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The Athens Journal of Education

(ATINER)

Volume 7, Issue 3, August 2020

Articles

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The Athens Journal of Education
ISSN NUMBER: 2241-7958 - DOI: 10.30958/aje
ISSN (print): 2407-9898
Volume 7, Issue 3, August 2020
Download the entire issue (PDF)

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The current issue is the third of the seventh volume of the *Athens Journal of Education (AJE), published by published by the Education Unit of ATINER.*

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Gregory T. Papanikos
President
ATINER

Athens Institute for Education and Research

A World Association of Academics and Researchers

23rd Annual International Conference on Education
17-20 May 2021, Athens, Greece

The Education Unit of ATINER organizes its **23rd Annual International Conference on Education, 17-20 May 2021, Athens, Greece** sponsored by the Athens Journal of Education. The aim of the conference is to bring together scholars and students of education and other related disciplines. You may participate as **stream leader**, presenter of one paper, chair a session or observer. Papers (in English) from all areas of education are welcome. Please submit a proposal using the form available (https://www.atiner.gr/2021/FORM-EDU.doc).

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- **Dr. John Spiridakis**, Co-Editor, Athens Journal of Education & Professor, St. John University, USA.
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Important Dates

- Abstract Submission: **19 October 2020**
- Acceptance of Abstract: 4 Weeks after Submission
- Submission of Paper: **19 April 2021**

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The Impact of Mental Computation on Children's Mathematical Communication, Problem Solving, Reasoning, and Algebraic Thinking

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Tess McCafferty[‡]

Moving from arithmetic to algebraic thinking at early grades is foundational in the study of number patterns and number relationships. This qualitative study investigates mental computational activity in a third grade classroom's and its relationship to algebraic thinking and reasoning. The data sources include classroom observations, field notes, students' verbal and written communications, and interviews. The study occurs in two phases; phase one includes establishing roles, rules, and expectations regarding how to talk about mathematical ideas; and phase two involves creating a classroom community that encourages participation, active listening, students' voices, and multiple perspectives. The findings of the study suggest that students' verbal communication enhances their problem-solving, reasoning, and communication. In addition, the findings suggest that creating learning opportunities for all students to do sophisticated mathematics requires competent and caring teachers who know their students' backgrounds, who understand the subject, and have strong pedagogical knowledge.

Keywords: algebraic reasoning, communication, children's mathematical thinking, mental computation.

Introduction

Mental computation refers to the process of working on a problem in one's head and obtaining the exact or approximate answers mentally, without the use of paper, a calculator, or other means (Jordan, Glutting, & Ramineni 2010; Heirdsfield, 2011). Mental computation is important for children to learn, but the focus should not be limited to helping children develop mental computation strategies, but also to develop higher order thinking, reasoning, and critiquing, along with the ability to make sense of numbers and number operations (Carvalho & da Ponte 2013; Erdem & Gurbuz, 2015; Erdem, Gurbuz, & Duran, 2011). It is an important thinking process because it enables children to: learn more in depth about how numbers relate to each other, make decisions about procedures, and create strategies for calculating (Tsao, 2011; Everett, Harsy, Hupp, & Jewell, 2014). Mental computation is the most common form of computation used in everyday life. It is used for quick calculations and estimations, but is more than

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mental arithmetic. When calculating mentally, students select from a range of strategies depending on the presenting problem (Bacon, 2012). As they develop their repertoire of strategies, students select those that are more efficient and effective for them. These thinking processes provide learners opportunities to construct relational understanding and algebraic thinking (O'Nan, 2003; Parrish, 2010, 2011; Obersteiner, Reiss, & Ufer, 2013; Morin, 2017).

Algebra has been considered advanced mathematics for centuries and is typically taught in early middle school in the United States with the rationale being that middle school students have already mastered fundamental arithmetic and are prepared to use their cumulative acquired knowledge in mathematics towards algebraic concepts (Katz & Parshall, 2014; Pyke & LeFevre, 2011). Research has informed academia of the advantages of introducing algebraic thinking in early elementary years to foster a formidable learning of vital mathematics concepts in which children can then understand and apply to their future education (Gargiulo & Metcalf, 2013).

The National Council of Teachers of Mathematics (NCTM, 2000) supports early algebra instruction to promote a foundation of principles and thought processes that will enrich analytical skills throughout life (Knuth, Stephens, Blanton, & Gardiner, 2016). Algebraic thinking permeates through the fields of study of mathematics and is represented in the branches of science, technology and engineering. Algebra is a way of understanding the parts of which make up a whole and how relationships construct meaning. As the United States pushes to improve students' overall performance in mathematics, the focus of how to fundamentally improve the public school system of teaching mathematics has been targeted.

The intention of this research study is to investigate the relationship between children's mental mathematics and mathematical reasoning. The research question is: How do daily mental computations impact children's mathematical reasoning and algebraic thinking? In what follows, we present a review of literature followed by the philosophical and theoretical assumptions of the study. Then the context of the study, design of the study, and the methodology are discussed. In the next section, we discuss the results of the study and the final section of the paper focuses on the discussions and the significance of the study.

Literature Review

Building a repertoire of mathematical reasoning is a long and arduous process but it is one that benefits students' future understandings of mathematical patterns and relationships. The logic of algebra and the basic understanding of the equal sign can impact a student's mathematical path into the future. Providing students with the ability to analyze mathematical relationships in terms of comparable quantities and pattern detection while understanding the function of an equal sign gives them the tools to be successful in more advanced mathematics. Knuth, Stephens, Blanton and Gardiner (2016) investigated a longitudinal study on the impact of early algebraic thinking on third and fifth grade students' success in later school years. Their study, Early Algebraic Learning Progression (LEAP), found that students who received fundamental instruction in algebraic thinking throughout the early grades, demonstrated stronger ability and skills in factors such as the relations of the "equal sign, the function of variables, and the properties of variables in equations" (Knuth, et al, 2016, p. 68).

Similarly, Molina, Castro, and Ambrose (2005) examined how third grade students responded to an introduction to algebraic number sentences over the course of five separate lessons. The study focused on developing relational thinking about the equal sign and identifying patterns in number sentences. Students exhibited understanding by answering true/false number sentences and verbalizing explanations of pattern recognition. Although, due to the small sample size of their study, results of the study were limited; the findings of the study supported interpretations of similar studies (Knuth et al., 2016; Fuchs et al., 2008; Kiziltoprak & Kose, 2017).

In a random sample from 789 second grade students, Powell and Fuchs (2014) compared students with mathematics difficulties in two different areas. They identified the two areas of focus as calculation and word-problem difficulties, in this study that spanned across 12 schools. Powell and Fuchs (2014) found that students who exhibited more challenges with word problems were less prepared for algebraic thinking. These findings also reinforce that students are capable of learning the fundamentals of algebraic thinking and that with additional instruction, students with mathematics difficulties could do better in advanced mathematics in the future. Further, calculation difficulties in early years could be remedied more seamlessly than word problem difficulties. In an earlier study, Fuchs et al. (2008) examined a sample of 89, third-grade classrooms to measure mathematical competence in computation and problem solving. Their findings were consistent with other research studies in that problem solving showed a stronger indication of mathematical encumbrance in algebraic thinking than that of computational challenges.

Congruent interpretations were found by Hart, Petrill, Thompson, and Plomin (2009) when they conducted a longitudinal study of 314 sets of twins in the United States, which assessed "cognitive ability, along with a myriad of mathematical ability in calculation, fluency, problem solving, and mathematical knowledge" (p. 5). Their testing extended into literacy abilities, as well as mathematical comprehension. The study found that word problem deficiencies were directly related to reading and mathematics skills, whereas calculation errors, were not found to have a correspondence with literacy or cognitive abilities.

In a qualitative study, Kiziltoprak and Kose (2017) met with six students in the fifth- grade on eight occasions to examine their "development of relational thinking" (p. 131). The researchers found that "even though [algebra] is first taught in secondary school years, importance should be given to the development of skills and concepts that will facilitate transition to algebra via student experiences and in-class discussions in early stages" (p. 131). They go on to define relational thinking as discerning the relationships between quantities with less concern on the final outcome or answer, but on the understanding the thought process to arrive at the answer based on the most logical relationship. They argue that arithmetic negates establishing relationships and therefore omits opportunities for deeper thinking processes to promote mathematical understanding, as in algebra. Rather, arithmetic is taught as an obscure and narrow sighted thought about one skill at a time. Their findings led them to recommend professional development programs for elementary teachers to incorporate relational thinking and number sense into their instructional approach in mathematics.

Since there is a close relationship between teachers' epistemology on how students learn mathematics and the way they teach it, a single most important factor for transforming the culture of mathematics classrooms is the epistemological change teachers must make on how students learn mathematics. Teachers become more aware of their instructional limitations and are more willing to re-examine their own methods and strategies through reflections on their own teaching and on their students' learning. Hofer and Pintrich (1997) assert that "beliefs about learning and teaching are related to how knowledge is acquired" (p. 116). Similarly, Cobb, Wood, and Yackel (1990) demonstrate how a second-grade teacher integrated affective practices into her mathematics instruction. They state that the classroom teacher's self-reflections on her teaching and her students' learning; her interactions with the researchers; and her active collaboration with her colleagues; were primarily responsible for her epistemological transformation. The classroom teacher promoted independent problem-solving to strengthen student autonomy. The researchers suggest that establishing classroom social norms and clearly communicating expectations regarding the teacher's role and students' role in a mathematics classroom were crucial for creating learning opportunities for all students. In addition, they argue that discussion on how to talk about mathematical ideas, and what constitutes as a viable solution is a significant step toward creating a safe and caring learning community. Building a relationship with students is an important attribute for transforming and sustaining the culture of a mathematics classroom.

Philosophical and Theoretical Assumptions

The Philosophical and theoretical assumptions of this study is grounded in the Autopoiesis (Maturana, 1980, 1981, 1988) and Social Constructivist Epistemology (Cobb, 1994; Cobb, Wood, & Yackel, 1990; Cobb & Yackel, 1996). According to the Autopoiesis, living systems such as humans are structurally autonomous beings. It means they have their own individualities and their own identities. At the same time living beings are interactively open systems, which means they are capable of adapting themselves with new living environment. Maturana (1980; 1981; 1988) calls it structural coupling with the environment and with other beings. These structural couplings and interactions may facilitate, dis-equilibrate, and re-equilibrate one's ways of adaptation but these structural couplings cannot determine the direction and reconstruction of this adaptation. The process of adaptation is complex, non-linear, and probabilistic. Autopoiesis is consistent with Social Constructivist Epistemology (Cobb, 1994; Cobb, Wood, & Yackel, 1990; Cobb & Yackel, 1996). The Social Constructivist's perspective asserts that knowing and learning occur both individually and socially as the learner participates in and contributes to classroom activities. In this sense, knowing is inherently social and cultural activities**.** Autopoiesis and Social Constructivist Epistemology have significant pedagogical implications for transforming the traditional culture of teaching and learning mathematics.

The pedagogical approach tends to be presented either as teacher-centered or as students-centered, rather than exogenic and endogenic. Gergen (2001) presents these terms for educators to reflect on Piagetian theoretical foundations of accommodation and assimilation in the cognitive processes of students with regard to epistemological functioning. While Hofer and Pintrich (1997) contend Piaget prioritized ontogenesis, or individual development, Gergen (2001) posits that the foundation of epistemology lies in social relationships and through those social interactions knowledge is acquired. Therefore, students and teachers are in a position to enhance learning through social interaction and communicative practices that provide meaningful opportunities for multiple perspectives and multiple representations.

Mathematics instruction has traditionally been taught in a direct instruction approach where the teacher is the sole authority for validating the student's answer. In this traditional setting, usually the teacher asks a question followed by the student's response to the question, and teacher's evaluation of the response. The interaction between teacher and students is linear. In this teacher-centered mathematics classroom the emphasis is in the right answer rather than student's thinking process. The NCTM (1989, 1991, 1995, & 2000) addresses the importance of problem solving, reasoning and proofs, mathematical communication, mathematical connection, and multiple representations. Similarly, Confrey (1990) insists students must construct ideas to grow their abilities and knowledge of mathematics across discipline, independent of rote memorization. This motivates students to take responsibility for their learning by "posing, constructing, exploring, solving and justifying mathematical problems and concepts…to develop in students the capacity to reflect on and evaluate the quality of their construction" (Confrey, 1990, p. 112). Breaking the cycle of traditional direct-instruction teaching method may be as simple as engaging teachers in mathematical problem-solving situations so that they can see how it works and reflect on their own pedagogical approaches and transform their epistemologies and practices. Encouraging teachers and students to deviate from direct-instruction methods empowers both to develop thought processes and solutions that may not have been otherwise accessible.

Context of the Study, Research Design and Methodology

The participants in this research study attend an urban school in a Midwestern state during the 2016-2017 school year. The school serves approximately 594 students in Kindergarten through eighth grade. All 34 participants in this action research project are third grade students; 18 boys and 16 girls. The students are in a single, shared classroom with two full-time teachers; both of them are members of the research team. Of the total students, 14 of the students receive gifted services while one student receives special education services.

The study occurred in two phases. The first phase of the study began at the start of the school year and ran until roughly the middle of the second quarter. The second phase of the study started around the middle of the second quarter and ended at the end of the school year. During the first phase, the classroom teachers communicated with the students regarding the rules, roles, and expectations. For example, the teachers communicated with their students how to talk about mathematics, how to listen to one another's ideas and perspectives, and how to challenge each other's solutions during the problem solving activities. Not all students actively participated during the first phase of the study. One of the goals during the second phase of the study was the classroom teachers to encourage more students' voices, multiple perspectives, and student dialogues. Another goal of the instruction was to create autonomous learners who could communicate their thinking and reasoning with confidence. The classroom teachers tried to create a classroom community where critical thinking could thrive and active listening was encouraged.

This qualitative, descriptive, and interpretive research is grounded in constructivist inquiry (Guba & Lincoln, 1994; 1989; Lincoln & Guba, 1985). The study is context-specific by focusing on one third-grade classroom. Data sources include students' notebooks, weekly mental computation quizzes, recorded classroom discussions and debates, the pre- and post-test data, students' reflections on their attitudes toward mathematics and mental computations, classroom observations, and field notes.. An important aspect of trustworthiness of data analysis outlined by Guba and Lincoln (1994; 1989) is triangulation of data. In this study triangulation of data processes occurred in three ways. First, the two classroom teachers triangulated data on daily bases as they interacted with their students every day during their breaks and after school. Second, the primary researcher and the two classroom teachers triangulated data once a month for consistency and clarification of their understanding and interpretations. Third, the data were triangulated via ongoing conversation between the two classroom teachers and students before and after classroom activities as follow-up clarifications and modifications of students' understanding and interpretations. Data collection and data analysis occurred simultaneously using constant comparative analysis (Guba & Lincoln, 1994; 1989; Lincoln & Guba, 1985) for understanding and interpreting the impact of daily mental computations on the students' mathematical reasoning and algebraic thinking

Results

First Phase of the Children's Mental Computations and Communication

During the first phase of the study, the classroom teachers would begin the mathematics activity by giving an interesting and challenging mental computation problem for the students to solve. Then they would allow students time to think and respond verbally. They would encourage students' multiple perspectives and would make sure that the goals of planning were fulfilled (e.g. clear communication, reasoning, and viable solutions). While observing, the teachers would listen actively to students' multiple perspectives and would record their solutions on the board. After all perspectives were presented and recorded on the board, the teachers would invite students to communicate their solutions. Examples below demonstrate the students' mental mathematics activities during the first phase of the study. In this sample, "T" stands for the classroom teachers and "S" stands for the participating students.

T: [She wrote a subtraction problem on the board, 339 - 117. The teachers provided students a wait time to think and respond. Only four students participated by offering their solutions: 223, 236, 234, and 232. The teacher called a student by her name and asked her to present her solution verbally.]
T: S1, please tell us how you got your solution.
S1: I got 222.
T: How did you get it?
S1: Well, I subtracted 17 from 39 and I got 22. [The teacher recorded on the board what the student said verbally, 39 - 17 = 22.] Then, I subtracted 100 from 300 and I got 200. [The teacher wrote on the board 300 – 100 = 200]. Then I added 22 to 200 and I got 222. [The teacher recorded the solution on the board 200 + 22 = 222].

Some students were listening to the classroom conversation. However, not all of them were actively participating and contributing to the classroom activity. The three other students, who presented their solutions differently, accepted their peer's solution without any discussions. As the study evolved, the classroom teachers presented more challenging division problems with the intention of creating learning opportunities and more classroom interactions.

T: [She wrote on the board, 93 / 3. After the wait time she called students for their solutions.]
S1: I changed 93 to 60 and 33. Then I divided 60 by 3 and I got 20. Then I divided 33 by 3 and I got 11. I added 20 plus 11 and I got 31.
T: [She recorded the student's verbal solution on the board]. Very good, any other solution?
S2: I got 31 but I did it differently.
T: Tell us about your strategy.
S2: I changed 93 to 21 and 72. I divided 21 by 3 and I got 7. Then I divided 72 by 3 and I got 24. I added 7 to 24 and I got 31.
T: Very good, any other way that you solved the problem using different method?
S3: I came up with the same answer but did it differently. I changed 93 to 90 and 3. Then I divided 90 by 3 and I got 30. I divided 3 by 3 and it is 1. 30 plus 1 is 31.

There are several important observations regarding the first phase of the classroom activities. First, although the classroom teachers encouraged all students for participation and contributions to the classroom mental mathematics activity, only three or four students were the main talkers and contributors of the activities. The rest of the students were passive recipients of the solution provided by a few students. Second, the main interactions were between the classroom teachers and three to four students. Interactions among students were not present during the first phase of the study. Third, the classroom teachers were the validators of the students' solutions. Dialogues among students were absent during this phase.

Second Phase of the Children's Mental Computations and Communication

As the study changed into its second phase, the classroom teachers used several new strategies for engaging more students in the classroom discussions. For example, they noticed that some students did not answer when prompted with mental mathematics problems. Through conversations with the students, the classroom teachers determined not all felt proficient in their addition and subtraction. Because they were struggling with the basics, adding and subtracting mentally became a burden. The classroom teachers provided their students with opportunities for online practice, hoping this strategy would help some of their struggling students learn the basics. This strategy seemed to bridge some of the gaps students had in their computational knowledge. As students become more proficient in basic computation, they were more willing to take risks presenting their solutions during the classroom discussions. The classroom teachers also decided to add a weekly quiz to phase two for assessing their students' mathematical growth. In addition, during this phase, the classroom teachers spent extra time before and after school conferencing individually with students who were not able to work through problems. Furthermore, they used peer tutoring for those students who were potentially at risk. In what follows, we elaborate on a sample of the students' mental computations and communication during the second phase of the study.

T: [She wrote the problem on the board. 19 X 199. She waited for student to think mentally and then to verbalize their solutions.]

S1: I got 3,781.

T: How did you get it?

S1: Well, I added one to 199 and I got 200. [The classroom teacher recorded 199 + 1 = 200.] Then I broke 19 to 10 and 9. 200 times 10 is 2,000. [The teacher is recording the student's solution strategy 200 X 10 = 2,000. All other students were actively listening and observing.] Then, I multiplied 200 by 9 and I got 1,800. [The teacher recorded 200 X 9 = 1,800.] Then I added 2,000 and 1,800 and I got 3,800. [The teacher recorded exactly what the student said, 2,000 + 1,800 = 3,800.] Then, I subtracted 19 from 3,800 and I got my answer 3,781. [The teacher wrote on the board 3,800 – 19 = 3,781.]

T: Any questions? [Students were thinking.]

S2: Well, I got different answer. I got 3,782.

T: Tell us your strategy.

S2: I added one to 19 and changed it to 20. Then, I added one to 199 and changed it to 200. I multiplied 20 and 200 and I got 4,000. I subtracted 199 from 4,000 and I got 3,801. Then I subtracted 19 from 3,801 and I got 3,782. [The teacher recorded exactly what the student was communicating verbally. 19 + 1 = 20. 199 + 1 = 200. 200 X 20 = 4,000. 4,000 - 199 = 3,801. 3,801 – 19 = 3,782.]

T: Now, we have two different solutions. What do you think? [She was asking the whole classroom community for their reflections and comments.]

S3: [He is looking at the S2 and communicating with him directly.] I think you need to subtract one from 3,782 to get to 3,781.

S2: But why? [S3 couldn't answer S2 question]

S4: Because S1 answer is 3,781 and your answer is 3,782, you need to subtract one from it to get your answer.

S2: I think my answer is correct. Why should I subtract one form it. [S4 couldn't challenge S2 either. The instructional time was almost over.}

T: Obviously, we have differences of opinions. I think we are almost out of our instructional time. I would suggest we revisit this problem tomorrow. I would like you to think and come up with your clear explanation as to which one of these two solutions is correct.

In this episode of the classroom activity, several observations are important to note. First, the direction of the classroom communication shifted from teacher-student communication to student-student communication and dialogues. Second, unlike the first phase of the study, the second phase illustrates the role of the classroom teachers as the facilitators and coaches rather than the dispensers of knowledge and the sole validators of students' solutions. Third, more students' participations and contributions to the classroom activities denote significant shift on the participating students' self-confidence and self-esteem. Fourth, the above episode demonstrates two sophisticated strategies from S1 and S2 for moving from arithmetic to algebraic thinking, namely, distributive properties of numbers. These ways of knowing and doing mathematics is foundation for further mathematical problem solving, reasoning, communication, and algebraic thinking.

