Capturing expert mental models of quantum sensing using concept maps

Namitha Pradeep
School of Physics and Astronomy, Rochester Institute of Technology, 84 Lomb Memorial Drive, Rochester, NY, 14623

Benjamin M. Zwickl
Center for Computing in Science Education, University of Oslo, 0316 Oslo, Norway and
School of Physics and Astronomy, Rochester Institute of Technology, 84 Lomb Memorial Drive, Rochester, NY, 14623

Capturing expert knowledge is a common approach in domains that are not yet well mapped out or lack an established body of canonical knowledge. As the need to develop the quantum information science and engineering (QISE) workforce grows, we need to equip students with necessary quantum technology competencies and skills. Quantum sensing receives far less focus in existing curricula compared to quantum computing and communication. There are no standard textbooks, structured curriculum, or established conceptual frameworks for understanding quantum sensing. To address this gap, curriculum developers can draw on the knowledge of experts actively working in the field. This paper presents a methodology for eliciting expert knowledge through semi-structured interviews with a concept mapping activity. We detail the process from participant recruitment to the analysis of the resulting concept maps. Through this approach, we were able to identify detailed mental models of experts on specific quantum sensing protocols. The insights gained from this work will directly inform the development of quantum sensing curriculum and this methodology will be useful for educators and curriculum designers.

2025 PERC Proceedings edited by Pawl, Zwolak, and Leak; Peer-reviewed, doi.org/10.1119/perc.2025.pr.Pradeep

I. INTRODUCTION

The ability to design, fabricate, and manipulate quantum systems and to leverage properties such as superposition and entanglement has led to the rapid development of new quantum technologies that outperform classical systems. As part of this so-called 'second quantum revolution' [1], three pillars of quantum information science and engineering (QISE) have been identified: computing, networking and communication, and sensing. There has been a call to expand the quantum workforce [2], and it is therefore important for these topics to be incorporated into existing curricula, so as to equip students with the necessary competencies and skills.

Quantum sensing refers to the use of a quantum system and its quantum properties like superposition and entanglement to measure any physical quantity [3]. It spans a diverse range of hardware platforms, requires integrating knowledge from many physics subfields, and has a stronger emphasis on concepts related to measurement and metrology, unlike other 'QISE pillars'. Hence, a dedicated curriculum can help connect abstract quantum concepts to real-world sensing challenges while equipping students with interdisciplinary and hardware-based knowledge/skills.

A growing number of QISE courses are currently being offered [4], but the 'QISE pillar' most often emphasized is quantum computing [5]. A survey of 63 QISE courses showed that only 22% include topics related to quantum sensing[6]. Also, none of these courses were dedicated to quantum sensing, while many were focused on quantum computing. This presents a significant gap, as quantum sensing is a rapidly advancing field with real-world commercial applications (e.g., atom interferometer and atomic clocks in navigation, quantum gravimeters, etc.), which have emerged sooner than practical applications of quantum computers [3]. Despite this, there are no standard textbooks dedicated to quantum sensing, and the subject receives little attention in the most widely used textbooks in modern physics, quantum mechanics, and quantum computing courses. Additionally, a survey of experts revealed that they feel less competent in quantum sensing compared to other areas within QISE [7]. Given the rapidly evolving nature of the field, educators have reported that, as non-experts in the field, primary literature is often difficult for them to access and interpret [5]. So in this project, we aim to capture expert knowledge on quantum sensing and use it to develop curricular resources that can be integrated into existing quantum-related courses at the undergraduate level.

Experts possess deeply structured knowledge organized in intricate networks, where the activation of different parts of the network is context-dependent [8]. Their mental models consist not of isolated facts, but of meaningful patterns that are closely aligned with disciplinary norms. This has been demonstrated through numerous studies across a range of disciplines, including computer science [9], history [10], and mathematics [11]. The structure of mental models, such as hierarchical versus single-level organization of information, also impacts performance on tasks [12]. Therefore, eliciting and characterizing expert knowledge and understanding how experts organize their mental models is valuable not only for teaching novices but also for supporting the development of proficiency in general.

