Using Think-aloud Concept Map Activity to Probe Students' Understanding of Particle Physics in an Undergraduate Online Course

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This study investigates how undergraduate students conceptualize particle physics through a think-aloud concept mapping task. Participants, drawn from an online upper-division particle physics course offered across Hispanic-Serving Institutions (HSIs), constructed digital concept maps via an online diagram app using a curated set of terms related to different particles and fundamental interactions. Building on prior work using concept maps, we developed a concept map activity to investigate how students understand what particle physics is, through organizing their core ideas using the concept map. Responses ranged from process-oriented structures highlighting particle behaviors (e.g., annihilation, scattering) to more classification-driven maps reflecting textbook frameworks. While students often correctly linked bosons with fundamental forces, many showed difficulty articulating relationships between particle families, the roles of mediators, or distinctions among categories like quarks, leptons, and mesons. Several participants referenced external resources during the task, offering insight into areas of productive struggle and conceptual uncertainty. Our findings suggest that think-aloud concept mapping is a promising tool for surfacing students' implicit reasoning and structural understanding of complex topics. We discuss implications for supporting advanced concept development in upper-division coursework and online learning environments.

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I. INTRODUCTION

Public university systems and primarily undergraduate institutions like the California State University (CSU) often face systemic barriers that limit equitable access to advanced physics content and undergraduate research experiences. Consequently, students at these institutions may enter upper-division coursework or research pathways with less preparation or confidence than peers at research-intensive universities [1]. As a step toward offering high-impact educational experiences to these students, we developed and offered an undergraduate level particle physics course through CSU Fully Online—a platform accessible to all CSU campuses and partnering community colleges. This broader project also includes paid research internships at CERN and a suite of physics education research activities aimed at understanding student learning in particle physics.

There has been relatively little research on how undergraduate students learn particle physics concepts, with most research being conducted internationally outside of the U.S., [2-4]. This is partly because the course is often an advanced elective requiring quantum mechanics, which limits student access and, consequently, educational research in the field. As a result, there is both limited curricular exposure and sparse education research in this domain, especially at the undergraduate level. This course, Introduction to Particle Physics (PHYS 163), is designed to be more accessible, especially for undergraduates, requiring only modern physics or special relativity as a prerequisite. It emphasizes relativistic kinematics, conservation laws, and experimental reasoning to explore particle interactions and classifications, thus broadening early student exposure to these cutting-edge topics.

Particle physics poses unique learning challenges and provides a rich soil for investigating students' reasoning. Particle Physics contains unfamiliar representations, multiple classification systems across diverse physical regimes, and integrating overlapping frameworks—particles, interactions, and the theories that describe them, making it an ideal context for exploring how learners organize and make sense of complex scientific domains. Particle physics at this level naturally overlaps with other key courses such as Quantum Mechanics, Special Relativity and Modern Physics [5-10], making it relevant to a broader segment of the undergraduate curriculum. As students navigate these courses, they are often encountering fundamental shifts in perspective—from classical to quantum reasoning, and from macroscopic to subatomic scales—creating a "golden window" where more complex, nuanced conceptual frameworks begin to take root.

Concept maps and knowledge maps are powerful visual tools that help organize complex information and assess understanding. They allow us to see how well students connect different ideas [11-17]. As a first step toward investigating students' understanding of particle physics, we used a semi-structured concept mapping activity to explore students' understanding of particle physics. In a prior study, Gourlay [11] used concept maps to assess UK A-Level (grade 12, 16–17-year-old) students' grasp of particle composition. While Gourlay's study involved a physical Post-it notes sorting task, our research adapted this method for an online environment and broadened the exploration of students' understanding to include the four core pillars of particle physics: classifications, properties, interactions, and theoretical frameworks. This paper presents preliminary findings from interviews with students in the course. Our goal is to uncover patterns in students' reasoning, identify areas of conceptual confusion or misclassification, and inform the development of future assessments and instructional interventions.

II. METHODS

We conducted one-on-one think-aloud interviews with student volunteers via Zoom, after obtaining informed consent. The seven student volunteers came from five different campuses; two were master's students and the remaining five were undergraduates. During each session, students used an online concept-mapping tool (https://app.diagrams.net/) while sharing their screen, with video and transcript recording enabled. Students were asked to verbalize their thought process as they constructed the map, while the interviewer remained largely observational, prompting only for clarification or to encourage continued explanation.

