Promoting and Assessing Metacognition

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Abstract

This paper addresses the concept of metacognition. While there does not seem to be a well-defined definition of metacognition, the general definition, “thinking about thinking” seems to provide a starting framework. We divide metacognition into two categories: procedural knowledge and strategic competence. Procedural knowledge refers to being able to solve a problem in a known environment with most, if not all, information provided, and employing well defined procedures. Solving a quadratic equation knowing the formula or computing an optimum code for a source message code, are just two examples. Strategic competence, on the other hand, is the ability to navigate through a new problem, that requires a confluence of abilities: identify in general terms what is needed to get to the solution, choose from a variety of techniques that may or may not initially appear relevant to the current problem, employ logic and intuition to solve the problem and finally, to assess the validity of the chosen approach. In the literature, such categories have also been defined as crystallized intelligence and fluid intelligence. Procedural knowledge can be imparted via the standard instructional settings. Strategic competence cannot be “taught.” However, providing several illustrative examples, an environment can be created that promotes the development of strategic competence. This paper discusses several instances of metacognition and proposes an approach to assessing learning in the classroom. Examples will be given from high school geometry and a few junior to senior level courses in electrical engineering. Recommendations for incorporating metacognitive processes into the curriculum and assessment are made.

Introduction

It is a well-established fact that school students in the U.S. generally fare poorer than their counterparts in other nations, notably from Asian countries. For instance, the PISA (Programme for International Student Assessment) test results, from 2015, placed the U.S. an unimpressive 38th out of 72 countries in math and 24th in science. Among the 35 members of the Organization for Economic Cooperation and Development, which sponsors the PISA initiative, the U.S. ranked 30th in math and 19th in science. The US saw an 11-point drop in average score for math, while remaining relatively flat in reading and science. A comparison of the PISA Test with the standard state examinations such as the STAAR (State of Texas Assessments of Academic Readiness) or EOC (End Of Course) Tests, shows very clearly that the level of instruction in classes and the level of testing are at lower levels in terms of critical thinking and ability to formulate and solve problems. These results raise questions about the global competitiveness of the US educational system.
While there is a considerable literature on metacognition, its definitions, etc. our definition of metacognition is in terms of the level of complexity required to solve a given problem. The 2012 PISA Report characterizes six levels of proficiency in mathematics. “Students in the United States have particular weaknesses in performing mathematics tasks with higher cognitive demands, such as taking real-world situations, translating them into mathematical terms, and interpreting mathematical aspects in real-world problems.”

At Level 5, “students can develop and work with models for complex situations, identifying constraints and specifying assumptions. They can select, compare, and evaluate appropriate problem-solving strategies for dealing with complex problems related to these models. Students at this level can work strategically using broad, well-developed thinking and reasoning skills, appropriate linked representations, symbolic and formal characterizations, and insight pertaining to these situations. They begin to reflect on their work and can formulate and communicate their interpretations and reasoning.”

At Level 6, “students can conceptualize, generalize and utilize information based on their investigations and modeling of complex problem situations, can use their knowledge in relatively non-standard contexts. They can link different information sources and representations and flexibly translate among them. Students at this level are capable of advanced mathematical thinking and reasoning. These students can apply this insight and understanding, along with a mastery of symbolic and formal mathematical operations and relationships, to develop new approaches and strategies for attacking novel situations.”

The new requirements from ABET also require competency at these levels. For instance, Student Outcome #1 requires: “An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.”

This paper addresses the question, “How do we enhance metacognitive ability in our students?” The question arises from the fact that most instruction in schools, and even at college level, consists of one or two-step problems, in a multiple-choice answer format, and essentially follows the “teaching to the test” approach, closely based on state standards. Even at the college level, especially at freshman and sophomore levels, mathematics and science instruction deal with such approaches, which can at best be considered procedural. On the other hand, solution of complex real-world problems whose solutions require multiple steps – formulation of the problem, exploration of multiple approaches towards the solution, choice of one or more of these approaches, execution of the approach at nested multiple levels and analyzing the solution, is rarely addressed. In the following, we will discuss specific instances of metacognition and attempts to enhance the same with several examples. A sample of literature addressing these issues appears in the References Section.

Let us consider four examples.

Example 1: After learning that the interior angles of any triangle add up to 180° (irrespective of the shape or size of the triangle), the student is posed a question about the sum of all the interior angles of a quadrilateral. Invariably, most students’ response is to draw a diagonal and show that the all interior angles add up to 360° (again irrespective of the shape and size of the quadrilateral).
I consider this the most elementary example of metacognition. The ability of a student to think beyond what is explicitly given and seek a viable answer.