Cognitive Task Analysis (CTA) is a method used to understand how individuals structure their knowledge and apply their cognitive skills and strategies to complete a task. There are various approaches within CTA, including the Critical Decision Method, Work Domain Analysis, Task-Knowledge Structures, and Concept Mapping [13]. Concept mapping is a technique for visually organizing information in which the relationships between different concepts and propositions are explicitly represented. It was originally developed by Joseph Novak's research group in the 1970s as part of a long-term study investigating the impact of early instruction in basic science concepts on later science learning [14].

Research using concept maps on experts has primarily focused on eliciting mental models and decision-making processes of professionals - insights that can be used to construct sophisticated knowledge frameworks and support instruction. For example, concept mapping has been used to identify the tacit dimensions of clinical expertise [15], to model the reasoning processes of weather forecasting experts [16], and to develop expert-guided models of health literacy [17]. In addition, concept mapping has been used to elicit canonical disciplinary knowledge held by experts. Examples include eliciting experts' understanding and representations of statistics [18], mapping the content of engineering statics curricula to enable information visualization for educational purposes [19], and exploring how experts contextualize concepts related to sustainability [20].

In this paper, we describe in detail our methods for eliciting expert knowledge on quantum sensing using semi-structured interviews in which a concept mapping activity played a central role. We outline the interview protocol, explain how the concept mapping activity was carried out, and discuss our approach to analyzing the maps. The goal of this paper is to explain a research method that shows promise, but has rarely been used within physics education. Concerning the authors' positionality, our research background includes both quantum PER and QISE.

II. METHODS: DEVELOPING A CONCEPT MAP

Participants and Recruitment - Our target population include advanced graduate students, postdoctoral researchers, faculty, or research scientists from academia or industry who are working on quantum sensing or related platforms. People in these roles who have worked on sensing-related projects for a reasonable amount of time (around 2 years or more) can be considered experts for the purpose of our study because they have domain-specific knowledge and practical experience modeling or experimenting with devices.

We conducted a broad search within the network of re-

searchers we knew were actively working in the field of quantum sensing to identify individuals from diverse sensing backgrounds who met our criteria for expertise. We contacted them via email and scheduled interviews with those who agreed to participate. We have conducted five interviews so far, with two graduate students, one postdoctoral researcher, and two faculty members.

Interview preparation and training - About a week before the interview, we share training materials with the participants to help them prepare for the interview. This includes a short tutorial video we created on how to use Lucidspark, a virtual whiteboard software used for the concept mapping activity. The video provides a brief overview of what a concept map is, along with basic instructions on using Lucidspark - such as how to create sticky notes (to represent concepts), make connections between concepts, and navigate the interface. In addition to the video, we provide a practice concept map on the topic of quantum measurement that participants can view and modify before the interview. Participants are encouraged to engage with the practice map by adding new concepts, editing existing ones, and creating new connections in order to become familiar with both the concept mapping process and the Lucidspark platform. We also share an outline of the interview protocol in advance so that participants know what general questions to expect during the session.

Interview and concept mapping activity - The interview is conducted on Zoom and is fully recorded with the participant's consent. Each session typically involves two interviewers, with one interviewer primarily focusing on asking the questions and following up on the responses, while the other helped out with the concept mapping activity. The interview begins with a few background questions about the participant's experience with quantum sensing, the type of platform they work on, and any prior experience teaching sensing-related content. Following this, the interview is organized into three main sections - exploring the big picture related to sensing, focusing on the participant's specific platform of interest through the concept mapping activity, and finally, discussing ideas for teaching quantum sensing.

In the first section (lasting approximately 10 minutes), we aim to understand how experts conceptualize quantum sensing and metrology more broadly. For example, we ask how they differentiate between quantum and classical sensors, how they contextualize quantum advantage, and how they distinguish between sensing and measurement.

