE content into pre-college educational spaces is necessary to increase public literacy around nuclear energy generally, which is in turn a key step towards developing conditions where more people could be "informed voters," choosing to consent (or not) to the many aspects of nuclear technology lifecycles. In a context where energy demand is growing, and there is increasing acceptance of calls for less polluting and lower carbon energy production, the near total absence of NSE content in publicly accessible education is a significant barrier to achieving accurate and collaborative community dialogue related to the specific risks and benefits of CISFs and other nuclear technologies and infrastructures. For the near-term goal of engaging potential CISF host communities, there is a need to create learning modules that can build capacity for understanding complex topics within the limited time constraints that community members have, or may be willing to commit, for understanding the potential impacts of hosting a federal CISF.

To aid in the cultivation of "nuclear systems literacies," including those related to consent-based processes, the novel learning modules we developed aim to aid in the rapid acquisition of requisite expertise at the "informed voter" level. While there is no universally accepted definition of consent in the context of building nuclear facilities, our team assumes *informed* consent is implied, requiring communities to have requisite nuclear knowledge to enable educated decision-making. Furthermore, there is a need to encourage and support critical thinking within communities to build capacity to analyze the various aspects of the negotiations around potential CISF infrastructure in their communities and collaboratively participate in deliberation and decision making. While these methods were demonstrated and evaluated in an informal STEM environment, they are equally applicable to formal learning environments, which will be further considered in forthcoming publications.

Engineering education in the nuclear sciences

The nomenclature for the Small-To-Big Physics (S2BP) framework was derived as a contrast to the traditional method of teaching STEM concepts. The history and nature of the modern education system is such that new concepts are added as they are needed, typically in service of workforce development in support of industrial careers. This chronology informs how STEM concepts are sequenced in the education process. Since the ancients first formalized celestial scale phenomena, followed by terrestrial, chemical, and increasingly smaller topics, the mainstream method of STEM education can be referred to as Big-to-Small Physics (B2SP). An unavoidable consequence of B2SP is that recently developed physics concepts, including those focusing on the nuclear scale, are only encountered in relatively few higher education environments without an equivalent amount of exposure to prerequisite education when compared to classic physics concepts. This results in a correspondingly shorter duration for building basic NSE literacy, let alone mastery. Since NSE concepts are rarely taught in B2SP high school curricula, the development of a voter population thoroughly informed about nuclear technology infrastructure risks and benefits is not occurring consistently with other public interests.

A fundamental assumption of our S2BP framework is that STEM curricula can be variable, instead of constant as managed in B2SP frameworks. For the general purpose of developing a pre-college NSE curriculum, and the specific purpose of CBS process development, we designed a learning module to familiarize PREFACE participants with the fundamental structure and forces of the atomic nucleus, without prerequisite knowledge or mathematics. The first step of the learning process was for students to gain an understanding of nuclear forces by *feeling* how combinations of particles behave through tactile exercises. With the principles established through these tactile exercises serving as prior knowledge, subsequent learning modules could be introduced to teach chemical structure, fusion and fission processes, or any related content of interest. In support of CBS process development, subsequent learning modules introduced various aspects of reactor fuel concepts and radiation safety concepts. These and other subsequent learning modules will be further considered in forthcoming publications.

Empirical cognitive model

The ECM guiding our development of these learning modules was derived from a combination of multiple learning theories and practical experience. Two novel hypotheses in the ECM centrally inform our NSE learning module development. First, the signal sent from the sensory processor to working memory is a function of the sensory channels (sight, sound, taste, touch, and smell) that receive input from environmental stimulation [2, 3]. Second, the long-term memory of each individual will contain a unique repository of schemata [4].

Participants engaged in the CBS process need to have sufficient and accurate prior knowledge to make informed decisions. To maximize the cognitive efficiency and effectiveness of learning activities, the learning objectives and learning modules are designed and sequenced to exploit the efficiencies within the sensory processor and limitations of working memory. The relationship between the ECM, the curriculum's learning objectives, and learning modules is shown in Figure 1.