**Example 2:** The following sequence of four-letter words has a hidden message, in fact a famous saying. What is this famous saying?

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zain yain xain wain vain uain tain sain rain qain oain nain main lain kain jain iain hain fain eain
dain cain bain aain
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Answer: No pain, no gain. In a backwards sequence, every alphabetical letter comes with the suffix "ain" except "p" and "g" and hence "no p-ain", "no g-ain".

**Example 3:** Consider the following problem posed in a Korean second grade class. The objective is to find which of the following four integer arrays is unique. Nothing else is given, what to look for, what criteria to use, etc. The process of solution consists of first exploring the four arrays, noting different aspects of each pattern, and identifying what, if any, is a unique property of each array.
One answer clearly is the 4th array, noting that the number of edges around each number corresponds to the number. For instance, the number ‘2’ has two edges, the number “3” has three edges, and so on.

**Example 4:** Consider the shape in Figure 2 – a hexagon, octagon, pentagon and a square, all of equal sides. Given the perimeter of the composite figure is 170 in, compute the side of each figure and its perimeter. Is there a discrepancy in the two perimeters? Why? Hence compute the area of each figure and of the composite figure. Is there at least one other composite figure that can be made of these same shapes, with the same area but with a shorter perimeter? Is there an upper bound as well as a lower bound on the perimeter of the composite figure, given the same area?

![Figure 3. A Composite Shape](image)

**The Question – Where Did The Idea Come From? Explicit Vs. Implicit Instruction**

In the examples above the question arises, “What made one draw a line to divide the quadrilateral into two triangles?” or “How did one come up with the idea to look for alphabets in reverse order?” or “How did one come up with the idea to look for a correlation between the number in a square and its boundaries?” or “What makes for a compact composite shape while keeping the total area the same?” And so on. The answer lies in the fact that it is a part of the intuition and creative process that is impossible to quantify and equally impossible to “teach” as explicit knowledge. Some students naturally possess such intuition and others can develop such intuition once shown how.

In the words of Lockhart: “Now where did this idea of mine come from? How did I know to draw that line? How does a painter know where to put his brush? Inspiration, experience, trial and error, dumb luck. That’s the art of it, creating these beautiful little poems of thought, these sonnets of pure reason. There is something so wonderfully transformational about this art form. The relationship between the triangle and the rectangle was a mystery, and then that one little line made it obvious. I couldn’t see, and then all of a sudden I could. Somehow, I was able to create a profound simple beauty out of nothing, and change myself in the process. Isn’t that what art is all about?”

Lockhart is laying the framework for metacognition.
In this paper, we propose interventions to current instruction and testing to reach Level 5. We believe that for students to be successful in professional fields such as the sciences, engineering, medicine and business, attainment of Level 5 should be a minimum requirement.

Unstructured Problem Environments

Let us consider examples of two “unstructured” problems that appear in Figure 3.

**Problem 1:** Consider Figure 5a. At first sight, one notices that no radius is given. One has to first identify all possible geometrical characteristics of the figure – center of the circle, radii, tangents, special right triangle, etc. Once the identification is made as in Figure 4b, one can begin to see that DOFB forms a square of side radius, tangent segments AD and AE, BD and BF, and CE and CF, are equal to each other. This, combined with Pythagoras theorem, yields a value for the radius ‘r.’ Hence compute the area of the circle. A complete discussion is available at PreMath.⁹

**Problem 2:** This problem requires a higher level of metacognition. As seen in Figures 6a, 6b and 6c, note the symmetry of the figure, add an identical rectangle on the other side, draw the chords AB and CD (note that AB is also the diameter), apply the chord product theorem and hence obtain the radius of the circle. A complete discussion is available at PreMath.¹⁰
“Strategies” to Teach Metacognition
Relevance, Integration, Scaffolding, Transference, Reflection (RISTR)

Our proposed RISTR Model enhances students’ abilities to transfer or adapt their learning to new contexts and tasks. The following describes five broad stages of the process.

- **Relevance**: Make the problem relevant – something that appeals to the student’s interest.
- **Integration**: Teach the same concept across several disciplines – horizontal integration.
- **Scaffolding**: Approaching a solution to a problem at different levels of complexity.
- **Transference**: Applying a given technique to several different problems and different disciplines.
- **Reflection**: Reflecting on the thinking and the approaches that led to the solution.

