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Understanding and Developing Complex Problem-Solving Competency: An Exploration Based on Engineering Teachers' Perspectives

Dr. Ji Yu, Tsinghua University

Ji Yu is an Assistant Professor in the Institute of Education, Tsinghua University. She is also a member in the Centre of Engineering Education at the University. She received her PhD degree from the University of Cambridge, with an interdisciplinary background - a Master's degree in education and a Bachelor's degree in engineering. Her research and teaching interests include university innovation, especially how to cultivate engineers with innovative ability, and complex problem-solving ability. Her works have been published with journals like Higher Education Research & Development, Educational Research in China, and been released by Springer and Sense. Recently she is working closely with engineering teachers to enhance the connection between research and engineering education practice.

Wangqi Shen, Tsinghua University

Wangqi Shen is a PhD student in the Institute of Education, Tsinghua University, majoring in Engineering Education. He got his master's and bachelor's degree in Educational Technology and has published some academic outcomes in Interactive Learning Environments and at international conferences such as AECT and SITE. Recently his works include international education strategies comparison, enterprise in engineering education and complex engineering problem-solving.

Anqi Ma, Tsinghua University

Anqi Ma is a second-year master student in the Institute of Education at Tsinghua University with the guidance of Dr. Yu. She has a bachelor's degree in vehicle engineering and now focuses on engineering education. Her research tends to be at the micro-scale, focused on the individual level perspective of how engineering education can become more effective, efficient, and inclusive. Recently her works include engineering students' identity and complex problem-solving skills.

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Background

Complex problem-solving (CPS) has been considered as one of the key competencies for professional engineers [1]-[2] and has been increasingly emphasized by international engineering education certification bodies (for instance, ABET [3]). However, general observations of engineering education practice show that although cultivating students' complex engineering problem-solving competency has become a common vision for education researchers and practitioners, there is an obvious gap between research progress and real classroom practice [4]-[6]. Although different frameworks have been presented by researchers to understand CPS [7]-[8], few studies have explored the status quo of how to develop students' CPS competency in teaching practice. In this paper, we first review current conceptualizations on CPS capability in research and then use in-depth semi-structured interviews to explore teachers' ideas and practice on CPS competency in their teaching activities. We wish this work to fill the gaps in two aspects: 1) to understand how teachers conceptualize the concept of complex engineering problem solving; 2) to investigate how engineering teachers develop students' CPS ability in class and the factors that affect teachers' engagement, and by doing so, feed back into the research domain.

Research on complex engineering problem-solving competency

A common opinion in understanding complex engineering problem-solving competency is based on the acquisition of cognitive skills [9]-[10]. For example, a team of scholars represented by Van Merrienboer proposed a Four Component Instructional Model (4C/ID) for the cultivation of complex problem-solving skills, in which they indicated that the formulation of complex skills is decomposed by the acquisition of a series of situational, proficiently mastered, operational and procedural cognitive skills [11]-[12]. More studies emphasized the reasoning and decision-making process in solving complex problems. For instance, Mendez proposed a generic procedure including comprehension, application of the methods, justification and clarity, results, efficiency, and critical analysis [13]; Argenta et al. determined a detailed framework that includes 29 experts' decision-making towards CPS, including goals, criteria and constraints, predictive framework, priorities, etc.[7]

The procedure of engineering design has been also recognized as the manifestation of the internal decision-making process of engineers when solving complex problems and has been regarded as a prior guide and tool for designing and implementing the CPS curriculum [14]-[15]. Scholars like Crismond and Adams have raised the Informed Design Teaching and Learning Matrix that integrates engineering design trajectories, the differences between novice and expert design patterns, the instructional goals of students in each step of design, and the teaching strategies for teachers, so as to help teachers to develop their knowledge of informed design teaching [16].

Some researchers also consider CPS competency development as a process of social knowledge construction. Therefore, collaborative ability, engineering empathy in balancing differences and conflicts, as well as offering problem solutions that minimize disadvantages are emphasized [17]-[20].

