Conceptual understanding of quantum physics across varying levels of expertise

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Conceptual understanding in quantum physics acts as a bridge between the abstract mathematical framework and the physical reality it describes, fostering intuition, guiding research, and enabling communication. Although, accurately pinpointing or describing an individual's conceptual understanding is challenging, language, imagery, and gestures could offer a proxy, as is suggested by Conceptual Metaphor Theory (CMT). A core idea in CMT is that we understand abstract concepts by relating them to concrete physical experiences or familiar knowledge via metaphors, images, or actions. Adopting a CMT perspective, this poster explores how individuals, across varying levels of expertise, express a conceptual understanding of quantum physics. Through classroom observations, focus groups, and interviews with expert-physicists, physics teachers, and students, recurring metaphorical mappings within the field of quantum physics were identified. The findings revealed increasingly interconnected metaphorical structures with greater expertise: experts demonstrated richer, integrated networks of metaphors, while novices showed fragmented and less developed conceptualizations.

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I. INTRODUCTION

Given the growing relevance of quantum mechanics in cutting-edge industries, a basic understanding of its principles is valuable even for those who won't pursue a career in physics [1]. To ensure the general population understands its counterintuitive, probabilistic nature, quantum concepts should be introduced early. However, since most high school students lack the mathematical prowess for its complex formalism, instruction at this level must focus on building a strong conceptual foundation. This early conceptual understanding is also crucial for physics students, as a weak grasp of quantum mechanical core ideas can hinder more advanced learning later on [2].

The challenge lies in defining what this "conceptual understanding" truly entails, and how we can measure it. Conceptual metaphor theory, a framework within embodied cognition, posits that our conceptual understanding stems either from direct sensory-motor experiences or from making connections between abstract concepts and these physical activities through conceptual metaphors [3]. These conceptual metaphors can be expressed through language, images, and gestures, and can give us an observable way of describing and measuring conceptual understanding.

Conceptual metaphors are essential for teaching and learning physics and are used extensively by physics teachers and physicists alike [4, 5]. Without them, abstract physics, such as quantum mechanics, has no grounding in the world and meaning making, arguably, cannot be achieved [6]. To improve instruction, we can compare expert and novice conceptual metaphors to see how to build a more robust understanding.

A. Research Aim

If the primary aim of instruction is to cultivate expertise, then a comparative analysis of novice and expert conceptual understandings is important: by comparing these two groups, this study provides a blueprint for what expertise looks like, offering crucial insights that can lead to more targeted and effective teaching methods. Therefor, the research question guiding this study is: How do the metaphorical frameworks for quantum physics differ between novices and experts?

This paper introduces conceptual metaphor theory, outlines a research design guided by it, and presents findings that compare expert and novice understanding through conceptual maps, concluding with the pedagogical implications for quantum physics.

II. THEORETICAL BACKGROUND

Conceptual metaphor theory proposes that our understanding of abstract concepts is rooted in our physical engagement with the world [3,7–9]. The central claim of this theory is that abstract concepts, such as those that define quantum physics, can only be understood metaphorically in terms of more concrete knowledge structures, facilitating meaning-making and reasoning. The theory indicates that a conceptual metaphor operates by mapping from a concrete source domain to an abstract target domain, and it may be linked to language but can also manifest in the form of models, gestures, visuals, and bodily activities [10, 11, 12].

In this study, quantum mechanics serves as the abstract (and target) domain. This field is inherently abstract and challenging to visualize through direct experience, leading to the heavy reliance on conceptual metaphors within its discourse [4]. Consequently, the conceptual understanding of quantum mechanics can be mapped by examining the specific conceptual metaphors employed to describe core ideas, such as entanglement, quantum tunneling, or superposition.

For instance, some common conceptual metaphors within the quantum physics domain revolve around wave-particle duality and quantum entities, such as electrons and photons, can be viewed as waves or as particles [13]. Quantum physics suggests that sometimes these entities act as particles, but on other occasions, these entities act as waves, therefore seeing them as both as a wave and a particle is essential to quantum physics understanding, even though these metaphors are considered contradictory. For a novice, it is often easier to settle on one metaphor [4] and typically this is the ELECTRON AS A PARTICLE metaphor, possibly because particles are easily visualizable [13]. But this would give us a false sense of understanding of what the electron actually is, and how it acts. Therefore, seeing the ELECTRON AS A WAVE is an essential addition to our quantum physics conceptual knowledge. Other conceptual metaphors are used for light and for other phenomena, such as superposition and entanglement [14].

