Using Construct-Centered Design to Align Curriculum, Instruction, and Assessment Development in Emerging Science

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Abstract: The National Center for Learning and Teaching in Nanoscale Science and Engineering was established to conduct research on how to effectively introduce emergent sciences into K-16 classrooms, using nanoscale science and engineering (NSE) as an example. One of the NCLT's main goals is to develop an approach to map out the knowledge domains (constructs) associated with NSE and use these domains to guide learning research and the development of instructional materials, assessment, and teacher education. These efforts have been aligned through the development and institution of *Construct-Centered Design* (CCD), a principled process that is based largely on evidence-centered assessment design (Mislevy, Steinberg, Almond, Haertel, & Penuel, 2003) and learning goal-driven design (Krajcik, McNeill & Reiser, 2007). This poster session provides an overview of the CCD process and illustrates how the use of this process has afforded alignment of learning research with the development of instructional materials and assessments.

Introduction

Research is rapidly developing strategies for creating new products and technologies by controlling matter at the nanoscale. The new information and technologies resulting from this research will have broad societal implications, and will be realized in the fields of health care, the sustainability of agriculture, food, water, energy, environment, and beyond. The U.S. federal government has prioritized nanoscale science and engineering (NSE) education in an effort to meet the predicted demand for skilled workers in this emerging field. The National Center for Learning and Teaching in Nanoscale Science and Engineering (NCLT) was established in 2004 by the National Science Foundation in order to conduct research and development on how to effectively introduce emergent sciences into K-16 classrooms, using NSE as an example.

One of the primary goals of the NCLT is to develop a Center-wide approach for defining the knowledge domains (constructs) associated with NSE. Having a set of NSE constructs that are clearly defined and developed helps ensure that all research and development efforts are aligned. The well-defined constructs drive the development of assessments embodying the desired student learning outcomes that, in turn, drive the development of instructional materials, resources and teacher education aimed at achieving these outcomes (Wiggins & McTighe, 1998). If rationally connected and coherent within and across grades, materials that are developed using these constructs can help students build a thorough understanding of the relevant scientific concepts and to see the importance of NSE in their lives (Stevens, Sutherland, Schank & Krajcik, 2007).

To guide learning research, and the development of associated instructional materials, assessment, and teacher education in a consistent, principled way, NCLT researchers developed a process consistent with the contemporary literature on designing and constructing valid assessments (Pellegrino, Chudowsky, & Glaser, 2001; Mislevy, et al., 2003) and instructional materials (Wiggins & McTighe, 1998; Gagné, Wager, Golas, & Keller, 2005). This process combines aspects of learning-goal-driven design (Krajcik et al., 2007) and evidence-centered assessment design (Mislevy et al., 2003). Because the foundation of the process lies in the definition and explicit specification of content that lies within NSE constructs, the process is termed construct-centered design (CCD).

Session Format

In this poster session, we will present the NSE constructs, the CCD process, and examples of how these are guiding work throughout the NCLT. The first poster describes the constructs for NSE that guide the work of the NCLT and how they were defined. The second poster provides a detailed description of the construct-centered design process itself. The remaining posters illustrate the application of CCD to learning research or the design of assessment or instructional materials in areas of NSE defined by the constructs.

The definition and elaboration of the constructs is crucial for organizing and aligning the efforts of a large and diverse group of researchers working at multiple institutions to study and improve student learning, instruction, and assessment of concepts important to NSE. This is illustrated by the three posters on size and scale (Posters 3, 4 and 5). The NSE construct of size and scale includes ideas related to defining and representing size through the use of measurement units, scales or "worlds" (e.g., microscale or microworld), relative size, and proportionality. Poster 3 examines undergraduates' understanding of scale, in particular how they represent the size of objects (10^{-10} – 10^{2} m in size) and the relationships between those sizes. Poster 4 focuses on the development of a learning progression that describes how students' knowledge of size and scale grows richer and more connected over time. Findings from this study led researchers to develop a technology tool that employs both audio and visual representations to support student learning about relative size (Poster 5), The researchers used the thorough definition of size and scale in order to explore complementary aspects of this construct, allowing effective collaboration Likewise, having well-defined constructs can help researchers focus on science content accessible to a certain grade level. For example, Posters 6 and 7 focus on aspects of the NSE constructs that are accessible for middle school students. Poster 6 explores how the manner in which domain-specific language is introduced affects the development of conceptual understanding of a complex idea such as self-assembly. The study described in Poster 7 provides a characterization of student understanding of the effect of changes in the surface area-to-volume ratio on the properties of matter. The final Poster (#8) directly applies the CCD process to the *full* set of NSE constructs. This work elaborates a protocol for developing assessment items for concept inventories for the NSE constructs.

