Board 96: The Seven C's of Solving Engineering Problems

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1. Introduction

Most engineering courses involve problem solving, and solving problems requires the development of several types of knowledge and skills. From course to course, the kinds of problems that are solved and the specific knowledge and skills required can be very different. But across a wide range of courses we can define categories of knowledge and skills that are required for solving most problems. By referring to these categories while teaching, studying and practicing, we can develop a framework for learning. This framework provides a location and a structure for storing important knowledge, making it easier to recall.

Let’s call these learning categories the *Seven C’s*.

1. *Concepts* are the fundamental ideas, laws, principles, theories, hypotheses and models that form the basis for most of what we understand and do as engineers. By themselves, they are often not sufficient to solve problems, but they are required to formulate problems, develop solutions and interpret results.

2. *Compass* is a guide, or a set of suggested steps, for solving a certain class of problems. It is not usually a detailed process because the nature of each problem is unique and requires some creativity in the application of the relevant concepts. A Compass connects all of the other C’s for a given problem type.

3. *Computations* include the mathematical skills required to solve a problem (e.g., algebra, calculus, vector operations) and to present data (e.g., significant digits, units). These are often thought of as “turn the crank” sorts of operations, but a rich set of tools and a deep understanding of them is necessary to be a good problem solver.

4. *Communication* takes many forms, but its purpose is always to tell a story. In the context of problem solving, communication skills are needed to define the problem, justify the assumptions, describe the detailed solution steps and interpret the results. Key features include overall organization and structure, step-wise clarity and flow, diagrams, drawings and plots.

5. *Consistency* is instrumental in the development of good problem solving habits, skills and communication. This refers to, for example, the repeated use of reliable step-by-step procedures, convenient sign conventions and coordinate systems, meaningful notations

and more. Solving similar problems a different way every time is sometimes possible, but it’s not very effective in practice or in the early stages of learning.

6. *Checks* are strategies and methods to validate the accuracy of solutions. The most relevant approaches to use depend on the type of problem being solved. Examples include repeating (double-checking) computations, confirming that a final solution satisfies the boundary conditions, verifying that conservation laws are satisfied and so on.

7. *Collaboration* plays an integral role in nearly every phase of engineering. Examples include interdisciplinary teams working on design projects and students in a study group practicing solutions to challenging problems. The success of a team usually depends on the leadership, goal setting, task planning and other teamwork skills of its members.

Note that these are not steps for engineering problem solving. Rather, they are the main components or ingredients that are required to solve problems. In most problems, many of the Seven C’s will play a role, though perhaps not all of them at once.

In addition to providing a framework for organizing new knowledge and skills, the structure and vocabulary of the Seven C’s can be used to identify specific areas of learning strength and weakness. A general statement such as, “I am not good at solving this type of problem” might be replaced with a more precise “I don’t understand why this term is zero for this problem” (Concept) or “I don’t know how to use this information to calculate the temperature” (Compass) or “I seem to get the wrong sign whenever I take a cross-product” (Computation) and so on. Then, additional instruction and practice can be targeted where it will help the most.

This sort of diagnosis is aided by listing, for example, the relevant Concepts, Compass steps or Computations involved in the problem at hand. An inability to do so indicates a lack of knowledge, understanding or skill related to those items that should be on the list.

When practicing problem solving, identifying the role played by each of the C’s helps to reinforce both the distinctions and the connections among them. This simple act helps learners to better appreciate the broad set of skills and knowledge needed to be a good engineer, which in turn seems to motivate and guide more purposeful study. Further, this reflective activity increases both understanding and retention.

The Seven C’s were introduced to students in several Mechanics of Materials classes during a recent multi-year study on assessment methods [1]. Though they were not a formal part of the study itself, it was observed that the C’s played a key role in student success. (The only C not emphasized in these classes was Collaboration, though it could have been.) By introducing these learning categories early and referring to them often, they gradually became part of the vocabulary both in the class and in office hours. The remarkable improvement of student performance in the study [1] is largely attributed to the motivation of students to study differently due to the modified assessment approach. Nevertheless, based on observations and discussions with students, it is believed that using the structure of the Seven C’s played a role in helping these motivated students to achieve the desired level of problem solving proficiency.

The objective of the current paper is to describe the Seven C’s and the roles that they play in problem solving. Suggestions for how to use these learning categories are provided for both instructors and students.