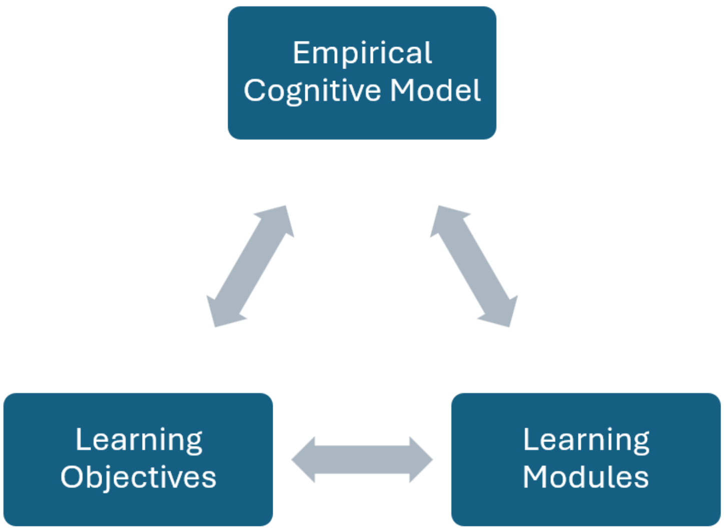

Figure 1:Elements of Cognitively Efficient Curricula Development

Our fundamental research goal was to construct and deliver a prescribed series of environmental stimuli that would efficiently establish a common set of NSE schemata in PREFACE participants prior to having facilitated dialogues regarding nuclear waste management, including hypothetical support, or lack thereof, for hosting a CISF in their home communities.

The following subsections present a description of each of the ECM elements shown in simplified form in Figure 2 and their consequences for learning.

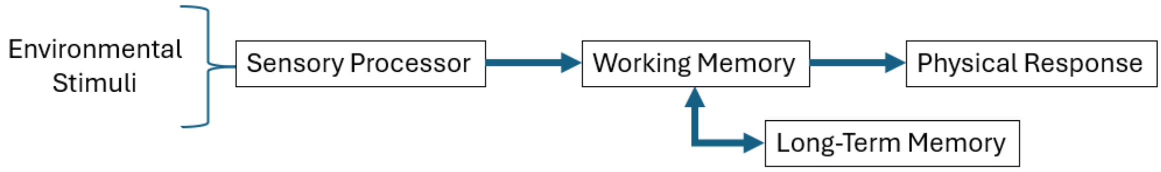

Figure 2: Simplified Block Diagram of the Empirical Cognitive Model

Memory in learning

The focus of this research is on the establishment of environmental stimuli sequencing and techniques, in the form of learning modules, that consider the limitations of working memory in the context of the prior knowledge of students (i.e., long-term memory).

Memory is a fundamental component in how humans work to solve problems and traverse their environment [5]. Of particular importance is the influence of memory in the interpretation of the available information humans have and how that information is processed and applied to the task at hand [6]. To do this, there are multiple stages towards the generation of behaviors. Figure 2 indicates how information that is obtained through the sensory processor (i.e. touch, visual, auditory, etc.) is received and stored in working memory, then either utilized (creating a behavior or physical response) or rehearsed and encoded (to be kept into long-term memory) [6, 7]. The focus of this research is on the establishment of environmental stimuli sequencing and techniques, in the form of learning modules, that consider the limitations of working memory in the context of the prior knowledge of students (i.e., long-term memory). The following subsections describe the types of memories and their effects on learning.

From sensory processors to cognition

Previous research has established the importance of the senses in the processing of information for solving problems and executing tasks [3, 11]. Sensory processors are the initial step in processing information from perception to cognition [8, 9]. Information received in the form of environmental stimuli must be selected, organized, and interpreted. This processing, guided by rules in the working memory, affects behaviors and is regulated by rules in the working memory aimed at achieving certain outcomes associated with survival [10, 11]. The processes by which perception is transformed into cognition affects not only immediate behaviors, but also how future environments and stimuli are interpreted [3].

Different types of information received via different senses (i.e., visual, tactile, auditory) inform a wide variety of strategies for navigating the world [12] and performing tasks [13-15]. Although there has been extensive research and experiments on the effects of audiovisual stimuli on cognition [11], there has been less work on touch through haptics [12, 16, 17] and the combination of senses in learning complex tasks such as music [8]. Recent developments in "embodied cognition" have revealed the significant influence of sensory and motor systems on cognition [9, 16, 17]. Given the importance of the sensory processor in our cognition and how humans traverse the world, there needs to be a greater focus in future research on how sensory processors affect learning.