Poster 1: Defining the Construct: The Big Ideas of Nanoscale Science and Engineering

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Every scientific domain is built upon a set of core principles or "big ideas", the understanding of which is essential to the domain. Alone or in combination, these core concepts help shape the development of a field, explain phenomena relevant to a field, and contribute to broader conceptual understanding by connecting the field to prior foundational ideas and establishing new foundations. They are critical because deeper understanding depends on these basic ideas as the building blocks for future science understanding. Due to the novelty of the field, core principles for NSE education had not been previously formulated.

In response to this need, a series of national workshops was held to address the challenges of bringing emerging science into the classroom. In June, 2006, the National Science Foundation (NSF) funded a national workshop held jointly by the NCLT and SRI that was dedicated to identifying and reaching consensus on the Big Ideas for nanoscience that would be appropriate for grade 7-12 learners. Participants included leading scientists and science educators, chosen to represent those scientific disciplines that are involved in nanoscale science and engineering research, learning sciences, and science education. In August 2006, at the NCLT Faculty Nanoscale Science and Engineering Education (NSEE) Workshop, participants considered the big ideas that would be appropriate for grade 13-16 students. The resulting set of nine big ideas involve content relating to: Size and Scale, Structure of Matter, Size-Dependent Properties, Forces & Interactions, Self-Assembly, Tools & Instrumentation, Models & Simulations, Quantum Effects, and Science, Technology & Society (Stevens, et al., 2007). These big ideas are the *constructs* that guide the development of instructional materials, assessment, teacher education, and associated learning research within NCLT. This poster explicates the big ideas and their primary science content, and presents some illustrative phenomena.

Poster 2: Construct-Centered Design

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This poster provides an overview of the components of the NCLT-developed "Construct-Centered Design" (CCD) process and discusses their application to concepts contained in the big ideas in NSE. The goal has been to develop an initial framework that can provide a principled approach for describing learning progressions for components of the big ideas. This approach is an adaptation of learning-goal-driven design (LGD) (Krajcik, McNeill, & Reiser, 2007), which builds upon and extends the backward design approach presented by Wiggins and McTighe (1998) and current instructional design frameworks (Gagné, et al., 2005). The LGD design model includes three stages: (a) identifying learning goals and specifying the science content they contain, (b) designing and developing materials, and (c) gathering feedback to develop, test, and revise instructional materials that support students in learning science concepts. Aspects of Mislevy's evidence-centered design (ECD) model (Mislevy, et al., 2003) were adapted and added to the design process. The ECD approach centers around three facets: (a) stating a claim that describes what knowledge, skills, or other attributes students should have; (b) providing evidence that describes what behaviors or performances are needed to support the claim; and (c) developing tasks or situations that will elicit those behaviors in order to assess student knowledge. The evidence also guides the design and development of instructional materials.

Another modification made to LGD is the use of a big idea to define the construct instead of a learning goal. Big ideas are comprehensive, and as such, to completely define the construct, the selected big idea must be broken apart to explicitly describe the content contained within it, a process called unpacking. The unpacking also includes identifying and describing what prior knowledge students will need and potential difficulties or alternative ideas that they may have related to the content. Based upon the unpacking, a set of claims and the evidence and tasks that support them is developed. The components in the process and their linkages are described and illustrated in a way that complements the subsequent posters in the session, each of which then illustrates applications to the design of assessment, research, or instructional materials in key areas of NSE.

Poster 3: Exploring Undergraduate Students' Conceptions of *Size and Scale*

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Size and scale are fundamental concepts of NSE, because changes in size and scale lead to changes in how objects behave and interact with the environment, particularly at the nanoscale. While undergraduate students are often assumed to have gained the ability to conceptualize the size differences of objects along the entire size spectrum (i.e., very small to very big), and to apply appropriate scales to represent such size differences, recent research suggests that this assumption is inaccurate (Drane, Swarat, Light, Hersam, & Mason, in press). In this poster, we present a preliminary effort to gain an understanding of size and scale, in the undergraduate context, and develop a set of assessment tools to evaluate student understanding.