Apart from these, some international and local organizations present systematic and comprehensive guidelines to define complex engineering problems. The most widely recognized one is the Washington Accord, which provides seven attributes of complex engineering problems [21]. Engineers Australia also proposed the Engineers Australia Stage 1 Competency Standard for the Professional Engineer, putting forward 9 indicators of graduates' ability in complex engineering problem-solving [22].

In empirical works, researchers have put forward three main approaches to evaluate complex engineering problem-solving ability: evaluation based on expert experience; evaluation based on decomposing complex engineering problem structure; and evaluation based on a matrix of competency criteria and curriculum objective. More details can be found in Table 1.

Table1. Typical Evaluation Approaches of Complex Engineering Problem-Solving Competency

Evaluation approaches	References	Content	Procedure
Evaluation based on expert experience	Burkholder, Hwang, & Wieman [22]	Problem-solving steps from domain experts; e.g. program feasibility, design errors and improvements, safety, information request, information ranking, and the process of improvement.	✧ Create an engineering program under real problem situations ✧ Evaluate the degree and effectiveness of students' implementation of the problem-solving steps in the program through a final assignment.
Evaluation based on decomposed complex skills	Melo & Miranda [12]	Operational process; e.g. identify circuit symbols, identify circuit representation methods, make circuit diagrams, and analyze series and parallel ideas.	✧ Create a comprehensive engineering task under the real problem situation ✧ Evaluate students' ability to solve problems according to operational steps in the course tasks.
Evaluation based on the matrix of competency criteria and curriculum objective	Isa et al.[24]	Curriculum objectives related to the Washington Accord; e.g. environment and sustainability, abstract thinking and originality in analysis to formulate suitable models.	✧ Select an engineering project outcome (PO) in the corresponding standard for the learning outcome (CO) required by professional courses ✧ Construct the CO-PO matrix ✧ Evaluate students' ability on different aspects of their competencies through mid-term exams, final exams, project work, project reports, or project presentations.

Although different conceptualizations and evaluation frameworks have been formulated as presented above, their feasibility and transferability among real teaching activities have still remained unclear. Few studies involve teachers' perspectives. Therefore, as an effort to extend current research, the study uses a bottom-up strategy to explore how engineering teachers understand and practice this concept in class.

Method

We conducted 6 semi-structured interviews with teachers from 3 leading universities （aliases “A” “B” and “C”) in engineering education in China. The interviewees came from four different subjects. The questions include:

- Demographic information of the teacher (major, years of teaching, courses…)
- What methods does the teacher use in his/her courses?
- What kind of knowledge and abilities does the teacher aim to foster in his/her classes?
- How does the teacher understand the concept of CPS ability?
- How does the teacher cultivate students’ CPS ability in his/her teaching?
- What does the teacher consider the feasibility and suitability of the current conceptualization and evaluation of CPS in research?
- What factors foster or hinder teachers’ engagement to develop CPS in teaching practice?

Each interview lasts 60-80 minutes. The participants’ information is displayed in Table 2. The data was analyzed following an inductive approach, during which concepts and meanings were derived from the narratives of transcriptions. In the initial scanning of the data, we found interviewees’ opinions showed both similarities and differences in their understanding of CPS, much relying on their teaching courses. Therefore, instead of using coding to present commonness, our strategy is to present a comprehensive picture that can capture different ideas. The main qualitative tactics used include ***noting patterns/relations, building logical evidence, and making contrasts*** [25]. The interviews were conducted in Chinese, quotations were selected and translated into English. The translation was confirmed with the interviewees.

Table 2. The information of participants

Participants	Major	Teaching course(s) *	Years of teaching experience	University
T1	Mechanical engineering	Computer simulation of material processing (Specialized Course); Capstone	22	A
T2	Mechanical engineering	Engineering graphics (Specialized Courses)	1	A
T3	Opto-Electronic Engineering	Foundation of science and technology research (Foundation Courses); Photoelectric imaging system (Specialized Course)	17	B
T4	Materials science and engineering	Modern research methods for materials (Foundation Courses); The beauty of microscience (Introductory Courses)	2	C
T5	Civil Engineering	Architectural steel structure design (Specialized Course)	21	C
T6	Civil Engineering	Design principle of concrete structure (Specialized Courses); Selection of building structure (Specialized Course); Capstone	38	C

* The types of courses are based on the categories in the training programs.