The above two solution strategies presented by two students are traditionally known as FOIL Method. Without knowing the FOIL method, the two participating students presented their solutions to the arithmetical problem of 19 X 199 algebraically such as (10 + 9) (200 - 1) or (20 - 1) (200 - 1). Although, the students were not introduced to distributive properties of the numbers, and hence, were not able to defend their ideas in convincing ways, the classroom teachers acknowledged the students' thinking processes. They valued the virtues of not having figure out yet.

Discussions

We noticed several benefits of the classroom mental mathematics activities and communication. In general students became more comfortable with discussing their mathematical ideas, verbalizing their mathematical strategies, and providing each other mathematical supports when they were struggling with understanding various strategies during classroom discussions. As their knowledge about mathematical reasoning grew, students became comfortable challenging each other. Students also became more accepting of having more than one reasonable answer to a problem. It is important that children receive many opportunities to develop the skills and strategies associated with mental computations. Having number sense is necessary to understanding mathematical concepts, yet it is frequently lacking in many of today's elementary schools. Mental computation strategies help children develop higher order thinking, reasoning, critiquing, and making sense of number and number operations. Mental mathematics will not only serve students well in school but outside of the classroom as well. Students who master the strategies of mental mathematics will find that the strategy helps them in many situations.

Not all students will develop rapid mental mathematics to the same degree. Because of the students' different mathematical backgrounds and their different learning styles, some students may find their strength in mathematics through other avenues, such as visual or graphic representations when solving problems. No matter what strategies a student uses, mental mathematics has a clear place in school mathematics. The findings of the study suggest that the participating students developed a strong understanding of number patterns and number relationships. In addition, as they study evolved, the students became better problem solvers and better communicators. The levels of students' reasoning and argumentations significantly increased as they became more engaged in mathematical activities and gained more experience. In addition, their levels of social skills improved in terms of respecting one another's explanations. By actively listening to each other's solutions helped the students transforming themselves from passive recipients of the information to active participants. These achievements became actualized through competent and caring teachers who had both good content knowledge and strong pedagogical content knowledge. They created a classroom milieu conducive to learning mathematics. They trusted that all of their students could learn and do sophisticated mathematics if they were provided with adequate support mechanisms.

Concluding Remarks

The verbal communication among students has multiple benefits. First, it encourages students to reflect and communicate their thinking and reasoning (e.g. meta-cognition) which promotes critical thinking practices. Second, as the students verbalize their solutions, these practices provide the classroom teachers opportunities to assess students understanding and as a result, enhance their learning. Third, the classroom dialogues compel the teachers to reflect on their teaching and inform their instructions.

In addition, the study is significant in two important ways. First, the notion of a caring community was present from the beginning of the study and it continued consistently throughout the school year. The classroom teachers knew their students' backgrounds and built strong relationships with them. They trusted that all of their students could learn mathematics. Second, the students trusted their teachers and valued mathematical problem solving, reasoning, and communication. The students provided each other support during their cooperative learning. They would ask each other for help when they needed it before asking their classroom teachers for help. Incorporating number talk in early elementary by stimulating algebraic thinking seems to foster a foundation for success in a student's future.

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Athens Journal of Education - Volume 7, Issue 3, July 2020 – Pages 255-272

Deploying Engineering-Based Learning in High School Students STEM Learning

By Abe Zeid[*]

Teaching STEM concepts to today's high school students has been challenging. Span of attention is short. Students are glued to their electronic devices. They cannot appreciate the abstract method of teaching, meaning covering concepts followed by solving problems from a textbook. Research has shown that students become excited and motivated to learn STEM abstract concepts when they are related to their daily lives as applied to products and devices. Acknowledging this research finding, the question is how to change the traditional high school teaching approach to incorporate hands-on problem solving? Before we answer this question, we must bear in mind the many academic school year challenges and constraints. First, the curriculum is jammed. There is no room to add new courses. Second, it is hard to add new content to courses. Teachers must prepare students to take mandated standardized tests. Third, schools operate on tight budgets, making it hard to buy materials and supplies for student projects. One common teaching method that overcome these challenges and allow students hands-on experience is problem-based learning (PBL). A teacher using PBL assigns the students in class an open-ended problem that focuses on some STEM concepts. Students research the problem and solve it. The main advantage of PBL is that it helps students solve open-ended problems. It allows a teacher to assign a class an ill-defined problem to solve using STEM concepts. Typically, there is no one solution to such kind of a problem, unlike a science-based problem that has only one closed-form solution. The author has conceived, implemented, and tested an alternative method for PBL. It is EBL; engineering-based learning. EBL has the same spirit as PBL but it has its roots in engineering design. It is the structural nature of EBL that makes it easy and systematic to use in STEM classrooms. The structure is based on the well-known engineering design process. The paper discusses EBL in more details.

Keywords: Engineering-based Learning (EBL), Engineering Design Process (EDP), Open-ended problems, STEM.

Introduction

STEM (Science, technology, Engineering, Mathematics) subjects have been traditionally hard to teach to school students in all grades. The traditional method of instructions is as follows. Teachers develop their lesson plans. They use a textbook. They deliver the lecture in class to students. They solve examples in the classroom and assign problems from the back of the textbook.

This model of teaching has eroded over time and is very much ineffective in

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todays learning, due to many reasons. Today's students grow in different environments and use different daily tools and technologies that were not available decades ago. Electronic tools from computers to cell phones have forged students to use the tools more than thinking about them. Thus, we need to develop new pedagogical methods that fit the learning styles of the students to entice them to pursue STEM careers.

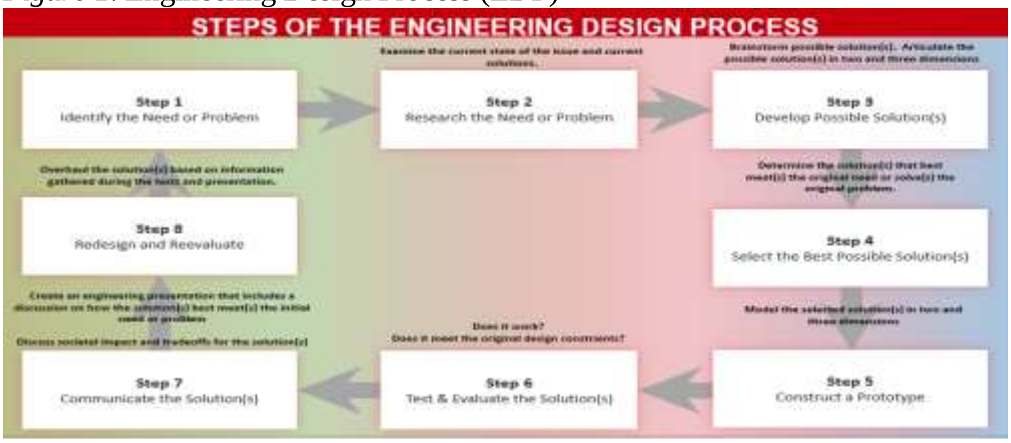
Current STEM teaching methodologies are shown to be ineffective in sustaining long-term interest among school students since they focus on memorizing the theory without providing enough technical integration with real-world applications. A possible solution to alleviate traditional lecture-based approaches is through real-world design challenges.

One method that gained popularity for STEM teaching is PBL. PBL is defined as group learning method to solve challenging problems and had emerged as an incremental innovation in teaching pedagogy that past research has extensively documented its corresponding benefits. Further, PBL has shown the benefits of more experiential learning in school classrooms. A similar method is challenge-based learning (Ktoridou & Doukanari, 2016, p. 61 – 71; YESICT EU project, 2018). It is almost identical to PBL, but a different name.

An alternative method to PBL is EBL. EBL has its roots in engineering design courses taught at college level. The core of these courses are capstone design projects. Capstone design projects present a culmination experience for college engineering students in ABET accredited engineering programs in the US (Dym, Agogino, Eris, Frey, & Leifer, 2005, p. 103 – 120). Students work on open ended projects sponsored by faculty advisors and/or industry. These projects are open ended and could result in patents as well as start-ups. Students work in groups, typically of 4 students for one semester. They present their designs and prototypes to a panel of judges who select the best projects for certificate awards.

What makes these projects successful is the structured engineering design process, shown in Figure 1, that students follow. All students follow the 8 steps shown in Figure 1 regardless of the details of their project. These steps are very important as they focus the students activities in their quest to solve the design problem at hand.

Figure 1. Engineering Design Process (EDP)



As more engineering faculty take on STEM research, they began to use their design thinking in helping high school students and teachers to learn and deploy EDP in their STEM courses.

Literature Review

The research reported in this paper is motivated by national and local needs for STEM/IT workforce and professional development for teachers. The Bureau of Labor Statistics identified IT as the U.S. economy's fastest growing industry (Berman, 2001) for the 2000-10 period. The US Labor Department echoes similar needs (1991, 2000). In Massachusetts, similar observations are made by Boston Redevelopment Agency (BRA, 2001). Regarding professional development of teachers, the National Research Council's (NRC, 2001) reports that "… most teachers lack the professional development and support (e.g., training and release time) needed to incorporate information technology into daily instruction, and as a result, significant numbers of such teachers either ignore the pedagogical uses of technology or use technology ineffectively." Gatta (2001) and Winschitl (2002) have documented the need for allocating more resources for professional development of teachers rather than for just acquiring more computer soft-ware and hardware.

When it comes to the state, Massachusetts Science and Technology/ Engineering Curriculum Framework (Massachusetts, 2003) requires school districts to follow and implement statewide guidelines for teaching, learning, and assessment in science and technology/engineering. All Massachusetts school districts face the challenge of meeting these framework requirements.

Reporting on underrepresented groups for STEM career, the National Research Council (NRC, 2001) characterized the current IT workforce as "predominantly white, male, young, educated, and U.S. born." Gatta (2001; Gatta & Trigg, 2001) has documented the reasons for such imbalance and traces it back to loss of interest in STEM courses among school girls and underrepresented students. Without a core group of girls in STEM classes, female students are at risk of social isolation in the classroom (American Association of University Women, 2000) and not participating in the IT workforce (CIO Insight, 2007; Daley, 1998).

Both girl and African-American and Hispanic-American are most likely to find project-based learning model quite appealing (Hale-Benson, 1986). According to the report "New Formulas for Ameri-ca's Workforce: Girls in Science and Engineering," girls respond positively to hands-on activities (NSF, 2003). Girls of all ages like their math and science to be useful and relevant to their everyday lives. Furthermore, girls prefer clubs, communities, and face-to-face interactions to independent study. Research has shown that traditional classroom instruction methods likewise may fail to engage African-American and Hispanic-American students (Guild, 2001). To a greater degree than their classmates, underrepresented students respond to learning experiences that emphasize oral skills, physical activity, and strong personal relationships (Shade, 1989; Hilliard, 1989). As a result, collaboration, discussion, and active projects in the classroom tend to be more engaging for minority students than work involving independent study and competition (Guild, 2001).

Methodology

The Engineering Based Learning (EBL) methodology is summarized as follows. Engineering faculty and high school teachers work together during summer when teachers are off. The engineering faculty educates and introduces the teachers to EBL. EBL is contrasted against PBL so teachers can understand it quickly. Teachers are then introduced to sample engineering projects. Finally, teachers are requested to map EBL to their classroom teaching by modifying their lesson plans for one course to incorporate EBL and define an open ended design project for the class students. The details of EBL follows.

We use the engineering design process (EDP) commonly used at universities and delineated in the Massachusetts Framework (Massachusetts, 2003) as the basis for teachers' professional development and for formulating students' capstone projects. Working on their project in accordance with EDP steps, students will deliver the problem solution in the form of prototypes, reports, and presentations.

The pedagogical framework to implement project design principles and deliver instructions for both teachers and students are based on the following research on learning in two areas:

Table 1. Learning Pedagogy

Area	**Pedagogy**
Professional development models (Conley, Ressler, Lenox, & Samples, 2000, p. 31-38, Dennis, 2001, p. 24-27)	The project team will use the T4E (Teaching Teachers to Teach Engineering) teaching model developed and conducted by the US Military Academy (West Point) during 1996-1998. Its successors ExCEEd (Excellence in Civil Engineering Education) and ExcEEd (Excellence in Engineering Education) were offered during 1999-2004. The key features of T4E model include active learning, learning objectives, content organization, clear expectations, lesson planning, effective delivery, and teaching styles variation.
Project-based learning model (Shade, 1989, p. 137-155; AAUW, 2000)	This approach offers many benefits to students. They gain deeper knowledge of subject matter, show increased self-direction and motivation, and acquire improved research and problem-solving skills. They feel of more responsibility for and control over their own learning.

The EBL curriculum adopts and adapts an existing innovative STEM/IT course curriculum entitled as "Engineering the future (EtF): Designing the World of the 21st Century." This course has been developed by NCTL (National Center for Technological Literacy) at Boston MoS. NCTL has successfully led professional development.

Table 2. EBL Course Material

Course Material	**Description**
The Engineer's Notebook	The notebook guides students in the laboratory studies. It mimics the way engineers undertake projects in practice: learn the concepts and acquire the skills required to successfully complete the projects, and report their research, testing, and final solutions.
The Textbook	The book is written by practicing engineers. Men and women, from various ethnic and cultural backgrounds, tell what it is like to practice their profession and how they came to do what they do.
The Teacher's Guide	The guide provides detailed recommendations for presenting project-based learning pedagogy and laboratory activities to students and for leading classroom discussions. The Guide also provides connections to educational standards, a list of laboratory supplies, and background science reading.

The EBL methodology does not necessarily require the introduction of an additional new course in high schools. Instead, EBL can be incorporated into an existing courses or after-school program. School districts have the flexibility to adapt EBL material to fit their specific needs by selecting the modules and projects that fits their students' the best.

The teachers training provides an intensive, two-week workshop for 20 teachers every summer. It provides 80 hours of professional development for each participating teacher. At these workshops, teachers will learn to implement the EBL model. Further, each teacher gets 40 hours of contact time in follow-up sessions through the school year.

- ***Week 1 Teacher Training:*** In week 1, teachers will learn the fundamentals of technology, EDP, project-based learning pedagogy, and teamwork. The instruction is divided as follows:

Table 3. Week 1 Training Themes

Day	**Theme and Brief Description**
Day 1	***STEM workforce Overview:*** We engage guest speakers to share with teachers how engineering and STEM is put into practice. We invite industry partners to provide overview of selected products from nanotechnology and sensing technology.
Day 2	***Engineering Design Process (EDP):*** We cover the steps of EDP, its application to engineering problems solving, and illustrate the process by designing a cell phone holder
Day 3	***CAD (Computer Aided Design) Modeling:*** We cover basic concepts to sketch design models, create drawings, and render 3D design models
Day 4	***Nanotechnology:*** We cover the basic concepts of nanotechnology
Day 5	***Sensing technology:*** We cover the basic concepts of sensing technology

The activities for each day consist of a mix of presentations, hands-on activities, and discussions. For example, Table 4 shows the schedule for Day 2:

Table 4 Schedule for Day 2

9:00-9:15	Comment cards from Day 1
9:15 – 10:45	***Introduction to the EDP:*** • IDEO Video. • Quick-build cell phone holder
10:45-11:00	Break
11:00-11:30	***Compare Design and Inquiry:*** •Reflections on activity. •Design and Inquiry side-by-side
11:30-12:00	***Reflect on EDP:*** •Outline the cell phone holder designs created by each team. • Explain the EDP steps. • Illustrate the EDP steps using the holder design
12:00-12:45	Lunch
12:45-1:15	***Teamwork:*** •Personal experience of a teacher. • Importance of teamwork. • Forming teams for organizer project. • Organizer challenge
1:15-2:30	***Organizer Activity:*** • Teams identify projects. • Build mock-up. • Report results.
2:30-2:45	Break
2:45-3:15	***Project Based Learning Resources:*** • Course Modules. • TEC Reviews – online. • ERC in the Museum's Library.
3:15-3:45	Engineering Scheduling & Tracking
3:45-4:00	Comment Cards for Day 2 feedback

- ***Week 2 Teacher Practicum:*** Week 2 serves as a practicum for teachers. It gives them the opportunity to put into action the EBL learning concepts that they have learned in week 1. Each teacher is required to select a course they will teach in the Fall semester, conceive an open-ended design project, and develop a lesson plan. At end of week 2, each teacher delivers a poster and a presentation to all teachers attending the summer course. Follow-ups during the following academic year are conducted to hear teachers experience and provide further help.

Teachers are recruited from urban schools such as the greater Boston area Public schools where the majority of students are underrepresented as shown Table 2.

Table 5. Demographics of Greater Boston School District Students

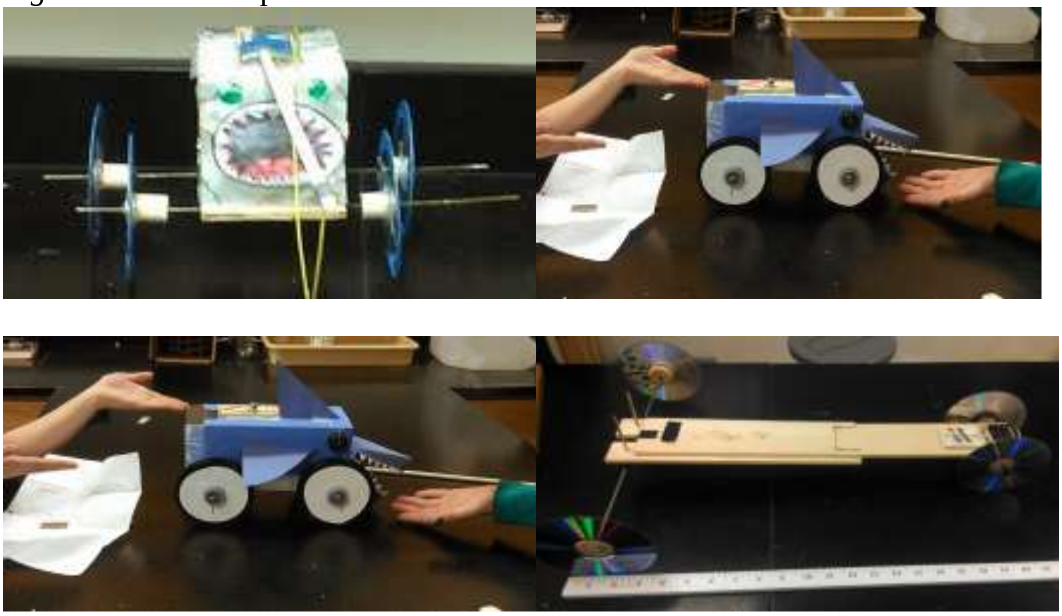
Race/Gender	**% of School District Students**						
	Boston	*Cambridge*	*Everett*	*Framingham*	*Randolph*	*Revere*	*State*
African American	45.5	39.1	10.9	7.3	45.0	4.9	8.9
Hispanic	31.2	14.8	18.0	18.0	6.9	26.2	11.8
Native American	0.4	0.6	0.2	0.3	0.3	0.3	0.3
Female	48.6	47.7	48.5	50	48.3	48.1	48.5
Total Enrollment	57,742	6,183	5,347	8,065	3,628	5,613	975,911

Findings/Results

The EBL concept was piloted to 90 teachers over three year period during the NSF grant. Teachers have reported excellent results. We provide sample projects and feedback.

The physics teachers in one high school embraced the idea of imbedding project based learning into our daily activities. The teachers decided on a project centered on the creation of a mouse trap powered car that could go 10 meters. Teachers created project description, deliverables, required material, and a timeline for the students to follow. The idea behind the project is for the students to use physics principles and concepts and apply the related equation to drive the powered car as far as possible. Teachers guided the students through the steps of the EDP. Students build prototypes of their final design. Student teams show cased their prototypes in a one-day competition. Figures 2 show different car designs.

Figure 2. Mouse Trap Powered Car Models



Other teachers in another school decided to create a robotics course, which fully embedded EBL into the curriculum. The goal of this robotics course is two-fold: 1) Combine engineering, math, science, and art/creativity into one course; and 2) engineering-based learning can impact the way students learn STEAM principles, retain STEAM theory, and apply them to real world, relevant applications.

The initial implementation plans for the robotics course design along with a course syllabus were presented to the school administration for approval. Curriculum design was focused on designing a robotics course that would attract students who were historically uninterested in math and science to this type of course. The focus of this robotics course was to expose students to explore circuitry with snap circuit ROVS. Students would further experience the true design process through learning and using Solidworks™.

In the Fall semester following course approval, teachers introduced two new semester course electives to the STEAM program. Both were hybrid robotics and EBL, engineering specific courses. The courses were an introduction to the engineering design process and how engineering can lead to various careers in math, science, and biotechnology. We had surveyed upcoming freshmen and sophomores in the spring to gather where their interests lie concerning science and engineering. The results of that survey indicated that students wanted a robotics program and would be more open to trying EBL courses if we offered one. Figure 3 shows different robots designs.

Figure 3. Robot Models

Evaluation

The project results were analyzed by an independent external evaluator as a requirement of the funding agency, NSF. The University of Massachusetts Donahue Institute served as the external evaluator of the project.

The evaluation design integrated a mixed-methods approach into an objective-based evaluation, yielding quantitative and qualitative data that will serve both formative and summative purposes. The evaluation is structured to measure the effectiveness of: (1) summer professional development (PD) for STEM teachers; and (2) EBL pedagogy in classroom STEM teaching. A comprehensive evaluation of the research program and its activities occurred over the three-year grant period. Both quantitative and qualitative methods were employed to collect evaluation data and provide formative feedback and summative evaluation of the grant's goals and objectives.

