Exploring Students' Quantum Physics Knowledge Construction through Peer Collaboration and Metacognitive Assessment

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ABSTRACT

This work is included in the Focused Collection of Research on Quantum Education: Exploring and Enhancing It. Quantum physics, one of the most influential physics theories, describes atomic or quantum systems and provide the necessary knowledge for technological advancement. It is based on physical concepts and stated mathematically. Students have a hard time grasping the ideas that require them to abandon their classical thinking, and this is due in large part to the nature of quantum physics knowledge. Students benefited in problem solving, comprehension, and knowledge construction when they discussed quantum physics phenomena with peers, according to earlier study. Based on the kind of quantum physics issues and the organisation of the groups, we observed students' knowledge development in a variety of quantum physics themes via peer conversations. The presence of knowledge creation is linked to factors such as group size and gender makeup, rather than the kind of issues, according to an analysis of students' reflection reports for four sessions during the semester and exams with 45 quantum physics problems. Constructing knowledge in quantum physics relies on group conflicts and contentment with existing knowledge, both of which are influenced by the size of the group.

KEYWORDS: Quantum physics, physics issues, peer conversations etc.

I. INTRODUCTION

Having a solid grasp of quantum physics is crucial for scientists, engineers, and educators in order to propel science and technology forward. This is because quantum technologies provide benefits above current technologies. Teaching and studying quantum physics is tough due to its abstract, counterintuitive, and mathematical character. Several concepts in quantum physics, including the Schrödinger equation, measurement, wave function, Hilbert space, angular momentum and spin, atomic spectra, quantisation, superposition, probability, energy levels and transition, wave-particle duality, uncertainty, Zeeman effect, operators, observables, eigenvalues, and potential wells and tunnelling, have been found to be challenging for students in previous pedagogical studies on quantum physics learning. Students' quantum physics performance varied, and they were unable to properly grasp the concepts taught in various physics classes, according to the study.

The problems with students' thinking were also like those in basic physics classes, including a failure to distinguish between related ideas, an inability to understand formalism, and an overgeneralisation of concepts in context. Underpreparedness, hazy objectives, lack of drive, and the paradigm shift might all contribute to students' struggles in quantum physics, just as they did in classical physics. In contrast, the article explains that students may be struggling in quantum physics because they are incorrectly framing the issues. By using an appropriate epistemological framework in quantum physics learning, effective research-based instructional approaches and materials were created to help students overcome their difficulties, increase their conceptual comprehension, and enable productive problem solving. The developed computer software such as visual quantum mechanics, quantum mechanics visualisation (QuVis), and PhET simulations is designed to assist students in visualising and understanding various quantum mechanics concepts, including but not limited to: matter waves, probability, wave functions, uncertainty, spin, photon, wave packets, photoelectricity, blackbody radiation, hydrogen atoms, and quantum tunnelling. There are quantum physics tutorials that are similar to those for basic physics, such as Quantum Interactive Learning, and Tutorials for Quantum Physics.

The Quantum Information and Learning Tutorials (QuILTs), the Quantum Entities Thinking Tutorials, and the Quantum Mechanics Tutorials in Physics. In a group setting, students may use these resources to improve their reasoning, comprehension, problem-solving, and metacognitive awareness abilities. Students in quantum physics classes were given the opportunity to talk about quantum phenomena with their classmates using an adaptation of the peer education approach that had been created for basic physics classes. Considering that learning is a social process from the standpoint of sociocultural theory, these materials and strategies all aim to improve student engagement in quantum physics classrooms. Furthermore, students may benefit from discussing quantum events in order to develop their own formulations for the recently acquired quantum physics ideas.

Theoretical Framework and Literature

Constructing knowledge and engaging in metacognition Examining how students' social environments impact their cognition, this study focusses on how students build knowledge in quantum physics in groups and how they reflect on their learning. It takes a look at how people learn and how it connects to understanding how people think from a cognitive and sociocultural standpoint.

According to Vygotsky's sociocultural theory of learning, people learn via interacting with one another in social contexts. Collaborating pairs supply the zone of proximal growth that individuals cannot reach alone, which improves common knowledge due to the social character of knowledge building. One probable reason for why students' success in collaborative physics problem solving relies on their interactions rather than their aptitude alone is that in peer problem-solving situations, students do better when they work together rather than alone.