As little is known about student conceptions of size and scale at the undergraduate level, we began exploring students' ideas of size and scale by engaging twelve undergraduate engineering students of diverse demographic and academic background in a semi-structured think-aloud interview. The interview protocol was composed of two related tasks. The first asked the participants to order seven objects of widely varying sizes along a line, so that the order represented their relative sizes. The second required the participants to assign a numerical scale to their ordering. Participants were asked to explain their responses as they completed the tasks. These tasks and probing questions were open-ended, which we believe allowed students abundant space to express their ideas and/or beliefs regarding size differences and scale applications. Interview responses were coded independently by two researchers, and discrepancies were resolved through conversations. Overall response patterns and between-individual differences were examined to identify the variations between student conceptions of size and scale (Light, Swarat, Park, Drane, Tevaarwerk, & Mason, 2007).

The results suggested that while most participants were able to order the objects correctly and place them in the appropriate "worlds" (e.g. macro-, micro-, and nanoworlds), their conceptions differed primarily along two dimensions (summarized in Table 1): (a) beliefs regarding the nature of continuum for the different "worlds" – that is, whether objects belonging to different "worlds" are on a size continuum, and could be represented by one continuous scale; (b) ability to apply appropriate numerical scales to represent the wide range of objects – the variations here include the application of a logarithmic scale (most appropriate), a linear scale (least appropriate), and a "hybrid" between the two. Detailed descriptions regarding these dimensions can be found in Light et al., 2007.

Table 1: Dimensions of variation for undergraduate students' conceptions of size and scale

Dimension	**Variations**				
Nature of continuum for the "worlds"	Continuous			Fragmented	
Categories of scale applied	Logarithmic A	Logarithmic B	Hybrid	Linear A	Linear B
Number of students exhibiting the variation	4	1	2	2	3

These identified variations underlying undergraduate students' conceptions of size and scale were then used to design assessment items following the CCD process. Table 2 describes an example item following the "Claim-Evidence-Task(s)" structure that corresponds to one of the two conception variation dimensions discovered through the interview study, namely students' abilities to apply the appropriate numerical scale – in this case, the logarithmic scale – to represent objects of widely varying size.

In a follow-up study, we have recently administered items including the one shown here to a larger engineering student population in order to (a) evaluate the efficacy of these items, and (b) refine our understanding of students' conceptions. Preliminary data analysis (Light, Swarat, Drane, & Park, 2008) suggested that these items are effective in identifying variations regarding how students understand the concept of size and scale, and useful in confirming and expanding the conceptual variation dimensions reported in this poster. It is our hope that analysis of student responses on these items can be used to inform instructional design that can help students develop sophisticated understanding of this critical NSE concept.

Table 2: An example item to assess undergraduate students' conceptions of size and scale

Claim	The student is able to apply a coherent logarithmic scale to represent objects of widely varying size.
Evidence	Given the sizes of objects varying widely in size, the student's work includes constructing an appropriately labeled logarithmic number line, on which the objects' positions and the spacing between the objects correspond respectively to their sizes and size differences in terms of orders of magnitude.
Task	Given the sizes of various objects (e.g. football field, elephant, hair, virus, and atom) in decimal notation, label their appropriate positions on a logarithmic scale, and explain the size differences, in terms of orders of magnitude, of the following pairs of objects: Football field, Atom; Elephant, Hair; Hair, Virus; Virus, Atom.

Poster 4: Development of a Learning Progression for Size and Scale

César Delgado, Shawn Y. Stevens, Namsoo Shin, and Joseph S. Krajcik, University of Michigan

The concepts of size and scale are important in science learning but are poorly comprehended by students (American Association for the Advancement of Science, 1993; Tretter, Jones, Andre, Negishi, & Minogue, 2006). This study describes the development of an empirical learning progression for size and scale. Learning progressions describe learners' successively more sophisticated ways of thinking about a scientific topic over an extended period of time and can guide improvements in curriculum, instruction, and assessment (Duschl, Schweingruber, & Shouse, 2007).

Following a construct-centered design process, we identified four critical concepts within the "big idea" of size and scale. These deal with: what size is; how we conceptualize and symbolically represent size; the effects of changes in size; and the effects of changes in shape. When unpacked, the first critical concept includes ideas such as the one-, two-, and three -dimensional measures of size (length, area, volume). It also identifies four facets of size and scale, which involve comparing one object to another object or to a conventional unit (e.g., a meter). Two qualitative facets are ordering and grouping by size. Two quantitative facets are relative size (the number of times bigger or smaller one object is than a reference object) and absolute size (e.g., 14 nm). These unpacked ideas were then used in generating claims, evidence, and tasks suitable for measuring the knowledge of students over a range of grades (See representative example, Table 3.)