To assess the effectiveness of the summer PD in achieving its goals, all teachers participated in content-specific pre- and post-tests related to the materials and activities they are presented with during week 1 (i.e. fundamentals of technology, EDP, and project-based learning skills). These pre- and post-tests were developed by the professional development instructor with the assistance of the external evaluator. At the end of week 1 teachers will also be asked to complete a survey related to their perceptions of the training and their levels of preparedness for the following week.

During week 2, each participating teacher practiced integrating the skills they learned during week 1 to solve a specific STEM project problem, design and build a prototype, and present their designs to an audience of STEM professionals. An overall evaluation of the summer workshop experience was administered to all teachers at the end of the two-week period to assess teachers' understanding of how to implement newly acquired knowledge, materials, and activities into their classrooms.

In addition to pre- and post-surveys, focus groups of randomly selected group of 10 teachers were conducted. The goal is to capture the qualitative value of the research and concepts that are hard to articulate quantitatively in survey questions.

Data collection for the evaluation of the research project included teacher pre- and post-surveys during the summer course; two focus groups, one at the end of the summer course and one in April of the subsequent school year; a final survey for all cohorts at the end the grant period; and a student survey. These data collection activities for the evaluation are described below. All instruments were designed collaboratively by UMass Donahue Institute researchers and the research team.

The pre-survey, conducted on the first morning of the summer PD, asked teachers to provide demographic and background information including sex, ethnicity, subjects and grades taught, and full-time equivalent years as a certified teacher. Teachers also rated their prior level of experience with the course's main topics of the engineering design process, computer-aided design, capstone projects, and the manufacturing process. Finally, it included multiple-choice assessment items as an objective measure of teachers' knowledge in these four domains.

The post-survey, conducted on the last day of the summer PD, asked teachers to rate the usefulness of several major course components, the course's success on a range of intended outcomes, and the quality of aspects such as presenter preparedness and time provided for collegial exchange. The post-survey also included the same content knowledge items as the pre-survey, so that gains across the 10 days of the PD could be assessed. Finally, three open-ended items asked teachers to describe what aspects of the PD they found most valuable, what they would recommend changing, and any other comments or suggestions they might have.

On the final day of each PD, teachers participated in a one-hour focus group with a UMass Donahue Institute researcher. Discussion focused on components of the course they felt would most benefit their teaching practice, which aspects they found most challenging or frustrating, how prepared they felt to implement engineering capstone projects in their classrooms, supports they anticipated needing during the school year, and advice for teachers who take the course in the future. The transcripts of the focus groups were analyzed to identify common themes and divergent views.

During the spring callback day, teachers participated in a focus group with a UMass Donahue Institute researcher to discuss a range of topics related to the implementation of EBL activities and capstone projects in their classrooms.

During spring of year 3 of the project, a final survey was administered to all participants in the three-year program. This survey consisted of 28 multiple-choice and open-ended questions to learn about teachers' experiences implementing EBL-based activities in their classrooms, such as: the perceived effectiveness of the course in providing the knowledge needed to implement, implementation experiences, barriers to implementation, effect on student learning and interest in STEM, and activities/contact the participant would like to continue with Northeastern University's STEM Center.

Participant teachers were asked to administer two surveys to their students—one pre-survey and one post-survey. The pre-survey collected data concerning students' interests in STEM fields, their attitudes toward certain processes, and their awareness of multiple aspects of STEM. The survey also included an eight-question content-based test of knowledge. The post-survey included all of pre-survey questions, as well as four additional questions concerning capstone experiences. A total of 721 surveys were collected: 64 from Cohort 1, 281 from Cohort 2, and 426 from Cohort 3.

Survey responses were analyzed using descriptive statistics. To assess growth across data points on attitude questions, chi square analyses the non-parametric Wilcoxon signed ranks test were performed to determine whether there are a statistically significant differences between pre- and post-test scores.

To assess growth on teacher and student pre–post content questions, paired-samples t-tests were performed to determine if there were statistically significant differences between the scores.

Statistically significant differences in the distributions are indicated by a probability level of significance (p) that is equal to or less than .05. Statistical significance refers to the probability that differences between pre-survey and post-survey distributions are not due to chance and may be attributable to the intervention.

Open-ended responses were analyzed using a standard qualitative technique that involved multiple readings of the data set and assignment of themes around recurring ideas. Once themes were identified, each response was coded by its appropriate theme. Coded responses were then analyzed in their thematic groupings to identify patterns.

The participating teachers reported teaching included physics (43%), engineering (40%), technology (30%), mathematics (25%), biology (19%), chemistry (15%), environmental science (13%) and "other subjects" (21%). Two respondents reported teaching robotics, two anatomy and physiology, and another two computer science. Each of the following was taught by one teacher: earth science, forensic science, and oceanography. See Table 6.

Table 6. Subjects Taught by Participants

Table 2. Subjects Taught by Participants

	n	%		n	%
Physics	36	43%	Environmental Science	11	13%
Engineering	34	40%	Anatomy and Physiology	2	2%
Technology	25	30%	Computer Science	2	2%
Mathematics	22	26%	Robotics	2	2%
Other subjects	18	21%	Earth Science	1	1%
Biology	16	19%	Forensic Science	1	1%
Chemistry	13	15%	Oceanography	1	1%

n=84. Respondents could select more than one subject.

Years of experience of teachers ranged from 1 to 35 years, with more than half of them having 7 or more years of experience. The average number of years was nine, and the modal number of years was three.

Grade levels taught by participants included 9th (63%), 10th (58%), 11th (74%), and 12th (76%), with many of the respondents teaching multiple grades (Table 7).

Table 7. Grade Levels Taught by Participants

Table 3. Grade Levels Taught by Participants

	n	%
Grade 9	53	63%
Grade 10	49	58%
Grade 11	62	74%
Grade 12	64	76%
Other grades	13	15%

n=84. Respondents could select more than one grade.

Figures 8-12 Show sample survey results of teachers.

Figure 8. Teachers Motivation due to Summer PD

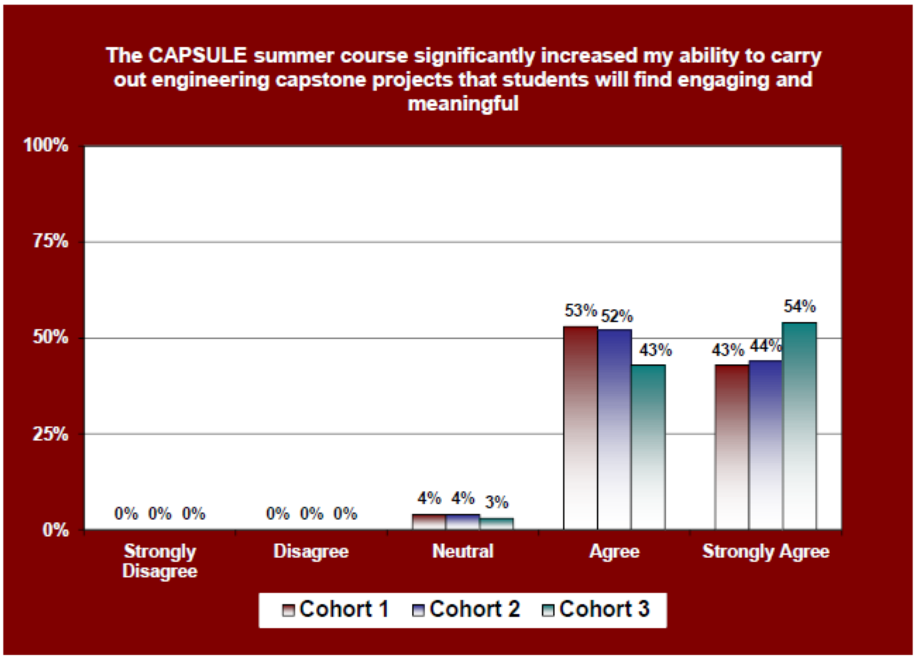


Figure 9. Teachers Intention to Use EBL in STEM Classroom Teaching

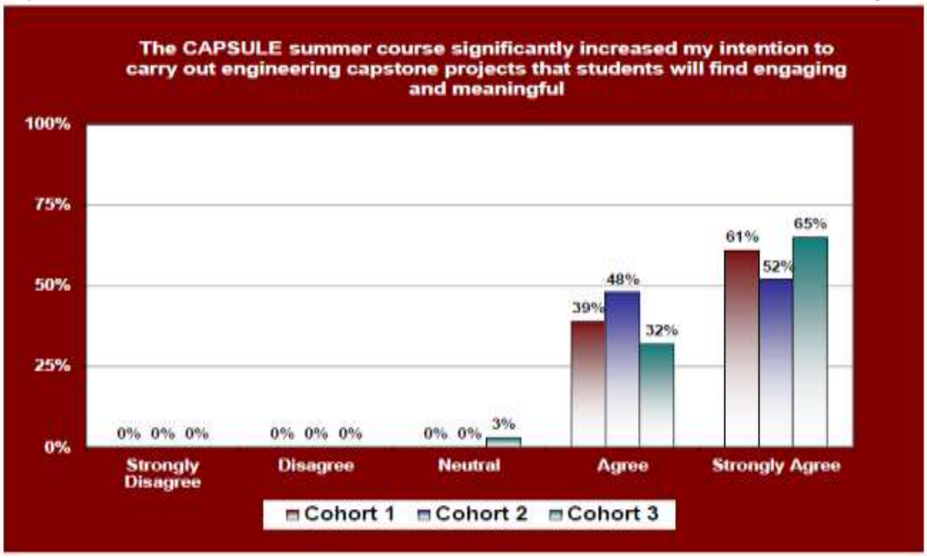


Figure 10. Teachers View on EBL Effectiveness

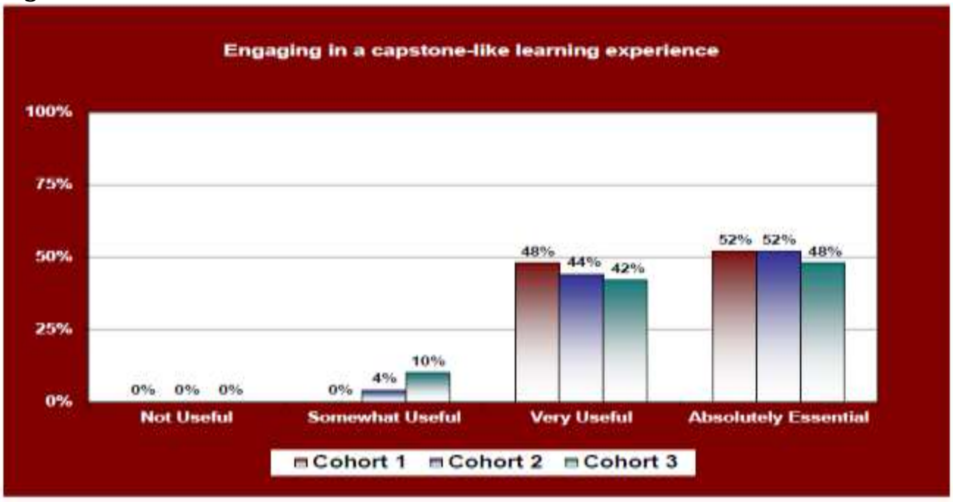


Figure 11. Effectiveness of Summer Professional Development

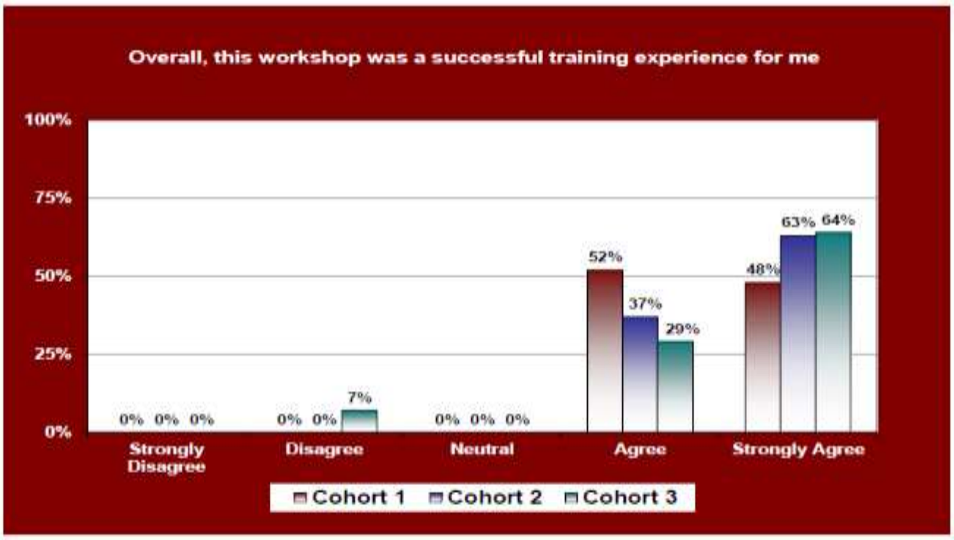


Figure 12. Effectiveness of Summer Professional Development

The results of the three focus groups over the project three years were mostly positive. Here is the summary of the third year focus group. When asked for other comments and suggestions, 18 respondents provided a variety of thoughts, though many served to underline previous comments. Four of the 18 (22%) addressed the need for more time, including one suggestion that the course be three weeks long and two suggestions that more time be provided for engagement in a reflective process. Another four respondents addressed issues of organization, with two noting that the expectations were unclear and another commenting that it seemed like the instructor "phoned it in." Positive remarks came from three respondents, two noting that it was among the best PD in which they had participated and the third stating that it was the "best educational experience of my 20+ years of teaching." One participant noted liking that the professor adjusted his lectures in response to participants' comments, and one mentioned looking forward to call back days.

Teachers were asked about the impact of EBL on their students STEM learning experience. The majority of respondents across all cohorts agreed or strongly agreed that students in their classes were more interested in STEM after completing a capstone project (66%); 21% neither agreed nor disagreed, and 5% disagreed; no teacher strongly disagreed. The majority of respondents across all cohorts also agreed or strongly agreed that students are motivated to complete their capstone projects (71%), with 18% neutral, and 3% in disagreement.

Nearly half (47%) of respondents across all cohorts agreed or strongly agreed that EBL training made their engagement with high needs students more effective. Cohorts 1 and 2 tended to be more positive, with 64% and 62% respectively, while only 21% of Cohort 3 agreed or strongly agreed. However, 36% of Cohort 3 respondents neither agreed nor disagreed, which may indicate their lack of opportunity to engage with high needs students since they completed the EBL program.

Student surveys included attitude questions about interest, enjoyment, confidence, and awareness. Responses were analyzed by cohort to determine whether there were any statistically significant differences between the pre- and post-survey responses. For example, an analysis of Cohort 3 surveys indicates that although there were mean gains on some items, only one was statistically significant. Students enrolled in classes taught by Cohort 3 teachers were found to have a statistically significant increase in their agreement with the item, "I know what a capstone project/experience is" (29% to 59%, $p<.01$). Additionally, when students were asked about their preferred mode for learning hard sciences (engineering, math, physical sciences), approximately two-thirds of students selected a combination rather than either lecture (teacher presents material in front of class) or project-based (learning through hands-on projects and experiments).

Student surveys showed many increases in interest and awareness of STEM subjects. Some indicated increased interest in learning about STEM subjects, finding out how things work, working in teams to solve open-ended projects, and learning how classroom concepts and theories are used in the real world. Many reported that doing projects and designing experiments helps them to understand STEM concepts and that classroom teaching and learning is more effective with capstone projects than without. Students also reported an increased understanding of EDP and how it is used, what an open-ended problem is, and what a capstone project is. Students were asked at post-survey about their capstone experience. About three-quarters felt the capstone project was very positive and about two-thirds felt the capstone experience helped them understand STEM subjects and courses. About half agreed that the capstone projects made STEM more interesting. Perhaps most interesting, nearly half of students reported that the capstone experience and EDP made them think seriously about a STEM major in college.

Discussion

Incorporation of EBL into high school STEM curriculum works very effectively. Student interest has encouraged teachers to inquire about EBL training for cross curriculum lessons. Schools continue to collaborate and create partnerships with other schools, industry, and postsecondary institutions to offer other courses. High school teachers are working on incorporating EBL at the middle school level as an introductory for our high school programs. Other schools will be creating more engineering courses and integrating more engineering in core classes in the future. A chemistry teacher is using EBL as part of their chemistry class. EBL has inspired school administrations to budget for further teacher professional development and the incorporation of some type of "maker program" for their students.

What is more compelling to report is the lasting effect EBL has left on teachers and students long after the research has concluded. Here are some quotes from a teachers survey we have conducted

> "They [students] are surprised to enjoy digital circuitry, and I even had a student become a computer engineering major after he developed an interest for it in my class."

> "We have many more students entering College with a STEM field in mind."

> "Students feel challenged but also very proud when they make something"

> "Most students enjoy making presentations and presenting what they have learned."

> "Students engage in real-world application of knowledge"

> "Students like the independent nature of CAPSULE; it prepares them for college."
> "Because of the rigor of the projects students must be engaged in the lesson taught. Also students develop strong problem solving skills as they design and improve upon their designs."

"I think a big impact on my students has been in their ownership of their learning as they navigate the problem they are trying to solve."

Conclusions

Overall, the EBL project has been very successful in working with teachers to integrate engineering concepts into their STEM classes. Both teachers and their students report success through increased knowledge, tools, and extensive use of new resources, EDP, and capstone projects in classes. Introducing engineering to high school students has proven to be a valuable method to get them to appreciate and understand the abstract STEM concepts that discourage them. EBL makes implementing engineering in high school STEM courses that much easier due to its well defined structure and steps. The key to successful implementation of EBL in schools is to give schools the complete freedom to implement it. It could be one week long in a course, one semester long, one year (2 semesters) long, or it could be a full elective course. It all depends on the school specific needs and time allocated for engineering in school curriculum.

Acknowledgments

This work is supported by the National Science Foundation under grant numbers DRL 0833636. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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Athens Journal of Education - Volume 7, Issue 3, July 2020 – Pages 273-296

D-STEM Equity Model: Diversifying the STEM Education to Career Pathway

*By Adrienne Coleman**

According to the National Science Foundation, "the U.S. STEM workforce must be considered in the context of an expanding and vibrant global scientific and technological enterprise" (2014). "The National Academy of Sciences further suggests that, without the participation of individuals of all races and genders, the increasing demand for workers in STEM fields will not be met, potentially compromising the position of the United States as a global leader" (2014). The stark reality is that there are a disproportionate number of Black and Latinx students who lack the access and exposure to become STEM-literate. In order for the U.S. to remain a global STEM leader, an intricate look at STEM inequity on a national scale must occur and diversifying the STEM education to career pathway must be a priority. The Illinois Mathematics and Science Academy sought to gain a better understanding of how to diversify this STEM education to career pathway. Thus, a study was conducted on the motivation of Black and Latinx students to engage in STEM as well as two Diversifying STEM Think Tanks held, to understand and address the racial STEM divide. From the perspectives of 415 STEM Stakeholders (students, parents, professionals, and educators) the D-STEM Equity Model to diversify the STEM Education to Career Pathway with national implications and global scalability was developed. This model suggests "diversifying STEM policies" need to be developed that mandate funding for racially-based collaborative STEM initiatives to be implemented, that work towards achieving equity by addressing the identified problems collectively and integrating factors of Black and Latinx student STEM motivation into STEM programming as well as encourage culturally responsive STEM educator training.

Keywords: STEM, diversity, equity, race/ethnicity, innovation

Introduction

According to the National Science Foundation, "the U.S. STEM workforce must be considered in the context of an expanding and vibrant global scientific and technological enterprise" (2014). As a global powerhouse, the United States (U.S.) has demonstrated leadership in economics, military, political influence, innovation, and culture/lifestyle (Bremmer, 2015). Specifically as it relates to innovation, the U.S. has superb scientific institutions of higher education and is home of the majority of tech companies in the world (Bremmer, 2015). Despite this, research suggests that the United States is struggling to maintain its competitive edge in innovation, especially in the global STEM (science, technology, engineering and mathematics) space. "For over a decade, indicators data have shown that other

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nations, led by China, South Korea, and Brazil have been increasing their innovation capacity by investing heavily in higher education as well as research and development" (Organisation for Economic Co-Operating and Development, 2007).

While other nations continue to strengthen their innovation practices and improve STEM education, the U.S. is lagging behind; the World Economic Forum ranks the U.S. 47th worldwide in the quality of its math and science education (Miller & Horrigan, 2014). This is evident in the 2012 Programme for International Student Assessment (PISA), in which American 15 year-olds ranked 26th in math and 21st in science, with an average score of 481 and 497; while Shanghai-China ranked first, with an average score of 613 and 580 (Organization for Economic Co-Operating and Development, 2014). This U.S. Global STEM education inequity is further evident in the 2015 Trends in International Mathematics and Science Study (TIMSS), which found that the United States ranked 10th in 4th and 8th grade math, 10th in 4th grade science and 11th in 8th grade science (National Center for Education Statistics, 2015). These trends indicate the U.S. is in dire need of improving the quality of STEM education and ensuring that everyone has access in order to be competitive in the global STEM economy (Miller & Horrigan, 2014).