As an alternative, building mental models, which are cohesive systems of information, also requires human interactions. People utilise the information they have previously acquired to provide explanations for occurrences. Individuals' "dissatisfaction" with their prior conceptions is necessary for their knowledge to be reorganised, for either weak or complete change (conceptual change) from a cogni-tive standpoint, as is the new conception's intelligibility, plausibility, and fruitfulness. When peers are unable to resolve the physics issues necessary for knowledge organisation, they may communicate their discontent with their prior beliefs to one another via competing ideas.

Peers play a crucial role in each other's metacognitive processes by providing introspective feedback, just as more informed peers might provide a zone of proximal growth to less knowing ones. Individuals' knowledge and experiences of their own cognition and knowledge-edge relate to metacognition, often known as the cognition of cognition. One aspect of metacognition is knowledge, which is being aware of one's own cognition; another aspect is experience, which is controlling one's own cognitive processing. Some studies in the field of physics education have sought to improve students' understanding of the subject by enhancing their metacognitive knowledge and abilities via classroom activities, as this is seen to be the most potent predictor of learning. Therefore, the cognitive process of building knowledge relies heavily on metacognition. Recent studies have evaluated metacognitive abilities in learning advanced quantum mechanics and shown that metacognition influences the development and maintenance of mental models of quantisation.

Colleagues in the field of quantum physics

Peer groups answer the questions independently in the first round of a two-round physics problem-solving environment, and then they collaborate in the second round. Group problem-solving performance improved in two-round problem-solving situations across a range of chemistry, biology, and physics disciplines. It is possible for some group members to be right and for all members to be incorrect at the same time in the individual round in certain group instances. Two concepts regarding knowledge construction arose from prior research on the topic when taking into account the accuracy of the answers given in the individual round: "co-construction," in which case no one in the group got the question right in the individual round but the group got it right in the group round, and "construction of knowledge," in which case at least one person in the group got it right in the individual round but not all of them. The majority of scenarios (such as questions in an implemented exam) were found to include construction, whereas cocon-construction was less common and happened at different rates. The nature of students' peer conversations during problem-solving activities has also been the subject of some studies in physics education. Students in physics classrooms using Peer Instruction experimented out, implemented, and debated new ideas with their classmates while completing clicker questions. Students worked on tutorials in groups, where they asked and answered questions about the material, addressed practical concerns, laid the groundwork for future discussions, and provided feedback in the form of contemplation, disagreement, confirmation, explanation, and elaboration. Only 38% of students' chats with their peers followed the typical format, wherein they covered all the bases for at least one multiple-choice question and the answers they gave when given clicker questions. Unexpected student ideas, misunderstanding statistical feedback, and conversation traps that lead to ineffective interactions made up the remaining 62% of nonstandard conversations. Students' peer talks may include disciplinary, discursive, and social topics, according to research.

For improved quantum physics learning, it is crucial to have research that examines peer conversations and instructional designs that facilitate peer discussions based on that research. Deslauriers and Wieman looked at how well university students learnt and remembered quantum mechanics concepts. Two classes taught by instructors with backgrounds in engineering physics were used in the research. Both groups received the same amount of instruction, but one group used more conventional lecture techniques while the other used more interactive engagement strategies, such as small group work and peer discussion. Following a few months of testing, the Quantum Mechanics Conceptual Survey (QMCS) was used for retesting. Both groups maintained a high percentage of recall, but the experimental group that received instruction via group projects and other forms of active learning outperformed the control group that received textbook instruction. Similar to the findings of Deslauriers and Wieman, Singh and Zhu found that students' quantum mechanics performance improved when they discussed the topic with their peers. In addition, the researchers looked at how well ConcepTests worked in junior-senior level quantum mechanics classrooms where students were taught by their peers. The students' quiz results were compared across three experimental groups administered across separate semesters, with one control group receiving more conventional training. Students' performance on the ConcepTests showed a significant improvement when they discussed the questions with their classmates in quantum mechanics seminars. On the topic of quantum measurement alone, a comparable result was discovered. Along with other studies on performance improvements, Sayer et al. established a connection between students' ability to create knowledge and their performance in answering questions on quantum physics. Using a tweaked version of peer education in a graduate-level quantum physics course, the researchers examined the impact of group discussions. Various devices, including those that the researchers had developed over the years to answer quantum physics puzzles, were used to gather the data. These included open-ended quizzes, group concept tests (GCTs), individual concept tests (ICTs), and quizzes taken before lectures. The students in these courses were given information and communication technologies (ICTs) to use in a modified way to answer clicker questions on various quantum mechanical subjects, such as the Schrödinger equation, perturbation theory, identical particles, quantum statistical mechanics, and hydrogen atoms. Following their solo rounds, students were to use GCTs to answer the identical questions that had been discussed in their groups. Peer conversations enhanced GCT for all groups, according to the study. There were not many organisations whose partnerships were more fruitful. Researchers also found that 31% of the time, because to what they called the "coconstruction of knowledge," all group members could get the GCT questions right, even when everyone got the ICT questions incorrect in the individual round.