**Relevance**: Making the problem or its application relevant to the student’s interest should motivate the student and explore potential solutions to the problem. Seymour Papert, in his book Mindstorms, states that anything is easy if it can be assimilated into one’s collection of models. This is somewhat analogous to Piaget’s Constructivist Approach, however, Piaget stresses the cognitive aspect. Papert argues that learning also has an affective component. A solid approach employing PBI – Project/Problem Based Instruction – is needed.

In Papert’s case, he was fascinated with automobile parts, in particular, the differential. “I no longer think much about gears, but I have never turned away from the questions that started with that discovery. ... What an individual can learn, and how he learns it, depends on what models he has available. This raises, recursively, the question of how he learned these models. Thus the “laws of learning” must be about how intellectual structures grow out of one another and about how, in the process, they acquire both logical and emotional form.”

The Nobel Prize winner, P.W. Anderson, speaks of his collection of models that originated with his investigation of electron spin. Anderson had an unusually strong grasp of spin, perhaps one of the more difficult concepts to understand in quantum mechanics. He later recounted that almost every problem he solved he first framed it in terms of spin and later translated it into the current problem.
Integration: Students often have difficulty in recognizing a concept or a technique when it appears outside of the environment or discipline they were first taught in. For instance, a student recognizes a quadratic equation in Algebra but when the same equation appears in the context of a projectile, they draw a blank. Or, when they see a forced second order differential equation in circuit theory (a typical RLC circuit), they do not recognize it as the same equation they saw in dynamics. Displaying the similarities of apparently diverse systems has the potential to build a “collection of models.”

Scaffolding refers to a variety of instructional techniques used to move students progressively toward stronger understanding and, ultimately, greater independence in the learning process. The term itself offers the relevant descriptive metaphor: teachers provide successive levels of temporary support that help students reach higher levels of comprehension and skill acquisition that they would not be able to achieve without assistance. Like physical scaffolding, the supportive strategies are incrementally removed when they are no longer needed, and the teacher gradually shifts more responsibility over the learning process to the student.13,14

Transference: Transference refers to transference of skills. When one faces a new problem, the ability to address its solution begins with identifying possible analogies within the collection of models one already possesses. When a student asks a typical question, “Why do I have to learn trigonometry to manipulate angles when I can just use a calculator?” they miss the point that the skill they used to manipulate the angles is the same in controlling the satellites in orbit. Or, the apparently “useless” of prime numbers are behind the most secure algorithms that banks use to protect our accounts.15

Reflection: The ability to reflect at each stage of a problem-solving process enhances the critical thinking ability as well as allows for exploring alternate solutions to the problem at hand. For instance, in Example 4 (Figure 3), how many distinct composite shapes are possible with the same area? Does one need to draw each explicitly or can one logically infer that number by examining the minimum number of shared sides necessary to remain a composite? In Problem 2 (Figure 5) if the problem was different, with an inscribed square instead of an inscribed circle, would the same approach work? What difference(s) does one need to introduce to affect a solution?

![Figure 7. A square inscribed in a circle](image_url)
Two Sample Problems Demonstrating the RISTR Approach

To illustrate our approach to enhancing metacognition, we begin with progressively introducing complexity into a problem. In the following we demonstrate this approach based on two example ill-structured problems. Questions are posed at two different levels of metacognition – procedural and strategic competence.

Oil Spill Spread: Consider the following problem. An oil tanker at sea struck a rock, making a hole in the oil storage tanks. The tanker was about 65 km from land. After a number of days the oil had spread, as shown on the map below.\textsuperscript{16}

![An Oil Spill](image)

\textbf{Figure 8. An Oil Spill}

(a) Using the map scale, estimate the area of the oil spill in square kilometers (km\textsuperscript{2}). (Procedural)

(b) If the spill is spreading in size at the rate of 5\% each day, how long does it take to cover an area of 4000 km\textsuperscript{2}? (Procedural)

(c) Assuming the same rate of expansion, how long ago did the spill originate? (Procedural)

(d) There is a fish farm 80 meters away from the oil tanker. If the spill reaches this farm, the fish life will be severely threatened. How long does it take for the spill to reach this farm? (Procedural)

(e) Examine the effects of an oil spill – how the oil will dissipate, how it affects the marine life and other ecological, physical and chemical effects. (Strategic Competence)

(f) Does the problem as posed here contain all the necessary information to answer the questions? What other information would you need? (Strategic Competence)
Communication System (Information Theory): An important step in processing information transfer from a source to destination is the operation of source coding, so as to exploit any built-in redundancy in the source message. One such technique is Huffman Coding, which is based on the relative occurrences of the alphabet in a given language. For instance, English language has several types of redundancies that can be removed while coding the source message. For instance, grapheme redundancy – most frequently occurring letters may be eliminated during the coding process – the letter ‘e’ occurring most frequently. Another type of redundancy – verbal redundancy – is in the language usage where phrases are redundant, such as: ‘subject matter,’ ‘a variety of different terms,’ ‘free gift,’ ‘end result,’ ‘kill something dead,’ etc. Removing such redundancies can vastly reduce the size of the message to be transmitted.