In a study conducted by the National Science Board, some analyst "contend that the United States has or will soon face a shortage of STEM workers" (National Science Foundation [NSF], 2014). There are several indicators that suggest STEM jobs are growing rapidly in the U.S. and are scheduled to increase by 17 % by 2024 (Coleman, 2016; Department for Professional Employees [DPE], 2016; U.S. Department of Commerce [DOC], 2011; Department of Education [DOE], 2016). With such increased growth being forecast for the STEM industry, if the U.S. is unable to meet this demand, its' global leadership status will be jeopardized. Recent analyses indicate that during the next five years, major American companies will need to add nearly 1.6 million employees to their workforce; 945,000 who are STEM-literate and 635,000 with advanced STEM knowledge (DOE, 2016). This year alone, technology companies, such as Facebook, Amazon, and Apple, will need to hire for more than 650,000 (Ouimet, 2015). Considering this potential rapid growth in the STEM space, the U.S. global status of STEM education and the challenge of remaining a global leader, the United States must address the inequities in STEM education and prioritize the development of a STEM-literate workforce.

The increasing demand for STEM-skilled professionals is a global trend, so diversifying the STEM education to career pathway will benefit the global STEM market (Richards, 2018).

"The additional benefit of developing a STEM-literate and well-trained domestic workforce is that this ensures that we adequately address challenges related to healthcare improvement, national production capacity, and research excellence" (Allen-Ramdia & Campbell, 2014). The reality is that the future workforce will rely much less on having content-based knowledge and more on possessing the skills needed to analyze, reflect, and solve difficult problems. "The learning and doing of STEM helps develop these skills and prepare students for a workforce where success results not just from what one knows, but what one is able to do with that knowledge…a strong STEM education is becoming increasingly recognized as a key driver of opportunity, and data shows the need for STEM knowledge and skills will grow and continue into the future" (DOE, 2016). With readily available resources, the ability to create new knowledge through STEM skills for innovative solutions to solve the pressing problems of society is paramount.

If the U.S. wants to maintain its' status as a global leader in STEM, be competitive in the STEM space, and address global challenges; diversifying the STEM education to career pathway must be a take precedence. "STEM and diversity are integral to the sustainability of our schools, the innovation of our businesses, the prosperity of communities and the global competitiveness of our economies" (Richards, 2018). The U.S. must take intentional and strategic action to not be left behind in the innovative, global STEM space. The duration of this paper will take an intricate look at the global and national value of Diversifying STEM in the United States of America. We will examine the racial inequities in the STEM education to career pathway, gain an understanding of why these inequities exist, reflect on how these inequities have been addressed and introduce a model to address these racial inequities; ultimately diversifying the STEM Education to Career Pathway with both national and global implications.

Literature Review

"The National Academy of Sciences suggests that, without the participation of individuals of all races and genders, the increasing demand for workers in STEM fields will not be met, potentially compromising the position of the United States as a global leader" (NSF, 2014). In order for the U.S. to remain a global STEM leader, an intricate look at STEM inequity on a national scale must occur. The stark reality is that a disproportionate number of people of color, particularly Black and Latinx persons, are even further away from becoming STEM-literate and having the ability to thrive in a hyper-competitive, global marketplace (Miller & Horrigan, 2014). "The nation has persistent inequities in access, participation, and success in STEM subjects that exist along racial lines, which threaten the nation's ability to close education and poverty gaps, meet the demands of a technology-driven economy, ensure national security, and maintain preeminence in scientific research and technological innovation" (DOE, 2016). This leads to the underrepresentation of Black and Latinx persons in STEM education and careers.

The 2013 U.S. Census Bureau indicates that Black and Latinx populations are underrepresented in STEM, with them each making up less than 10% of the STEM workforce; while White individuals are overrepresented, making up 70% of the workforce (DPE, 2016; Landivar, 2013). In terms of readiness to enter a STEM major and ultimately a career, only 6% of Black students and 13% of Latinx students, compared to 36% of Whites and 53% of Asians, are actually prepared (Coleman, 2016). Among students taking the 2017 National Assessment of Educational Progress (NAEP), the average math test score gap between Black and White fourth graders was 25 points and for eighth grade students, the gap was 33 points, while the math gap between White and Latinx students was 19 points for fourth graders and 24 points for eighth graders. Asians outperformed all other racial and ethnic groups in both grades, in mathematics (National Center for Education Statistics [NCES], 2018). In addition, NAEP demonstrates that only 13% of Black students and 20% of Latinx students scored at or above proficiency in 8th grade mathematics; compared with 44 percent of White students and 62 percent of Asian students (NCES, 2018). Additional data suggests that in 2013, on the math component of the SAT exam, college-bound Black and Latinx students scored disproportionately lower than their White and Asian Counterparts; Black students averaged 429, Latinx students averaged 459, White students averaged 534 and Asian students averaged 597 (Miller & Horrigan, 2014). One might assume that Black and Latinx students have no inclination to enter STEM; however, research actually suggests that they have both an interest and intent to pursue STEM more often than their White counterparts (Byars, 2013; Educational Research Center of America [ERCA], 2016; Riegle-Crumb & King, 2010). According to a study conducted by the Research Consortium on STEM Career Pathways, 59% of Black students and 62% of Latinx students have STEM career aspirations (ERCA, 2016). This data suggests that racial inequity exists in STEM education, unrelated to aspiration, needs to be addressed to enhance global STEM sustainability.

Not only does diversifying STEM in the United States assist with global leadership, but it will also help Black and Latinx communities with economic growth, leading to a better standard of living (Miller & Horrigan, 2014). Workers in STEM occupations earn more on average than their counterparts in other jobs, regardless of their educational attainment. (DOC, 2011). Considering this, Latinx and Black households earned a median income of $38,624 and $32,229, respectively, in 2011; however, today's median wage for Black persons employed in U.S. STEM jobs is $75,000 and around $77,000 for Latinx persons, (Coleman, 2016; Ouimet, 2015). According to the U.S. Department of Education Office for Civil Rights', the STEM fields "are the gateway to America's continued economic competitiveness and national security, and the price of admission to higher education and higher standards of living for the country's historically underrepresented populations" (2014).

Being that the United States is such a global force, one should be curious as to why racially based STEM education and career inequities exist. Research suggests that it is a multifaceted problem resulting from; a lack of exposure to STEM in K-12 education, mathematics phobia, students' misperceptions of what science is, lack of real-life application of science, lack of motivation to succeed, and peer pressure that devalues high achievement (Coleman, 2016). Other sources have indicated the issue of inadequate funding, "favoring schools and communities that have access to the most resources, knowledge, and expertise", which typically does not include the Black and Latinx communities (Riegle-Crumb & King, 2010). In addition, strong STEM pedagogy and resources are typically lacking in these schools and there's an inclination to "address a perceived deficit with the student, rather than a focus on changing the system and delivery of STEM instruction to more effectively support and draw on students' strengths" (Henderson & Lawson, 2015). This is evident in the deficit mind-set that exists with school district professionals related to poorly resourced schools, especially in STEM (Robinson, personal communication, June 19, 2018). Google conducted a study to gain an understanding of who was less likely to pursue computer science and why. The study concluded that Black and Latinx students were less likely to pursue computer science for the following reason: lack of exposure to computer science, lack of opportunity to learn computer science, lack of encouragement from others to learn and lack of computer science role models (Google Inc. & Gallup Inc., 2016). Additional research suggests other social and environmental factors, including college affordability, lack of self-confidence, feelings of isolation, and having lower expectations for students of color leads to a lack of diversity in STEM (NSF, 2014; Riegle-Crumb & King, 2010).

These lower expectations are a result of implicit bias, "when teachers' hidden attitudes and beliefs about students are based on race, ethnicity, and/or gender, they may unwittingly communicate negative messages to their Black, Brown, and Female students about their abilities to tackle STEM subjects" (Holsington, 2017). A prevalent attitude of bias towards Black and Latinx students is that they do not have the intellectual capacity to think spatially or scientifically (Byars-Winston, 2013). An outcome of this bias is Black/Latinx groups are not provided with STEM career information as often as their White and Asian counterparts (Byars-Winston, 2013). This is evident in Silicon Valley, which "is still too white, too male, and too focused on solving the problems of the young, single, and wealthy," said Owen Grover, the senior vice president and general manager of iHeartRadio (Meyer, 2015). Thus, it is suggested that diversifying STEM beyond race, to be more inclusive of low-income individuals and females, would be valuable. "The question of diversity is not just one about the numbers, or even a question about the culture of hostility and willful exclusion toward diversity for Black and Latinx people…it's about the deep level of comfort with being in all-white spaces (or only-white and Asian spaces), and not understanding the impact of that exclusion on the work and society" (Meyer, 2015).

To combat this racial STEM divide, an evidence-based STEM pathway must be established. Loma Linda University evaluated their Summer Health Disparities Research Program to determine its' effectiveness; finding that a focus on self-efficacy enhances STEM identity and leads to a stronger STEM career commitment (Salto, Riggs, Casiano, & De Leon, 2014). "The critical development of science self-efficacy as it influences the development of deeper measures of integration is supported by Estrada-Hollenbeck's work that found that while self-efficacy was related to identity and values, the relative influence of each on long-term STEM career commitment may be mediated by the progression of the student through the academic pipeline" (Salto et al. 2014). The National Science Foundation further states that there must be a focus on strengthening the STEM workforce using the following approach:

- Monitor and assess the condition of workforce pathways and identify risks and challenges to them,

- Ensure that all individuals have access to high quality education,
- Address roadblocks to the participation of groups traditionally underrepresented in STEM (2014).

This is consistent with the U.S. Department of Education STEM 2026 challenge, which places an emphasis on societal and cultural images and environments that promote diversity and opportunity in STEM, put this way:

> *In STEM 2026, how STEM is messaged to youth and their families is transformed. Research shows that repeated exposure to images, themes, and ideas affect people's beliefs, behaviors, and attitudes. In STEM 2026, popular media, toy developers, and retailers consider issues of racial, cultural, and gender diversity and identity in portrayals of STEM professionals and STEM-themed toys and games. These images counter historical biases that have prevented the full participation of certain groups of individuals in STEM education and career pathways. These portrayals include diverse pictures, descriptions, or images of what STEM work entails, including the array of jobs and activities that use STEM; and who is seen doing and leading STEM-related work. Communities and youth in all neighborhoods and geographic locations around the country are equally exposed to social and popular media outlets that focus on STEM, and a wide diversity of STEM-themed toys and games that are accessible and inclusive and effectively promote a belief among all students that they are empowered to understand and shape the world through the STEM disciplines* (DOE, 2016).

Methodology

The Illinois Mathematics and Science Academy (IMSA), a residential high school for gifted/talented students, sought to gain a better understanding of how to diversify the STEM education to career pathway. IMSA conducted a study on the motivation of Black and Latino students to engage in STEM as well as held two Diversifying STEM Think Tanks to understand and address the racial STEM divide. These studies are rooted in Critical Race Theory (CRT), which attempts to understand American education and reform, acknowledging the unique perspective and voice of people of color as victims of oppression in racial matters and valuing their storytelling as a legitimate way to convey knowledge (Khalifa, Dunbar, & Douglas, 2013). Qualitative methodologies were employed allowing participants to share their stories related to the intersection of race and STEM. The 415 participants included students, parents, educators, professionals, and community organizations who are all actively engaged in STEM.

For purposes of these studies, STEM Education was defined as:

> *"an interdisciplinary approach to learning where rigorous academic concepts are coupled with real-world lessons as students apply science, technology, engineering, and mathematics in contexts that make connections between*

school, community, work, and the global enterprise enabling the development of STEM literacy and with it the ability to compete in the new economy" (Gubbins et al., 2013)

The initial study focused on the motivation of Black and Latinx students' engagement in STEM education, with the premise that understanding the motivation factors to inform STEM programming specific for Black and Latinx students may lead to a more diverse STEM education to career pathway. Participants yielded from the Illinois Mathematics and Science Academy, the James R. Jordan Foundation, Biostatistics and Research Awareness Network, Inc. and the Diversity Initiatives in Research for Underrepresented Minorities, as well as from three geographic locations including Illinois, Ohio and Washington, D.C. This included 106 high school students, 86 middle school students, 27 STEM educators, 51 parents and 11 college students; a total of 281 participants. Through a design of interviews with adult participants and focus groups with student participants, the student participants were asked the following questions:

- Discuss your intrinsic motivation ("behaviors performed out of interest and enjoyment") as it relates to you being a student engaged in STEM education and provide examples in which your motivation to engage in STEM was developed…
- Discuss your extrinsic motivation ("behaviors carried out to attain contingent outcomes") as it relates to you being a student engaged in STEM education and provide examples in which your motivation to engage in STEM was enhanced.

While the STEM educators and parents were asked the following questions:

- What do you perceive to be the intrinsic motivators ("behaviors performed out of interest and enjoyment") that lead Black and Latinx students to engage in STEM education…provide examples in which this motivation was observed?
- What do you perceive to be the extrinsic motivators ("behaviors carried out to attain contingent outcomes") that lead Black and Latinx students to engage in STEM education…provide examples in which this motivation was observed?

With an enhanced understanding of STEM motivational factors in Black and Latinx students, IMSA sought to then gain a more informed perspective of the racially-based problems that serve as barriers to diversifying STEM with the goal of developing an approach to address those barriers. Thus, IMSA held two Diversifying STEM Think Tanks with the following goal:

- To understand from the perspectives of STEM professionals, Educators, and Diversity/Inclusion Officers strategies to diversify and strengthen the STEM education to career pipeline.

There was a combined total of 134 STEM professionals, educators, and affiliates from 64 organizations who shared their perspectives on diversifying STEM (see table 1 below):

Table 1. Diversifying STEM Think Tank Organization Participants

Aceism Creative Illustration and Design, Inc.	Chicago Public Schools	Grace United Methodist Church	National Society of Black Engineers	The Illinois Mathematics and Science Academy
African American Heritage Advisory Board	Citi	IMSA Parents Association	Northwestern University	The Morton Arboretum
Alpha Alpha Sigma Zeta Chapter of Zeta Phi Beta Sorority, Inc.	Combat Training	IN2	Oswego School District 308	The Office of the Inspector General
Aurora Chamber of Commerce	Crete Monee Middle School	Indian Prairie School District #294	Plano CUSD 88/P.H. Miller Elementary School	The University of Chicago - Institute for Molecular Engineering
Aurora University	DePaul University	International Studies Abroad Program	Project SYNCERE	U-46
Baxter Healthcare Corporation	District 365U	John T. McCutcheon Elementary School	Resilient Mind Consulting	Union of Concerned Scientists
Bethel New Life Church	DuPage County Regional Office of Education	Kane County Sheriff's	Roosevelt University	Unity Partnership, NFP
Bridging the Gap	Educational Opportunity Program – U.S. Department of Education	LaCrosse Central High School	Saratoga Elementary School	University of Wisconsin - Madison
British Petroleum	Fermilab	Lewis University	Society of Hispanic Professional Engineers	United States Air Force
Byron CUSD 226	Fischer Middle School	Metea Valley HS	Stanford University	Washington University in St. Louis
Carver Military Academy	Girls 4 Science	Mettler Toledo	Staples	West Aurora School District 129
Caterpillar Inc.	Girls IN2 STEM	Murray Language Academy	Take Your Place, Inc.	Yorkville Middle School
Chicago Public Library Foundation	Goodwin Elementary	National Association for the Advancement of Colored People	Technology For Women, Inc.	YWCA Aurora

Regarding the format of the Diversifying STEM Think Tank, participants first heard from a group of STEM experts who focused on diversifying STEM, then had small groups discussions focused on identifying and addressing the barriers related to the lack of diversity in STEM education and careers. The first Think Tank consisted of a panel of professionals that included:

- Dr. Michael Horn, Assistant Professor in Computer Sciences at Northwestern University
- Dr. Anna Kaatz, Director of Computational Sciences at Center for Women's Health Research at University of Wisconsin-Madison
- Dr. Terrence Mayes, former Associate Dean, Graduate Education and Director at Stanford University
- Dr. Norman "Storm" Robinson III, Panel Moderator and Executive Director of Professional Field Services at the Illinois Mathematics and Science Academy
- Mr. Mike Salazar, President of the Society for Hispanic Professional Engineers
- Dr. Lateefah Stanford, Senior Scientist—Separations and Mass Spectrometry at British Petroleum

Participants were asked the following question during the small group discussion component of the Think Tank:

> The literature suggests that there is racially-based gap STEM majors/career gap in which Black and Latinx students do not major in or enter STEM fields as often as their White and Asian counterparts…Why do you think this racially-based STEM gap exists?

During the second Diversifying STEM Think Tank, the results from the initial event in which problems were identified was shared with participants, along with specific data on the actual number of Black and Latinx professionals engaged in STEM education and careers. STEM professionals then shared their STEM-related experiences as well as how they have contributed to diversifying STEM in the format of STEM Talks; modeled after TED (Technology, Entertainment, Design) Talks, "short, powerful talks" (2018). The STEMTalks experts included:

- Dr. Adrienne Coleman, STEMTalks Moderator and Director of Equity and Inclusion at the Illinois Mathematics and Science Academy
- Dr. Don Dosch, Biology Faculty at the Illinois Mathematics and Science Academy
- Dr. Brian Nord, Associate Scientist in Fermilab's new Machine Intelligence Group
- Dr. Kelly Page, IMSA Fellow, Communications and Learning Consultant. Social Design Ethnographer. Research Scientist. Founder and Curator of Grateful4Her
- Dr. Kenyatta Ruffin, U.S. Air Force Major and Founder of Legacy Flight Academy *(The Legacy Flight Academy is an independent, 501(c)(3) non-*

profit organization. The appearance of U.S. Department of Defense (DoD) visual information does not imply or constitute DoD endorsement)

- Dr. Anita White, PROMISE (PRoviding Opportunity in Math and Science Enrichment) Director and Chemistry Faculty at the Illinois Mathematics and Science Academy

After being informed about the overall problem and hearing the stories of STEM professionals, small groups were given a specific problem, defined in the initial Think Tank and asked to discuss the following:

Based on this definition, what strategies to address the problem should be implemented and why? Let's think about this from three different perspectives, educational institutions, community organizations, and the STEM industry. Recommend policies to be adopted.

Below are images of marketing utilized to promote the Diversifying STEM Think Tanks:

Figure 1. Diversifying STEM Think Tank Marketing

Data collected from the initial study on STEM Motivation and the two Diversifying Think Tanks was transcribed and analyzed utilizing software transcription and word analysis programs, along with a qualitative management system. Then an inductive analysis process was conducted, which identified patterns and unconvered concepts; "ultimately, the qualitative data analyst aimed to create a shared understanding that forms a coherent structure between the studies, a unified whole" (Suter, 2012). Thus, a model to diversifying the STEM education to career pathway was developed.

Results

Factors that motivate Black and Latinx students to engage in STEM

The initial study on the factors that motivate Black and Latinx students to engage in STEM yielded some powerful results. When 281 participants were asked to identify the factors that motivate STEM engagement in Black and Latinx students, 655 responses were generated. The major themes that emerged include obligation to Black/Latinx communities to break negative stigma and be different; future success because STEM is a prominent, progressive field; learning/discovery of STEM knowledge and real-life applicability; STEM passion/enjoyment; and solve problems to advance humanity.

The primary theme to emerge was obligation to the Black and Latinx communities to break negative perceptions and be different, reported by 122 (43%) of 281participants. This suggests that Black and Latinx students who are engaged in STEM have demonstrated resilience and have been able to positively combat the stereotypical perspectives and implicit bias that the literature states as a barrier to diversifying the STEM education to career pathway. It further suggests that in order to motivate Black and Latinx students that the STEM pathway must normalize STEM, using a culturally responsive approach. This is evident in participant comments below:

> *Because there is a lot of racism that affects them with their learning and can lead to think that they aren't smart and cause them to think they can't join these types of programs.*
>
> Middle School Student

> *It's more of an obligation and not necessarily to anyone around me, but to my ancestry. As I have gone through my education and gotten older the struggle of African Americans in America has grown more and more important to me as a person and I feel like the opportunities that I'm offered, no matter how good or bad they are, they are education…the more that I am offered these opportunities and I know I need to do well because the people before me did not have these opportunities and they paved the way to make sure I did have these opportunities…so when I do get the chance to learn something new I take it as chance to take advantage and appreciate what other people have done for me…when I get out into the world I know that what I'm doing was someone else's dream…I know that the work that I am doing and the knowledge that I have is because someone worked for me.*
>
> High School Student

> *A lot of the accomplishments and things that I see from my peers, that inspires and motivates me. In turn that kind of motivates me to just want to be successful for the sake of people who might look up to me so that I can be a role model to other people the same way that other people have been a role model to me so like at school. I'm part of the National Black Society of Engineers, so I can be a positive role model to all the underclassmen;*

especially going to a school where there's not a lot of Black people in general, especially in STEM. I feel like it's really important for me to be able to do well so you can go to that school and be in STEM and succeed.

College Student

His intrinsic motivators are most likely his love to solve critical problems quickly. In elementary school, his nickname was calculator, because he could solve problems faster than someone could insert into a calculator. In addition, he wants to represent Latinx doctors in STEM because when he was seven years old, he asked me in the hospital, "Where the Latinx doctors are at?" I remember replying that there are Latinx doctors, but there are few of them. You can become one when you grow up. After that, he made it his goal to want to become a doctor, for his want to represent the Latinx race.

Parent

His motivation is basically society always saying that African American males are not capable of. He feels like they are not put to the test. If there is a white student that is in the same class as them, that they are not expected to do as well as, and so he feels that he's motivated by hearing that you're not able and he says that I am able and that I am going to succeed. I think that goes for a lot of our youth. I think if they keep hearing, sometimes the more you hear that you can't do something, you know that you can do something. That's the motivation for a lot of our Black males right now.