Also covered in was the importance of students working together in a quantum physics course for undergraduates. The "Quantum Mechanics Formalism and Postulates Survey (QMFPS)" was carried out by the researchers.

With "at least one correct answer" in the individual round and "no correct answer" in the group round, researchers compared the group performances using the terms "construction" and "co-construction," respectively, to determine the groups' overall performance. Knowledge building happened at greater rates in quantum physics disciplines, while co-creation was detected at varying rates (0%-71%), according to the data. In their research on the role of peers in knowledge formation, Didiş Körhasan et al. looked at how undergraduate physics and physics teacher education students in Turkey's contemporary physics classrooms were taught to build mental models of the quantisation of physical observables. Peers were recognised as one aspect of the teaching process that impacts students' mental models. Peer interactions were essential for students to build mental models of quantum physics concepts even in a lecture-based conventional classroom. Students' common mental models for the identical instances of the phenomena was revealed via analyses of their social interactions, particularly those involving the closest person with whom they engaged. The researchers highlighted the importance of students' peers in learning quantum physics via the creation of knowledge and connections. In a rather different vein, Bungum et al. investigated the feasibility of small-group talks in the context of quantum physics education by researching pre-university students through the lens of the sociocultural viewpoint on learning. Their goal was to uncover additional impacts of peer discussion. Information was gathered from nine physics courses in seven Norwegian high schools. Students worked in pairs or small groups, and their cellphones recorded 96 peer talks; 55 of them discussed wave-particle duality, while 41 discussed Schrödinger's cat. After reviewing these recordings that allowed for ontological and epistemological enquiries, the researchers came to the conclusion that small group discussions could improve the comprehension of abstract ideas because 70% of the peer discussions were productive talk, with exploratory and cumulative explanations that deepened the understanding of quantum physics. Shi has highlighted the metacognitive and emotional advantages of peer conversations in addition to the cognitive gains.

The impact of social contact between students

Using an experimental design, students from two groups of electronics engineering majors in a Chinese university's introductory quantum physics course learn the fundamentals of the subject. Students in the experimental group were given conceptual questions and were given two chances to answer each issue when the class couldn't reach an agreement. To measure progress before and after the experiment, both the control and experimental groups were given the two-point Chinese version of Ireson's scale. Although both groups' pretest and posttest scores were comparable, T-test analysis of the findings from the one-semester experiment showed that the experimental group students outperformed the control group on the post-test. Consistent peer interactions in quantum physics courses encouraged students to reflect on their own ideas and, if unhappy with them, to seek out alternate perspectives.

Collaborating with classmates in quantum physics classes has been associated with improved performance on problems, deeper understanding, and the creation and co-construction of knowledge, according to prior research on the topic. But, we still need to look at how students and teachers in quantum physics talk to one other about the subject's unique challenges. Take quantum physics as an example. As a mathematical theory grounded on physical principles, what types of issues may be modified for students to engage in fruitful peer debates in this subject? For two-round physics problem-solving, prior studies have looked at how gender composition, group formation, and group type affect group round result. However, it is unclear how this may vary for quantum physics issues. A student's level of self-awareness of his or her own knowledge may also be low, even after engaging in reflective thinking via class discussions. One way to get a better grasp of group dynamics in quantum physics education is to have students reflect on and discuss their actual performance in problem-solving groups. This is why we set out to investigate how undergraduate physics majors build their understanding of quantum physics in groups, taking into account factors like the number of individuals and whether the questions were conceptual, mathematical, or visual in character.

Metacognitive assessments, in which students reflect on their own knowledge and experiences while learning from one another, were another area we intended to investigate. As a consequence, we have the following enquiries for further study:

- What kind of quantum physics difficulties are most often associated with knowledge construction?
- Knowledge creation is more common in what types of groups?
- What methods do students use to reflect on their learning journey as they go along?