Next, we move on to the main portion of the interview, in which participants engage in a concept mapping activity while discussing a specific quantum sensing platform, how it works, and the foundational ideas necessary to understand it. Participants are first asked to give a brief outline of the quantum sensing platform they would like to focus on. As they respond, one of the interviewers identifies concepts mentioned and places them in a temporary holding space, called the "parking lot" (see Fig. 1A). Around 10-20 concepts are typically identified at this stage, depending on how detailed the initial description is. On Lucidspark, we use a framed region on the board as the parking lot and use digital sticky notes to represent individual concepts. Once this initial stage is complete, participants are invited to open the Lucidspark document on their own computer to begin constructing the concept map. Since Lucidspark supports real-time collaboration, both the interviewers and the participant can work on the map simultaneously. We also share our screen on Zoom during this time so that the entire mapping process is included as part of the Zoom recording. We then prompt participants to start with the ideas in the parking lot, move these ideas on to the 'mapping canvas', group and arrange them spatially, and make explicit connections between them that indicate the nature of their relationships. Arrows with text are used to show relationships between concepts. As much as possible, we encourage participants to physically move the sticky notes, organize related ideas, and draw links while thinking aloud. Throughout the process, interviewers use follow-up prompts to elicit additional information, leading to the addition of new concepts and connections. For example, if a participant mentions the Ramsey sequence and the Bloch sphere, we might follow-up on related topics like visualization of the sequence using Bloch sphere, other geometric or mathematical representations, etc. Our goal is to capture the complete sensing protocol being discussed - from the initial steps (e.g., state preparation), measuring the final state of the system, and inferring the value of the sensed quantity (e.g., magnetic field strength), and most of the questions are centered around that. At each stage, we prompt participants to articulate the underlying physics required to understand the process. Toward the end of this section, we also ask about other relevant aspects, such as quantifying sensor performance, potential application areas, and what features make the sensor distinctly "quantum". This concept-mapping portion of the interview typically lasts around 40 minutes.

The third and final section of the interview, lasting approximately 10 minutes, focuses on ideas for teaching quantum sensing. We ask the participant to reflect on what undergraduate-level physics concepts are required for understanding the ideas presented in their concept map. We also try to identify common student misconceptions or difficulties related to sensing or sensing-adjacent topics that they might have encountered. A key part of this section is discussing any "toy models" they might be familiar with that can be used to teach sensing concepts that are made visible in the concept map. While we do not necessarily engage with the concept map during this section, we might revisit it to add new concepts or connections if something significant arises during the discussion. This section is kept brief because the key focus of the interviews is on eliciting experts' mental models to identify key concepts, not on teaching methods. As most participants do not generally teach sensing related courses, teaching discussions were minimal. Finally, participants are encouraged to share with us any instructional materials — such as homework problems or class activities— they have developed or used, if possible. The interview concludes with a few optional demographic questions.

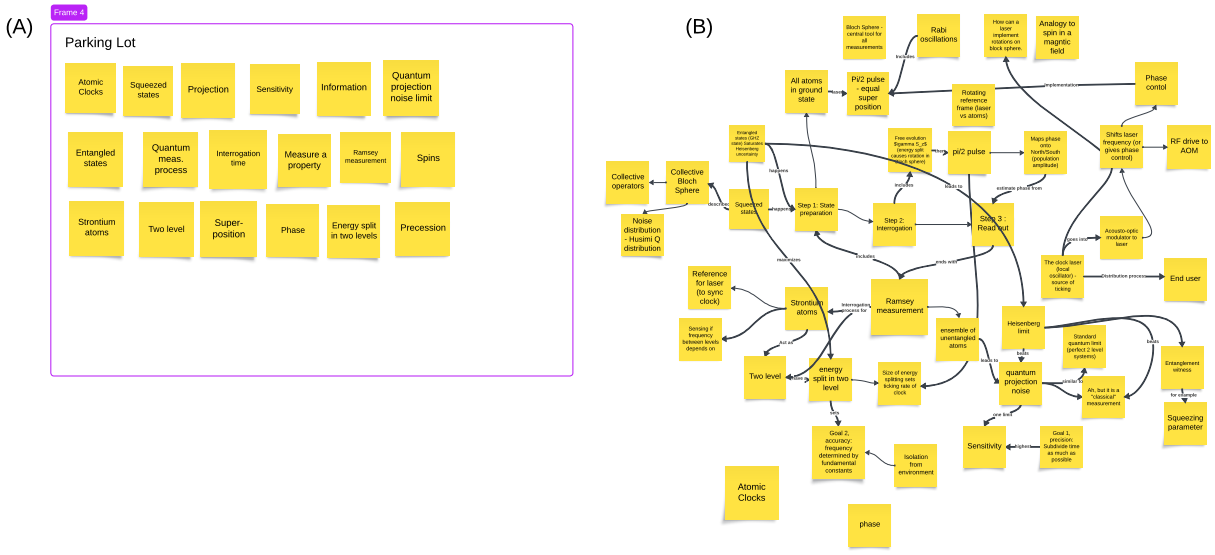

FIG. 1. (A) The original parking lot made during the first stage of the interview and (B) the concept map made by the expert