Table 3: Construct-centered design - representative example of claim, evidence, and task

Claim	The student is able to estimate the size of a range of objects in terms of a convenient and familiar reference object.
Evidence	Given a series of objects and a reference object of known size, the student's work includes estimates of sizes that are accurate to within one order of magnitude.
Task (grades 7-12)	How many times bigger or smaller than the head of a pin (1 mm in diameter) do you think the following objects are, in length/diameter: human, earth, red blood cell, atom?

Current conceptions of learning stress the importance of connections between concepts (Bransford, Brown, & Cocking, 1996), so we developed tasks designed to detect not only content knowledge of the size of objects, but also whether students are making connections across facets of size. For example, we developed an item parallel to the task above, asking students to estimate the *absolute size* of the same four objects. This pair of linked items allows us to see if students connect relative and absolute size by examining whether their answers are consistent.

We then used some of these tasks to investigate student knowledge. We conducted interviews with approximately 90 middle and high school students from seven different public and private schools, as well as six undergraduates at a research university, in the Midwestern USA. We are using our findings to generate a learning progression for size and scale for grades 6-undergraduate.

In general, while students in more advanced science courses have more sophisticated conceptions, there is wide variation between students in a given class. Most students cannot use the number of times bigger/smaller an unfamiliar object is compared to an object of known size to find the size of the unfamiliar object, and twothirds do not believe that the actual sizes and relative sizes are necessarily and logically related. Other connections, such as between ordering and grouping, are much more widespread. We have detected the order in which students tend to establish connections across facets of size and scale, and are studying how this progression is related to the accumulation of accurate content knowledge about the size of objects.

Poster 5: Design and assessment of a computer simulation for helping learners develop submacroscopic size conceptions.

Minyoung Song and Chris Quintana, University of Michigan

This study describes the development of a learning technology tool to help develop middle school students' conceptions of the submacroscopic scale (i.e., where objects are too small to see with the naked eye). By unpacking concepts in the NSE construct of size and scale, we were able to identify and generate claims and evidence for each concept (See Table 4 for the construct, corresponding claim, and evidence used in this study). However, prior research reveals the challenges that middle school students face in understanding the absolute and relative sizes of submacroscopic objects (e.g., Tretter et al., 2006). Because students are not able to directly see and experience submacroscopic objects, we are exploring a new tool that uses multiple modalities in a supportive capacity to address the challenges of dealing with the submacroscopic scale.

Table 4: The construct, claim, evidence, and challenges used in the development of a learning technology

Construct	… large changes in magnitude can conceptually be divided into 'worlds' (e.g.,macro-, micro-, nano-, and sub-nanoworlds), with their corresponding landmark objects, tools, dominant force, unit, models that best explain phenomena, etc…
Target learners	Middle school students
Claim	The student is able to identify, describe, and distinguish between different size regimes, including the macro-, micro-, nano-, and sub-nano scales, or worlds.
Evidence	Given key scientific objects, or other objects and their size, the students should correctly classify these objects as belonging to the macro-, micro-, nano- or sub-nanoworld.
Task	Students classify the key scientific objects into groups of similar sizes
Representative misconception	Students tend to think that all objects that are too small to be seen with the naked eye are roughly the same size, whereas in fact their relative sizes may be vastly different. Therefore they categorize them into one group (Tretter et al., 2006).
Representative challenge	The objects in the unseen world cannot be experienced and manipulated directly.

We have designed a simulation that incorporates *aural-visual representations* to illustrate the sizes of submacroscopic objects. Sound is used to represent size since objects at this scale are too small to see, and visual representations are added when the phenomenon enters the macroscopic scale. We are exploring the use of sound because of the limitations people face in trying to process complex visual information. For example, Pavio (1990) and Mayer (2001) each describe a "dual-coding theory" of how people process sound and images in parallel. These theories illustrate how solely relying on the visual channel to convey information about size can be problematic for students. First, since students cannot see submacroscopic objects without other instruments, it is difficult to compare the sizes of these and other objects. Second, while other approaches compare and link visual representations of different objects and their sizes (e.g., the popular "Powers of Ten" movie [Eames & Eames, 1977]), these representations may actually overload the visual channel by forcing students to maintain certain representations in working memory while looking at new representations to make size comparisons. By introducing sound as a modality to convey size, we are exploring whether students can simultaneously use both aural and visual representations to distinguish the sizes of different objects by processing this information in the parallel manner described by the dual-coding theories. This use of sound mirrors similar research where sound is incorporated in tools to help people process large amounts of information more effectively (e.g., Kramer, 1994).