A typical problem or project will be posed as follows.

(a) Choose a text message in English language. Write a MatLab program to compute the relative occurrences of each letter, and generate a minimum variance Huffman code. Hence compute the text compression ratio and the coding efficiency. (Procedural)

(b) Examine the passage for verbal redundancies and check if they might be removed to achieve greater efficiency. (Procedural)

(c) Translate the text passage into at least one other language – Spanish, Swahili, French, Chinese, German, to mention a few – and repeat Part (a). (Strategic Competence)

(d) Some languages with the same Latin script as the English language might offer more verbal redundancy. For instance, ‘I want to go to the movies,’ translates into Spanish as ‘Quiero ir al cine,’ – twenty-six letters compared to seventeen. The same passage into Swahili appears as, ‘Ninataka kwenda kwenye sinema,’ – twenty-nine letters! Repeat Parts (a) and (b). (Strategic Competence)

(e) If you were to extend this scheme to a language based on characters such as Chinese, Japanese or Korean for instance, what would be necessary steps?

In both problems above, the answers to the posed questions invoke the RISTR Model discussed earlier. The Relevance is its connection with a real-life situation, whether from the spate of oil spills in the recent years or in designing an efficient communication system. The Integration in the oil spill problem is in the application of static geometric principles to a dynamic situation, where the shape of the spill might be changing continually. The Integration in the communication system problem lies in the application of probability and statistics in a different environment. The Scaffolding is in the “layers” of complexity depending upon the details of the problem. The Transference occurs in examining the initial odd shape of the spill and asking which set of prior knowledge aspects is needed to begin computing the area. In particular, the spread of the spill – is it just diffusion or combined with a different type of transport – tests the ability to transfer skills. In the communication system problem the transference occurs in exploring source compression in a different language. Finally, Reflection occurs in the last question as well as in revisiting the earlier answering stages.
Recommendations for Incorporating Metacognition

Metacognitive approaches should ideally be included into the engineering curriculum at all stages, from engineering concepts in the first freshman semester to capstone projects in the senior year. Project/Problem/Inquiry-Based approach to instruction is the best way to address this aspect. For instance, the Department of Mechanical Engineering at Penn State University has a course – Bicycle Dissection Labs – whose purpose is “To learn more about the most widely used transportation vehicle in the world - how it functions, how it evolved, and how to keep yours in better condition.”¹⁷ The stability of a bicycle has also been discussed in physics literature.¹⁸ Such a “hands-on” approach coupled with a computer simulation (or even better, in a virtual reality rendering) will provide a true learning experience, in addition to enhancing retention of knowledge gained. The engineering program at Ashesi University in Accra, Ghana, stipulates a two-semester course in the freshman year on Foundations of Design and Entrepreneurship, that provides a great environment “to cultivate within students, the critical thinking skills, the concern for others, and the courage it will take to transform the continent.”¹⁹

Assessment

The assessment of student progress should accompany instruction. Typical summative assessments do not serve the purpose of helping students to improve their performance during a given semester. Formative assessment should be conducted throughout the semester. Students should be required to develop an ePortfolio of their projects and other artefacts they may have created so that they can keep track of their own progress in terms of knowledge gained as well as reflect on their experiences.

Summary and Conclusions

In this paper, we addressed the issue of metacognition and a few specific implementations to enhance it in mathematics and engineering. Details of calculations have been omitted in consideration of the length of the paper. A more detailed paper with explicit calculations and answers to questions posed will be forthcoming. Our approach towards enhancing metacognition is based on the belief that there are several levels of metacognition depending upon the complexity of the problem being addressed. While developing a strategy for teaching metacognition, we observe that some aspects of metacognition cannot be taught in a standard instructional format. Aspects such as intuition and ability to identify a framework for a solution, for instance, can be developed in an environment in which the students see several examples of “how to think” and begin to explore such avenues themselves. Recommendations for incorporating metacognition at all levels of engineering curriculum and assessment in terms of ePortfolios are made.

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