Faculty/Staff

The secondary theme to emerge is future success, as STEM is a prominent, progressive field, reported by 115 (41%) of 281 respondents. This suggests that when Black and Latinx students understand the variety of STEM careers/potential earnings and that STEM innovation is a global focus with potential for industry growth, they are motivated to engage in STEM. Black and Latinx students should have exposure to an array of STEM careers and positions that utilize STEM skills as well as learn about global STEM opportunities. This is evident in the remarks below:

I think my biggest motivation is, well actually I have two motivations, one of them is I just really like learning so I try to be as well rounded of a student as I can; so even if I wasn't super interested in history, I would still try to be as involved in STEM as possible. Like now even as a STEM student, I try to learn about the arts and be well rounded but other than that I want to be an environmental engineer and do something with urban agriculture. Just the impact that I believe this can have on the world and the many problems in society it can cause, I just think that my main motivation is looking toward the future and looking for not like job prospects per say, even though there are a lot of jobs in environmental engineering more and more each day, but I think it's more like the change I can make in the world and that's what I'm looking towards.

High School Student

I think that my parents had to struggle to provide the things for our family; they never made their struggle clear to the kids because those aren't children issues. But I wanted to get into a field where I can get a good salary, immediately after college without having to do further school and engineering is one of the only fields like that. So I wanted to be able to provide for my family and things like that. I think of college as a pre-professional development opportunity…I think that whatever you learn in college should be applicable to some position to some job in the future and I think that you definitely get that in science and math education; where as in humanities you never really know where you're going to use that information in the future, so I wanted to pursue something that would have some sort of tangible benefit for me, some type of return on my investment.

College Student

The tertiary theme to emerge is learning/discovery of STEM knowledge, reported by 115 (41%) of 281 participants. This suggests that Black and Latinx students are intrigued by STEM concepts and interested in being STEM literate. There is a need for Black and Latinx students to be exposed to consistent STEM teaching and learning that is engaging and inquiry-based to enhance motivation. This is evident in their responses below:

I do want to find out as much as I can…but I fell into STEM education. There's something unique about it that is not really relevant or apparent in any other aspects of learning…there's this knowledge that no matter how much you know, you will never know all of it so being part of STEM education drives me to know…throughout my years, I'll never get bored…I'll always have more things to find out…there's always my posterity to do…its inspiring to know that I'll be finding new things possibly, but there is always more to know.

High School Student

One of the things that I always personally admired was education and like knowledge in general and seeing people have access. I, myself, have always more or less gone towards STEM or gravitated towards it because I want to have it myself and have always liked being able to go and try new things and be able to attain new knowledge; especially something I focus on because for some reason I always like found plants very intriguing so I always wanted to learn and study about them, so because I wanted to learn about it, I sought what I needed to understand it.

College Student

My son has been passionate about math and science since he was a toddler. He's always been interested in the "why" and "how" something works. As a toddler, it wasn't enough for him to build the provided track layouts for his train set, he wanted to create his own and design layouts with hills and curves, understanding conceptually that hills had to be the right height so that *the train can go over it and not get stuck and curves couldn't be too steep or else it fell off the track. Not only did he enjoy learning how something worked, he liked to explain it to others, which deepened his understanding even further. His sense of accomplishment and pride has always been visible in his face and demeanor when concepts "click".*

Parent

Their intrinsic motivation comes from their confidence, knowing and learning and wanting to learn more, but it is also when they are successful. When they are successful, then they want to do more. Examples of that would be students at IMSA go up against a teacher that they feel that they never could communicate with or that teacher will never listen or help me. Once they realized that the teacher is there for them, and willing to help and guide them, the teacher is there to work with them or sometimes banter with then; then I believe that is when the tables turn a little bit. Confidence is built and they are finding success. It's also that sometimes it is fun. Sometimes I see the students doing different experiments with different peers, which look like they are having a lot of fun. I think that's where it comes from. IMSA students study STEM and their intrinsic motivation is also the fact that they know they could do and that it is something else out there. There is something beyond what is in their community. For others, it is there because they want to be better or learn.

Faculty/staff

The next theme that arose is STEM passion/enjoyment, reported by 97 (35%) of 281 participants. Some Black and Latinx students have a natural inclination towards STEM and are genuinely interested. Although, it may be hard to develop this in students, it is important to expose students to STEM and nurture their STEM development to enhance motivation, as evident in the comments below:

Now, I'm engaged in STEM because I love it so much, it's very entertaining and interesting to me…but, I have to credit my parents for my engagement and involvement in STEM. As far as I've been told and can remember when I was younger my parents would put me in front of the computer and have me doing math problems before I was even in preschool and things like that. So I had an early interest for STEM and throughout the years it's become bigger and bigger because I have a natural infinity for it, I toyed more and more with it and I help other people with it and so it's just always been a part of me.

High School Student

It's not some sort of higher calling or money. It's always been passion for STEM…growing up I never knew what I wanted to do until I discovered my passion for STEM…the fact that I wanted to study STEM and my number one college choice is very STEM heavy, Cal tech, and if I get in, I will be studying STEM very thoroughly and the reason I want to do that is because I like to learn about STEM. I find it fun, I think the concepts are interesting and what

I do with STEM… there is a good possibility that I will advance the human condition…but for me and motivation to do STEM is because I am very interested in the subject matter.

High School Student

Well I think when he was younger, when he was about 2 years old and he was counting real high and I was amazed he was counting to like 200 and 300 and he recognized patterns with numbers right away and when I saw that we just kept going with it. He enjoyed that he was so good at it so he wanted to keep going with it and find out how far he could go with it. He would get books on his own, he would try to solve problems in different ways, other than what he was being taught in school … and he just liked being able to do this. He noticed right away that other kids were not able to do it; but what I think made it intrinsic in him, is that he knew he was good at it.

Parent

The fifth theme to emerge is solve problems to advance humanity, reported by 69 (25%) of 281 participants. This suggests that to motivate Black and Latinx students to engage in STEM, they need to work on solving societal and global issues, especially those that culturally/personally relate to them. It also suggests that Black and Latinx students need to understand the complexity of the problems, such as contributing social, environmental and economic factors. Below are participant remarks that suggest solving problems motivates STEM engagement in Black and Latinx students:

I think the gap exists because humanity is tearing us apart. Something that would motivate me to engage in STEM is us Blacks and Latinos working together to make the world a better and more positive place and for us not to think we can't follow our dreams.

Middle School Student

When I was in middle school, my motivation in STEM and I loved math, started off with a problem I could not solve and working my way through it and feeling the success of. I problem solved and I used my abilities to solve something to get an answer correct. I think that was my motivation, to get a correct answer…and now I like at my SIR [student inquiry and research]. I was doing rounds and there was one patient who literally the day before, his colon was in bad shape, and they removed it and he was on the verge of death and it changed from death to life in literally a matter of hours and I just find that fascinating and that drives me to go further, to push myself because I know that one life saved…if I become a doctor…one life saved is honestly, it's like the top. I don't know how to describe it…I've strayed away from the competition since I've been at IMSA…so I just want to prove to myself that I'm doing something useful worthwhile.

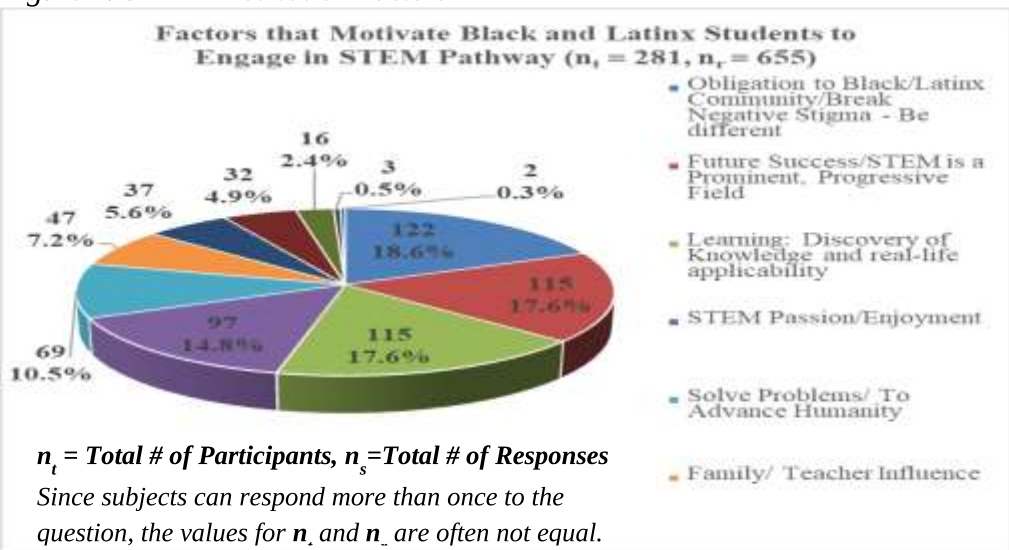
High School Student

> *It's always going to be a need for programmers and people to push the human condition forward and frankly as we grow forward, 10 years, 50 years from now; technology will be the only way to save ourselves as a culture because there are so many problems and not to sound, to have such a downer, but there are so many problems' and technology is going to be a way to fix a lot of those problems and not just technical problems; but problems with democracy, problems with communication, problems with just meeting people in fact science and technology is the way to solve a lot of those.*
>
> College Student

> *It started back in elementary, I would say puzzles, any kind of puzzle, anything that gets his mind going to solve something, he's always been gravitated to and when it comes to helping others rather it be through tutoring. He's always been one to volunteer for those types of things and I think he gets a lot of joy out of helping others and again solving mathematical or science types of things, equations, problems. That gets him going and part of it is this new range, he's very much into the internet as well as these textbox games, I think intrigues him; not just the game, but the ability to see how it works.*
>
> Parent

Other themes to emerge include family/teacher influence, challenge/ competitive nature of STEM, money, self-motivation, not good at math and leadership. There are both intrinsic and extrinsic factors that motivate Black and Latinx students to engage in STEM education and careers. The figure below shows the frequency of responses regarding the factors that motivate Black and Latinx students to engage in STEM, with a total of 655 responses:

Figure 2. STEM Motivation Factors



This research has built upon a preliminary study, Yes, STEM is for all: Diverse Perspectives on Black and Latinx STEM Motivation; adding the perspectives of middle school students, college students and geographic-based perspectives (i.e. high school students from the State of Ohio and Washington D.C.), 118 additional participants (Coleman et al., 2018). This previous qualitative study, consisting of data from focus groups with 85 students and interviews with 51 parents and 27 faculty/staff, put forth a 5-step approach to STEM motivation that was inclusive of early STEM exposure, IMSA as a model, Historical and Current News/Issues Discussion, Personalized Assessment and Evaluation, and STEM Leadership Development (Coleman et al., 2018).

Three of the steps, early STEM exposure, personalized assessment and evaluation and STEM leadership development were built upon, but remained consistent with the data. Two of the steps, IMSA as a model and historical and current news/issues discussion were collapsed into modified steps, culturally responsive STEM curriculum and conversations on race, and further developed to include additional data and demonstrate emerging trends. Being inclusive of the additional data that was collected on STEM motivation, the following 5-step approach to motivating Black and Latinx students to engage in STEM has been updated:

Table 2. A 5-Step Approach to STEM Motivation for Black and Latinx Students

1. Early STEM Exposure	▪ PreK-16 STEM immersion, in school and Saturday/Summer enrichment programs. ▪ Exposure to an array of STEM careers and careers that desire STEM skills, along with potential financial earnings. ▪ Bilingual STEM Advocacy Education and STEM Skill Development for parents.
2. Culturally Responsive STEM Curriculum	▪ Engage Black and Latinx students in becoming STEM literate and STEM thinking that is inquiry driven and rooted in solving problems that are of interest to them, their race and the world. ▪ Normalize Black and Latinx students being engaged in STEM education and careers through addressing implicit bias with teachers and stereotype threat with students, as well as provide visions of Black and Latinx people engage(d) in STEM; moving the students towards a growth mindset. ▪ Teaching and Learning should occur beyond a Westernized lens.
3. Conversations on Race	As indicated as a factor of motivation, Black and Latinx students are motivated to engage in STEM because of their obligation to the their respective communities to break negative stigmas and be role models; thus there needs to be space to discuss race through a historical, social and environmental lens, including this intersect between race and STEM.
4. Personalized Assessment and Evaluation	▪ Regular assessment of Black and Latinx students utilizing an asset-based approach, rather than a deficit-based approach. ▪ Growth-mindset coaching with Black and Latinx Students to help them develop confidence and the vision of themselves being engaged in STEM. ▪ Intentional relationship development between educators and students in order to identify potential STEM talent/passion from a relational perspective, as well as potentially have an understanding of what may be impeding STEM motivation.
5. STEM Leadership Development	"The STEM areas in which the Black and Latinx Students have demonstrated strength need to be complemented with a STEM lesson led by the student that has a problem-solving component. Opportunities to lead STEM research projects that advance humanity should be provided. Leadership opportunities outside of STEM are also important for leadership development and skill application. This will allow them to develop leadership skills needed to be successful STEM leaders in a global world" (Coleman et al., 2018).

Diversifying STEM Think Tank

Participants of the Diversifying STEM Think Tanks were asked to discuss why there was a racial STEM divide and strategies to diversify the STEM Education to Career Pathway. Eight major issues emerged; vision gap, opportunity gap, cultural perception gap, STEM education gap, generational gap, economic gap, identification gap, and STEM professional to educator gap. Although some of these issues have been discussed in professional literature, the main finding of this study is that these problems must be examined and resolved collectively and not in isolation, for the highest likelihood to diversify the STEM education to career pathway. In addition, it was agreed that there must be a policy-driven, collaborative STEM initiative between STEM educators, STEM professionals and the community. There was also a call to examine STEM teacher preparation issues, especially the decreasing number actually entering the field, along with implicit bias and inadequate cultural competence. Below are the defined problems along with solutions that emerged from the Diversifying STEM Think Tanks:

Table 3. Diversifying STEM Think Tank Results

Gap	Definition	Solution
Vision Gap	Lack of vision to enter a STEM field due to racial isolation in STEM courses/programs. Lack of Black and Latinx role models/mentors, stereotype of STEM "not being cool" so students suffer from the "cool pose" and a feeling of not belonging.	• Normalize STEM education, majors and careers as attainable and desirable for Black and Latinx students. • Engage Black and Latinx STEM professionals in STEM education and programming.
Opportunity Gap	Lack of both STEM access and exposure.	• Engage students in STEM pathway by providing educational, research and internship opportunities in local, national and global space for PreK – 16, Black and Latinx students at no to low cost.
Cultural Perception Gap	Resulting from systemic bias, negative stigma/misperception of Black and Latinx students related to their overall intelligence and STEM potential. Resulting from stereotype threat, Black/Latinx students hide their intelligence and STEM potential.	• Implicit bias and culturally responsive pedagogy training, with emphasis on STEM equity for educators, administrators and policy-makers. • Confront stereotype threat; create a public presence that visually displays diverse groups of STEM educators/professionals, specifically Black and Latinx.
STEM Education Gap	Lack of quality STEM education/teacher preparedness and interest. Lack of practical application in STEM teaching and learning	• STEM skill development experience for educators. • Professional development for educators on development of real-life, culturally responsive STEM curriculum. • Course on diversifying STEM fields with and intricate look at STEM

		inequity for school administrators and teacher certification programs.
Generational Gap	Parents lack of STEM skills and knowledge, as well as do not understand the significance of entering STEM, which results in a lack of STEM advocacy for their student. Linguistic and STEM literacy barriers.	• Host bilingual parent education sessions on how to advocate for their student in STEM engagement, resulting in a more STEM literate parents. • Provide professional learning opportunities in which parents develop STEM skills for possible career enhancement or change.
Economic Gap	Schools System Funding Issues/Funding for Families	• Create equity in school funding for STEM programs. • Inform families of free and low-cost STEM resources for families.
Identification Gap	Lack of STEM talent identification protocol or awareness education by teachers and/or parents - No training for teachers.	• Develop a culturally responsive STEM talent identity protocol, based on research and then provide professional learning that trains STEM educators and parents to implement.
STEM Professional to Educator Gap	Discouragement of STEM Professionals to become STEM Educators – it is challenging for STEM Professionals to become teachers due to certification guidelines.	• Collaborate with colleges and universities to develop an expedited teacher certification process for STEM Educators that takes into account their level of experience.

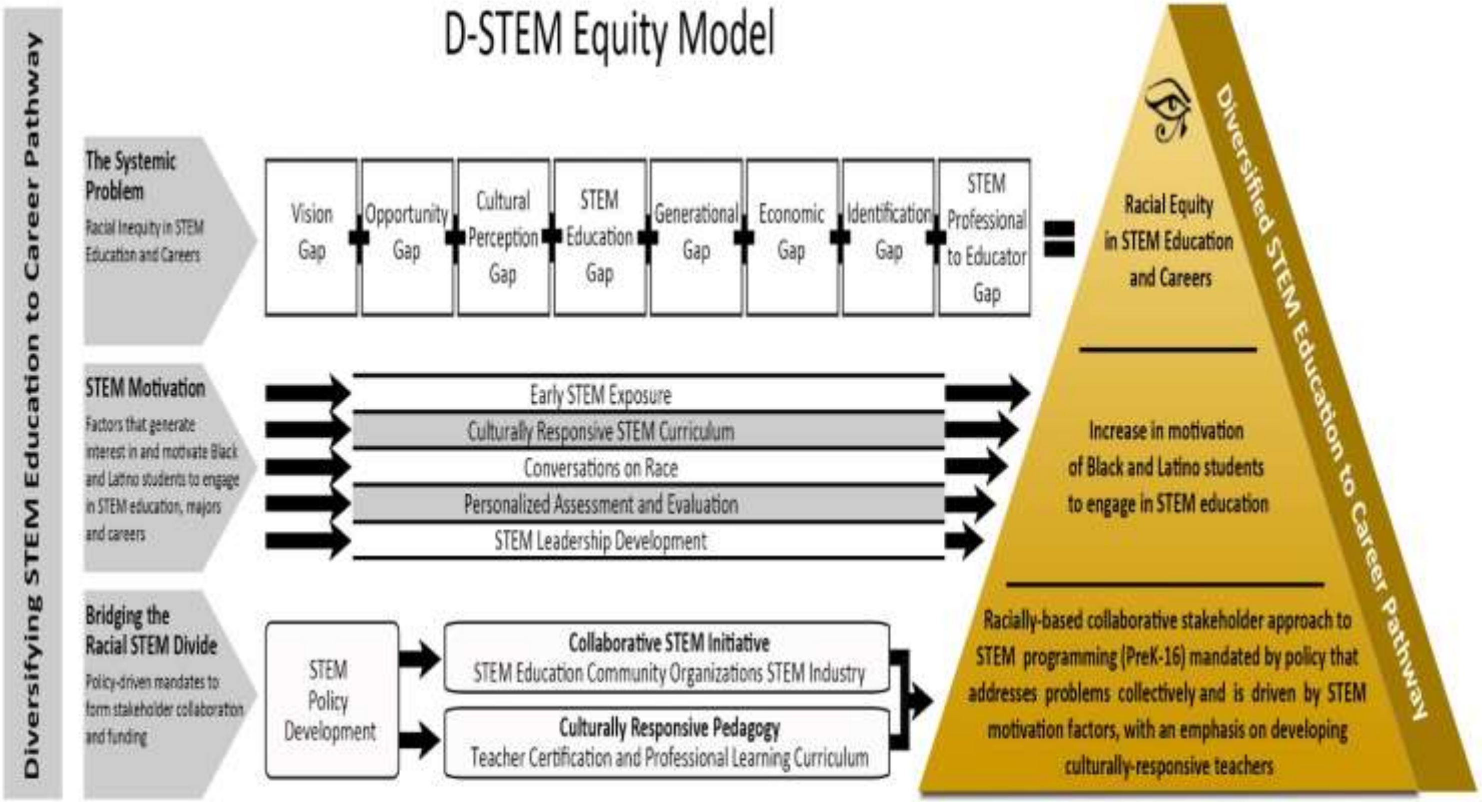
Discussion

"There is little prior research at the national level on how racial/ethnic differences in preparation contribute to inequity in STEM fields"; thus, the D-STEM Equity Model is a proposed national-based approach to diversifying the STEM education to career pathway with global scalability (Riegle-Crumb & King, 2010). It provides a comprehensive perspective of the problems related to racially-based STEM inequities, is rooted in factors that motivate STEM engagement in Black and Latinx students and emboldens a culturally-responsive collaborative strategy to address the racially-based STEM inequity holistically. The Diversifying STEM Equity Model (D-STEM Equity Model), connects two studies; one that focused on factors that motivate Black and Latinx students to engage in STEM, the other focused on identifying and addressing issues related to the racial STEM divide; with the goal of informing diversifying the STEM education to career pathway.

There are eight major problems contributing to racial inequity in STEM education and careers, specifically as it relates to Black and Latinx student STEM engagement; including vision, opportunity, cultural perception, STEM education, generational, economic, identification, and STEM professional to educator gaps. Using the strategies previously proposed in *Table 3,* the identified problems should be addressed holistically and not in isolation, which will lead to improved racial equity and assist in diversifying the STEM education to career pathway. There are also five significant factors that motivate Black and Latinx Students to engage in STEM that include early STEM exposure, culturally responsive STEM curriculum, conversations on race, personalized assessment and evaluation, and STEM leadership development, previously explained in *Table 2*. If students engage in one or more of these motivation pathways, it will lead to an increased interest and engagement in STEM, which too will assist in diversifying the STEM education to career pathway. Considering the intersection of motivation factors and the identified problems; early STEM exposure addresses the vision, opportunity, generational and STEM education gaps, culturally responsive STEM curriculum/ conversations on race/STEM leadership addresses the vision and cultural perception gaps and, personalized assessment and evaluation addresses the STEM education and identification gaps.