The learning activity paired with our simulation strictly addresses our specified goal (Table 4), and the students' final product involves the classification of the submacroscopic objects of similar size after having used the simulation. Through this activity, we want to explore whether the simulation helps learners better conceptualize submacroscopic scales. In this poster, we describe the iterative development process and we demonstrate and explain the final product.

Poster 6: Using construct-centered design to revise instruction and assessment in a nanoscale self-assemby design activity: A case study

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One of the “big ideas” of nanoscale science and engineering is the concept of self-assembly (Stevens et al., 2007). With nanoscale components, it is difficult and inefficient to assemble larger structures by the traditional means of “picking and placing” pieces into desired configurations. An alternative approach to the assembly problem is to design the components and the fluid environment in which they are contained so that the disordered components autonomously organize themselves, without explicit manipulation, into the desired formation through the use of attractive and repulsive forces such as van der Waals interactions (Whitesides & Grzybowski, 2002). Examples of molecular self-assembly include the folding of proteins to form quaternary structures and the construction of nanoscale filters.

In a one-week pilot study, we investigated the effects of the sequencing of the introduction of domain-specific terminology on students’ conceptual understandings and ability to perform simple nanoscale self-assembly design tasks. A sequence of instruction, in which the design task is introduced using morphological descriptors and is subsequently bridged to the domain terminology only after the design experience, allows students to “practice” in the domain through the completion of design tasks. This instructional method may mitigate issues that often arise with traditional didactic instruction, such as evoking alternative conceptions (Dykstra, Boyle & Monarch, 1992). In addition, providing students with an experiential frame of reference prior to direct instruction may allow them to acquire an overall deeper understanding of domain concepts (e.g., Schwartz & Bransford, 1998).

We employed a quasi-experimental design, assigning two intact urban sixth-grade classrooms with a combined total of 41 students to one of two treatments. In a “domain-framed” treatment, the phenomena were described in domain terms from the outset and followed the typical order of science instruction: formal instruction followed by more hands-on activities. In our “practice-framed” treatment, the phenomena were described using morphological nouns (e.g., “blobs” instead of “molecules”) and verbs common to younger learners (e.g., “sticking” rather than “bonding”); the design sessions were then followed by a “bridging lesson” that related the objects and verbs of the design activity to their domain-specific vocabulary and concepts. The design activities were scripted using the Concord Consortium's Molecular Workbench (Concord Consortium, 2004), and allowed students to choose component molecular shapes and select the position, strength, and quantity of dipole charges to realize a sequence of target aggregate nanoscale structures.

Paper-and-pencil assessments of self-assembly content knowledge were administered to each group following the first instructional phase and again at the study’s completion. Eight multiple-choice questions tested student understanding of NSE-related concepts, including attraction, repulsion, stickiness between molecules, dipole charges, bond strength, reversibility, movement of molecules, and the role of heat in self-assembly. Students were also given two design tasks, one generative and one predictive, to examine their design proficiency.

While the outcomes of the pilot study favored the practice-framed treatment, item response differences related to more fundamental nanoscale concepts (forces and environments) prompted a reconsideration of the activity sequencing and assessment strategies for both treatments. Employing a construct-centered design methodology, we have identified a number of critical concepts, developed claims, and articulated evidentiary rubrics that we are using as the basis for modifications in both assessments and instruction. The poster focuses on the unpacking of one such critical concept—the interaction of forces—and the assessment and instructional designs that arose from the construct-centered analysis.

Poster 7: Exploring student mental models of size-dependent properties

Clara Cahill, Joseph S. Krajcik, University of Michigan

Helping students understand nanoscale science big ideas (Stevens et al., 2007) requires a thorough understanding of how these important concepts fit into student models of the way phenomena work . In this poster, we detail a study that uses construct-centered design to create a series of assessments to elaborate student models of properties and the relationship between properties and size. Our work has several aims: (a) to illuminate common student misconceptions and emergent conceptions encountered in these areas; (b) to create a conceptual inventory to directly assess student models and common misconceptions, and (c) to suggest some implications for practice and curriculum design towards addressing these emergent conceptions. To reach these aims, we employ two general phases of study.