Importance of sensory processors in learning

The traversal of humans through their environments, by developing and modifying behaviors that allow for their survival and correct performance of tasks, relies on learning [18]. Sensory input and processing are crucial in the development of learning frameworks and activities given the limited attention [19] and the type of information that is required to develop the concepts, associations, and/or rules that allow humans to perform in different environments [4, 20]. This foundational understanding of cognition informs the design of both pedagogical activities [20-22] and the learning environments in which these activities are experienced [23]. Conversely, pedagogical technologies and approaches have shaped how we understand the relationships between learning and the different senses.

The rise of the computer as a primary tool used for problem solving and the development of ubiquitous displays transformed education, and research on learning, to focus on audiovisual material [22, 25]. However, research has shown that our brain uses a combination of the information coming from the different sensory channels to build a holistic understanding of reality [20, 26]. The importance of all the senses has been demonstrated by researchers of learning in children [22, 27, 28] and people with disabilities [29, 30], informing the development of multisensory learning materials [28, 31, 32]. Tangible User Interfaces, for example, use displays in coordination with tangible objects to enhance collaboration and learning [33]. These multisensory tools make use of vision, hearing, and touch to enhance learning activities [34]. There remains much to be learned, however, about how working memory and long-term memory (and their respective strengths and limitations) shape the experience and effectiveness of learning activities.

Working memory to develop tasks

The information acquired through the sensory processors is then selected and interpreted through the working memory. Working memory is a type of memory system that is involved in the temporary maintenance and processing of information which can be used to perform complex tasks and manipulate long-term memory representations [35, 36]. This type of memory is linked with short-term memory as it relies on easily available information that can be used from and in immediate tasks [37]. However, working memory goes beyond only storing information and is used to reason and solve problems while performing tasks [5, 37, 38]. Additionally, working memory is also crucial in the thought creation and the connection of ideas between short- and long-term memory [38]. Nonetheless, working memory is limited in terms of its capacity [39]. Working memory limits appear as a function of temporal decay and the limitations in cognitive resources [19, 39]. Consequently, there is an important aspect in the consideration of working memory when developing tasks due to these limitations in terms of the amount of material and type presented. This is of particular importance in learning as working memory is what will mediate what is being used to solve a problem while also being selected for retention in the long-term memory.

Working memory in learning

Working memory capacity has been shown to be crucial in learning for a wide variety of domains [5, 36, 38, 40]. This is essential as working memory supports cognitive processing by being the interface between short-term memory, long-term memory, perceptions and actions [36]. However, working memory capacity limits what can be learned and understood at a given point in time [19, 36]. The general conclusion is that, without any shortcuts, a typical person can only hold four chunks of information at a given time [19, 36]. Other consequences of the limitations of working memory relate to not being able to filter irrelevant information [41] and the lack of capability of critical thinking when introduced to novel situations [38]. In multimedia learning cognitive load theory has become a main element of consideration given the limitations of working memory on what types of materials to present and in what order for a correct learning process [38, 42]. Given the human capacity of cognitive load at a particular point in time, there has been a focus on learning materials that manage the different sensory channels while presenting the necessary information [43]. This is also important given the link that attention has filtering the information towards working memory and the control of actions and behaviors [44]. What is presented in and processed in the working memory will define what long-term memory will be in a person and the types of schemata that people will use for similarly related tasks.

Working memory and long-term memory connection

A crucial aspect that happens in the transmission of information from working memory to long term memory is the establishment of schemata (set of rules) that guide the interpretation of future environmental stimuli and the development of given behaviors [4, 45]. The formation of schemata will have consequences on the information available in long-term memory when a new task requires an interpretation of novel information related to this memory [46]. At the same time, the new information acquired in working memory from environmental stimuli will work as feedback towards the accretion, tuning or restructuring of schemata [47] . The process of using the information in the working memory towards the proper generation of schemas into long-term memory has been the focus of research in instructional design towards better learning and the development of appropriate curriculums [47, 48].

