CU Thinking PROCESS: Promoting problem solving skills development in cornerstone courses

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Abstract - **The CU Thinking PROCESS was developed by a joint initiative between the Engineering and Science Education and General Engineering programs at Clemson University and is an innovative approach to learning and assessment that was developed based on a task analysis of problem solving attempts of students in a first-year engineering fundamentals course. There are several coordinating parts that work together to promote skills development of the cognitive and metacognitive tasks reflected successful problem solving solutions. The learning aids provide students with scaffolding to support the organization of their problem solving solution, promoting cognitive and metacognitive learning by assisting to reduce the student's mental workload through various tasks that have been shown to have correlations to accurate solutions. The rubric aids to provide standardization and consistency of evaluation while providing direct feedback that can be used to monitor progression of skill acquisition over time. The PROCESS structure was integrated into the cornerstone problem solving course in an active-learning SCALE-UP environment, and student's self-reported perceptions of the learning gains show that it is particularly effective for C students in our program. This workshop (and paper) will attempt to explain the acronym, lecture materials, scaffolding template, scoring rubric used by our program, as well as discuss future directions.**

Index Terms – problem-solving, scaffolding, cognition, metacognition, first-year engineering .

INTRODUCTION

To prepare for complex problem solving, students must develop conceptual and procedural knowledge that they can use as scaffolding throughout the learning process. For meaningful learning to occur, one must make sense out of newly presented information and form connections with relevant conceptual knowledge in order to anchor new ideas [1]. Gaps in a student's framework of relevant concepts and inferior problem solving skills can greatly influence how efficiently and successfully a student can solve problems in the intended manner [2]. When prior conceptual knowledge is lacking or inappropriate, rote learning or memorization may occur, which involves retention with little or no comprehension or transferability [3]. "Traditional pedagogical methods, such as requiring students to find information independently, assume a basic competence that not all students possess." [4]. Thus effective instruction that explicitly addresses problem solving skills that are relevant to engineering practice has the potential to engage students with diverse experiences and interests.

BACKGROUND

Research has identified several strategies used by expert problem solvers [2,5,6] , unfortunately, many of the techniques that experts use are not feasible for use by novices because of limitations of their cognitive processing capabilities [7]. Instructors often encourage students to use planning and problem representation tasks to overcome some of the hindrances experienced by novice learners [8]. However, a study of mathematical problem solving showed variability between the effectiveness of representations depending on whether the diagrams are simply pictorial or whether they are spatial representations, with spatial representations being correlated with higher success [9]. Research also shows that novice problem solvers often employ weak, self-defeating strategies. For example, attempting to find solutions by plugging numbers into equations with little focus on analyzing the problem state, understanding underlying concepts, or considering effective, strategic courses of action [2]. Given enough time, students may successfully solve problems through inefficient methods, often with little understanding of the appropriate approach to solving the problem [10]. Lack of awareness of performance errors has been shown to be one of the key indicators of differences in novice and expert solutions [2]. Recent studies on problem solving assess monitoring by counting the instances of performance error detection, reworking a part of the problem or expressing confusion or awareness of a challenge [11]. We set out to develop student-centered scaffolding to help develop skills in novice problem solvers that would help them not only in their cornerstone course, but in future courses.

ACTIVE RESEARCH

Our study of problem solving tasks, errors, and strategies used by successful novice problem solvers began in 2009 when we first began an exploratory evaluation of first-year engineering students' problem-solving attempts. The resulting taxonomy, shown in Figure 1 [12], was the inspiration for scaffolding aimed at improving problem solving performance among first-year engineering students.

Knowledge Access
- Identify equation
- Implicit equation identification
- Identify assumption
- Identify prior knowledge
- Identify conversion factor

Knowledge Generation
- Draw a picture / diagram
- Make a table
- Relate variables
- Manipulate equation
- Derive units
- Plug values in equation
- Document math
- Solve intermediate value

Self-Management
- Planning
  - Restate problem
  - Identify known value
  - Identify unknown value
  - Identify constraint
- Monitoring
  - Identify errors
- Revising
  - Labeling / Renaming
  - Erase work
  - Abandon process / Start over
- Evaluating
  - Check accuracy
  - Identify final answer

Management Errors
- Incorrect known value
- Incorrect unknown value
- Ignored problem constraints
- Irrelevant information
- Erasing correct work
- Inconsistent transcription
- Using incorrectly generated information
- Incorrect unit assignment
- Inconsistent units
- Missing Units Throughout