The first phase of this study followed twenty-two diverse public middle school students who participated in a two-week summer Nanoscience camp. The emergent conceptions of these students were explored through videotaped activities and summary interviews focusing on the big ideas and students’ overall understanding of nanoscale concepts. We transcribed student utterances, and categorized each utterance by topic. The utterances were further phenomenologically subcategorized into emergent themes. By investigating these themes within students' mental models of properties and the relationship between size and properties, we were able to evaluate how students attempt to make sense of complex nanoscale concepts.

Among the emergent themes were particular mental images and experiences that a number of students referred to in explaining and describing their understandings of material interactions and dimensional characteristics. These themes were instrumental in helping the student form their mental models of the concepts of interest. For example, students who were able to explain the size of bacteria compared to nanoparticles in a qualitative manner often connected their explanations to their experience seeing bacteria through a light microscope and the inability to view nanoparticles using the same tool. Students who did not connect their explanations to this direct experience typically equated the size of bacteria and nanoparticles. Thus, emphasizing this connection during the direct experience would seem to be important in helping shape students' conceptions of relative sizes. Additionally, some students tended to consider surface and surface area separately from volume, and were unable to link overall volume to overall surface in different sized objects. This confounded their attempts to compare and explain the difference in reactivity between small and large objects. Some students failed to consider the importance of surface overall, considering volume to be the important factor in an overall interaction. These findings have implications for curricular design and instruction, and can help inform the design of assessment to distinguish among different student models.

In the second phase, we are using a construct-centered design process, informed by our previous findings and by expert models of our focal big ideas, to create a set of open-ended interview questions. These questions aim to elaborate student mental models, detect misconceptions, and investigate levels of understanding in students. These questions will be tested iteratively, and will be used to inform instruction and to design short-answer assessments to access student conceptions deemed important to the understanding of size-dependent properties. This overall process, which incorporates CCD and a principled approach to evaluating and designing test items, is elaborated and exemplified fully in the poster.

Poster 8: Development of NSE Concept Inventories

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Concept inventory (CI) has been defined in the literature as an *instrument* for investigating and illuminating students' mental models and understandings of a small number of specific concepts (Pavelich, Jenkins, Birk, Bauer, & Krause, 2004). CI's are used for a variety of purposes: they help assess the effectiveness of different styles and methods of instruction, enable the comparison and evaluation of curriculum based on common learning goals, enable the categorization and clarification of student thinking for the instructor, and provide researchers with evidence of student thinking at different stages of their education (Lindell, Peak, & Foster, 2007). NCLT aims to develop principled, informative CI's organized around the NSE big ideas (see Stevens et al., 2007). This process is particularly confounded by the interdisciplinary nature of the big ideas, which requires the establishment of consensus upon what constitutes key concepts for students to learn across the conventional boundaries that distinguish traditional subject domains such as physics, chemistry, and biology. Additionally, NSE is a broad topic; that is, it entails a large number of concepts that likely fall within a hierarchical structure. Here, we elaborate on our progress in identifying the interdisciplinary key concepts in NSE so that the CCD principles (described in Poster 2) can then be utilized to streamline the creation of valid and reliable assessment items (please see Poster 3 for an illustration of item development).

Our various efforts to identify key NSE concepts have yielded a significant amount of qualitative data that were collected primarily through observations of and conducting exploratory semi-structured interviews with secondary school and university students. Specifically, Posters 3 and 7 detailed our preliminary findings in students' understanding of size and scale and properties of matter concepts. We have data also on the concepts of particulate nature of matter, structure of matter, surface-area-to-volume ratio, and dominant forces. In particular, we determined that, for our first-year undergraduate students, those who had already developed a solid understanding of the particulate nature of matter concepts through their studies of basic chemistry tended to organize their understanding of size, scale, and properties of matter around the atom. For example, by knowing what an atom was, students had demonstrated their abilities to justify the size of a carbon buckyball and its size relative to other microscopic and macroscopic objects. At the same time, they had also predicted that a group of ten to a hundred gold atoms (i.e., the nanoscale size of gold) would have the gold color (a misconception) since students had assumed that each gold atom, which makes up large, macroscopic pieces of gold, was also gold-colored (another misconception). Overall, our findings have been consistent with those reported previously in the limited literature, and in addition, we were able to better understand student-generated relationships between cross-disciplinary concepts and the implications of these relationships for our next phase of work – the development of CI-based assessment items.

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