III. RESULTS: EXAMPLE CONCEPT MAP

Fig. 1 shows the initial parking lot created during the first stage of the interview (A) and the final concept map created by the expert (B). After the interview, our analysis of the maps involve two rounds of revision. In the first round, we review the interview recordings and add any missing concepts, connections, or connecting words that were mentioned verbally by the expert during the interview but not captured on the original concept map. To distinguish these, we use color coding to differentiate between concepts added during the interview and those added during the analysis. In the second round, we add additional concepts and connections where clarification is needed. We also add extra notes where supplemental information would enhance our understanding of the map. We then identify meaningful clusters of concepts and make a note of these. Any ideas related to teaching quantum sensing that arose during the final portion of the interview are also added to the map, provided they are relevant and can be directly linked to existing concepts. These are also color coded to indicate that they are ideas related to teaching. Fig. 2 shows the map from Fig. 1 after final revisions.

One of the key goals of this project is to synthesize the individual concept maps and construct a high-level map representing a conceptual framework for quantum sensing, integrating ideas across multiple platforms. As a first step toward this goal, we tried to identify common themes or models across the expert maps. From the data collected thus far, we found that the model of an interferometer (i.e., the typical procedural sequence of interferometry) appears repeatedly across some sensing platforms. These sensing protocols (for example, atom interferometry for gravitational sensing) can be directly mapped onto this template of an interferometer. From an instructional perspective, this suggests that the interferometer model can serve as an effective entry point for teaching quantum sensing concepts and protocols. The details of this model are beyond the scope of the current paper and will not be discussed in detail here.

Issues / Challenges - Participants engaged with the concept mapping activity in different ways depending on how comfortable they felt with the Lucidspark interface. Some found it easy to create the map while thinking aloud, and even shared that the process of organizing concepts and making connections helped them clarify their own mental models. Others, however, seemed to experience cognitive overload and found it challenging to think, talk, and construct the map simultaneously. To quote the feedback from one of the participants, *"Thinking and working through the map and trying to speak at the same time was a little tricky..."*. Many participants also reported never having used Lucidspark before, which impacted their involvement in the mapping process. In such cases, the interviewers took a more active role adding content to the map that matched the interviewee's verbal discussions. The interviewee could see all the changes and provide additional feedback or comments in real time. The interviewer would also prompt the participant to explicitly talk about the relationships between concepts.

Another difficulty in this approach was ensuring that we captured as much as possible of the experts' mental models; not only the broad ideas, but also the finer details of the sensing protocols. Additionally, the discussion would sometimes move into some tangential topics, so to address this, we use a set of scaffolded and targeted prompts to guide the conversation back toward the main sensing protocol. These prompts would provide a general structure for the mapping process while still allowing enough flexibility to explore the ideas the participant mentions and discuss any necessary tangents.