Conceptual Errors
- Incorrectly relate variables
- Misuse governing equation
- Incorrect visual/graphic representation
- Incorrect assumptions

Mechanics Errors
- Incorrectly manipulate equation
- Incorrect calculation
- Incorrect unit derivation

Strategies
- Segmentation
- Chunking
- Plug and chug
- Guess and Check
- Means-ends analysis
- Forward chaining

Answer States
- Correct Answer
- Correct but Missing or Incorrect Units
- Incomplete Answer
- Incorrect Answer

FIGURE 1
TAXONOMY OF PROBLEM TASKS AND ERRORS EVIDENT IN SOLUTION ATTEMPTS OF FIRST YEAR ENGINEERING STUDENTS

INSTRUCTIONAL SCAFFOLDING

The two instructional aids provided to students to promote problem solving skills development are shown in Figures 2 and 3. The visual flow in Figure 2 reminds students several factors have to be considered before starting calculations using a theoretical equation to model the system, while the handout in Figure 3 highlights common errors to avoid. Both give advice on practices to include if they are struggling with their problem solving practice. The acronym itself reminds students to break problem solving down into manageable steps, and provides a means for helping students recall those steps.

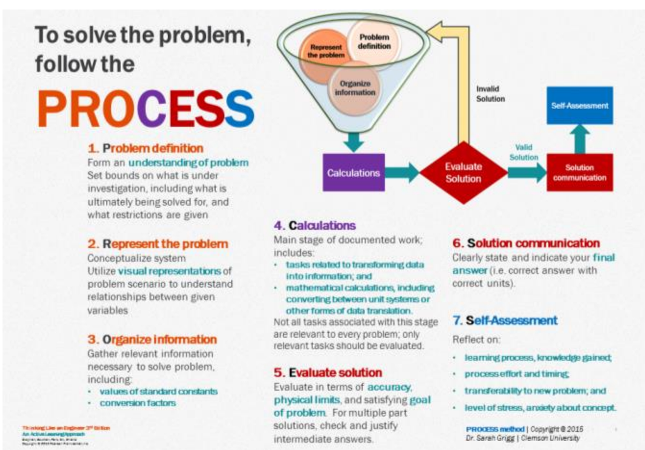

FIGURE 2
CU THINKING PROCESS FLOW DEPICTING PROBLEM SOLVING STAGES AND A DESCRIPTION OF SUGGESTED TASKS TO COMPLETE.

ASSESSMENT TOOLS

The assessment tool has undergone several iterations, in an attempt to find balance between providing quality feedback and ease of use. Our instructors tend to have around 150-200 students taking this course with them at one time, which led to the adoption of electronically graded homework paired with assignments graded by graduate student graders.

	Procedure stages	Recommended tasks	Common errors to avoid
1. Plan the approach	**Problem Definition**		
	Use provided information to form an understanding of the problem. Set bounds on what is under investigation, including what is ultimately being solved for, and restrictions on possible solutions.	✓ Identify desired variable and units ✓ Identify problem constraints ✓ Communicate assumptions	☒ Fail to identify the correct unknown quantity to solve for ☒ Ignore or misinterpret constraints on possible solutions ☒ Assign invalid assumptions
	Represent the Problem		
	Identify which theory is applicable to the conditions under investigation. Utilize visual representations to depict the relationships between variables under investigation	✓ Identify which theoretical concept is being investigated ✓ Represent the conditions with a sketch, diagram, or table ✓ Match the conditions to theoretical variables	☒ Use a theory that is not applicable to the condition under investigation ☒ Incorrectly assign relationships between variables ☒ Input the wrong given quantities into the equation
	Organizing Information		
	Gather additional information necessary to solve the problem: • values of relevant standard constants • conversion factors • equations	✓ Identify conversion factors ✓ Identify required physical constants ✓ Identify reasonable limits of dimension ✓ Identify relevant theoretical equations	☒ Use an incorrect conversion factor or reverse the conversion factor ☒ Use the incorrect theoretical equation to model your system
2. Analyze the system	**Calculations**		
	Analytical work; including: • Tasks related to transforming data into information • Converting between units • Translating data into new information using equations	✓ Solve for unknown variable algebraically ✓ Document intermediate steps ✓ Convert given values to SI units (p. 159) ✓ Input values into equation (p. 174) ✓ Convert to desired units (p. 159)	☒ Fail to convert units so that all are consistent and cancel properly ☒ Incorrectly manipulate equations (or other algebra mistakes) ☒ Miscalculation. Be careful entering numbers into your calculator!
3. Test the recommendation	**Evaluate Solution**		
	Evaluate in terms of accuracy, physical limits, and the goal For multiple part solutions, check and justify intermediate answers	✓ Check the physical limitations of possible solutions based on conditions ✓ Check that units are present and match what was asked for ✓ Confirm the solution answers the question posed; justify your reasoning	☒ Propose a solution that is physically unreasonable for the environment ☒ Report the answer in units other than the desired units ☒ Did not answer the question asked. ☒ Inadequate or flawed reasoning
	Solution Communication		
	• Clearly indicate your final answer (Correct answer with correct units including justification as requested)	✓ Check that the answer quantity is reasonable based on expected values ✓ Check that the solution precision is reasonable. ✓ Clearly indicate final answer and units	☒ Report quantities that are excessively too large or too small ☒ Report the solution with too many or too few digits ☒ Only report a quantity, without associated units and the variable
4. Hindsight Review	**Self-Assessment**		
	Reflect on: • the knowledge and skills required to solve this problem • level of stress or insecurity about the problem or concept.	✓ Rate personal performance on material ✓ If you aren't confident, review material and try again!	☒ Not reflecting on knowledge gained, concepts requiring clarification