Preliminary Results

Teachers’ understanding of the concept of CPS competency

Similarly, all teachers showed more or less an underlying awareness of the importance of CPS ability, no matter whether they have participated in the professional accreditation of engineering education or been exposed to the concept academically. Their comprehension came from their understanding of engineering, scientific research experience, as well as teaching practices. They all consider students' CPS competency as a comprehensive ability, with multiple interweaving attributes, instead of a single concept with clear boundaries.

The differences mainly come from two aspects: 1) how CPS ability can be cultivated? 2) how CPS shows up in a specific course? For instance, some teachers consider the methodological attribute is most dominant in developing CPS ability, for instance:

> "Each discipline has a similar methodology when it comes to complex problems, which is to resolve complex problems into basic problems and solve them using basic methods...knowledge is infinite, new knowledge comes out at any time, so a 'knowledge tree' is the most important… I will sum it up into two phases: first, decompose the complex problem into basic problems; second, solve the basic problems in the right order. " (T2)

> "We are talking about complex engineering problems, but more importantly, we're teaching students how to think... sometimes when you can't solve a big problem, you have to jump into a bigger circle, instead of just focusing on itself, from a small perspective. In teaching, this is just one solution that we need to teach the students, we can't limit students to this method." (T4)

Another perspective is to consider the capability to solve complex problems requires the accumulation of knowledge and experiences. For instance:

> "I'm working on the big science engineering program…it is very complex. To have CPS ability, students need first to have a deep understanding of basic professional knowledge, and then the ability to communicate with a team and express their ideas. " (T4)

> "After mastering the meaning of engineering, students should be equipped with a series of operational skills, experience, and practical thinking in the process of turning knowledge theories into real products... so in my opinion, the cultivating process of CPS competency is through a step-by-step accumulation, rather than being given directly a complex engineering problem." (T2)

> "The ability to solve problems may involve mathematics, engineering design and experimental operation, etc. In the course on Photoelectric Imaging Systems, I will give students several themes, which are problems to be solved in real life. Students will choose themes and figure out strategies to solve the problems." (T3)

> "Capstone is an effective way to develop students' CPS competency, but before capstone, it is an incremental process. CPS refers to the nature of engineering itself, it involves design, construction, and management - the whole life cycle of engineering. They contribute different aspects of complex engineering problem-solving. In the design course, we teach design abilities both for simple and complex problem-solving. For instance, the design for a beam, or a column is simple, while the design for a masonry structure and factory is complex. " (T6)

Since teachers' conceptualization of the concept is highly related to the courses they were responsible for, we further look into their illustrations regarding specific courses and construct an integrated picture to encompass the differentiated focus in various types of courses and learning phrases, as displayed in Figure 1. To strengthen the finding, the figure has been presented to the interviewees and revised based on their feedback (see the initial figure in Appendix A). It can be seen that different aspects of CPS, including engineering knowledge, tool usage, on-site management, collaboration work, and life-long learning have all been involved at different stages to formulate CPS competency. More specifically, in introductory courses for freshmen, students' understanding of engineering subjects and identity is considered as the primary objective. In specialized courses, teachers offer more guidance to help students master the methods and tools to solve CPS. In internship and practice training, students are equipped with collaborative skills and exposed to industry norms. In the capstone, students need to deal with increasing the complexity of real engineering problems and consider the social and economic impact of engineering. After graduation, the ability to life-long learning and experience in larger engineering projects is important to continuously develop CPS competency.