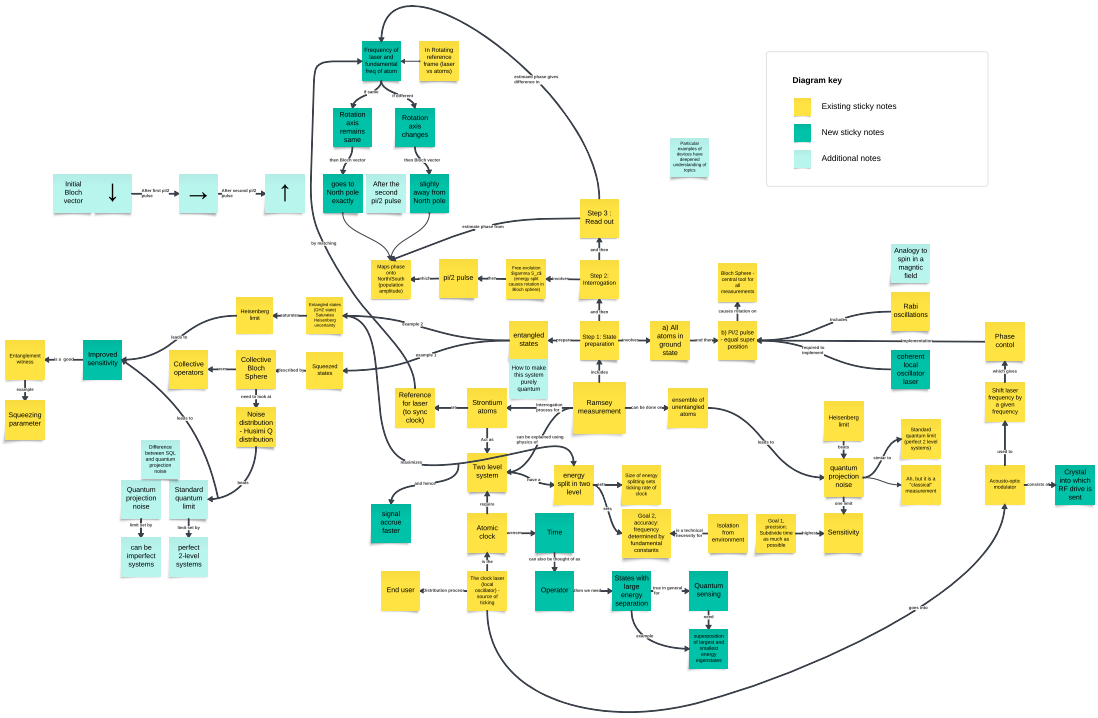

FIG. 2. The concept map after two rounds of revision. The yellow sticky notes are the concepts from the original concept map, the teal blue sticky notes were added to the map during analysis, and the light blue sticky notes represent additional notes made during analysis to clarify some ideas on the map.

IV. DISCUSSION

Here we have outlined a methodology for eliciting expert knowledge on quantum sensing through the use of concept maps in semi-structured interviews. The goal of this paper was to share a technique for uncovering experts' complex mental models. This approach is particularly interesting because it allows us to visualize expert knowledge in a way that reveals both the structure and depth of understanding, including connections between foundational ideas and advanced applications. Although concept mapping has not been widely used in physics education research to elicit expert knowledge, this work suggests that this method could be a powerful tool for this purpose, with the potential to support instruction and curriculum design. Some challenges of this methodology include capturing all the specific details, maintaining focus on the sensing protocol while allowing sufficient flexibility, and managing participants' cognitive overload.

Using this method, we have been able to generate rich and detailed concept maps that effectively visualize sensing protocols, along with the foundational ideas necessary to understand them. Our longer-term goal is to synthesize several individual maps into coherent knowledge structures or conceptual frameworks that can support the teaching of quantum sensing. This synthesis, however, presents a significant challenge due to the diversity of sensing platforms, each with its own theoretical basis and implementation. For this synthesis, we plan to first identify any toy models or common conceptual structures that appear across multiple maps.

We plan to conduct additional interviews with experts across a diverse range of sensing platforms and hardware. Identifying coherent conceptual frameworks for quantum sensing from the concept maps will inform our curriculum development efforts. By identifying meaningful connection points between the existing intro-level quantum curriculum and the novel ideas on quantum sensing, we plan to bridge the two, similar to efforts to guide curriculum structure in statistics [18] and engineering statics [19].

These concept maps can be useful tools in lesson planning, as they highlight the key concepts used across different sensing platforms, making it easier to identify what ideas should be included in instruction. Their visual structure also reveals the hierarchical relationships among concepts, indicating which ideas build upon others. This could be particularly useful for designing learning progressions and also for developing modular curricular resources that can be integrated into existing courses. Hence this methodology can be very beneficial for both instructors and curriculum developers working to incorporate any topic into the broader curriculum, as it will help to identify what to teach in a course and when.

We thank Dr. Gregory Howland for his valuable input and feedback on the interview protocol and analysis. This work is funded by NSF Award 2315691.

[1] J. P. Dowling and G. J. Milburn, Quantum technology: the second quantum revolution, Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences **361**, 1655 (2003).