Consequently, grasping abstract scientific concepts may necessitate the use of multiple metaphorical mappings across diverse contexts [15]. Although conceptual metaphors are overarching, abstract, and systematic mappings between two conceptual domains, they do not usually provide a one-to-one mapping [16]. Instead, the mappings are said to be incomplete, yet flexible, and dynamic. Each conceptual metaphor provides a partial understanding of the concept and at the same time hides other understandings [5, 11].

Single analogies can be misleading and/or incomplete, particularly for understanding and communicating complex topics [16–18]. Therefore, teachers and experts typically employ multiple analogies and metaphors. For teachers, it is important to layer these metaphors in a manner that scaffolds meaning because different metaphors prove productive for teaching various aspects of related knowledge [5]. For experts, the process of layering analogies and conceptual blending contributes to the increased abstraction of ideas [18]. In fact, expert physicists easily switch between different metaphors to ponder or explain complex ideas, moving from general concepts to specific calculations adapting them to different levels of conceptual

understanding [17]. In addition, experts in the field of quantum physics adeptly employ and coordinate a range of conceptual metaphors that are not even coherent and can jump between these seemingly conflicting metaphors with ease, as they see necessary [4, 6].

Conceptual blending theory asserts that conceptual blends, or integration networks, are the key for developing more complex ideas [16–18]. Conceptual understanding is not the result of a single mapping but involves multiple components and achieves systematic compressions or automatizations, which allow for more efficient processing of complex conceptual structures. Moreover, the understanding of complex concepts in these integration networks emerges from the robust network, allowing for simultaneous access to all nodes, relationships, and dynamic nature of the metaphorical network blend [16]. The more metaphors and the more intricately connected the metaphors are, the more robust the conceptual understanding becomes. This complex network of conceptual metaphors arguably is the conceptual understanding of a concept.

In contrast to experts, novices possess a less developed network of conceptual metaphors. They often treat metaphors as isolated entities, relying on rote memorization rather than flexible application. This limits their ability to seamlessly integrate diverse metaphorical mappings [9]. The comparison of expert-novice conceptual networks for quantum physics is the topic of this paper.

III. RESEARCH DESIGN

The research involved conducting interviews and focus groups with quantum physics researchers, physics teachers, and high school students. These groups represent a continuum of expertise, allowing for a comparison of their conceptual understanding. For brevity, this paper presents two representative conceptual networks, one from an expert and one from a novice teacher, while still discussing the overarching themes found across all participants.

A. Participants & Procedure

Volunteer sampling [19] was implemented to select participants interested in quantum pedagogy research. The sample included ten high school physics teachers, five physics Ph.D. students or postdoctoral researchers working on quantum physics research, four university professors specializing in quantum physics. In addition, 56 high school students were recruited from participating teachers' classes.

To compare participants' conceptual metaphors, I used semi-structured interviews, which offer the flexibility to explore emergent topics while providing a consistent structure for comparison[19]. The interview included questions tailored to each participant group. Expert scientists were asked about their research and their methods for explaining quantum phenomena to novices. Teachers were asked to describe their pedagogical approaches, such as the sequencing of topics and their use of experiments or visuals.

All participants were asked a common set of questions designed to probe their conceptual understanding. These included describing their preferred representations of an electron and a photon, explaining the nature and meaning of the wave function, and discussing other fundamental topics they deemed relevant, like superposition or entanglement.

The interview did not specifically ask the participants to recall the metaphors or analogies they use, although these were prevalent in the conversations. Sample interview questions are listed in Table I.

Table I. Sample questions from the interviews

For Scientist	For Teacher
If you were invited to a high school classroom, how would you answer the question "what is quantum physics?"	How do you describe what quantum physics is all about to your physics students?
When you taught/explained quantum physics to someone not in the field, what were the issues/misconceptions you found with explaining it?	What are the major hurdles for your students to understand quantum physics? What are the easy pieces of the unit that students quite easily understand?
How can an electron be a wave and a particle? What does it look like for the electron to act like a wave? What are some of the ways you picture it? So, for you, What is an electron?	

To ensure a complete record of both verbal and non-verbal communication, all interviews were audio- and video-recorded. This method allowed for the analysis of gestures and drawings alongside the verbal metaphors.

B. Analysis

The interviews were transcribed, with relevant gestures and any images produced by participants. The transcripts were then inductively coded to identify conceptual metaphors for quantum physics concepts. Table II provides a sample of this analysis, showing an excerpt of a transcript, anonymized screenshots of a participant's gesture, and the associated conceptual metaphors.

For some participants, the transcripts were densely packed with quantum conceptual metaphors, while for others, the conceptual metaphors were few and far between.