2. The Seven C’s

Concepts

Of all the Seven C’s, this is the one we emphasize the most when teaching. We believe, mostly because it’s true, that gaining a deep understanding of key concepts is the most important thing our students can do.

Concepts are the fundamental ideas, laws, principles, theories, hypotheses and models that form the basis for most of what we understand and do as engineers. They are required to formulate problems, develop solutions and interpret results.

Concepts are the bricks and the beams used to construct solutions. But how many of our incoming students could build a decent structure given only a pile of bricks and beams?
To build a structure, they would also need:

- a work plan (Compass),
- many kinds of tools (Computations),
- design drawings (Communication),
- an agreed upon set of best practices (Consistency),
- oversight and formal inspections (Checks), and
- teamwork (Collaboration).

In other words, they would need some form of all the Seven C’s to successfully build a structure. The same is true for solving interesting engineering problems. We should not expect students to be able to solve these problems based solely on our amazing lectures that cover a few main concepts. This provides only bricks and beams.

The typical classroom lecture as well as the typical textbook chapter consists mostly of an introduction to new concepts and the formulation of key equations. Then, based on this information, homework problems are assigned and examinations are given that require students to solve problems.

In other words, we tend to teach concepts and then test process.

The homework and test problems are intended to give students practice and test their ability in applying the new concepts. But much of what they need for successful practice and success on exams is missing.

For example, we must also clearly demonstrate and provide a guide (a Compass) for how these concepts connect to solving problems and interpreting real life situations. These connections are the key to understanding.

Compass

We want our students to be able to *use* concepts, not just *understand* them. These are not necessarily the same thing, even though the best way to demonstrate understanding of a concept may be to apply it properly in the solution to a problem. This explains why most examinations involve problem solving.

Further, the more often we successfully apply a concept the better we understand it, especially when the applications are sufficiently different. So purposeful practice on a variety of problems not only increases our ability to use concepts, but also deepens our understanding of them [2,3].

It follows that the best way to help our students understand and use concepts is to teach them how to apply those concepts to a broad set of problems. A Compass plays a large role in this critical learning activity.

A Compass is a guide, or a set of suggested steps, for solving a certain class of problems. It is not usually a detailed process because the nature of each problem is unique and requires some creativity in the application of the relevant concepts. Even more than relating concepts, a Compass connects all of the other C’s to a solution process for a given type of problem.

Here is an example Compass for drawing a FBD of a beam, truss or frame structure:

1. Create a *new* drawing of the structure, representing each member as a line.
2. Represent internal connections as either pinned or welded.
3. Define a global coordinate system (GCS) that is convenient for the current problem.
4. Replace all boundary icon symbols with the reaction forces and moments that these boundary supports impose on the structure.
5. Draw all external loads.
6. Include all key dimensions, including units.
7. Label all points corresponding to boundaries, joints, load discontinuities and key sections.

The word Compass is appropriate here, because its role is to suggest what direction to go next rather than which detailed steps to take. The details of each step may depend on the particular problem, and these are left to the problem solver to determine, though a Compass may recommend a few options.

Rather than limiting creativity, a Compass facilitates it by reducing the mental load associated with developing an overall solution process. With practice, the solution steps in a Compass become habitual. This consistency frees the mind to focus on the unique aspects of a problem that do require some creativity of thought, or to concentrate on performing accurate computations.

A Compass also provides structure to a solution process that is naturally reflected in the communication of each worked solution. This makes solutions easier to read, understand and check for accuracy. Accuracy checks (solution validation methods) should be included in a Compass.

Note how Concepts, Computations, Communication, Consistency and Checks are all linked within a Compass. When Collaboration is an integral part of the solution process, it will also be part of the Compass.

A Compass eliminates many common questions such as, “Where do I start?” Further, by emphasizing the order and the role of each step in the solution process, it discourages the skipping of steps, a common reason many students get stuck when trying to solve problems.

Is there concern that students might become overly dependent on a Compass? In the beginning, this is an acceptable result because we do want to mold behavior and build healthy habits. But in the long run, observations of student behavior suggest that a Compass is like training wheels on a bicycle. They enable you to ride without falling when you first get started, but you shed them quickly when you gain confidence in your own abilities.