[2] L. R.-T.-. Rep. Smith, H.R.6227 - 115th Congress (2017-2018): National Quantum Initiative Act (2018), archive Location: 2018-06-26.

[3] C. Degen, F. Reinhard, and P. Cappellaro, Quantum sensing, Reviews of Modern Physics **89**, 035002 (2017).

[4] A. R. Pina, S. El-Adawy, M. Verostek, B. T. Boyle, M. Cacheiro, M. Lawler, N. Pradeep, E. Watts, C. G. West, H. J. Lewandowski, and B. M. Zwickl, Landscape of Quantum Information Science and Engineering Education: From Physics Foundations to Interdisciplinary Frontiers (2025), arXiv:2504.13719 [physics].

[5] J. C. Meyer, G. Passante, S. J. Pollock, and B. R. Wilcox, Today's interdisciplinary quantum information classroom: Themes from a survey of quantum information science instructors, Physical Review Physics Education Research **18**, 010150 (2022).

[6] J. C. Meyer, G. Passante, S. J. Pollock, and B. R. Wilcox, Introductory quantum information science coursework at US institutions: content coverage, EPJ Quantum Technology **11**, 16 (2024).

[7] F. Greinert, R. Müller, P. Bitzenbauer, M. S. Ubben, and K.-A. Weber, Future quantum workforce: Competences, requirements, and forecasts, Physical Review Physics Education Research **19**, 010137 (2023).

[8] *How People Learn: Brain, Mind, Experience, and School: Expanded Edition* (National Academies Press, Washington, D.C., 2000).

[9] E. Soloway and K. Ehrlich, Empirical Studies of Programming Knowledge, IEEE Transactions on Software Engineering **SE-10**, 595 (1984).

[10] S. S. Wineburg, Historical problem solving: A study of the cognitive processes used in the evaluation of documentary and pictorial evidence., Journal of Educational Psychology **83**, 73 (1991).

[11] M. Inglis and L. Alcock, Expert and Novice Approaches to Reading Mathematical Proofs, Journal for Research in Mathematics Education **43**, 358 (2012), publisher: National Council of Teachers of Mathematics.

[12] B.-S. Eylon and F. Reif, Effects of Knowledge Organization on Task Performance, Cognition and Instruction **1**, 5 (1984), publisher: Taylor & Francis, Ltd.

[13] B. Crandall, G. A. Klein, and R. R. Hoffman, *Working Minds: A Practitioner's Guide to Cognitive Task Analysis* (The MIT Press, 2006).

[14] J. D. Novak, Human constructivism: A unification of psychological and epistemological phenomena in meaning making, International Journal of Personal Construct Psychology **6**, 167 (1993).

[15] I. Kinchin, L. Cabot, and D. Hay, Using concept mapping to locate the tacit dimension of clinical expertise: Towards a theoretical framework to support critical reflection on teaching, LEARNING IN HEALTH AND SOCIAL CARE **7(2)**, 93 (2008).

[16] R. R. Hoffman and J. W. Coffey, Weather Forecasting and the Principles of Complex Cognitive Systems, Proceedings of the Human Factors and Ergonomics Society Annual Meeting **48**, 315 (2004).

[17] R. Soellner, N. Lenartz, and G. Rudinger, Concept mapping as an approach for expert-guided model building: The example of health literacy, Evaluation and Program Planning **60**, 245 (2017).

[18] N. C. Lavigne and R. Glaser, *Assessing expert knowledge representations of introductory statistics (CSE Report 600)* (Los Angeles: University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST), 2003).

[19] J. Moore, R. Pierce, and C. Williams, Towards an "Adaptive Concept Map": Creating an Expert-Generated Concept Map of an Engineering Statics Curriculum, in *2012 ASEE Annual Conference & Exposition Proceedings* (ASEE Conferences, San Antonio, Texas, 2012) pp. 25.1365.1–25.1365.13.

[20] J. Segalàs, K. F. Mulder, and D. Ferrer-Balas, What do EESD "experts" think sustainability is? Which pedagogy is suitable to learn it?, International Journal of Sustainability in Higher Education **13**, 293 (2012), publisher: Emerald Group Publishing Limited.