The coding process involved identifying conceptual metaphors by systematically mapping source domains (e.g., "clouds," "waves") to target domains within quantum physics (e.g., electrons, quantum states). To ensure reliability, this coding scheme was first validated on a sample transcript with a colleague. Following a discussion to refine the approach, the primary researcher then coded the remaining transcripts independently.

After identifying specific source-to-target metaphors, I grouped the source domain instantiations into broader conceptual categories. For example, specific metaphors like "an electron acts like a water wave" and "an electron is a harmonic oscillator," while distinct, were both classified under the overarching conceptual metaphor of ELECTRON IS

TABLE II. Excerpt from a transcript (left column) and coding of quantum conceptual metaphors (right column).

Transcript & Gestures	Code/Metaphor or Analogy
 So you know, you can have photons that are entangled with each other.	Photons can be entangled with each other = gesture of two hands interacting with each other to mimic an entanglement. ENTANGLEMENT IS AN INTERACTION
You can generate those and send those over a network.	Entangled photons can be generated ENTANGLED PHOTONS ARE THINGS THAT ARE GENERATED (FROM NOTHING) Photons (entities) are sent over a network. This also implies that photons can be manipulated by us (i.e. verbs used: generated, send). PHOTONS ARE ENTITIES THAT CAN BE SENT OVER PREDETERMINED PATHS
And then we go over to the to the matter interaction.	Photons can interact with matter. PHOTONS ARE NOT MATTER BUT INTERACT WITH MATTER
And we have a particular platform that we've chosen for this, which is a kind of crystal that has dopants in it and these dopants are the atoms that interact with the light. And they behave sort of like a frozen gas inside of this crystal.	Dopants are like a frozen gas inside the crystal. This is an analogy: the word "like" typically signifies that the participant is aware of analogical thinking. Also, here, crystal is a container, and the dopants reside inside the boundary of the container. DOPANTS ARE LIKE A FROZEN GAS CRYSTAL IS A CONTAINER FOR THE DOPANTS

AN ENTITY WITH WAVE-LIKE NATURE. Grouping similar source-domain instantiations in this way established several broad conceptual categories. On the network map, each of these categories corresponds to a distinct region.

The analysis revealed that the roles of concepts within metaphors were flexible. A concept could act as a source domain in one context and a target domain in another. For instance, in the metaphor ELECTRON IS A WAVE FUNCTION, the wave function acted as the source domain. Conversely, in the metaphor WAVE FUNCTION IS A PHYSICAL WAVE, the wave function became the target domain.

To visualize the data, Python was used to create a force-directed network map for each participant. In these maps, the nodes represent the source and target domains, while the directional edges represent the metaphorical mappings from source to target. This process generated a unique network map for each participant, visually representing their individual conceptual understanding of quantum physics.

IV. FINDINGS

To illustrate the maximum contrast between novice and expert understanding, this section presents two metaphorical networks from opposite ends of the expertise spectrum. The novice example is from a teacher just beginning their physics career, while the expert is a scientist leading a cutting-edge quantum physics lab. While both maps originate from similar one-hour interviews, their representativeness should be considered. The complexity of the expert's map is typical of the expert cohort in this study, in terms of number of nodes and connectivity. In contrast, with only two novice teachers participating, it is difficult to generalize from the presented novice map. Nevertheless, the map's structure and complexity are consistent with the other novice participant.

A. Expert-Novice Comparison

The experts' conceptual networks demonstrated a dense web of interconnected metaphors, a finding consistent with previous research [16, 17]. To illustrate this, Figure 1 presents a filtered view showing only the mappings to the 'electron' target domain. Even in this simplified map, the 'electron' receives 18 distinct metaphorical inputs and shows further complexity through its interconnections with other key concepts, such as the wave function and matter. The analysis also reveals that while the conceptual metaphorical networks of different experts shared common features, each expert also presented unique metaphorical mappings.

Figure 2 shows the novice teacher's metaphorical network, filtered to display only the 'electron' target domain. The network demonstrates low complexity and relies on a limited number of conceptual metaphors, a finding that aligns with literatue on novice understanding [5, 13].

The findings reveal distinct patterns in the metaphorical mappings across the novice-expert continuum. Experts demonstrated more complex and interconnected metaphorical structures. They possessed a wider repertoire of metaphors and exhibited a greater degree of integration between these metaphors. Their mappings often involved multiple source domains contributing to a richer understanding of a single target domain. While there was overlap in the metaphors used by different experts, individual variations were also observed, suggesting unique conceptualizations within the expert community. This implies that while there is a shared understanding within the expert community, their individual experiences and research specializations lead to different metaphorical mappings.