FIGURE 3
HANDOUT WITH STAGES, RECOMMENDED TASKS, AND COMMON ERRORS TO AVOID WHILE COMPLETING PROBLEM SOLVING ATTEMPTS

Alpha version (shown in Figure 4) - In 2014, the PROCESS assessment tool was integrated into half of the classrooms in the foundations course. The assessment tool was intended as a means of standardizing feedback to students and ensure consistency of grading scores and feedback among graders. When asked to rate the effectiveness of the PROCESS rubric, students earning a C in the class had higher ratings than A students (3.7 to 3.3 respectively). Instructors found the PROCESS assessment useful for communicating solutions (4.6) and recognized the need for feedback (4.3). However, in 2015, when instructors resumed grading for the course, few wanted to use the assessment tool themselves because of the high level of detail required for its use.

Problem Solving PROCESS	Quality			Accuracy	Stage Score
(7 iterative stages)	Missing/ Indiscernible	Vague/ Incomplete	Fully Documented	Errors occurring within the stage detract from the stage score	Quality minus error penalty
Problem Definition □ Summarize the problem □ Identify desired value & units □ Identify constraint(s) □ Communicate assumption(s)	0	1	2	□ Problem text copied word for word □ Mistook what to solve for (unknown) □ Ignored constraints □ Misinterpreted constraint(s) □ Invalid assumption(s)	
Represent the Problem □ Sketch a representation □ Relate variables	0	1	2	□ Incorrect variables represented □ Incorrect relationship between variables	
Organize Information □ Identify known values □ Identify equations □ Identify conversion factors	0	1	2	□ Misused known values □ Wrong/flawed equation □ Invalid conversion factor (unit system) □ Invalid conversion factor (SI prefix)	
Calculations □ Convert to SI units □ Manipulate equation □ Document math □ Convert to desired units	0	1	2	□ Inconsistent units (failed to convert) □ Incorrect unit derivation □ Incorrectly manipulated equation □ Miscalculation (work correct/value not) □ Other	
Evaluate Solution □ Check accuracy □ Check reasonableness □ Check units	0	3	5	□ Unreasonable precision (# of digits) □ Physically unreasonable (impossible) □ Missing / Incorrect units on solution □ Other incorrect solution	
Solution Communication □ Indicate final answer □ Justify solution	0	3	5	□ Answer is difficult to locate □ Inadequate/flawed reasoning □ Did not answer the question	
Self-Assessment □ Rate your performance above	0	1	2	□ Responses were out of range □ Responses without showing work	
				Actual Score	____/20

FIGURE 4
2014 ALPHA VERSION – 20 POINT PROCESS RUBRIC - PRELIMINARY ASSESSMENT TOOL FOR PERFORMANCE ON PROBLEM-SOLVING ATTEMPTS DURING THE TRIAL TESTING OF THE SCAFFOLDING