To address the additional economic and STEM professional to educator gaps and truly bridge the racial STEM divide, policy must be implemented that provides funding for a collaborative PreK-16 STEM initiative and culturally responsive training for STEM educators and those in preparation, as well as STEM professionals who want to enter academe. "Diversifying STEM policies" need to be developed that mandate funding for racially-based collaborative STEM initiatives to be implemented, that work towards achieving equity by addressing the identified problems collectively and integrating factors of Black and Latinx student STEM motivation into STEM programming; as well as encourages culturally responsive training for state/national teacher certification and current STEM educators. This will lead to a diversified STEM education to career pathway, as displayed in the D-STEM Equity Model below:

Figure 3. Diversifying STEM Equity Model



Conclusions

An intricate examination of the racial STEM divide and strategies to address that gap along with a racially-based STEM motivation approach were presented throughout this paper. Connecting this data led to the development of the D-STEM Equity Model as an approach to diversify the STEM Education to Career Pathway model, which can be applied on local, state, regional or national levels. Governmental agencies, educational institutions, STEM industry and community organizations are encouraged to collaboratively adopt this model to build upon the research by testing its' effectiveness, while increasing Black and Latinx persons' engagement in STEM education and careers.

Considering that those underrepresented in STEM extend beyond race in the United States, the D-STEM Equity Model can be applied on a global scale. Utilizing the research methodology approach discussed in this study, additional research must be conducted on the underrepresented group in order to gain a better understanding of the problem, strategies to address the problem and motivation of those from the underrepresented group who are engaged in STEM. The following steps should be taken to scale the D-STEM Equity Model for global application:

1. Identify groups who are underrepresented in STEM and host "Diversifying STEM Think Tanks" to gain a better perspective as to why STEM inequities exist within the respective group(s) and strategies to address.
2. Hold focus groups with members of identified group who are engaged in STEM to understand what motivates them to engage in STEM.
3. Identify stakeholders who will value from diversifying STEM and policy-makers who are STEM advocates to move toward a collaborative STEM initiative.
4. Identify other barriers to diversifying STEM that exists for the respective group(s).
5. Based on the data collected, modify the language in the D-STEM equity model to include identified problem, motivation factors, bridging component, which include stakeholders and additional barriers.

Application of the evidence-based D-STEM Equity Model can definitely assist in addressing the global demand for STEM professionals and those who possess STEM skills. It can also assist the United States in bridging the racial STEM divide, which can indirectly influence unemployment, address issues of poverty and impact economic growth in Black and Latinx communities. This is STEM Innovation!

Acknowledgment

Special thanks to the Illinois Mathematics and Science Academy for prioritizing equity in STEM and allowing the space for diversifying STEM research to be conducted.

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Athens Journal of Education - Volume 7, Issue 3, July 2020 – Pages 297-312

KaLeP: A Holistic Case-based Action Learning Environment to Educate Successful Future Engineers

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The working environment of future university graduates is characterized by highly dynamic and complex product development processes. In addition to disciplinary competence, it is essential to build up methodical and social competence as well as to foster the elaboration and creativity potential of students. In order to meet industrial requirements the Karlsruhe Education Model for Product Development (KaLeP) was implemented. One element of this holistic education model is a design methods internship called ProVIL - Product Development in a Virtual Idea Laboratory. The above mentioned integrated understanding of product development and the competences derived from it are successfully taught in the case-based action learning environment ProVIL. Additionally, the very important aspect of multidisciplinary product development in site-distributed teams is taken into account and generates an added value to the progression of the KaLeP. In this work the authors present the dimensions of competence which should be aimed for a holistic teaching approach for the interdisciplinary student courses in ProVIL. An example illustrates how a continuous alignment and the necessary adaption of competences of student project teams can be achieved within ProVIL.

Keywords: action learning, competency model, education model, product development.

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Introduction

With increasing complexity of the development process from the idea to the product, the expectation of the industry towards an engineering graduate is constantly rising. Due to higher quality, time and cost pressures in the development environment, the integration of interdisciplinary knowledge is necessary to design new processes and methods. Furthermore, the engineer's work in the industrial and professional field is mostly characterized by teamwork nowadays. Therefore, pure professional expertise is unsatisfactory. In addition, methodological and social skills as well as creativity are required. In order to gain these competences, a holistic education model can meet the industries' expectations and foster the development of diverse competences which are vital for becoming a successful engineer.

This leads towards new approaches for university teaching which support the students in the development of broad professional competences. The KaLeP is a general education concept orientated at the real industrial development process and designed to promote competence in product development (Albers, Burkardt, & Matthiesen, 2001). Next to the education of mechanical specialists, the KaLeP realizes the teaching of broad professional competences through a holistic approach including consecutive courses and individual events in different settings accompanied by intensive project work in student teams. It is mainly based on tripartite teaching in all areas starting with the mediation of knowledge in the first part, then extending it in the second and finally deepening it intensively in the third part (Albers, Burkardt, Robens, & Deigendesch, 2009). The projects are design methods internships for students with the goal to consolidate theoretical knowledge and build up important skills, such as social abilities for teamwork and soft skills like creative potential. One example for these design methods internships is ProVIL, which is an interdisciplinary and inter-institutional education model as well.

Literature Review

Competence Model and Learning Strategies

The fact that a person must be able to master various types of competences in order to succeed at school, at work or simply in interacting with other people is not a recent realization, however. Since many years, pedagogues and educationalists have been studying the complex field of learning and have concluded that different approaches and strategies can lead to the acquisition of different kinds of desirable skills. In the following, some important models are illustrated which aim at structuring and classifying those methods and levels of teaching and learning with regard to the targeted outcomes, thus shaping the KaLeP model as it is today.

Learning Strategies. For the successful education of engineers, different learning and thinking strategies should be taken into account, considering that those strategies determine learning success as well as development of intellectual properties to a great extent.

While there are various ways of classifying such strategies in order to facilitate exchange between educators, Mandl and Friedrich (Mandl & Friedrich, 1992) were able to identify a few approaches, which are most commonly used. One of them is the distinction in primary and support strategies. In this sense, primary strategies are defined as methods with direct influence on knowledge acquisition by actively improving the ability of grasping, memorizing, reproducing and applying knowledge in the same or a deviant context than originally taught. They are widely known as cognitive strategies and include a range of different methods, which describe exactly how information is processed (Mandl & Friedrich, 1992; Mandl & Friedrich, 2006):

- *Elaboration strategies* support the memorisation and reproduction of information by connecting it with already familiar knowledge, thus establishing multiple ways of accessing the information. Examples for elaboration strategies are posing questions, taking notes, creating images, etc.
- *Organisation strategies* describe the arrangement of information in order to form logic units of knowledge since it is easier to process chunks of data than detailed information. These strategies incorporate methods like summarising, classifying, etc.
- *Knowledge-use strategies* deal with methods regarding the transfer of information into another context than the original one. This can be exercised by leading discussions, writing essays, etc.

In comparison to these primary strategies, support strategies only have indirect influence on knowledge acquisition by affecting e.g. motivation, concentration or time management. Amongst others, they encompass the following strategies: (Mandl & Friedrich, 1992; Mandl & Friedrich 2006)

- Motivational and emotional strategies promote aspects like motivation, attention over time, endeavour, etc. These factors have a great effect on the successful application of primary strategies and are affected by e.g. interest in the learning objective, the desire to broaden one's own knowledge or beneficial surroundings.
- Cooperation strategies regulate the learning within a group, e. g. school classes or working groups. On the one hand, this enhances motivation because participants motivate each other. On the other hand, it adds value to cognitive processes since each person introduces new knowledge others can benefit from.
- Meta-cognitive strategies or control strategies are superior to cognitive strategies, yet only providing supporting functions regarding knowledge acquisition. They incorporate all methods aiming at self-reflection of one's own knowledge acquisition processes, including the act of planning, monitoring and evaluating.

While the above explanations only show a very compressed characterisation of different learning strategies, Mandl and Friedrich explicitly state that such classification systems are not complete since there are still strategies and methods not included in the scheme. Furthermore, it sometimes can be very difficult or even impossible to exclusively assign a strategy to one single category (Mandl & Friedrich, 1992).

Categorization of Knowledge. In order to apply these learning strategies, which have an active influence on knowledge acquisition; it is important to categorize the goals of teaching. A set of consistent definitions of abilities that students acquire through the teaching process will support the educators in designing syllabuses and exam papers that serve the targeted teaching goals. Therefore, Benjamin Bloom (1974) developed the Bloom's Taxonomy in 1948. It is a classification system which consists of six categories, each containing several subcategories (except the third category) arranged from low to high level of complexity and abstraction. By this means, it becomes clear that in order to perform high ranked abilities, it is necessary to master lower ranked abilities beforehand (Bloom, 1974).

The six main categories of Bloom's Taxonomy are the following:

1. *Knowledge:* It encompasses the act of remembering information and reproducing it in the same or a similar way that it was taught.
2. *Comprehension:* A student does not simply remember a specific information but is able to understand its meaning in order to modify or develop the information further.
3. *Application:* A student is able to identify a situation similar to known problems, select a suitable information or method and exercise the solution on his own.
4. *Analysis:* It describes the ability to break down the structure of information and identify relations and interactions between the elements.
5. *Synthesis:* A student can combine components of different information in order to form new information that did not exist before.
6. *Evaluation:* A student is able to assess information according to specific criteria, enabling him to form an opinion based on facts rather than expressing a subjective judgement (Bloom, 1974).

After several years, Lorin Anderson and David R. Krathwohl (Krathwohl, 2002) adjusted the original taxonomy as shown above, hence giving it the name *Bloom's Revised Taxonomy*. Since the category *Knowledge* encompasses not only the teaching goal (remembering and reproducing) but numerous types of information as well, it can be split up into the *Knowledge Dimension*, consisting of *Factual, Conceptual, Procedural* and *Metacognitive Knowledge*, and the *Cognitive Process Dimension* containing the six main categories of Bloom's original taxonomy (Anderson & Krathwohl, 1974). In addition, the original categories were renamed and *Synthesis* and *Evaluation* were exchanged (Krathwohl, 2002).

Consequently, it is now possible to make statements about the quality of a course according to the diversity of tasks as well as to identify neglected teaching goals which should be included stronger into the syllabus (Krathwohl, 2002).

Education Models for University Teaching. The already named KaLeP is an example for a holistic education model for product engineers. It aims to train integrated product developers who have already been successfully educated in all relevant fields of competence. These competences are embedded in a so-called competence spider which includes the following aspects:

- Disciplinary competence (e. g. basic knowledge in mathematics, machine parts, foreign language)
- Methodological competence (e. g. development methods, FMEA, CAD)
- Social competence (e. g. communication and teamwork, presentation skills)
- Creative potential (e. g. creativity techniques, problem solving capability, courage for new solutions)
- Elaboration potential (e. g. focus on customer view, cost awareness, put theoretical knowledge into practice)

As mentioned beforehand, the model is divided into three parts. It starts with teaching the theoretical knowledge in lectures, followed by tutorials where the students apply the gained knowledge and the implementation of the knowledge in a workshop with a case-based project. Within these consecutives courses a product development-specific knowledge in systems, methods and processes is taught. The workshops are embedded in an industry-near development environment (Albers, Burkardt, & Duser, 2006). This goes back to the benefits of the education method called Action Learning.

As a pedagogical method, Action Learning is based on its originators, Reginald W. Revans, assumption that learning has two major components: *Programmed Knowledge* and *Questioning Insight* (Revans, 1982).

Programmed knowledge is understood as all the expertise a person possesses whereas questioning insight describes one’s ability to pose the right questions in order to solve new problems with uncertain outcomes, thus helping to identify required knowledge and to re-structure it to serve the purpose. Considering this, Revans (Revans, 1983; Hauser, 2012) set up the following equation:

$$L = P + Q$$

It states that learning (L) can only be successful if both factors, programmed knowledge (P) as well as questioning insight (Q), are involved. However, especially in this day and age, in which surrounding conditions become more and more volatile and change is omnipresent it cannot be sufficient anymore to simply rely on knowledge from the past. The significance of Q rises as the need of adaption to previously unknown situations becomes greater (Revans, 1984). Therefore, in Revans opinion, conventional teaching methods in which an expert explains his special knowledge to his students are not adequate anymore (Revans, 1982). Instead, he asks for a practical learning environment, where students encounter and resolve problems, risk and uncertainty as they do in their everyday work. When practicing Action Learning, students form so-called learning communities in which they discuss arising problems at eye level. For this purpose, they meet on a regular basis and introduce each other to currently difficult situations. They tackle problems together by sharing opinions, proposing possible solutions, and putting them into practice. This approach is beneficial to each member of the learning community. From time to time everyone finds himself in the position of either giving or receiving advice and everyone can benefit from the advice given by other members of the group. While special expertise might still be necessary to some extent, the role of a tutor can be transferred onto the group because each member has different knowledge that he can share with the rest of the community (Revans, 1983; 1999).

Another advantage of seeking support among like-minded students is that their commitment is usually higher than it is the case with theoretical experts and tutors. While tutors are not involved in the same way future managers are and not responsible for the outcome of practical implementation of their theoretical knowledge, the members of the learning community are far more motivated to find appropriate answers because they might be in need of them at some point as well (Hauser, 2012; Revans, 1984).

In conclusion, one must mention that there is no predefined step-by-step procedure for carrying out Action Learning. It is an open concept on group learning and each learning community must figure out for itself how to learn and improve most effectively (Hauser, 2012).

Live-Labs as Real-World Validation Environments

Live-Labs are validation environments, which are used by design researchers to investigate design processes, methods and tools under realistic conditions in the context of product engineering. At the same time, they allow the design researcher a high controllability of boundary conditions (Albers, Bursac, Walter, Hahn, & Schröder, 2016a). A common example for Live-Labs is innovation projects with companies and students where the main objective is to develop technical solutions for customers while using predefined project resources. Due to the real-world character of Live-Labs, it is possible to examine the suitability of design processes, methods and tools regarding their intended use within a real-world application (Walter, Albers, Benesch, & Bursac, 2017a). Hereby, it is possible to increase the external validity of the validation results through the systematic design of the Live-Lab environment. Therefore, it is necessary to analyze the attributes of the real-world application of design processes, methods and tools in detail to decide how the attributes of the Live-Lab environment need to be designed. There are four different cases to decide on the value of the respective Live-Lab attribute, as simulation, variation, exploration and boundary condition check. In general, these four cases enable the design researcher to design the boundary conditions of the Live-Lab study in detail, thus increasing the external validity of the validation results (Albers, Walter, Wilmsen, & Bursac, 2018).

In order to investigate the currently most relevant challenges of product engineering teams, the Live-Lab ProVIL – Product Engineering in a Virtual Idea Laboratory – was generated. Within ProVIL, mechanical engineering master students develop technical solutions for future customers in cooperation with industrial engineering and international management master students (Hahn et al., 2017). Furthermore, every ProVIL participant has a different specialization within their master courses. By this means, each team consists of future design engineers as well as test or automation engineers and business experts (Albers, Bursac, Heimicke, Walter, & Reiß, 2017a). Thus, it is possible to examine the challenges of interdisciplinary collaboration within product engineering projects. Another important challenge of modern product engineering teams is the distributed collaboration, caused by the increasing globalization and internationalization of companies. To mirror this challenge within ProVIL, the students are working with different online tools, such as Jira for project management or SAP Innovation Management for evaluating product ideas and concept within the community (Walter, Albers, Heck, & Bursac, 2016). Thereby, the Live-Lab ProVIL enables design researchers to investigate design processes, methods and tools for interdisciplinary and (partly) distributed product engineering teams. For example, in ProVIL 2017 two method variants of the scenario-technique for distributed product engineering teams were developed and successfully researched through an extensive Live-Lab study. Live-Labs thus contribute to the development and research of design processes, methods and tools for the PGE - Product Generation Engineering (Walter, Wilmsen, Albers, & Bursac, 2017b). The approach of PGE "is understood as the development of products based on reference products (precursor or competitor products). The subsystems are either adapted to the new product generation by means of carryover or they are newly developed based on shape variation or principle variation" (Albers, Behrendt, Klingler, Reiß, & Bursac, 2017b).

Integrated Product Development

The iPeM - integrated Product engineering Model is a unique metamodel for modelling product development in the context of the PGE (Albers, Reiß, Bursac, & Richter, 2016b). It is based on a systems theory and represents a central element of the Karlsruhe School of Product Development (KaSPro). With iPeM, product development processes can be modelled holistically.

The iPeM is based on the elements of the triple based systems theory according to Ropohl (Ropohl, 1975) which describes product development with the following three interacting systems: the system of objectives, the system of actions and the system of objects [meaning "subject system" according to (Ropohl, 1979). He describes the connection between the system of objectives, the system of actions and the system of objects with a control loop.

Since this paper deals with holistic development in teams, the system of actions will be discussed in more detail below. It creates the system of objects on the basis of the system of objectives or further develops an existing system of objectives (Albers & Braun, 2011). The system of actions is a socio-technical scheme consisting of structured activities, methods and processes. It also contains all resources necessary for the realization of a product development, e. g. developer, budget and equipment (Meboldt, 2009; Albers, Lohmeyer, & Ebel, 2011). In the course of the product engineering process, the system of actions can be expanded (e. g. new team members or equipment) or minimized (elimination of resources).

In the system of actions of the iPeM, different layers are modelled. The first levels describe the development of a product. One level is added for each subsequent product generation. The development of validation and action systems and strategy development form a separate level as well. This allows relationships between different products, product generations, validation and production systems. Additionally, corporate strategies can be mapped and resources and goals can be planned across multiple product generations (Albers, Reiß, Bursac, & Richter, 2016b).

In order to be able to implement the activities of product development in the system of actions, iPeM applies the problem-solving method SPALTEN. In the first step of the SPALTEN process, a suitable problem-solving team is assembled for each situation. This is repeated between each further SPALTEN step (Braun, 2013).

Through the consideration of all activities in the product development process, their planning and implementation in the phase model, the mapping of the entire company process across the various levels and the company-wide consideration of three interacting systems, as well as the relationship of all elements mentioned, the iPeM supports the holistic development in the team. Above all, this applies to the modelling of the system of actions as a socio-technical system since it supports the problem-solving team with concrete methods.

Methodology

The state of the art implicates that a holistic education model which is based on case-based action learning fosters the development of diverse competences for the education of future engineers. Within the KaLeP, Live-Labs are used to intensively deepen the students' expertise as well as develop competences in situations which require diverse and connected sets of competences. Especially in the Live-Lab ProVIL, the interdisciplinary and distributed teamwork with different disciplines is mediated. This contribution focuses on the research about the integration of different learning strategies and competence models in a holistic teaching model referring to the following research questions:

1. Which dimensions of competence should be aimed for a holistic teaching approach for the interdisciplinary student courses in ProVIL?
2. How could a continuous alignment and the necessary adaption of competences of the student project teams be achieved within ProVIL?

In order to answer these research questions, the authors initially analyzed which competence profile is required for successful future product engineers. For this purpose, both the state of the art and an interview with two professors from the fields of product development and innovation management were analyzed, thereby making it possible to determine the target competences of product engineers with a mechanical engineering and an economic focus. In particular, existing competence models of literature became a basis for creating characteristic competence profiles. In the next step, the different Live-Labs, especially ProVIL, were analyzed with regard to the competences imparted here. In several joint workshops with Live-Lab experts the competences taught within ProVIL were evaluated by using the already mentioned competence models from literature. Finally, the target competences of future product engineers were compared with the competences imparted in ProVIL. Deviations between the target and actual competence profiles were determined. These deviations were carefully considered and it was evaluated to what extent it is necessary to expand the Live-Lab ProVIL. Further considerations concerned the question whether additional courses should be offered or whether this competence is already sufficiently covered by other courses of the master's program.

Results

Within ProVIL, the education models of the two courses for master students at the Karlsruhe Institute of Technology (KIT) and the University of Applied Sciences Karlsruhe (HsKA) were analyzed. The courses, which are integrated in the product development project, encompass the likewise named design method internship *ProVIL* for Mechanical Engineering students and the course called *Innovation Process Coaching* for International Management and Industrial Engineering students at the HsKA.

Both courses are based on the action learning approach, which means that students acquire knowledge by working on the development project with a defined project process. Additionally, there are three Kickoffs at the beginning of each project phase. During the Kickoffs, students learn about the theoretical background of the tasks, deliverables and goals of the next phase. Furthermore, there are some special training workshops for methods such as a creativity method workshop or a business model generation workshop to methodologically prepare the students for the upcoming tasks. In conclusion, the action learning approach got expanded with some theoretical training.