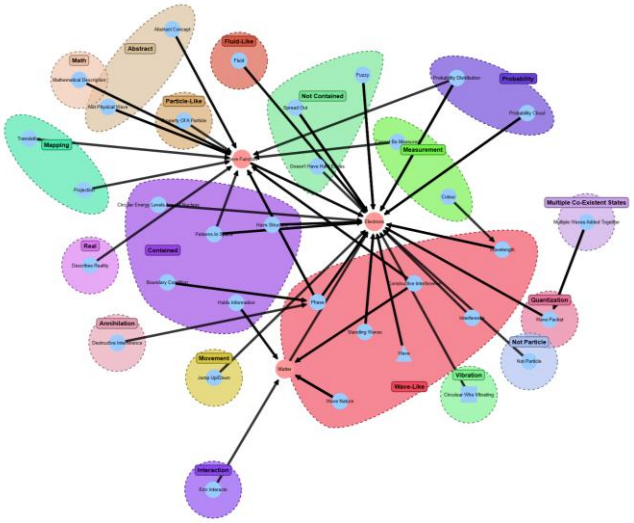

FIG. 1. The conceptual metaphorical network derived from an interview with a quantum physicist, filtered for only the 'electron' target domain. Within this network, colored clusters denote broader source domains. The thickness of each connection reflects the frequency of a particular conceptual metaphor instantiation.

In contrast, novices exhibited more fragmented and less developed metaphorical mappings. They had access to fewer conceptual metaphors, and these metaphors were often isolated and lacked interconnectivity, implying a less nuanced and less integrated understanding of quantum physics concepts. Unlike experts who used integrated networks of metaphors, novices often relied on more literal metaphorical mappings.

Beyond network complexity, a key distinction emerged in the types of source domains favored by novices versus experts. Novices predominantly relied on 'particle-like' metaphors. While they acknowledged wave-particle duality, it often seemed to be a rote recitation; when probed, they frequently admitted not understanding the concept and rarely used wave-based descriptions spontaneously. In contrast, experts more readily employed 'wave-like' source domains. Their metaphorical choices were also more varied and sophisticated, with some favoring the 'wave function,' others using 'probability,' and many drawing on metaphors from their specific sub-fields (e.g., atomic physics, quantum information). This observed shift from a particle-centric to a more wave-centric or abstract framework is a cornerstone of developing quantum understanding, a transition clearly visualized in the network maps of metaphors.

V. CONCLUSIONS

The network maps created for this study visually reveal the profound differences between novice and expert conceptual structures. They succeed because they model understanding not as isolated ideas, but as a complex, blended network of metaphors. This aligns with the cognitive reality that knowledge begins as simple mappings but quickly evolves into an intricate, interconnected system.

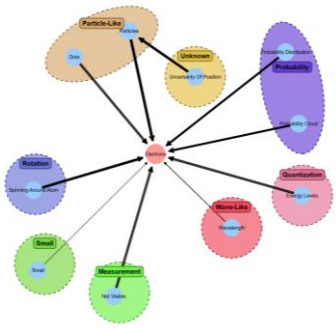

FIG. 2. Novice Teacher's Conceptual Network for the 'electron.' Note the network's lower complexity (fewer metaphors, categories, and connections) compared to that of the expert.

This research demonstrates that conceptual understanding in quantum physics is not a collection of isolated, one-to-one mappings, but rather a complex, blended network of interconnected metaphors. While the expert-novice gap in knowledge structure is well-documented in STEM fields [4-5, 13-14], the primary contribution of this work is the development of a visual network map – a powerful new tool for analyzing and representing this cognitive architecture.

The metaphorical network map offers significant practical applications. It moves beyond simply stating that expert knowledge is more complex; it shows precisely how. The map can reveal conceptual "holes" in a novice's framework, highlight the most prevalent ideas for any individual, and allow for direct comparison between learners. On a larger scale, this tool could be invaluable for curriculum design, helping educators identify which metaphors are already common knowledge and which concepts require more deliberate pedagogical emphasis.

Moreover, this research points toward a crucial pedagogical shift: the need to cultivate "metaphorical literacy" in our students. This framework moves beyond rote memorization to make the use of metaphor a conscious and strategic skill. Instruction designed around this principle would help learners recognize that they often reason through metaphor, that these structures evolve with mastery, and that they have the power to construct, deconstruct, and critique them. By fostering this metacognitive awareness, we can guide students beyond simply using metaphors to a place where they can notice, invent, and evaluate them, leading to a more robust, flexible, and durable understanding of abstract scientific concepts.

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