Will students just memorize the steps in a Compass? Hopefully they do initially, until those steps become instinctual. It is preferable for a student to memorize a process for solving a broad set of problems than to memorize the particular solution to a few selected problems [1].

An example of a broader Compass used in a sophomore-level Mechanics of Materials course is provided in [4]. The long version of this Compass includes lots of information and suggestions. It is most useful in the early stages of practice, when students are still learning how the various concepts and computational tools work together to create the desired result. A shorter version is also available for advanced users who have already mastered most of the steps and just need a reminder of the high-level process.

A Compass can be developed for most, if not all, types of problems in science, engineering and math. This is truly a key ingredient for successful practice at becoming a skilled problem solver.

Computations

By the time our students start taking mid-level engineering courses, we often take for granted that they can perform basic mathematical operations and calculations, understand and properly use significant digits and convert familiar units of measure to express a solution correctly and completely. This is a risky assumption.

Though students have been exposed to these topics numerous times in high school and introductory college courses, often their learning has not been assessed in a way that motivates or requires the expected level of proficiency [1]. Then, when grading is based on a loose notion of "correct approach" in subsequent engineering courses, there is essentially no penalty for computational errors. What motivation is there for students to develop a high level of computational skill?

Being vaguely familiar with the basic ideas is enough to pass many courses under most modern grading philosophies, and that is precisely the level of capability in many of our students. This is not apparent until a different assessment approach is implemented [1].

Even worse, students often believe they know "well enough" how to perform these computations, so there is no need for a higher level of competency or precision. Their high grades have convinced them that this is true. The result is that both students and instructors overestimate students' abilities to perform computational operations.

It seems there is a diminished appreciation for the value of accuracy, the significance of significant figures, or the magnitude of units. Yet these are essential parts of the practice and the culture of engineering, and they must become part of the mindset of engineers.

It should not be necessary here to give examples of engineering disasters caused by erroneous calculations or incorrect units, but a few can be found in [5,6] just in case. When we repeatedly overlook our students' mistakes in these areas, we are telling them it is ok to make these errors. And they are listening.

Moreover, a lack of mastery in computational skills can be a significant barrier to learning more advanced topics. As described in [2] (p. 15), "Knowledge is foundational: we won't have the structures in place to do deep thinking if we haven't spent time mastering a body of knowledge related to that thinking."

When students have not mastered basic computational skills, they have a more difficult time with new concepts or complex solution processes that involve those skills. This might be because their mental energy is spent on how to do the computations instead of higher level thought. When these computations become habitual, the mind is freed to focus on the relevant concepts and the unique aspects of the problem at hand.

Improving computational skills is mostly a matter of practice, but this practice will be meaningful only when there is proper motivation. Ideally, the origin of this motivation would be a deep appreciation for accuracy. For a small number of students, pointing to previous engineering disasters caused by numerical errors is sufficient to achieve this. But for most students, the primary motivating factor is the course grade [1].

We must make computational accuracy a key part of the assessment process and an integral part of the attitude of engineering students.

Ideally, we could influence the grading styles or expectations in prerequisite courses or even in high school level courses, where many of these computational skills are taught, but it’s difficult to change things we don’t control. We do control and we can use assessment to maintain an expected level of performance for our own science and engineering students.

Raising the bar in this way late in a student’s career is sometimes painful, as it reveals weaknesses that were carefully hidden for a long time. If we are steadfast, then word of these expectations may eventually trickle down to those courses that support the core science and engineering curricula.

This discussion on accuracy would not be complete without the concession that no one is perfect – we all make mistakes. That is true, of course. But the point of that statement is to remind us we are human when we do make a mistake. It is not an excuse for making errors regularly and without concern, which is the way it is often interpreted and practiced.

The expectation is not perfection, but rather the demonstrated ability to achieve correct solutions and the deep-seated belief that correctness matters.

Communication

When engineers think about communication, we mainly think about writing various types of reports and making presentations. With a little more thought, we can expand the list to include writing emails and memos, specifications and codes, operating procedures, proposals and other documents. There are many forms of graphics communications, including charts, diagrams, assembly drawings and more. And what about listening, which is at least one-half of communication?

Seldom do homework or exam-style problem formulations and solution procedures appear on such a list, yet engineering students practice this form of communication almost daily, often poorly. This may be our largest and best opportunity to teach important aspects of communication, as we know that many elements of effective communication are common across all types.