In light of these three concerns, it is possible that results from studies on the production and co-construction of knowledge in quantum physics with peers could aid in the development of productive settings for such discussions.

METHODOLOGY

With an emphasis on building quantum physics knowledge via peer debates, this research is a case study, which is described as a "in-depth description and analysis of a bounded system". Quantification of qualitative data was used for statistical tests, despite the fact that the study was qualitative in character and primarily concerned with answering "what" and "how" queries.

A. Sample and course

Participants in this research were third-year physics majors enrolled in an introductory quantum mechanics course. Topics covered in the course include: angular momentum, spin, harmonic oscillator, one-dimensional basic problems, eigen-functions, eigenvalues, operators, and the postulates of quantum mechanics. Prerequisites included engineering mathematics, current physics, and advanced calculus.

Each week, students in Quantum Mechanics I spend two hours learning the material and one hour working on problems. There is a final exam, two midterms, and weekly assignments that all consist of written and open-ended questions. Conventional lecture is the primary method of education. The registered students (N = 40) are expected to actively participate in class during the autumn semester of 2022–23. There are about three times as many female pupils as male students.

Issues and papers in quantum physics

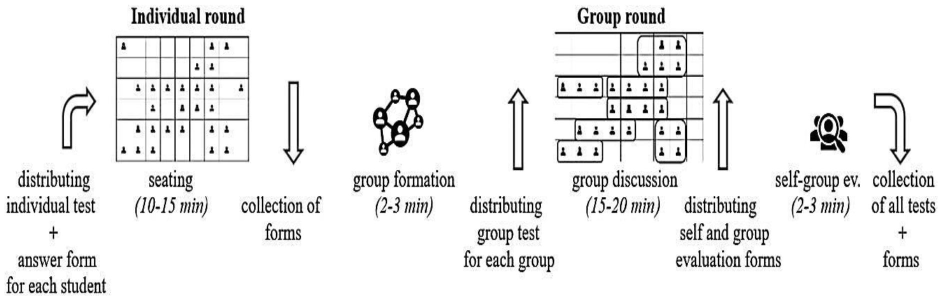
Tests using quantum physics issues and reflection reports (both individual and group reports) provided the data used in this study. The tests were based on quantum physics problems taken from various research-based instruments, including Quantum Mechanics Survey (QMS), Quantum Interactive Learning Tutorials (QuILTs) Quantum Mechanics Conceptual Survey (QMCS), Quantum Mechanics Formalism and Postulates Survey (QMFPS), Quantum Mechanics Conceptual Test (QMCT), Quantum Mechanics Visualisation Instrument (QMVI), and Quantum Mechanics Concept Assessment (QMCA) in PhysPort. The course material informed the selection of 45 research-based multiple-choice questions, with changing numbers of issues for each exam.

By choosing up to three things from a provided list that were most relevant to their experiences, students expressed how the peer talks helped them in the self-reflection reports. in small groups, discussing the topics they chose and providing justifications for their choices (e.g., "I have learnt the concepts that I never knew," "I have learnt the concepts that I knew little," etc.). For the group reports, students were asked to think back on the group discussions and explain why they changed their answers from the individual round. They were also asked to rate how difficult it was to come up with a group answer after discussions and which problems they worked on the most or least well. Furthermore, from the provided list of statements established about conceptual change, students were asked to choose up to three. During class discussion, students reflected on their experiences interacting with classmates. This section sought to determine how many students participated in group talks with the goal of addressing quantum physics issues, and how many of those conversations were fruitful. Students also noted any other concerns in their individual and group evaluations. Student reports, both individual and collective, elaborated on their experiences with quantum physics and the nature of the difficulties and groups they encountered.

Background of the study

Across four sessions spread out over the course of fifteen weeks, students were presented with forty-five tasks pertaining to quantum physics. Implemented after two or three conventional instructor-centered lectures, each group problem-solving session was well-aligned with the subjects covered. In their self-designed groups, students first worked through the challenges alone, and then they discussed possible solutions with one another. In Figure 1, we can see an example of the group problem-solving procedure, complete with student seating arrangements for both the individual and group rounds, as well as the instruments used.

Figure 1 shows that after each of the four lecture hall group problem-solving sessions, students were given a printed exam including quantum physics questions and a response sheet. Every student had around ten to fifteen minutes to complete the exam on their own. On the exam papers and the response sheets, they indicated their solution options and worked through the difficulties. Because we assumed that pupils would make do with their



This was also used to manage potential validity threats, such as the likelihood of members modifying their round responses in response to the responses of other members or group choices. Neither the timing of the exams nor any comments on the individual round were communicated to the students.