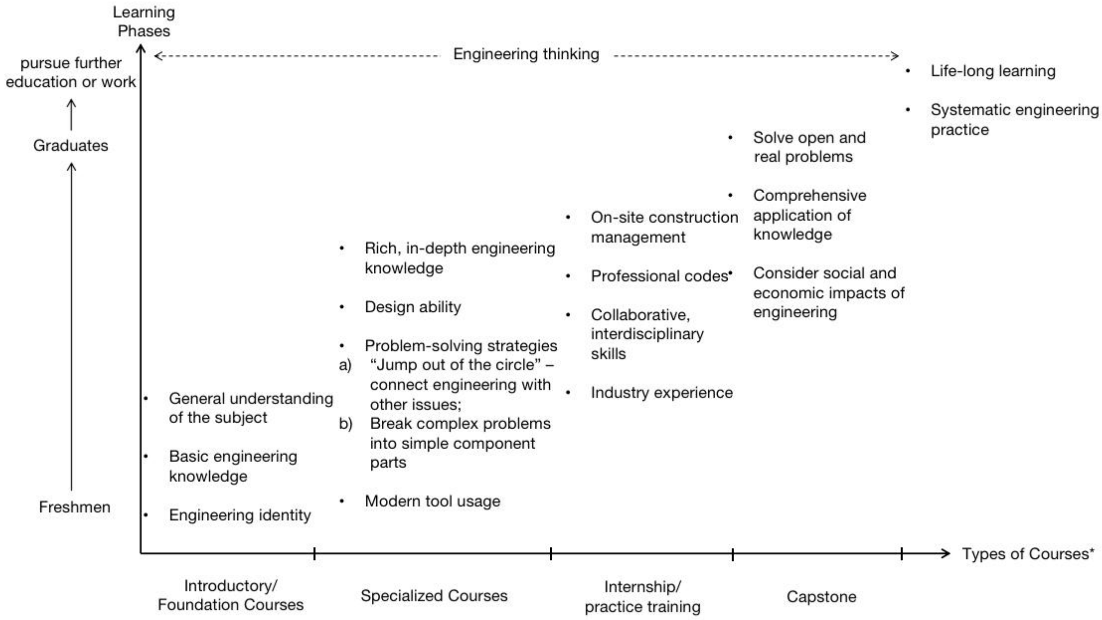

Figure 1. An integrated model of developing complex problem-solving competency in different phases and different courses
* The courses are classified according to the categories in the training programs

Factors that affect teachers' engagement in cultivating and evaluating students' CPS in class

According to the interviews, teachers' current attention and engagement in CPS competency are highly based on their individual interests and self-motivation, instead of on official, organizational initiations. Below are some quotes from the data:

> "No one asked me to evaluate this ability...we have the motivation to evaluate our curriculum objectives, but there is no incentive to evaluate the ability to solve complex engineering problems alone. So complex engineering problem competency should be included in professional certification standards, and that's where the impetus comes from." (T1)

> "My motivation mainly comes from my own 'obsessive-compulsive disorder'. I may be a little obsessed with... if a person becomes talented, I want to know whether my course is effective in this process." (T3)

> "CPS is important, especially when technologies change rapidly nowadays. But our assessments do not include this, I will say, the industry is ahead of education in this issue." (T3)

In the meantime, some interviewees pointed out that the scientific-oriented engineering education and heavy daily work (especially for young teachers) also largely influence teachers' input in developing students' CPS ability.

> "For teachers in our school, what we mainly cultivate is students' ability to do research, write papers, so we have no motivation to develop students' practical abilities, for instance, CPS." (T1)

> "I'm not motivated at all now because there are so many things going on. This is an honest answer, and it is too complex to develop, not a little time." (T4)

Conclusion and next step of the research

The study is an effort to explore teachers' understanding and practice of CPS. It can be seen that engineering teachers recognize the value of developing competency and have formed a basic understanding of CPS competency from their own experience. However, the difficulties in developing and evaluating students' CPS ability have also emerged clearly. The study has several implications for research and practice.

First, there is a clear misperception that CPS is not as important to engineering teachers as it is to practicing engineers. There might be two reasons for this: 1) The three universities in the study are all top universities in engineering education in China, highly research and academic-orientated. Although CPS ability is also important to researchers, its nature in terms of students' cultivation may be different from course training. For instance, in this study, T1, who has 22 years of teaching and participated in the program's accreditation, considered undergraduate students' working with potential supervisors on research projects actually demolishes their chances to practice complex problem skills. 2) The competing demands on faculty actually temper teachers' enthusiasm and input in developing CPS ability. In fact, after joining the Washington Agreement in 2016, Chinese universities have accelerated the process of engineering education reform [26]. Although China's engineering education certification standards mandate the inclusion of CPS competency as a graduation requirement, universities have not yet implemented a specific training plan to meet these requirements due to various constraints. As a result, teachers have no extrinsic motivation to focus on students' CPS competency cultivation in particular.