Long-term memory as prior knowledge (pre-existing or none)

Long-term memory is defined as the vast store of knowledge humans acquire through their lives and a record of prior events [37]. This type of memory is distinct from short-term memory in terms of duration and capacity [6, 37]. Duration refers to the amount of time the information is available and how fast elements of this memory decay in time [37]. The duration of the information depends on the type of memory (short term vs long-term) that is used during different contexts. While short term memory and working memory deals with immediate events, long-term memory oversees the storage of information while also interpreting the consequences of the actions of the human represented in the environment and the behaviors of others through heuristics, insights and rules [48, 49]. These rules and heuristics are based on declarative memory which involves the representation of facts and events [50]. Humans take facts and events on declarative memory and model a set of rules that will be further used for any novel situation that has similarities with previous tasks [46]. Given that humans are constantly creating schemata to make sense of the world and to use them in future tasks, the schemata made during instruction and learning are fundamental to the acquisition of novel and useful knowledge [45]. The facts accessed during learning will relate to the new interpretations students come up with and the changes to the schemata developed [6, 7]. The rules created during this process will serve as prior knowledge and work directly as a guidance towards making decisions in future contexts and environments [48, 51]. The development of methods to facilitate the creation and reinforcement of these rules and schemata will shape how people confront challenges, especially in complex problems.

Learning in consent-based processes

There has been a history in the U.S. of having individuals and communities affected by processes where there was no input regarding the nature of the decisions requested [52]. Examples of this are experiments [53], medical procedures [54], and the use of data from digital technologies [55]. When developing processes of consent, participants must be informed of the different consequences upon deciding [56]. This notion arose from the development of ethical principles while performing research experiments that involved human subjects and has been translated into frameworks such as the Belmont Principles [57]. A crucial aspect in the process of informing is the development of methods that provide individuals and communities with sufficient and useful information to understand the risk and benefits of their decisions [58]. However, many of these interactions are based on the initial knowledge people or communities have [59] and the time that they have to understand and apply the information that is being presented [60]. The question arises on how to develop methods that facilitate learning in areas where people may not have a deep understanding when required to make decisions. The ECM presented previously, and the generation of the learning modules provide an approach to addressing these challenges with the objective of providing frameworks towards the design and definition of consent-based processes, in particular, areas where the topics involved are complex and sociotechnical such as nuclear waste management [61].

The following section presents the description of the learning modules designed for PREFACE and the questions of the surveys that relate to the effects of the learning modules on the students.

Methodology

As presented previously, of the five available sensory channels, sight and sound are most commonly used in learning environments. Substantial research exists to guide curricula developers in the most effective methods to achieve learning objectives without overloading cognitive processes. In practice, NSE learning outcomes have been disproportionately difficult to achieve in comparison to other STEM frameworks. While there is also significant research related to hands-on learning, access to sufficient practical exercises to provide PREFACE participants with a working knowledge of NSE concepts relevant to CISF decision-making was not available. Our companion paper, “A Cognitive Approach to Nuclear Education – A Building Block to Consent Based Siting” in the 2025 Waste Management Conference (WM2025) Proceedings, outlines the overall strategy used for PREFACE curriculum development. The initial learning module delivered to PREFACE participants consists of some series of object formation using a combination of BBs, various types of magnets, and magnetic putty. A set of materials, optimized by physical features (size, magnetic strength, etc.), was assembled from bulk purchases for an average price of ~$12. To aid the facilitator in ensuring students are using the correct polarity for the activities, black shrink-wrap was added to a common pole of all bar magnets. A sample of the materials used for the nuclear forces tactile learning module are shown Figure *3*in Figure 3.

Figure 3: Materials for Nuclear Forces Tactile Learning Module

A core concept within NSE theoretical frameworks is the structure and stability of the atomic nucleus. While many models describing the structure and configuration of particles exist, each requires advanced mathematics to understand. PREFACE participants were led through a series of exercises that allowed them to feel how subatomic particles work together to form nuclei. Although it is possible to demonstrate these activities in such a way that participants can see and hear the learning module steps, we propose that the act of building the prescribed configurations provides input through the touch sensory channel, which establishes a more efficient schema formation process than sight and sound combined. The learning modules described are the first series of activities developed for students. The objective of these learning modules is to provide a basis for understanding how nuclear energy is produced and further along the way incorporate the concept of nuclear waste and nuclear waste management.