At the start of each interview, we explained what a concept map is and provided an example based on Newtonian mechanics. Students were then given a pre-constructed list of words and relational arrows (e.g., "is," "made of," "contains") in the form of a template that can be uploaded to the mapping tool. They were told the list was not exhaustive and were encouraged to add or delete terms as needed. Internet searches were permitted, as long as students stated when they were doing so.

The concept map activity was structured around four central dimensions of a particle physics course: (1) particle names and categories, (2) particle properties, (3) types of interactions and mediators, and (4) theories describing those interactions. The word list was designed to prompt associations while avoiding redundancy. For instance, if a category (e.g., "lepton") was included, exemplar particles (e.g., "electron") were omitted; conversely, if a specific particle (e.g., "proton") was included, broader categories (e.g., "baryon") were excluded. The final word list included: *particle, antiparticle, decay, annihilate, scatter, force (interaction), matter, lepton, meson, boson, quark, muon, proton, gluon, Higgs, photon, spin, color, positive, up, charm, strange, strong, electromagnetic, general relativity, quantum electrodynamics, electroweak theory*.

During the initial interviews, we followed a three-step protocol: (1) add or delete words, (2) sorts them into groups, and (3) create connections. However, we found this structured approach difficult to enforce remotely. Students often began mapping immediately, blending or skipping steps. As a result, we adopted a more flexible approach, offering the steps as guidance while encouraging students to work intuitively. Zoom interviews were recorded and auto-transcribed. Using an emergent approach, we analyzed four dimensions of particle physics by compiling correct ideas and omissions from transcripts, videos, and diagrams, then synthesizing these into higher-order themes describing student approaches (e.g., "emergent" vs. "clustered") and common error patterns.

III. RESULT

A. General organizing approach

During the concept map interviews, we observed distinct variations in how students approached the task. One key difference lay in the structural organization of the maps: some students employed a clustered approach, while others adopted a more emergent style. A second variation concerned the conceptual anchors students used: some centered their maps around particle actions (e.g., decay, annihilation), while others began with matter-based entities (e.g., quarks, bosons) and organized properties and interactions from there. These contrasting approaches offer insight into students' cognitive framing of the particle physics domain. Below we elaborate on these approaches.

Student	Cluster vs. Emergent	Action first vs. Matter first
S1	Cluster	Action first
S2	Emergent	Matter first
S3	Cluster	Matter first
S4	Cluster	Matter first
S5	Cluster	Matter first
S6	Emergent	Matter first
S7	Emergent	Neither (theory first)

TABLE I. Students' different organizing approaches, S1-7 numbering indicating interviewing order spanning a couple of weeks

1. Cluster vs. Emergent

During concept map interviews, we observed two distinct approaches to task completion. The 'Cluster' method involved students organizing all keywords into clusters before constructing the concept map. In contrast, the 'Emergent' method saw students incrementally adding and connecting terms as they built the map organically. Though 'Emergent' users formed mini-clusters, their process was distinguished by its organic, build-as-you-go nature. (Note: The interview protocol was adjusted after the second session, which may have influenced early participants' strategies.)

The methods were nearly evenly split: four students used 'Cluster' (S1, 3, 4, 5) and three used 'Emergent' (S2, 6, 7). This balance suggests diverse approaches to open-ended tasks, regardless of shared course context. These differences likely reflect variations in knowledge organization or responses to open-ended challenges. 'Cluster' maps tended to be more hierarchical, while 'Emergent' maps were often fluid and emphasized associative reasoning. These observed differences highlight a range of planning and reasoning strategies among students, which can inform future instructional design. Recognizing these natural planning styles, instructors can support both by offering multiple entry points into complex tasks and modeling different approaches.

2. Action first vs. Matter first

When developing the word list for the concept map activity, we intentionally included a small set of "action" terms, such as *annihilate, decay,* and *scatter*, despite initial concerns about ambiguity (e.g., *scatter* may involve either strong or electromagnetic forces) to offer diverse entry points for students. This decision allowed us to analyze if students organized their maps around particle process ('what particles *do*') or their compositional/property-based aspects (e.g., categories and constituent makeup). This orientation could reflect not only their understanding but also how they have internalized the framing of the course or the broader field of particle physics.

Our analysis of concept maps interviews revealed that most students (five of seven) primarily oriented their maps around particles properties, elaborating on categories or constituent makeup (e.g., quark flavors, lepton categories). This is notable given the course's strong experimental framing, taught by a experimental particle physicist. Students may default to familiar classification schemes that feel more stable, as interactions are complex and potentially not their initial entry point to particle physics. Additionally, concept mapping itself might favor taxonomic reasoning, especially with more static than dynamic terms in the word list or when "action" words are harder to semantically integrate (e.g., "scatter" can apply to multiple forces).