Categorized Competence Model of ProVIL

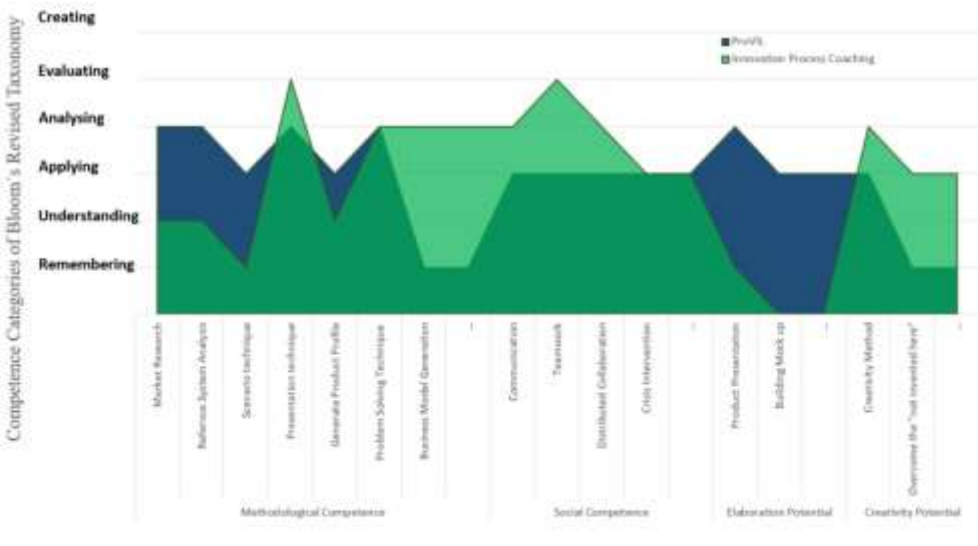
The research of the education models of these courses is based on the state of the art competence models and learning strategies. The action learning based knowledge transfer during the development process of generating new inventions in cooperation with an industrial partner fosters the different learning strategies. For example, the research activities the students perform in the analysis phase can be assigned to elaboration strategies because the students use their existing knowledge and reproduce new information through connecting it with the collected information from their research fields. Furthermore, the knowledge-use strategy is applied in activities in which the students use knowledge from market research and transfer the information into another context by using the scenario technique. Due to the real industrial challenge from the project partner company the students are eager to learn and apply new knowledge which represents motivational and emotional strategies.

In order to organize the taught knowledge, the different activities of the students in ProVIL are structured with the competences of the KaLeP competence spider and categorized by Bloom´s Revised Taxonomy. The adjusted taxonomy enables the categorization of activities with suitable descriptions due to the renamed categories.

Because of the fact that ProVIL is one of the courses of the third stage of the KaLeP, the teaching focus lies in the implementation of already gained knowledge. Therefore, the disciplinary competences are implied as given.

In Figure 1 some selected key activities of the students during ProVIL and the corresponding competence category for the two courses are presented on basis of Bloom´s Revised Taxonomy. These key activities are assigned to the teaching of methodological competence. The first example is the starting activity of an intensive market research towards the main research fields of the development challenge. The mechanical engineers participating in ProVIL conduct the tasks of market research and statistical analyzing. Therefore, their competence in these fields ranks in the fourth stage of analyzing. The students participating in Innovation Process Coaching who accompany in these tasks need to understand the methodological process they are running through.

Figure 1. Categorized competence model of ProVIL



Another example of the assigned activities is the presentations of the students at milestones. During the development project, there are three milestones during which the students present their current deliverables to the project management as well as to the industrial project partner. Upfront, there are pre-milestones during which they get feedback on their presentation from the project management and their fellow students. In regard to the presentation competence, the ProVIL students apply their case-based knowledge about presentation techniques. Due to their task to challenge and assess the given presentations in a clear and structured way, the Innovation Process Coaching students acquire the competence to analyze and evaluate presentation techniques.

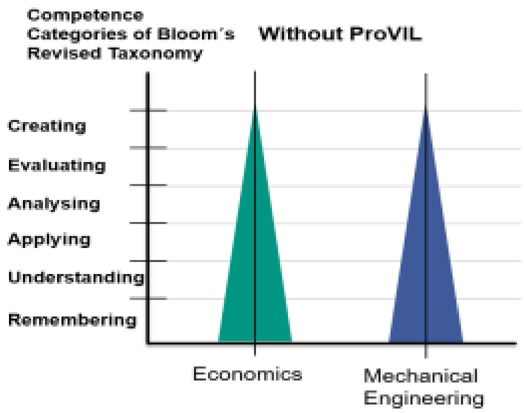
As a result of the interdisciplinary composition of the development teams, the students acquire social competences during the real product development process. Especially through the aspect of many virtual meetings, workshops and milestones, they learn how to communicate and collaborate in site-distributed teams. Due to the responsibility of the innovation coaches to moderate and organize the collaboration of the teams, they gain a high social competence.

Education Model for successful interdisciplinary Collaboration

As a Live Lab for distributed teams, ProVIL simulates, amongst others, the cooperation of project stakeholders from different specialist areas in a virtual space in the early phase of PGE. The students of the HsKA, working as Innovation Coaches in ProVIL, have an economic background. The product developers in ProVIL, however, study mechanical engineering.

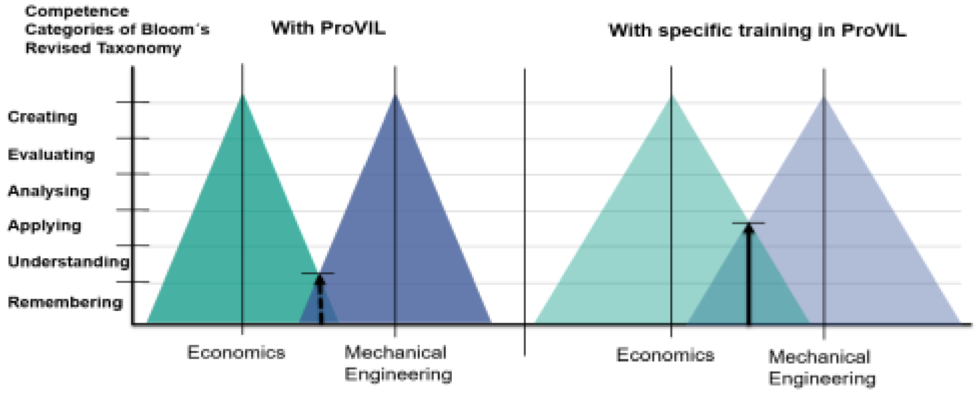
In order to enable cooperation, a common language must be established. Figure 2 shows the characteristics of the competences of innovation coaches and product engineers before the start of ProVIL, based on analysis of the project years 2016 and 2017. On closer examination of the competences that can be acquired in different study programmes, it becomes clear that the students build up knowledge and competences in the specific subject areas but learn little interdisciplinary knowledge. Figure 2 displays the resulting competency-triangles of the participants identified before the start of ProVIL. Both stakeholders have profound professional competences in the focus of their subject-specific study programmes up to the competence category *Creating* of the Bloom's revised Taxonomy.

Figure 2. Competence-triangles of Master Students without ProVIL



However, successful cooperation can only be guaranteed with a common language, e. g. an overlapping field of competence must be sought. In the course of the project, further competences (cf. Figure 1) are built up through sole participation in the project and the associated mandatory events such as kick-offs and milestones. The development of these additional competences leads to the ProVIL participants reaching the level of "understanding" by overlapping their fields of competence, thus facilitating cooperation (cf. 3). Additional targeted training during the process, such as the Pitch 2.0 workshop, in which ProVIL participants learn to present their ideas to the customer within a very short time to convince the customer of their ideas, maximise the range of the competence field additionally. A more effective cooperation can be achieved by expanding the competence-triangles of the participants and forming the competence overlap on a higher level of the competence fields according to Bloom's revised Taxonomy.

Figure 3. Competence-Triangles of Master Students with ProVIL (Left) and with Specific Training in ProVIL (Right)



Conclusion and Outlook

The holistic case-based action learning environment KaLeP shows an integrated teaching model to educate successful future engineers. The most important aspect is the extended competence model with methodological, social competences as well as elaboration and creative potential next to the disciplinary competence of an engineer. This integrated understanding of necessary product engineering competences is taught in regard to established learning strategies. On the basis of a structured categorization of activities and with it the taught competences, the case-based action learning course with additional trainings, called ProVIL, has been build up. It shows that the education model is very successful in teaching competences for interdisciplinary collaboration. Especially for future distributed collaboration and virtual workspaces, the importance of social competences of an engineer increases significantly.

Regarding the impressive outcomes of the ProVIL projects in 2016 and 2017, during which the students developed mock ups and physical prototypes of their inventions, the added value of the interdisciplinary project teams with mechanical engineers as product developer and economists as innovation coaches was exposed. The implemented product development process enabled the student teams to fit their complementary competences and efficiently generate inventions with high innovation potential.

Due to targeted analysis pointing out the lack of competences of participants, training courses could be used in order to maximize the competence triangles, thus enabling cooperation at higher levels according to Bloom. With further research on time-scalable and stakeholder specific training courses with a modular set up, the aim is to create complete a holistic competence model for successful collaboration within interdisciplinary product engineering teams.

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Athens Journal of Education - Volume 7, Issue 3, July 2020 – Pages 313-330

On Teaching Quantum Physics at High School

By Enzo Bonacci[*]

In the Italian education system, secondary students (ages 14-19) are confronted with the foundations of quantum physics during the final term of scientific high school (pre-university year). The Italian Ministry of Education, University and Research (acronym MIUR) has remarked its importance in the syllabus to address the high school exit examination (30% of the 5th year physics course) but, due to limited learning time and intrinsic difficulty, this branch of physics is neither assimilated nor appreciated as it should. We wish to illustrate six didactic suggestions focused on learning motivation, emerged during a 17-year long teaching experience, which could help to tackle the main problems found. The key references are two peer-reviewed talks given, respectively, in 2018 at the 6th Annual International Conference on Physics by the Athens Institute for Education and Research and in 2013 at the 2nd Rome workshop *Science Perception* by the Roma Tre University together with a concise and evocative poster outlining the history of quanta (Figure 1). Other useful resources are a 2015 conceptual diagram (Figure 2) and four invited lectures held in the years 2010-2017.

Keywords: Didactic Method, Quantum Physics, School Teaching, Science Perception, STEM.

Introduction

The twentieth century saw the affirmation of a physical theory nicely branded by the well-known Feynman's quote "I think I can safely say that nobody understands Quantum Mechanics" (Hey & Walters, 2003). Emblem of the Physics power to influence Philosophy and responsible for a good half of the hypotheses pervading the best science fiction movies, Quantum Mechanics is the second pillar of modern physics next to Einstein's relativity theory. Of this latter we know his aversion to the ontologically probabilistic character of the rival theory, expressed in the memorable correspondence with Max Born (Born & Einstein, 1971). Here we offer six didactic proposals which can positively address the numerous problems encountered in teaching basic Quantum Physics at science high schools. They come from two peer-reviewed talks (Bonacci, 2013a, 2018) together with a poster meant to be at the same time accessible and attractive to secondary school learners (Figure 1), whose *incipit* is Max Planck's study of Black Body Radiation (1900) but whose epistemological roots date back to ancient Oriental cultural traditions (Bonacci, 2013b). In what follows we will use interchangeably the terms Quantum Mechanics (QM for brevity) and Quantum Physics (QP for short) meaning the same course for high school students which does not go beyond the "first quantization" (semi-classical treatment). The legal framework and an up-to-

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date literature (Par. 2) are retrieved from current Italian institutional and sectorial websites.

Figure 1. The 2013 poster on Quantum Physics by Enzo Bonacci

Source: https://bit.ly/2GBqq6J

Physics in the Italian Scientific High School

The Scientific High School in Italy

According to the EU's recent attention to Science, Technology, Engineering and Mathematics activities (acronym STEM), the Italian Ministry of Education, University and Research (MIUR) clarifies that "The course of the scientific high school promotes the acquisition of the knowledge and methods of mathematics, physics and natural sciences. It guides the student to deepen and develop knowledge and skills, to mature the skills necessary to follow the development of scientific and technological research and to identify the interactions among the different forms of knowledge, ensuring the mastery of the relative languages, techniques and methodologies, also through laboratorial practice" (translated from the Italian website[1]).

[1]https://bit.ly/2GFr584.

Italian National Guidelines for Physics at the Scientific High School

The current study program of the "Liceo Scientifico" (Italian name for scientific high school) was established in the Decree of the President of the Italian Republic 89 of March 15, 2010 whose scheme of regulation was defined on October 7, 2010, by the Italian Interministerial decree n. 211. We extrapolate the text about the Physics course at the *Liceo Scientifico*: "At the end of the high school career the student will have learned the basic concepts of physics, the laws and theories that make them explicit, acquiring awareness of the cognitive value of the subject and the link between the development of physical knowledge and the historical and philosophical context in which it developed. In particular, the student will have acquired the following skills: observe and identify phenomena; formulate explanatory hypotheses using models, analogies and laws; formalize a physics problem and apply the mathematical and disciplinary tools relevant to its resolution; experience and explain the meaning of the various aspects of the experimental method, where the experiment is intended as a reasoned interrogation of natural phenomena, choice of significant variables, collection and critical analysis of data and reliability of a measurement process, construction and/or validation of models; understand and evaluate the scientific and technological choices concerning the society in which they live. The freedom, competence and sensitivity of the teacher - who will evaluate from time to time the most appropriate educational path for each class - will play a fundamental role in finding a connection with other teachings (in particular with those of mathematics, science, history and philosophy) and in promoting collaborations between his/her School and universities, research institutions, science museums and the world of work, mostly for the benefit of the students of the last two years" (translated from the Italian government's official journal[2]).

Learning Objectives for Physics in the Last Year of the Liceo Scientifico

The same Italian Interministerial decree n. 211 of October 7, 2010, elucidates the specific learning objectives of Physics in the *Liceo Scientifico*'s 5th year: "The student will complete the study of electromagnetism with magnetic induction and its applications, to arrive, favoring the conceptual aspects, to the synthesis formed by Maxwell's equations. The student will also study the electromagnetic waves, their production and propagation, their effects and their applications in the various frequency bands. The educational path will include the knowledge developed in the twentieth century related to the microcosm and the macrocosm, combining the problems that historically have led to new concepts of space and time, mass and energy. The teacher must pay attention to using a mathematical formalism accessible to students, always highlighting the founding concepts. The study of Einstein's theory of special relativity will lead the students to confront the simultaneity of events, the dilation of the times and the contraction of lengths; having faced the mass-energy equivalence will allow them to develop an energetic interpretation of nuclear phenomena (radioactivity, fission, fusion). The affirmation

[2]https://bit.ly/2XOD7SH.

of the model of the quantum of light can be introduced through the study of thermal radiation and the Planck hypothesis (even just in a qualitative way), and will be developed on the one hand with the study of the photoelectric effect and its interpretation by Einstein, and on the other side with the discussion of theories and experimental results that highlight the presence of discrete energetic levels in the atom. Experimental evidence of the undulatory nature of matter, postulated by De Broglie, and the uncertainty principle could conclude the path significantly. The experimental dimension can be further explored with activities to be carried out not only in the educational laboratory of the school, but also in laboratories of universities and research institutions, also adhering to guidance projects. In this context, the students will be able to elaborate themes of their interest, approaching the most recent discoveries of physics (for example in the field of astrophysics and cosmology, or in the field of particle physics) or deepening the relationship between science and technology (for example the issue of nuclear energy, to acquire the scientific terms useful to critically approach the current debate, or semiconductors, to understand the most current technologies also in relation to the effects on the problem of energy resources, or micro- and nanotechnologies for the development of new materials)" (translated from the government's official journal[3]).

Syllabus for Physics in the Last Year of the Liceo Scientifico

The Physics course of the *Liceo Scientifico* is more detailed than in any other Italian secondary schools. We may summarize the syllabus of the 5th year as follows: "Electromagnetic induction. The Faraday-Neumann Law. The Law of Lenz. The currents of Foucault. Self-induction and mutual induction. The inductance of the solenoid. The RL circuit. Energy and energy density of the magnetic field. The alternating electromotive force and the alternating current. The ohmic circuit, the inductive circuit, the capacitive circuit. AC circuits. The LC circuit. The transformer. The transformation of tensions and currents. The electromotive force of a generator and the induced electromotive force. The induced electric field. Maxwell's equations. The electromagnetic field. Electromagnetic waves and flat electromagnetic waves. The relativity of space and time. Reference systems. The Michelson-Morley experiment. The axioms of the theory of special relativity. Simultaneity. The dilation of the times. The paradox of the twins. The beta coefficient and the gamma coefficient. The contraction of lengths. The Lorentz transformations. The Doppler effect of light. Redshift and blueshift. Special relativity. The space-time and the invariant interval between two events. The velocity addition. Mass-energy equivalence. The total energy of a relativistic particle. Kinetic energy, mass and relativistic momentum. Free fall and weightlessness. Acceleration and weight. The principles of general relativity. Non-Euclidean geometries. Geodetic curves. Gravity and the curvature of space-time. Gravitational deflection of light. The gravitational wave. From classical mechanics to quantum physics. Bohr's atom. Orbitals and quanta. Newton vs Huygens. Light

[3]https://bit.ly/2XOD7SH.

both as particles and as waves: experimental evidences. The radiation of the black body. The photoelectric effect. The Heisenberg uncertainty principle. The superposition principle, the tunnel effect and the entanglement. Elements of nuclear physics and particle physics. Introduction to the Standard Model of Particles. Overview of astrophysics and cosmology" (translated from the Italian website[4]).

Quantum Physics in the 5th Year of the Italian Scientific High School

The MIUR Decree n.10 of January 29, 2015, provided two important innovations in the *Liceo Scientifico*: the recognition of Physics, in addition to the traditional Mathematics, as "characterizing" the high school leaving certificate (http://www.gazzettaufficiale.it/eli/id/2015/02/24/15G00021/sg) and the integration of ministerial programs of the last year with modern Physics, in particular QM (Table 1).

Table 1. The QM Curriculum in the Italian Scientific Pre-University Year

Category	**Contents of the subject**
Prerequisites	The Rutherford experiment and the atom model. Atomic spectra. Interference and diffraction (waves, optics). Discovery of the electron. Classic collisions.
Minimum essential topics	The emission of a black body and Planck's hypothesis. Lenard's experiment and Einstein's explanation of the photolectric effect. The Compton effect. Bohr's model of atom and interpretation of atomic spectra. The Franck-Hertz experiment. Wavelength of De Broglie. Wave-particle duality; validity limits of the classical description. Diffraction / interference of electrons. The uncertainty principle.
Skills	Explain the model of the black body and interpret its emission curve based on the Planck model. Apply the laws of Stefan-Boltzmann and Wien. Apply the Einstein equation of the photoelectric effect for the resolution of exercises. Illustrate and know how to apply the Compton effect. Calculate the frequencies emitted by transition from Bohr's atom levels. Describe the quantization condition of the Bohr atom using the De Broglie relationship. Calculate the quantum indeterminacy on the position / momentum of a particle. Calculate the wavelength of a particle. Recognize the limits of classical treatment in simple problems.
Expertise	Knowing how to recognize the role of quantum physics in real situations and technological applications.

Source: https://bit.ly/2GDOMNc.

[4]https://bit.ly/2LbqEqK.

The Opinion of the Italian Pre-University Teachers of Physics

On November 4, 2015, MIUR in collaboration with the Dept. of Physics of the University "Roma Tre" published a survey conducted on a sample of 423 teachers (representative of the whole population) with the aim to test the reference frame of the Physics course of the last year at the *Liceo Scientifico*. We infer (Table 2) that the pre-university physics teachers deem more appropriate a program extended on electromagnetism (+5,73%) and reduced in both quantum physics (-3,7%) and advanced physics (-1,52%). Such response is symptomatic of that vast professional unease in teaching QP at secondary school level which motivated this paper together with the scarcity of pedagogical solutions. Even the *constructivism* fails with respect to the peculiarities of this branch of Physics (Karakostas & Hadzidaki, 2009). In fact, apart from marginal exceptions, the *learning by doing* is inapplicable.

Table 2. Testing the Pre-University Physics Curriculum Framework

Module	Miur Guidelines	Teachers' Feedback
Electromagnetism	40%	45,73%
Relativity	20%	19,49%
Quantum Physics	30%	26,3%
Advanced Physics	10%	8,48%

Source: https://bit.ly/2Vo1LvH

The 2018 Italian Reform of the Secondary School Leaving Exam

The MIUR Decree n. 769 of 26 November 2018 has established the "Reference frameworks for drafting and conducting written test" and the "evaluation grids for scoring" for the State Exams of the secondary school[5], enforcing the role of Physics in the Italian Scientific High School. Let us report characteristics and objectives of the exam in Physics at the *Liceo Scientifico*.

Characteristics of the Physics exam at the Scientific High School. The Physics test lasts 4-6 hours and consists in the solution of a problem chosen by the candidate between two proposals and in the answer to four questions among eight proposals (see the mock exam papers by MIUR[6]). "It is aimed at ascertaining the acquisition of the concepts and methods of physics with reference to the Fundamental Thematic Nuclei (Table 3) that vertically connect the topics covered in the course of study, in relation to the contents supplied by the current National Guidelines for the *Liceo Scientifico*. In particular, the test aims to detect the understanding and mastery of the scientific method and the capacity for physical argumentation through the use of hypotheses, analogies and physical laws. With reference to the various thematic cores, the solution of problems through the construction and discussion of models, the mathematical formalization, and the qualitative argumentation, the critical analysis of data may be requested in relation

[5]https://bit.ly/2Vk7HpD
[6]https://bit.ly/2vul6gl.

to natural phenomena or experiments. The test may contain references to classical texts or significant historical moments in physics" (translated from https://bit.ly/2RRt0xJ).

Table 3. Fundamental Thematic Nuclei

Modules	Units
Measurement and representation of physical quantities	Measurement uncertainty. Representations of physical quantities.
Space, Time and Motion	Kinematic quantities. Reference systems and transformations. Motion of a material point and a rigid body. Classical and relativistic kinematics.
Energy and Matter	Work and energy. Energy conservation. Energy transformation. Emission, absorption and transport of energy.
Waves and Particles	Sound and electromagnetic harmonic waves. Interference phenomena. Wave-particle dualism.
Forces and Fields	Representation of forces through the concept of field. Gravitational field. Electromagnetic field. Electromagnetic induction.