It is said that the main purpose of communication is to tell a story. This is equally true for a fictional narrative and the solution to an engineering analysis problem.

Every story has a beginning that sets the scene and introduces the main characters and the major conflicts (problem definition); a middle that explores the main themes through the actions of the characters (application of concepts via the solution steps and assumptions); and an ending that brings resolution to the story (final results, including their interpretation and validation).

In addition to the overall organization and structure of the story, the detailed pieces of information within each part must be organized and related to one another through a logical flow. Random bits of information written in arbitrary locations and orientations on a page do not create a coherent story, even if there are a few crisscrossing arrows drawn between the parts.

Early in their engineering education career, most students try to arrive at the final answer to a problem as quickly as possible, and with as few steps and written details as possible. It's as though they believe only the final answer matters, and the random scribblings leading up to that result are a waste of time and pencil lead. (Of course, when they don't arrive at a correct answer they do expect partial credit for those sparse and haphazard scribblings.)

Equations are commonly written without labels and values are written without units. As a simple example, a student's work may take the form:

$$500 - R + 200 = 0$$

$$R = 700$$

This may be a perfectly good equation for the problem at hand, but it has no context. A few descriptors help this equation make sense to others who might read the work:

Equilibrium:

$$\xrightarrow{+} \sum F_x = 0$$

$$500 - R_x + 200 = 0$$

$$R_x = 700 \text{ N}$$

The concept being used here is Equilibrium, so let's say that. In particular, the sum of all forces acting in the x-direction must sum to zero, and we will assume that positive forces act toward the right. Let's specify those little details, too. Now, the equation: $500 - R_x + 200 = 0$ has meaning. Note that adding a subscript to R implies that the force R_x acts in the x-direction. That's helpful information. Further, $R_x = 700$ is incomplete without units. 700 N (Newtons) is quite different than 700 kN (kilo-Newtons) or 700 lbs (pounds).

Using a consistent vocabulary of labels, notation and sign conventions helps to make communications clearer, while reducing the amount of thought given to these matters.

Of course, the above solution still lacks context without a properly drawn free body diagram (FBD), which is a graphical representation of the equilibrium state and must precede the writing of any equilibrium equation. After adding a brief problem statement and a FBD, we now have a complete short story, or perhaps a chapter of a longer story (a multi-part problem).

The above communication thoughts do not come naturally to engineering students. They must be taught and enforced until they become instinctual. Though painful at first, somewhere along that process most students begin to realize the importance of clear communication, and their problem solving process is better for it.

A well-structured solution suggests that a student has developed a knowledge framework for organizing the pieces of knowledge used in the solution. This is true even if that structure is mimicked from instructor solutions to similar problems. In fact, this mimicking is often the best way for students to learn how to establish a solution structure and a line by line format. Ideally, this structure would follow an established Compass, as described above.

In the study performed in [1], section A of a mechanics course used a traditional style of assessment and did not emphasize a Compass or Communication conventions, while sections B and C of the same course used a modified assessment approach that emphasized accuracy and that was supported by a detailed Compass and consistent Communication protocols during all problem solving. At the end of the semester, a common final exam was administered across all three sections, and this exam was graded by the team of three instructors. Not only did sections B and C demonstrate significantly greater problem solving abilities than section A, but also it was observed that student solutions in Sections B and C had become very orderly and followed a logical flow. This made grading easier and made it easy to locate where a student's thinking was fuzzy. The instructors believed that the consistent use of the Compass and the suggested Communication conventions for instructor solutions to practice problems was mimicked by students trying to organize their own thoughts. It is not known whether clearer communication aided in problem solving or greater problem solving skills gave rise to clearer communication of solutions. But after three years of consistent trends, the instructors in the study believe there is some connection between these two factors.

Consistency

Companies establish processes and best practices to reduce errors, increase efficiency, align efforts and produce expected results, consistently. These same outcomes should be expected from our solution procedures, and they are enhanced by using consistent processes and communications.

Thus, instructors should faithfully follow a Compass as well as a set of Communication rules in the solution process for every example, homework and exam problem. Skipping a few steps or using a "short-hand" notation is tempting when in a hurry, and it might even seem justified in some problems. But students don't yet understand when it is ok, if indeed it ever is.