With a maximum of 12 hours of contact time to prepare PREFACE participants to engage in dialogue about hypothetically hosting a nuclear waste facility in their community, a series of hands-on activities were utilized to ensure participants had a consistent set of relevant prior knowledge among them. The first two hours of NSE content was a prescribed set of activities where PREFACE students used the prescribed sequence below:

1. Build a cube using BBs
    a. Students are asked to build a specified cube structure using solid materials (BBs) that lack an adhesive property or binding agent, within a given time constraint.
    b. The immediate learning outcome from this activity is that BBs, which will later be identified as a proxy for neutrons, lack sufficient force properties to create nuclear structures alone.
2. Build a cube using bar magnets
    a. Students are asked to build a specified cube structure using bar magnets, as shown in Figure 3, within a given time constraint. The assignment is possible, but difficult, and a spectrum of student outcomes is to be expected.
    b. There are no immediate learning outcomes from this activity.
3. Build a cube using bar magnets and BBs
    a. Students are asked to build the same cube structure as specified in Step 2, with BBs included as available materials, within a given time constraint. The assignment is significantly easier than using bar magnets alone and all students are expected to be able to successfully complete the assignment within a five-minute period.
    b. The learning outcomes from this activity and Step 2 are considered simultaneously, in the context of using magnets alone or a combination of magnetic and non-magnetic materials.
4. Build a chart using bar magnets and BBs
    a. Students are asked to methodically walk through a guided series of combining BBs and magnets to determine the maximum number of BBs that can form a specific structure using a prescribed number of magnets. Each successful attempt is to be marked on a chart to record progress for subsequent discussions.
    b. There are numerous learning outcomes for this activity, and facilitated discussions throughout the exercise are appropriate to ensure that the proper concept is introduced and mastered according to the moment the concept emerges.
        i. One significant concept to be discussed in real-time is the inability for magnets with the same polarity to be combined without a BB. The black markers on the bar magnets, as shown in Figure 3 indicate a common polarity. Facilitators are able to visually determine if students are properly following instructions by observing the relevant position of the black marker. The learning outcome for this observation is that neither BBs nor magnets can make any configurations without including the other.
        ii. A second concept to be discussed in real-time is the variability of the number of BBs that can be connected to a specific number and configuration of magnets. Students are expected to identify that a minimum number of BBs will be tightly affixed to the prescribed configuration and that additional BBs will be less tightly affixed for increasingly shorter durations up to a point that no additional BBs can be added. The learning outcome for this observation is that the number of BBs within a specific configuration have a stability component related to how long the component can exist before a BB falls off.
        iii. A third concept to be discussed in real-time is the increased number of BBs that are required to make the smallest possible object with an increasing number of BBs. For example, 1 BB is typically sufficient for the black ends of

two bar magnets to be connected, albeit for a very short period, and 2 BBs are typically sufficient for the black ends of three bar magnets to be connected at a similarly short duration of time. The learning outcome for this observation is that the BBs appear to dilute the magnetic field in such a way that objects can form if the correct balance between the amount of each type of material is present in the object.

5. Predict a chart
   a. The assessment for the learning objectives related to the activities described above is the ability for students to predict various aspects of the Chart of Nuclides, which contains a list of all known isotopes and relevant physical properties.
      i. The first learning assessment is for students to predict the trend of marks that would be documented in their charts by continuing Step 4 through all possible combinations of BBs and bar magnets. Students should be able to accurately predict that a nearly consistent ratio of BBs and bar magnets will be required for stable and semi-stable configurations. This predicted trend is consistent with the Line of Stability, a key concept in the Chart of Nuclides.
      ii. A second learning assessment is for students to predict the significance of various colors within the Chart of Nuclides. Students should be able to accurately predict that the different colors correlate to the lifetime of each isotope, commonly referred to as the half-life.
      iii. A third learning assessment is for students to explain why the Chart of Nuclides has a specific profile. Students should be able to explain that objects with too many magnets will pull themselves apart while objects with too many BBs will have the excess BBs fall off. These mechanisms for instability are directly related to radioactive decay, which may be discussed at this time or in future learning modules.