B. Four aspects of particle physics

1. Particle types and categories

Overall, most students demonstrated a basic grasp of particle categorization, successfully classifying basic examples such as muons, neutrino, protons, and neutrons. However, their understanding faltered when it came to recognizing the relationships between particle categories (navigating the fluidity and overlap of different classification schemes), revealing a challenge in how they ontologically structured the particle domain—that is, how they categorized and linked the main things in particle physics—particles, their properties, and interactions.

For instance, while many correctly assigned familiar particles to broad groups (e.g., placing muons and neutrinos under leptons), they often failed to extend these categories to include additional examples like electrons or taus. Students also struggled with broader classifications such as fermion or hadron. The term "fermion" was never used, and "hadron" appeared on only two maps, sometimes misapplied by linking protons to bosons or not connecting mesons to the boson category at all.

This indicates a potential over-reliance on memorized facts (e.g., “photons are bosons”) rather than a deeper understanding of underlying principles like particle spin or composition. Students might be better support by instructions that introduce a structured, hierarchical framework for particle classification, starting with fundamental divisions like matter particles (fermions) and force mediators (bosons), followed by more detailed groupings (quarks, leptons, mediators). Alternatively, a structure based on fundamental vs. composite particles could also be productive, though more conceptually demanding. Additionally, explicitly discussing the terminology and origins of particle names could help alleviate common confusions. Ultimately, these observations point to a clear need for enhanced instructional scaffolding of particle classification systems, focusing on both the organizational structure and the conceptual significance of particle groupings.

2. Particle properties

Particle properties can be broadly categorized into two types: phenomenological (e.g., mass, lifetime, magnetic moment) and intrinsic quantum numbers (e.g., spin, charge, color, flavor). For the concept map activity, the provided word template focused on these intrinsic quantum numbers, including terms like "spin," "color," and "positive," as well as specific quark flavors. Properties such as baryon number, lepton number, isospin, hypercharge, or parity were excluded as they were not central to the course. Interestingly, three students spontaneously included "mass" in their maps, possibly prompted by the term "Higgs" in the template.

Students generally showed strong factual knowledge of intrinsic properties. All but one student correctly listed all six quark flavors and most correctly associated color with quarks. While all students except S3 included "color," their understanding of charge was less consistent; two students omitted any mention of it, while four used "charge" explicitly or "positive" to represent it. Student 3, despite not completing a full concept map, was the only participant to explicitly include and note the conservation of baryon and lepton numbers.

Similarly, spin was frequently misunderstood or omitted. S1 conflated up/down quark flavors with spin states, likely reflecting a known misconception between isospin and spin. S2 correctly cited spin values for leptons and mesons but omitted bosons, indicating a lack of systematic application. Only two students (S5 and S6) explicitly grouped spin, color, and charge under the unifying category of "quantum numbers," demonstrating a more abstract and generalized mode of reasoning.

When organizing these properties, students' responses were variable and often lacked systemic structure. For example, though "positive" was in the word list, four out of seven students did not consider corresponding "negative" properties like the electron, which was omitted from three maps. This suggests a surface-level association rather than a relational understanding.

This analysis reveals that despite familiarity with particle types, students often lack an organized ontological framework for reasoning about particle properties. Their use of quantum numbers is fragmented, with limited spontaneous recall and weak connections to how these properties define particle identity and interaction behavior. This suggests a need for instruction to emphasize the systematic organization and conceptual meaning of particle properties.

3. Interaction types

Overall, students demonstrated a strong foundational understanding of the four fundamental interactions and their associated mediators. Four out of seven students correctly identified all four forces—strong, weak, electromagnetic, and gravity—and named their mediators, such as gluons, W/Z bosons, and photons. Among these four, only two explicitly mentioned the graviton, a hypothetical force carrier not included in the Standard Model. One of those students marked it with a question mark, indicating awareness of its speculative nature. This strong performance on naming mediators may reflect the instructional tools like Feynman diagrams will continue to be effective, which visually emphasize the role of mediators in interactions.