Just a few minutes after the solo round ended, students were asked to go into groups for the next phase, where they would have to debate topics with their peers. While this was going on, a few students moved about in their seats to form smaller groups. Every group of students was given a printed group exam. In the group round, students worked in pairs or small groups to discuss and solve each topic. Members of both small groups (two or three people) and big groups (four or more people) tried to engage in more conversation in order to have fruitful discussions. Students in the front rows of a peer group, for instance, would often spin around to face their classmates in the rear. And even when four kids were sitting next to each other, they still spoke quite loudly since they were so near. Students were not permitted to consult any external sources, including the Internet or their textbooks, during either the solo or group rounds of the procedure.

Furthermore, as a precaution to preserve the validity and reliability of research-based instruments, students were not allowed to copy or make notes on the problems. This was done to prevent students from having unsupervised access to the issues. Students were asked to reflect on their experience and share their thoughts and opinions about the challenges, their groups, and themselves using self- and group evaluation questionnaires that were given to them after the group round. After that, we gathered all of the paperwork and exams.

It required half an hour, or one class hour, for each problem-solving session. Details on sessions for group problem-solving are provided in the Appendix. A grand total of 389 instances of peer discussion groups were present in the four group problem-solving sessions, as shown by the number of issues and the number of groups. Each of the four exams included multiple-choice questions in quantum physics, with the suggested range for student responses being 8–14. Between two and six people made up each of the seven to ten peer groups that participated in the group problem-solving sessions. Groups' gender compositions differed. Groups of the same gender match up with the consisting of both male and female students, or a combination of the sexes. With 27–34 students participating over the course of four sessions, we were able to collect 119 individual and group reports (with 3 out of 122 being absent).

A. Using various types of quantum physics challenges to construct knowledge in the field

We used chi-square tests to look at how the kind of issues that were asked in the first study question—"In what kind of quantum physics problems does knowledge construction occur more?"—impact the results. Table III displays the knowledge construction test results broken down by issue type.

that the initial step was to compare the frequency of knowledge creation in the C and CC groups to that in the A, B, and D groups, broken down by the kind of issue (conceptual, mathematical, or visual) using a Chi-square test. Based on the kind of issues, there was no discernible variation in the frequency of knowledge building [χ2 ð2; 389Ð ¼ 1.797; p ¼ 0.407]. Next, a Chi-square test was run to compare the knowledge construction conditions (C versus CC groups) with respect to the types of issues. The results showed that there was no significant difference [χ2ð2; 185Ð ¼ 3.489; p ¼ 0.165].

Additional examination of the knowledge creation is also shown in Table III. To evaluate if there were any variations in the kind of challenges faced by the C1 and C2 groups, which had varying percentages of individual round accurate responses, we used a chi-square test. There was no discernible variation in the construction with respect to the number of right answers in each round, regardless of the kind of issues [χ2ð2; 172Ð ¼ 1.328; p ¼ 0.515]. No significant difference in the co-construction with different types of individual round incorrect answers depending on the kind of problems was found in the final Chi-square test that examined the differences in the co-construction with different types of wrong answers in the CC1, CC2, and CC3 groups [χ2 ð4; 13Ð ¼ 3.993; p ¼ 0.486]. This research disproves the hypothesis that issues arise when comparing constructions with various rates of individual round right responses or co-constructions with distinct sorts of individual round erroneous answers.

There was no statistically significant difference in the students' group report explanations for the questions that asked which issue their group had worked on the best or worse.

When we removed the answers "none of them," "all of them," and "no answer" from the equation, we found that the "best" issue that students worked on had 91 explanations and the "worst" problem had 70. When asked what kind of challenges they had encountered, students most often mentioned visual ones (46.2% for the highest group performance and 41.4% for the poorest). For this study, we used a chi-square test to look at how the students' best and worst issue attributions varied by problem type (conceptual, mathematical, and visual). Depending on the kind of difficulties, no significant variation was found in the attributions either [χ2ð2; 161Ð ¼ 1.185; p ¼ 0.553]. Students' or group members' insufficient understanding of quantum physics subjects and errors made while addressing problems constituted the bulk of the best and worst talks, according to qualitative results, regardless of the kind of challenge. Some students' accounts of positive and negative conversation experiences focused on problems with group communication over reaching agreements and persuading one another, while others highlighted an emphasis on outcomes rather than the discussion process itself, specifically how easily or difficultly they reached accords.