Additional sequences using magnetic putty to introduce concepts related to Einstein's energy and mass equivalency, $E = mc^2$ and mass defect [62], or drinking straws to introduce fusion concepts, or any other nuclear concept of interest can be completed in a myriad of ways. For PREFACE, the next step was to transition to fission learning modules, which will be described in detail in future discussions.

Evaluation of activity (Engagement and Nuclear Infrastructure)

An embedded design approach was developed with the use of surveys which had questions with Likert scales (quantitative data) and open-ended questions asking for the students' reasoning in some of the questions for the summer workshop. The focus for this paper is on the analysis of the questions with quantitative data and present prospects on the possible analysis for the qualitative data. For the learning modules, Question 1-3 were done to analyze the perception of student knowledge on nuclear science and what they needed to learn. Question 4 focused on the assessment of their interest before and after the activities to analyze how engaging the learning tools were. This is crucial for understanding what the current state of knowledge (prior knowledge) of students is and what elements they are conscious of but do not have knowledge of. Additionally, as the focus of PREFACE was on nuclear waste management, Question 7-8 addresses how students would feel with having a nuclear waste management facility close to their community (Question 7) and including a knowledge center (Question 8). The survey was presented to the students on Day 1 at the beginning of the session, on Day 3, and on Day 5 at the end of the event. The questions that had Likert-scales were counted and are presented in graphs on the Results section showing the answers students had pre, during and post the PREFACE activities. Students had 15 minutes to answer the questions, and their answers were not linked to an identifier. Consequently, the analysis of the quantitative questions revolves around the main perceptions of the students as a group.

Table 1: Survey for Students

ID	Questions	Type
1	Take a minute to turn off the editor in your head and just write as much as you can in response to this prompt: what do you currently know about nuclear energy? What do you not yet know?	Qualitative
2	How would you rate your current understanding of nuclear energy?	5-point Likert scale
3	What's your reasoning behind your rating of your current understanding of nuclear energy?	Qualitative
4	How interested are you in learning more about nuclear energy?	9-point Likert scale
7	Would you support or oppose a new nuclear waste facility in your community?	6-point Likert scale
8	Would you support or oppose a new nuclear waste facility in your community if it included a knowledge creation center?	6-point Likert scale

The following section provides the results of the quantitative questions of the survey presented to students in PREFACE.

Results

The graphs that follow visualize the percentage of students responding with each possible answer to Likert scale questions. We chose to show percentages because we had a 100% response rate for the first and last surveys, but due to time constraints while administering the middle survey, had a lower rate of response. Showing percentages gives a clearer sense of the overall trends from start to middle, to end.

Figure 4 shows how, by the end of the program, the most common self-assessment of nuclear energy understanding was “High,” with over 50% giving that response, compared to zero students selecting “High” or “Very high” at the start of the program. No students selected “Very low” after the program. This works as an indicator that students perceived the knowledge elements covered in PREFACE as highly relevant for an overall understanding of nuclear energy. The elements focused on in this program included the processes of fusion and fission, the causes and impacts of reactor accidents, and the dangers related to radiation.

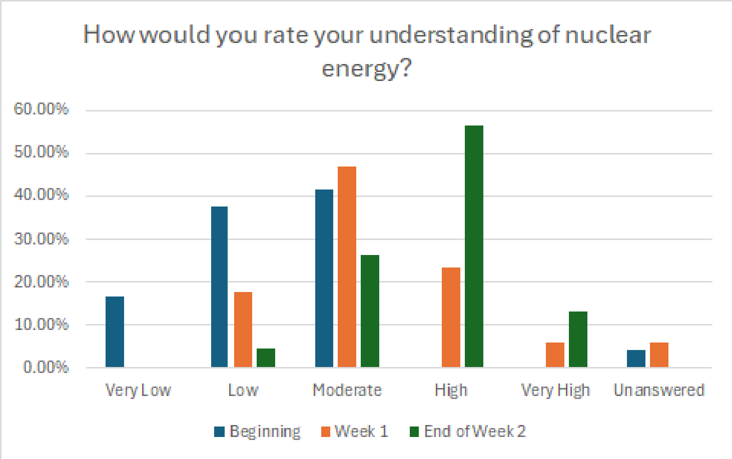

Figure 4: Perception of students of their understanding of nuclear energy fundamentals

Figure 5 shows the interest students had in learning during different stages of PREFACE. Although there was a decrease in interest between the beginning and the end in terms of the "Highly interested" category, there was an increase in students that were "Interested" and a small increase in the "Somewhat Interested" category.