Source: https://bit.ly/2PC4oVz.

Objectives of the Physics exam at the Scientific High School. With reference to the fundamental thematic nuclei (Table 3) and as expounded on the MIUR website[7], the Physics exam test aims to ascertain that the candidate is able to:

1. Represent, also graphically, the value of a physical quantity and its uncertainty in the appropriate units of measurement. Representing and interpreting, through a graph, the relationship between two physical quantities.
2. Evaluate the agreement between the experimental values of physical quantities in relation to measurement uncertainties in order to correctly describe the observed phenomenon.
3. Determine and discuss the motion of material points and rigid bodies under the action of forces.
4. Use the concept of center of mass in the study of the motion of two material points or of a rigid body.
5. Use the transformations of Galileo or Lorentz to express the values of kinematic and dynamic quantities in different reference systems.
6. Determine and discuss the relativistic motion of a material point under the action of a constant force or a Lorentz force.

[7]https://bit.ly/2FR3gfw.

7. Apply the relativistic relations on the dilation of the times and contraction of lengths and identify in which cases the non-relativistic limit is applied.
8. Determine the kinetic energy of a moving material point and the potential energy of a material point subjected to forces.
9. Link the variation of kinetic energy, potential energy and mechanical energy with the work done by the acting forces.
10. Use the conservation of energy in the study of the motion of material points and rigid bodies and in the transformations between work and heat
11. Use the conservation of energy in the study of the motion of material points and rigid bodies and in the transformations between work and heat.
12. Determine the energy density of electric and magnetic fields and apply the concept of energy transport by an electromagnetic wave.
13. Apply mass-energy equivalence in concrete situations taken from examples of radioactive decays, fission reactions or nuclear fusion.
14. Interpret the emission spectrum of the black body using the Planck distribution law.
15. Determine the frequencies emitted by transition between the energy levels of the Bohr atom.
16. Determine the wavelength, the frequency, the period, the phase and the speed of a harmonic wave and the relationships between these quantities.
17. Discuss interference phenomena with reference to sound or electromagnetic harmonic waves emitted by two coherent sources.
18. Discuss, also quantitatively, the wave-corpuscle duality.
19. Describe the quantization condition of the Bohr atom using the De Broglie relation.
20. Apply the Einstein equation of the photoelectric effect.
21. Describe the action of electric and magnetic gravitational forces through the concept of field. Represent an electric or magnetic field using the lines of force.
22. Employ the Gauss theorem to determine the characteristics of electric fields generated by symmetrical distributions of charges and to discuss the behavior of electrical charges in metals.
23. Employ the Ampère theorem to determine the characteristics of a magnetic field generated by a current wire and an ideal solenoid.
24. Describe and interpret electromagnetic induction phenomena and derive induced electromotive currents and forces.
25. Determine the force acting on an infinite-length current-carrying wire in the presence of a magnetic field, the force between two parallel current-carrying wires of infinite length and the force acting on a branch of a circuit moving in a magnetic field for the induced current. Determine the moment of the magnetic forces acting on a current-carrying loop in the presence of a uniform magnetic field.

Six Problems in Teaching Quantum Physics

The experience of seventeen years of teaching in a scientific high school allows to identify six macrocritical aspects that make learning Quantum Physics difficult for adolescents. They can be listed as follows:

1. The complexity of the QP theoretical system.
2. The standard probabilistic interpretation of QP.
3. An often misleading treatment of QP major themes in science-fiction.
4. The abstruseness of the mathematical formalism employed.
5. The multiplicity of approaches and discoveries structuring QP.
6. The low level of fame and/or charisma of the *Copenhageners*, i.e., the members of the so-called Copenhagen School.

How could we turn this series of apparently insurmountable obstacles to our advantage? We have found a solution through educational strategies to seize the corresponding opportunities summarized in the Table 4.

Table 4. Turning Six Problems into Opportunities while Teaching QP

Problem	Opportunity
Discouraging conceptual intricacy	Appealing epistemological richness
Difficult ontological indeterminacy	Interdisciplinary study of chance
Abuse of QP terminology in sci-fi	Curiosity about QP basic notions
Worrying mathematical formalism	Compact QP formulation
Non-linear development of QP	Unifying explanations of QP logic
Copenhageners' low popularity	Captivating narration of QP story

Source: https://bit.ly/2UTgcZ6.

Six Proposals to Improve High School Education

As highlighted by several researchers (Kohl, 2012), the peculiar world view advocated by Quantum Mechanics seems to have great affinity with old philosophical-religious traditions of the Indian subcontinent. Placing emphasis on this aspect, with further emotionally evocative stimuli from popular physics literature (Capra, 1977), might be of interest to pupils with a strong propensity towards introspective reflections, who usually show an apathetic detachment from scientific rationalism. The standard interpretation of $|\Psi|^2$ as the probability of finding the particle in a given volume element $dxdydz$ at time t raises two reflections. The first concerns the measure paradox and implies an investigation of the QM conventional ontologies approachable merely as quick hints during the high school period. The second one, instead, implies the *Probability Calculus* which is curricular for Mathematics but does not temporally coincide neither with Physics nor with Chemistry. Probability could therefore be taught in three different moments: as an anticipation when atomic and molecular orbitals are introduced in Chemistry, as an exhaustive study in Mathematics and as a reference when dealing with QM in Physics. This redundancy, allowed by the interdisciplinary nature of

Chance, surely benefits all the subjects involved. In order to avoid emotional barriers with the students passionate about science fiction and not to give a demoralizing impression of unintelligibility, it does not seem appropriate to correct immediately the inconsistencies related to quantum physics themes. Vice versa, it would be better to start from the zest that films and entertainment TV series arouse in young people to establish a common language and activate emotional intelligence (Parker, et al., 2004; Petrides, Frederickson, & Furnham, 2004). Only when the pupils have sufficient knowledge and a certain amount of interest towards QM we can return on detecting the science fiction's limits, through funny exercises like "find the mistake!". The heavy formalism adopted by QM can be useful in two moments: when we explicate the matrices in Mathematics, giving an outline of the *Matrizenmechanik*'s non-commutative algebra, and in the general introduction to the discipline, profiting from the extreme compactness of the formulas (combined with a qualitative elucidation of the topics) to diminish the fear in those who are about to study it. In this direction we put on a poster (Figure 1) eight of the fundamental formulas of the history of QM (Bonacci, 2013b). The illusion of a rapid comprehension of the equations will vanish progressively but without traumas, because in the meantime the students will have become acquainted with the most sophisticated mathematical operators. The tumultuous production of ideas in a very short time occurred for QM could make unsuccessful a chronological sequence. Even a classification by authors may not be convenient, since the same scientists returned to some questions repeatedly. The best report should be quasi-chronological, with small alterations permitting to build a logically sequential path. That is the reason why we put the Pauli exclusion principle in terms of state vector $|\Psi\rangle$ next to the Schrödinger wave equation (1926), although it was formulated in 1925, and we placed the matrix mechanics of Heisenberg (1927) after Dirac (1928), i.e., the last author of the wave method (Figure 1). A schematic flowchart (Figure 2) might as well help the pupils to understand the logic behind the QM non-linear advancement (Bonacci, 2015a). We can remedy the lack of histrionics of the *Copenhageners*, included Niels Bohr (Clegg, 2013), in various ways: either with a partially anecdotal narration of the 30 years that "shook Physics" (Gamow, 1985) and drawing on the discreet repertoire of jokes uttered by eminent quantum physicists like by Feynman, already quoted in the Introduction (Hey & Walters, 2003), both with the use of images that stimulate the students' imagination. With this purpose, the eight young scientists on the poster (Figure 1) are pictured in poses revealing their different personalities. Between the firm gaze of Pauli and the nice exuberance of Feynman there is a whole range of expressions in which each student can recognize the closest to him/herself. This means creating a sort of empathetic identification with one or more authors and arousing that impelling curiosity that drives the supporters to know every detail of their idols' life and production.

Results

The Pre-University Class 2007-2008

In order to improve the effectiveness of our teaching Quantum Physics, we decided to change didactic method in the 2007-2008 school year; the pilot class was the VA of the Scientific High School "G.B. Grassi" in Latina. By adopting the strategies described in the third paragraph and taking advantage of some educational material available on the Internet (Bonacci, 2008a), we tried to manage three of the six critical aspects mentioned in the second paragraph:

1. The probabilistic interpretation of quantum phenomenology.
2. The rigorous mathematical formulation of QP.
3. The low level of notoriety of the Copenhageners.

We obtained surprisingly good results with a genuine transport of learners to the QP topics and their domination of the basic mathematical tools. After years in which Electromagnetism and Relativity had been the only subjects chosen by the students for the leaving certificate, four out of the twenty exam papers were centered on Quantum Mechanics. Such "innovative talks of undoubted quality", as declared by the President of the assessment committee, were entitled: "Simultaneous realities and parallel universes", "Paradox of Schrödinger's catv", "Quantum consciousness", "Schrödinger equation".

The Pre-university Class 2008-2009

Thanks to the different attitude of the following year VA students, a class with an evident predisposition to philosophical reflections and existentialist meditations, we tried to solve the other three critical issues that had in the meantime emerged in the teaching of Quantum Mechanics:

1. The epistemological ramifications of quantum theory.
2. An approximate representation of some QM issues in successful films.
3. The manifold contributions behind a unitary discipline.

After adopting the strategies described before, with the help of new on-line documents (Bonacci, 2008b), we noticed a huge interest, even fervid, towards the historical-epistemological aspect of matter, in spite of some weakness in calculation (at least compared to the technically perfect experience of the previous year). To confirm this, even 7 of the 24 exam essays were on QM-related topics and they were judged "original works of cultural depth and noteworthy interdisciplinary value" by the whole appraisal commission. The selected titles were: "Anthropic principle: weak, strong, participatory, final", "Quantum entanglement", "Schrödinger equation in the Copenhagen interpretation and the Everett's multiverse", "Quantum paradoxes: EPR, retro-causality, déjà vu, Schrödinger's cat", "Ontological vs. gnoseological uncertainty", "Revision of the concept of movement at the quantum level", "Quantum decoherence and role of the observer".

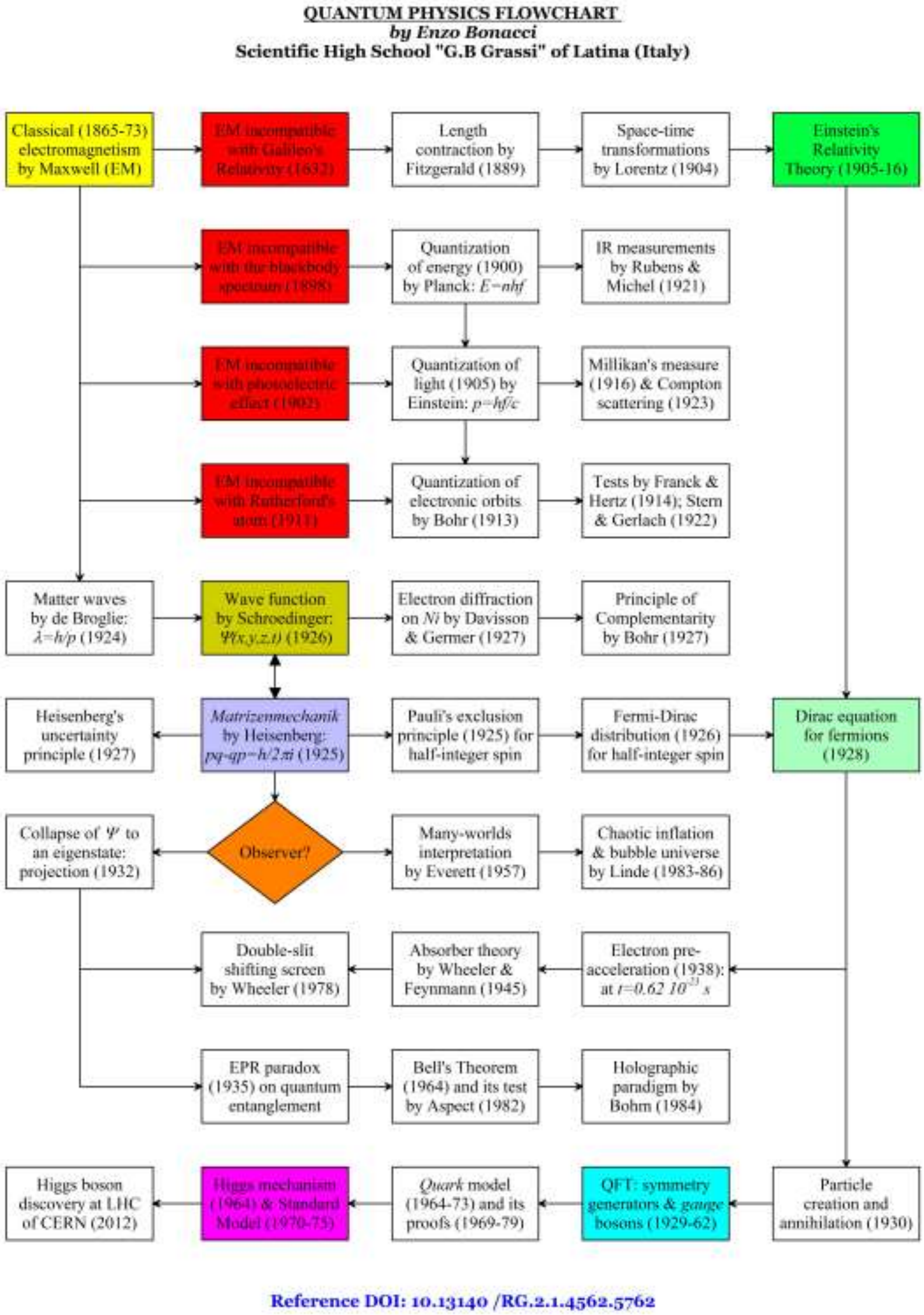
The Pre-university Classes in the Years 2009-2018

In the following years the material on contemporary Physics prepared for the pre-university classes has increased considerably thanks to:

- two invited lectures in the International Year of Astronomy 2009 (Bonacci, 2010a; 2010b);
- a photoelectric effect lab kit available since 2011;
- the activities of UniSchooLabS (http://unischoolabs.eun.org/);
- a peer-reviewed talk and poster at the *Science Perception* (Bonacci, 2013a; 2013b);
- a textbook aligned with the US physics program for grades 9-12 (Walker, 2014);
- a concept map for Italian-speaking students (Bonacci, 2015a), here translated into English (Figure 2);
- an invited lecture at the closing day of the Academic Year by the Astronomical Pontine Association (Bonacci, 2015b);
- an invited lecture in the *Aristotelian Paths* by the Italian Philosophical Society – Section of Latina "Feronia" (Bonacci, 2017);
- a peer-reviewed talk in the VI PHY ATINER (Bonacci, 2018);
- the resource repository of the SCIENTIX community for science education in Europe (http://www.scientix.eu/).

Once resolved the question of the sources, we tackled the critical aspects (always in the maximum number of three) trying different combinations with respect to 2–4–6 of the pilot year 2007-2008 and 1–3–5 of 2008-2009, but with overall lower marks. It seems indicative of an *optimum* result achievable only when some kind of problems (instead of others) are faced together, though we cannot state it with certainty. In this regard, we are looking forward to any feedback from colleagues who wish to implement our educational advice.

Figure 2. The 2015 Flowchart on Quantum Physics (translated into English)



Source: https://bit.ly/2GG9tcw.

Conclusions

In the tradition of the former project DESIRE (Disseminating Educational Science, Innovation and Research in Europe), which invited EU teachers to share their practical experiences and to integrate their teaching practices with inspiring tools (http://www.eun.org/projects/detail?articleId=706487), this paper has an empirical basis and is aimed to help concretely in an arduous task: teaching Quantum Physics at high school. It originates from the observation that introducing QP at secondary school can be such a tremendous shock that neither the finest educational psychology nor the most engaging textbook can avoid. The need for more empirical research into student difficulties and teaching strategies is underlined by the majority of literature focused on the improvement of the QP learning (Krijtenburg-Lewerissa, Pol, Brinkman, & van Joolingen, 2017). The educating community is called to supply *ad hoc* methods, efficacious to maximize the students' success. According to our working experience and personal re-elaboration, the high school teaching of Quantum Physics should benefit from:

1. A brief view on the Philosophy and Literature dealing with QP concepts;
2. A study of probability coordinated with Mathematics and Chemistry;
3. A gradual path of awareness about sci-fi: from enthusiasm to correction;
4. A familiarization with few fundamental QP formulas;
5. A scheme and a poster explaining the non-linear QP progress;
6. A popularizing narration of the QP vicissitudes and protagonists.

By virtue of the six didactic proposals advanced here, we should be able to overcome many of the obstacles we meet in our daily job. We should also be conscious of how utopian is to consider feasible the whole range of these professional tips, so that the selection of the most effective routes based on the needs and potential of the learners will ultimately be the true test of the pre-university teachers who will try themselves. We hope that an organic mosaic of experiential contributions on QP will enrich the current debate on STEM education (http://www.eun.org/it/focus-areas/stem) and, once consolidated this exploratory phase, such collective effort will eventually find its place in contemporary pedagogy.

Acknowledgments

I'm grateful to the Organizing and Scientific Committee of the VI PHY 2018 for having given me the opportunity to share a hopefully interesting educational experience in the marvelous venue of the ATINER in Greece. I also thank the double-blind peer reviewers for their careful reading of the manuscript and their precious comments and suggestions.

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Appendix: Description of the 2013 Poster

The 594x841 mm poster (Figure 1) consists of eight panels, arranged along two lines and four columns, each showing the face, in the foreground, of an important exponent of the QM with his surname, a contribution of him and the year of its introduction. While the educational reasons for this choice have already been widely ascertained, we are going to expound possible types of public presentation. Given that the ages of the photographed physicists do not necessarily correspond to the dates of publication of the formulas, whose succession is almost chronological to favor a thematic unification, the poster should be read from left to right and from top to bottom, that is, line by line. It covers the period 1900-1948, even if the main effort of defining the theory was accomplished in the first thirty years of the last century. In the first panel of the first line there is *Karl Ernst Ludwig Max Planck* and his equation on the energy quanta of 1900: $E = h\nu$. We may clear that it appeared, for the first time, in the black body radiation formula as the discrete energy of a single oscillator of the black cavity wall. In the second panel of the first line there is *Niels Henrik David Bohr* and his formula on the angular momentum of the electronic orbits allowed in an atom of 1913: $L = h/2\pi = \hbar$. One can clarify how the quantum condition for choosing stationary states is that the orbital angular momentum of the electron is an integer multiple of $\hbar$, a constant we will find in other formulas. In the third panel of the first row there is *Louis-Victor Pierre de Broglie* and his formula on the waves of matter of 1924: $p = mv = h/\lambda$. We can illustrate the analogy between the Undulatory Mechanics (based on the pilot waves of length $\lambda = h/p$) and the Undulatory Optics and then we may recall the first experimental confirmation in 1927 by Davisson and Germer with the electronic diffraction. In the fourth panel of the first row there is *Erwin Rudolf Josef Alexander Schrödinger* and his 1926 formula on the wave equation expressed in the form: $E\Psi = \hat{H}\Psi$. We can refer to the meaning of E as the eigenvalue of the energy for the system, of $\hat{H}$ as the Hamiltonian operator for a harmonic quantum oscillator and of Ψ as a wave function and we may clarify that the electronic population, corresponding to a certain level of energy (i.e., to a certain *eigenvalue* E) is represented by the eigenfunctions of the Hamiltonian operator, solutions of the equation. In the first panel of the second line there is *Wolfgang Ernst Pauli* and his 1925 exclusion principle in the form: $|\psi\psi\rangle = -|\psi\psi\rangle = 0$. We can mention how two half-integer spin particles (fermions) of the same species form totally antisymmetric states and the impossibility that they both occupy the same quantum state $|\psi\rangle$ because of the null ket. In the second panel of the second line there is *Paul Adrien Maurice Dirac* and his 1928 equation in the form: $i\hbar\gamma^{\mu}\partial_{\mu}\psi = mc\psi$. We could briefly say that it describes the motion of fermions in a relativistically invariant way, without further specification. We should however underline the theoretical prediction of the electron's antiparticle (positron), as well as the experimental confirmation of the positron obtained by Anderson in 1932 while analyzing the cosmic rays. In the third panel of the second line there is *Werner Karl Heisenberg* and the quantization condition of the *Matrizenmechanik* formulated in 1927: $[x, p_x] = xp_x - p_x x = i\hbar$. We may hint that the matrix mechanics describes the relation between the coordinate of position x and the conjugated moment p of a particle and that the indeterminacy $\Delta p \Delta x \geq \hbar/2$ descends from the quantization condition. In the fourth panel of the second row there is *Richard Phillips Feynman* with one of his homonymous diagrams (introduced in 1948) used to describe the annihilation and creation of the electron-positron pair: $e^+ + e^- \rightarrow \gamma \rightarrow e^+ + e^-$. One can point out the importance of Feynman diagrams in the description of any quantum interaction and the rapidity with which they were universally adopted. We may add another example $e^+ + e^- \rightarrow Z^0 \rightarrow \mu^+ + \mu^-$ allowing a connection to the two Italian Nobel Prizes Enrico Fermi (awarded in 1938) and Carlo Rubbia (awarded in 1984) as, respectively, starting and arrival point of the long path leading to the full comprehension of the electroweak interaction.