Second, the definition and evaluation tools of CPS competency need to be introduced to teachers in a more organized and systematic way. During the interviews, engineering teachers showed strong interest in the introduction of CPS' academic definitions and assessment methods (the sixth question in the interviews). It will be highly beneficial if more promotional content and corresponding handbooks can be provided to teachers. This finding is consistent with previous research conducted by Wang [4].

Third, CPS competency and relevant tasks may be manifested in different ways in different courses, and its formation is throughout a student's entire learning period. In this study, we involved participants from four traditional engineering disciplines, as one of the interviewees suggested, it would be beneficial to cover teachers from new emerging engineering subjects - technology has not only changed the nature of engineering problems, but also the way how subjects are organized. More subtle information about this complex issue would require further in-depth research.

To sum up, it is hoped that this exploratory work can contribute to the research arena of CPS competency and raise researchers' attention to the many interrelated factors involved in real teaching environments. As an in-progress study, the authors are working on enlarging the sample of teachers and also integrating inputs from engineering students in the near future.

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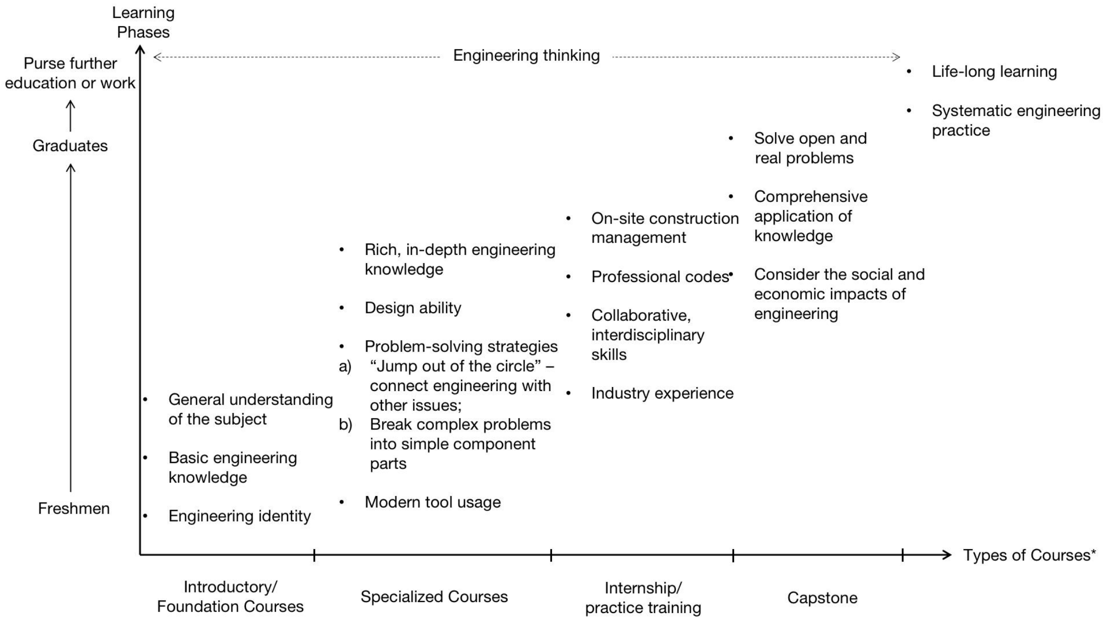
Appendix A:

The initial Figure 1 (presented to the interviewees for review)



The interviewees provided the following feedback:

- Foundation courses should be added to the horizontal axis of Introductory courses
- "Basic engineering knowledge" should be moved to the column of Introductory/Foundation courses
- "Problem analysis" should be placed above "Modern tool usage"
- "Design ability" should be added to the column of Specialized courses
- "Internship" should be added to the horizontal axis of course types
- "On-site construction management" and "Industry experience" should be added to the column of Internship/ Practice training
- "Practical operation" could be removed and replaced by "Professional codes"
- The capstone should involve a "comprehensive application of knowledge"
- Engineering thinking is an attribute involved in all types of courses