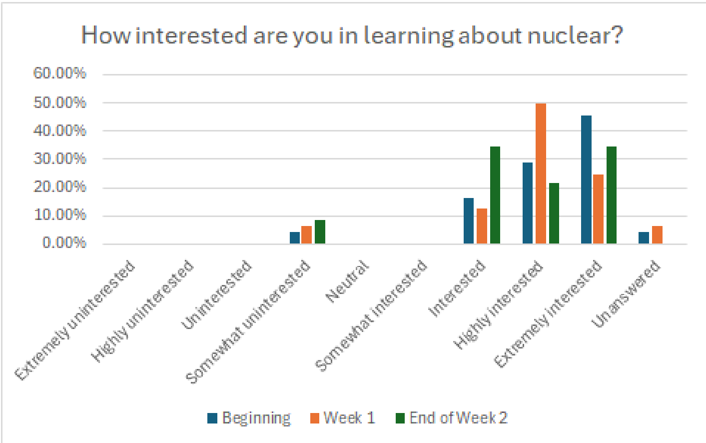

Figure 5: Interest of students in learning about nuclear energy

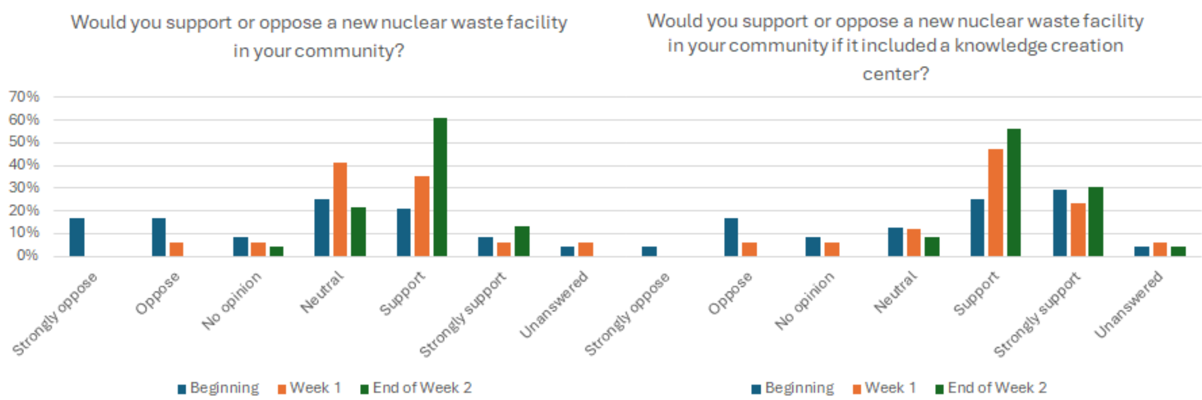

Figure 6: PREFACE Participant Support for a hypothetical nuclear waste facility.

Figure 6 presents the changes in support and opposition for the creation of a nuclear waste facility within their communities with and without a knowledge creation center. Students showed an increase in support ("Support" and "Strongly support") and a decrease in the "Oppose" categories for both questions. However, there was higher percentage in students answering a "Strongly support" for the development of a knowledge center. The definition of the knowledge center was left up to the students for the activities.

Conclusions and future work

The learning modules designed for PREFACE 2024 had the objective of informing and nurturing critical thinking in students on complex topics such as nuclear science. This is of particular importance given the social consequences that the development of nuclear energy could have for communities that are involved in the siting of nuclear infrastructure. Given the constraints in relation to time and the prior knowledge of the general population, the learning module of the BBs and magnets was designed for people to acquire knowledge on nuclear science fundamentals, which in turn enabled better dialogues around nuclear waste management. The development of NSE learning modules opens new possibilities for public debate and dialogue around scientifically and politically complex sociotechnical topics in a way that takes constraints in available time for engagement into account.