In contrast, specifying which particles participate in which interactions were less consistent, though this was not a central focus of the study. These relationships are more complex than the simpler mediator-to-interaction pairs, and we deliberately omitted the term “participates” from the relational arrows provided. Only two students (S5 and S7) attempted such connections. S5 noted that leptons participate in electromagnetic interactions but overlooked that neutrinos—neutral leptons—do not. S7 stated that the strong interaction “contains” quarks—an intuitive but imprecise phrasing that could be refined to “quarks participate in strong interactions, which are mediated by gluons.”

This imprecision extended to broader use of the term “mediate.” One student wrote that quarks are “mediated by gluons.” More precisely, gluons are what bind quarks together within hadrons, and the interaction among quarks is carried by gluons, not that quarks themselves are “mediated.” Another student constructed a conceptual chain in which “Higgs” mediates “mass,” which mediates “general relativity,” which in turn mediates “gravity.” This reflects a conflation of concepts from multiple physical frameworks and an overextension of the word “mediates.” The student applied it to a property (mass), a theory (general relativity), and a force (gravity). The diagram suggests an attempt to form a causal narrative, but one that overlooks the distinct roles these concepts play in different domains of physics.

These patterns suggest that while students recall interaction types and mediators, they lack a coherent framework for reasoning about particle interactions. This points to a deeper ontological challenge—shifting from simply categorizing entities to understanding their roles and relationships within interactions. Future instruction should explicitly highlight these relationships, focusing on not just the mediators, but also the types of particles involved and the contexts in which these interactions occur.

4. Theoretical framework

In the final aspect of the concept map activity, we included three theory names—Quantum Electrodynamics, Electroweak Theory, and General Relativity—in the pre-populated word list. While students were not explicitly asked to incorporate theoretical frameworks, their use (or omission) of these terms offers insight into how students connect abstract physics concepts to the fundamental interactions. Notably, Quantum Chromodynamics (QCD), which describes the strong interaction, was not included in the list, allowing us to observe whether students would spontaneously add it.

Students' approach to this aspect varies. Three students (S1, S2, S3) did not include any theory names in their maps. Among the remaining four, S4 and S6 correctly matched all three pre-listed theories to their corresponding interactions. S5 accurately paired electroweak theory with both the weak and electromagnetic interactions but did not explicitly connect QED to electromagnetic interaction or general relativity to gravity. S7 mentioned all four relevant theories, including QCD, but only paired three of them with the appropriate interaction types. Interestingly, S7’s concept map was structured around a theoretical framework, including additional terms such as classical mechanics and Newtonian gravity, with particle names playing a more peripheral role.

Across all seven students, none spontaneously added “QCD” to represent the strong interaction, though its absence is understandable. Like the other theories listed, QCD represents advanced content—typically introduced in graduate-level physics—and may not be deeply integrated into students’ mental models despite being mentioned in the course.

The small sample size limits definitive conclusions about response variability, but it may reflect the higher-level cognitive demands of connecting interactions to the theories that describe them. Unlike identifying particles—which relies on recall—associating interactions with theoretical frameworks requires synthesizing knowledge, a higher-order skill. Our findings suggest that some students are beginning to make these connections, but others may benefit from more explicit support to bridge their conceptual understanding with underlying theoretical structures. Further study with a larger sample is needed to fully explore students' relationship with theoretical frameworks in this subject.

IV. CONCLUSIONS AND DISCUSSIONS

We adapted Gourlay’s concept-mapping activity [11] for use in an online environment, enabling participants to create and modify their own maps in real time. This adaptation provided a flexible and accessible way to explore how undergraduates in a particle physics course organized their knowledge across four key areas: particle types, properties, interactions, and theoretical frameworks. While students demonstrated strong factual recall—especially regarding particle categories and mediators—their concept maps revealed gaps in structural understanding. Common challenges included navigating overlapping classification systems, fragmented reasoning about quantum properties, and imprecise use of terms like "mediates."

These findings suggest several instructional opportunities. Instructors might provide more explicit scaffolds for classification (e.g., fermion/boson or fundamental/composite distinctions), clarify links between properties and interaction behavior, and support integration of abstract theoretical concepts. Concept mapping also shows promise as a tool for surfacing student reasoning and guiding instructional refinement.

This study also highlights a viable method for conducting education research in online settings. Using Zoom to screen-record students’ workspace, along with automated transcription, streamlined the data collection process and allowed rich analysis without in-person interviews—enabling research to keep pace with online instructional environments.

As a small, self-selected sample, these findings are not broadly generalizable. However, they offer insights into how students reason about advanced topics in a non-quantum-mechanics-intensive course. Future work may examine how concept map structures evolve with further instruction or in different contexts, including in-person or hybrid courses.

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