IMPLICATIONS

In our study, numerous factors, including the frequency of knowledge construction, the nature of the knowledge construction, the rates of correct individual rounds, the types of incorrect individual rounds, students' reflections on the best and worst problems discussed, and the fact that the mean percentage of correct group rounds did not vary by problem type, all pointed to the fact that this variable was not significant for quantum physics knowledge construction in self-constructed peer groups. Different contributions, such computation, understanding new phenomena, or reasoning via the principles of quantum physics, aid in the solution process for any kind of issue in situations of knowledge construction. Since similar results may hold true for other areas of physics, In order to examine the effects of different media on students' peer problem-solving environments, such as computers or whiteboards, controlled studies might be planned.

For quantum physics knowledge building, the construction rate (C, 77.8%), is substantial, but 22.2% did not reach the right answer in the group round (D) while there is at least one (but not all) correct response in the individual round. In contrast, eighty-six percent of the time, group rounds were a failure for peer groups whose members had given incorrect responses in the individual rounds. But the remaining group (CC, 14.0%) managed to co-construct the right solution. Peer discussions improved conceptual understanding of concepts like wave function, measurement, Hilbert space, probability, uncertainty, operators, and spin, as shown in prior research and helped with mathematical difficulties. Understanding mathematical forms (such as the square of the absolute value of a wave function) and performing mathematical calculations (such as the calculation of probability and expectation value) using complex numbers, integration, or basic algebraic processes are examples of the structural and technical roles that mathematics plays in knowledge construction. One way in which peer conversations on knowledge production contribute conceptually is by helping to make sense of tunnelling for a genuine particle, which is completely quantum physical behaviour. In another case of co-construction, two same-gender peers have the identical wrong response in the individual round of a scattering issue but get it right in the group round after discussing possible solutions and coming up with the right waveform.

The finding that knowledge construction in quantum physics is solely correlated with group size and gender composition implies that students could benefit from working in larger or more diverse groups when solving problems related to quantum physics. This could lead to higher rates of group round correctness and more evidence of construction or co-construction. The amount of information that might be gained via higher group round results may be shown to instructors through this kind of evaluation. Different applications of two-round problem-solving sessions in physics classes may benefit from the findings of the relationship of knowledge creation condition with group size. If students are just starting out in a physics class and don't yet have well-developed mental models of the material, it may be more effective for them to work in smaller groups for peer discussions rather than larger ones for co-construction. Another option would be for the teacher to look at each student's round wrong responses before forming small groups. The opposite is true when it comes to topic practice; pupils were given the freedom to build their own group projects need more than three people to complete in order to facilitate group construction. This study's findings also point to the need for controlled trials that compare "instructor-constructed" and "self-constructed" peer groups in order to determine how the "instructor" contributes to the development of quantum physics knowledge.

The results of this study show that 61.8% of conversations are productive, which is similar to the findings of another study that found 70.0% of peer discussions to be productive. In this study, students discussed quantum physics concepts through cumulative and exploratory explanations, which deepened their understanding, in contrast to the findings of a previous study that found that nearly 38% of conversations were classified as standard in nature. Since students reported more fruitful talks about mathematically stated topics like quantum physics than about macroscopic matters, it's reasonable to assume that the nature of peer discussion in these two areas is comparable, despite the fact that the student groups are distinct. Students in peer problem-solving situations may engage in physics-related discussions, impart knowledge to others, and engage in metacognitive reflections, but they might converse in a way that results in answers based on tactics for guessing or on inaccurate knowledge that isn't represented in any of the alternatives. Results from this study suggest that groups C and CC were able to successfully construct and co-construct knowledge through weak and radical conceptual change as a result of emergent productive discussions (61.8% of the time), while groups A and D were unable to do so due to unproductive discussions, which included instances of confusion, guesswork, or a complete absence of discussion. Students' reasoning abilities, intellectual activity, and practice interpreting physical formalism may all be greatly enhanced by peer conversations, which are essential for developing a practical grasp of physics. Quantum physics classrooms might benefit from instructors using peer conversations to encourage and support students in constructively discussing phenomena in order to build coherent understanding of the subject and to help students become more self-aware and in control of their own learning.

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