The learning modules developed also consider the limitations and efficiencies of sensory processors to acquire information in ways that can be adapted for other STEM areas. Misunderstandings and misconceptions are common in STEM due in part to the gaps between the mathematical models used to develop theory and the practical applications of these models in areas ranging from chemistry to AI development. Tactile learning modules and other multisensory analogies of these systems can contribute to the development of schemata that give people tools to efficiently master, or at least gain requisite understanding of, these abstractions.

The efficient development of these schemata also improves accessibility for people who might have difficulties with a standard approach to teaching. In future work, we will build on this potential for our learning modules to work for a wider diversity of students. The tactile elements of the learning modules, for example, could be further designed to accommodate blindness. People with dyslexia that might have problems with reading equations and writing could also benefit from pedagogical approaches that go beyond the typical focus on audiovisual materials.

The surveys we deployed in PREFACE 2024 provide insights into student engagement with nuclear issues. The prior knowledge students displayed in the early surveys (some true, some not) in relation to nuclear science shaped the perceptions students had of nuclear energy and NSE, and dialogues with the PREFACE students revealed a wide variety of ways that student knowledge and perceptions were rooted in media representations of nuclear technologies and experiences they or others around them have had. The development of these learning modules provides an initial step into giving people the capacity to build on this experiential knowledge, and question preconceived notions, analyzing and thinking critically about these complex topics.

There are multiple limitations with the surveys developed to evaluate PREFACE 2024 and, therefore, the data obtained from them. First and foremost, we do not have a clear sense of the process students used to think through their degree for support (or not) for a CISF in their communities. Second, there were differences in the scales we used in the Likert questions that may have confused survey respondents. Third, the survey questions performed need to be workshopped and validated, as there may be points of confusion about the meaning of certain novel terms (i.e. what, exactly, a “knowledge center” would be). Future work will include the development of new measurements and activities that better map the prior knowledge of students in the context of nuclear science and nuclear waste management. Mind maps, for example, could allow students to make a representation of their own understanding of nuclear systems and show their thoughts on how the elements they think are important relate to one another. Because there will always be differences in how terms are understood, more open-ended questions that ask students to describe their understanding of key terms in the survey would improve our clarity of analysis. Conducting interviews would also help us gain a more precise understanding of the mental models that students are mobilizing in their changing understandings of nuclear infrastructure. Finally, although there was a degree of diversity among the students, there are still numerous underrepresented communities and voices that could not participate in this workshop. These groups that did not participate could provide insightful comments on their perception of nuclear infrastructure, consequences for their communities, and other prior knowledge that could deepen the conversation. Research on barriers and constraints to programs like PREFACE, therefore, could improve diversity of the participating students in ways that improve both the experience for the students and the research data generated.

Returning to the connection between these specific approaches and our big-picture goals, we have found that the learning modules we developed can create a common vocabulary that could help communities develop savvy questions for the DOE, industry stakeholders, and diverse experts. This shared language can, in turn, help various experts to effectively communicate their perspectives, contributing to the necessary conditions for dialogue. The absence of advanced math in the learning modules greatly improves the accessibility of fundamental NSE concepts, enabling far more people to feel empowered to meaningfully participate in dialogue and decision-making around nuclear waste management.

In the case of the BBs and magnets activity, for example, communities can ask about the importance of shape in the structure of atoms and which figures are the ones that could represent elements of nuclear energy such as Uranium 235 and other materials involved in this process. As learning modules such as this one are focused on the use of different sensory processors beyond sight and sound, haptic technologies could provide different ways to expand these modules in a digital space while keeping the sense of touch active and introducing a VR or AR environment that does not overload the sensory channels. Introducing these technologies could open possibilities for myriad activities.

Given the rise in complex problems that affect communities, there is a need to develop learning modules that are not a one-way channel of communication and that give students the necessary knowledge to make decisions while amplifying their ability to shape the outcomes that emerge from the CBS process in collaboration with other stakeholders. It is especially crucial that learning modules be developed that can increase the involvement of communities which have historically been excluded from these kinds of conversations and borne the brunt of infrastructural siting and development. The learning modules described in this paper show great promise to contribute to community-centered pedagogies, creating a foundation that can support open-ended dialogue, instead of assuming in advance what communities want or need, or what kinds of conversations need to happen.

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