Beta version (shown in Figure 5) – In 2016, the scaffolding template was used, integrating an abbreviated assessment to ease the grading burden on instructors, at the expense of standardized formative feedback to the student. The template and learning aides were accessible to all instructors, though its use was inconsistent. Some had their students complete every assigned problem on the templates and never graded them, others used the template only once per week on a particularly challenging problem completed by teams, while others graded one problem, assigning numerical scores only. This variability led to a wide variety of perspectives on the tool, resulting in lowered ratings of effectiveness from students (2.6 versus 3.5 with the alpha version), though maintaining ratings of its effectiveness at communicating problem solutions (3.3 versus 3.3)

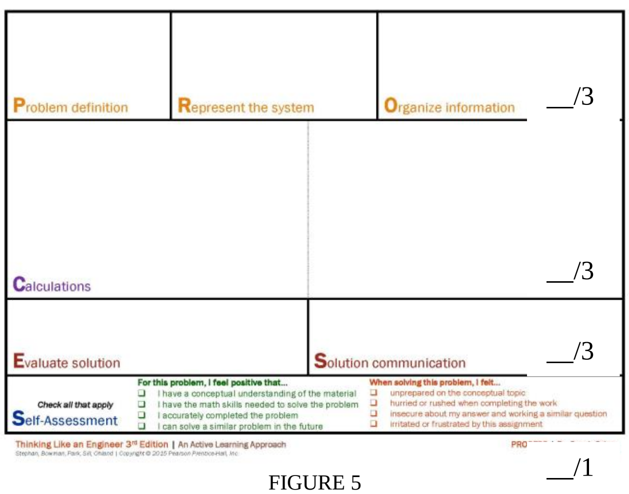

FIGURE 5

2016 BETA VERSION – 10 POINT ASSESSMENT - CU THINKING PROCESS TEMPLATE AND ABBREVIATED ASSESSMENT TOOL. INSTRUCTORS GRADED USING THEIR OWN METHODS WITHOUT FORMAL ERROR CODES.

Gamma version (shown in Figure 6) – In 2017, a subset of instructors will use the revised CU Thinking rubric in conjunction with an updated version of the template for a weekly lab problem requiring critical thinking, and will be graded using the assessment tool shown in Figure 6.

CONCLUSIONS AND FUTURE DIRECTIONS

The research efforts are ongoing, with next steps looking to use the CU Thinking PROCESS in niche groups of students. Specifically, it will be used in sections of the foundational engineering course that are cohorted into sections of the course specifically for students behind in their mathematics preparation, as well as a course on study skills. It is believed that this group of students will benefit more from this scaffolding and assessment approach than the traditional or advanced students. Instructors for these sections will undergo training and assessment scoring training similar to that which graduate graders received with the Alpha version of the assessment tool to ensure quality and consistent feedback. We are also looking to test this methodology in the K-12 learning community in related STEM courses.

This rubric is used to evaluate solutions for presented problems, those with prescribed conditions and a single-correct answer.

Learning Levels		G - Great (5 points)	A - Adequate (4 points)	I - Inadequate (2 point)	N - Not evident (0 points)	S - Score /40
Plan	P R O	**Present the Problem** Desired value Constraints Assumptions **Represent the System** Algorithms Visualization Mathematical Model **Obtain Relevant Information** Known values Theoretical Constants	Ignored constraint Flawed assumptions Incorrect relationship between variables Mislabel given values Misused conversion factor	Solving for other output than the desired variable Incorrect Formula or theory applied Used irrelevant values Undocumented	Missing problem definition Missing problem representation Missing assumptions and values	____/15 5 5 5
Analyze	C	**Consider the Choices** Convert inputs Calculate Convert to desired units	Algebra error (equation manipulation) Numerical computing error	Unit inconsistency Missing steps Illogical conclusion	Failed to convert inputs Undocumented calculations Failed to convert outputs	____/15 5 5 5
Test	E S	**Evaluate Solution** Reasonable precision of values Physically possible solution Solution accuracy Unit accuracy **State Recommendation** Logical conclusion / recommendation Justification	Too many/too few digits Recommendation is valid, but not expressed in desired units Recommendation implied but is unclear or unjustified	Exceeds physical limits Incorrect value (Other) Flawed reasoning	Did not complete Incorrect problem attempted	____/10 5 5
Hindsight	S	**Self-Reflection** Confident in performance Overall experience was positive	Took a long time to complete Took a lot of effort to complete	I could not solve a problem like this again Completing this was frustrating	I need more information to solve this I did not have the math skills to solve this correctly	

FIGURE 6

2017 GAMMA VERSION – 40 POINT ASSESSMENT - PROPOSED FOR EVALUATING PROBLEM SOLVING ATTEMPTS IN FALL 2017.

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