Studies have established that good habits are a strong determiner of overall success, while the opposite result is more common for those with bad habits (e.g., [7]). The current author has observed similar trends in engineering students and even in practicing engineers – that building consistent processes and a proper mindset for solving engineering problems leads to greater success in problem solving. This does not seem surprising, yet we tend not to emphasize this topic enough in our courses.

Checks

Checks refers to validation of solution results. The letter "v" may rhyme with "c", but the title of this paper is the Seven C's, so we must lead with the word "checks."

Many students are aware that validation of results is a critical part of the engineering process, but their knowledge and skills are not yet mature enough to invent ways to check their own results. If this is something that students are expected to do, then, as with most of the skills discussed herein, instructors must explicitly describe and illustrate the use of various ways to validate solutions. These techniques only seem obvious after they have been learned and practiced.

A common misconception among students is that there is no value in obtaining correct answers on exam questions. This attitude is reinforced by grading models that award generous partial credit based on a poorly defined concept of "correct approach." This creates a culture in which many students no longer feel the need to solve problems completely or correctly [1].

Many students also discount the value of getting correct answers because in the "real world" someone else will be checking their results. This faulty logic ignores the facts that they may also be asked to check the work of other engineers, and this checking process assumes that everyone involved has a deep understanding of the relevant concepts and the detailed solution method for the problem at hand. Otherwise, fundamental errors may go unnoticed, leading to potential disaster. No one with only a cursory knowledge of a problem can reliably solve it or check someone else's solution.

A deep understanding of concepts and solution processes is unlikely in the absence of a desire to obtain correct solutions. One of the few ways, if not the only way, to encourage students to strive for accuracy is to link the course grade to complete and correct solutions [1].

The author and his colleagues implemented an exam grading scheme that requires students to find their own mistakes and correct them in order to receive any partial credit for an incorrect solution [1]. Even then, partial credit was only awarded for very minor errors, not for conceptual misunderstandings, in order to motivate complete and correct solutions.

Locating, classifying and correcting errors on exams can be a very important part of the learning process. This is referred to as reflection by cognitive scientists [3]. Developing these skills may lead to higher accuracy as well as higher grades in the future, all while developing an engineering mindset for checking work and locating mistakes.

Collaboration

Teamwork best practices are relevant to any group activity, including group problem solving. This means that teamwork skills can be strengthened even within applied mathematics and engineering science courses.

For example, group practice exams are a great way to cause a small group of students to work toward a common goal, such as preparing for an upcoming exam. Assigning a small amount of course credit to this activity will encourage participation. A frequent outcome of group practice exams is the natural establishment of study groups, another opportunity to practice teamwork skills.

3. Tips for Students

Students can use the Seven C's to enhance their learning and practice. Here are a few tips.

Concepts. Before you start solving a practice problem, list the concepts that will be involved in the solution. Review this list (reflect) after solving the problem and make corrections, as needed.

Compass. If a compass or solution guide is not provided for you, develop one and use it for all practice problems. Update it when you find limitations or inconsistencies.

Computations. Practice key skills until you can perform them without much thought. Then you can focus more on the other aspects of a problem.

Communication. Develop an organized and clear way to communicate all solutions. Include all details, and don't skip steps. To assess how clear your work is, ask others to read your solutions and explain them to you.

Consistency. Develop best practices in your solution processes and communication, and don't vary from them. Be boring here and save the creativity for when it is actually useful.

Checks. A method used to check a solution should be different from the original method used. For example, calculate the components of a moment using the right-hand rule, then check them with the mathematical version (cross-product approach). Perform calculations on your calculator in a different order to check your original work. Or type calculations on your calculator using your right hand, then do it again using your left hand.

Collaboration. Take a leadership role in a club or in your study group. Try to use a few of the teamwork skills you have learned. Practicing team skills is a great way to improve a few of those talents that employers are looking for.

4. Conclusions

There are seven key ingredients to problem solving – Concepts, Compass, Computations, Communication, Consistency, Checks and Collaboration. These categories provide a vocabulary for discussing solution techniques and a mental framework for better understanding and using knowledge in problem solving. Recent studies suggest that emphasizing the Seven C's in a mechanics class played a role in helping motivated students to significantly improve their problem solving abilities. While it is common in some classes to place greater emphasis on Concepts, it is recommended that some emphasis be given to all of the Seven C's within problem solving courses.

5. References

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