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Using the Cognitive Apprenticeship Model to Develop Educational Learning Modules: An Example from Statics

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Abstract

We present a pedagogical model that incorporates cognitive apprenticeship and computational modeling as a means for overcoming engineering students' conceptual difficulties. Apprenticeship is rooted in helping novices become experts through guided learning. The pedagogical model focuses on the cognitive and metacognitive aspects in achieving expertise. These aspects are central to the design of a learning environment of the cognitive apprenticeship model. The cognitive apprenticeship model's framework has four dimensions: types of knowledge required for expertise, teaching methods to promote its development, sequencing of the learning activities, and the social characteristics of the learning environment. Using these dimensions, we developed educational learning modules to guide understanding of individual, difficult concepts in engineering statics, namely moment of a force, truss analysis, and second moment of area. Students' attention is directed to the nuances of a difficult concept through qualitative and quantitative activities. The quantitative computational modeling activities are integral to each educational learning module. When students formulate computational models, they develop understanding by engaging in the theory and observations of a situation. Students complete each educational learning module in about three hours outside of class after they have been introduced to the individual topic in lecture(s) and completed a series of homework problems. As students complete an activity, they are encouraged to refer to its corresponding grading rubric, which conveys expectations of quality across different levels of expertise. Our pedagogical model can be used to design learning modules for difficult concepts in other STEM subjects.

Keywords: cognitive apprenticeship, pedagogical model, engineering statics, MATLAB®.

Introduction

In developing curricular priorities and pedagogical practices, instructors aim to promote discipline-based expertise. To help students progress from novice to expert in a discipline, instructors teach students domain-specific knowledge, help students organize that knowledge skillfully, and provide opportunities for students to retrieve and use that knowledge in solving problems. From a pedagogical perspective, instructors understand what it means to be an expert in the discipline and identify the processes that help students work toward achieving expertise.

To examine the tacit processes that experts use when they solve difficult problems, Collins *et al.*[1] emphasized the importance of experts' cognitive and metacognitive strategies. They outlined teaching methods that can be integrated into a curriculum to teach the complex cognitive skills that experts employ when they apply knowledge to perform complex and or realistic tasks (Collins *et. al.*[1], p. 4). This set of methods merges the traditional model of apprenticeship with the concepts of situated learning and legitimate peripheral participation of Lave and Wenger.[2]

Our work uses the principles of cognitive apprenticeship to develop a pedagogical model that promotes students' acquisition of discipline-based expertise. This pedagogical model integrates a computational modeling activity as a way for students to express their conceptual understandings. The student's performance is evaluated with a rubric keyed to different levels of expertise. We illustrate the use of this pedagogical model with a practical example of designing an educational learning module (ELM) that targets a difficult concept in engineering statics. Unlike other previously developed learning modules, our ELMs are grounded in educational research.

Literature Review

Learning through apprenticeship dates back to ancient civilization. Visit any early museum around the world and you will come upon artifacts holding scientific, artistic, and historical importance largely created by persons who apprenticed under others in their community. Even today, training in trades (e.g., bricklayer, carpenter) relies on apprenticeship. In academia, apprenticeship performs an integral role in many pedagogical activities and continues to evolve.

In the last decade, there has been a focused shift to improve pedagogy, especially for STEM disciplines. [3, 4] In order to compete in a rapidly changing, globalized world, educators need to critically reexamine what skills engineers and scientists need in the future – and then design learning environments that cultivate those skills. Our review of the literature reveals the types of pedagogical models that address well-structured and ill-structured problems in authentic environments; they include situated learning, cognitive apprenticeship, problem-based learning, learning by design, and the Dreyfus model for skill acquisition. [1, 5, 6, 7, 8, 9]

Of special interest among pedagogical models is cognitive apprenticeship. Cognitive apprenticeship (CA) is a theoretical model that describes the design of a learning environment that helps novices become experts through guided learning. CA emphasizes the importance of learning in context.[1] Since we believe CA and its native teaching methods align well with any course's objective with an interest to cultivate discipline-specific expertise, we were surprised to find few prior examples that apply CA to a particular pedagogy. [10, 11, 12] Within these examples, it was not well understood how learning transferred to authentic environments.

We consider discipline-specific situations wherein the CA model could be applied to help students develop metacognitive and complex cognitive skills. Each academic discipline appears to have at least one course wherein the withdrawal and failure rate is related to difficulty in understanding abstract or difficult concepts. The standard course engineering statics includes a set of difficult concepts; [13, 14, 15] and is therefore proposed to be an exemplary candidate for this pedagogical research.

We can trace students' difficult concepts in engineering statics are problematic for many students is traced to students' knowledge and understanding of classical mechanics and Newton's laws of motion – first introduced to students in a prerequisite physics course. Research by members of the physics education research community identified misconceptions in learning forces and kinematics.[16, 17] Similarly, considerable research has been performed that identified the conceptual difficulties with engineering statics, the development of a concept inventory as a mode of assessment, and novel pedagogical approaches.[13, 14, 15, 18]

First we introduce our pedagogical model and then describe the design of a discipline-based ELM to help students learn difficult concepts in engineering statics.

The Pedagogical Model

The pedagogical model incorporates the four dimensions of the cognitive apprenticeship model shown in Table 1. The pedagogical model is then merged with a computational component. Within the CA model, Collins *et al.*[1] defines six teaching methods that promote the development of expertise that can be selectively chosen to guide the design of a learning environment. Defined in Table 1, these teaching methods are modeling, coaching, scaffolding, articulation, reflection, and exploration. Because the learning environment is context specific, its design may use only some of these teaching methods, or some more than others.

Content	**Types of knowledge required for expertise** • *Domain knowledge*: subject matter specific concepts, facts, and procedures • *Heuristic strategies*: generally applicable techniques for accomplishing tasks • *Control strategies*: general approaches for directing one's solution process • *Learning strategies*: knowledge about how to learn new concepts, facts, and procedures
Method	**Ways to promote development of expertise** • *Modeling*: teacher performs a task so students can observe • *Coaching*: teacher observes and facilitates while students perform a task • *Scaffolding*: teacher provides supports to help the student perform a task • *Articulation*: tteacher encourages students to verbalize their knowledge and thinking • *Reflection*: teacher enables students to compare their performance with others • *Exploration*: teacher invites students to pose and solve their own problems
Sequencing	**Keys to ordering learning activities** • *Inceasing complexity*: meaningful tasks gradually increasing in difficulty • *Increasing diversity*: practice in a variety of situations to emphasize broad application • *Global to local skills*: focus on conceptualizing the whole task before executing the parts
Sociology	**Social characteristics of learning environments** • *Situated learning*: students learn in the context of working on realistic tasks • *Community of practice*: communication about different ways to accomplish meaningful tasks • *Intrinsic motivation*: students set personal goals to seek skills and solutions • *Cooperation*: students work together to accomplish their goals

Table 1: The cognitive apprenticeship model for designing learning environments.[19]

The computational component is the means by which students explore the nuances of a difficult concept to engage with simulations of real-life examples, observe, and apply their knowledge as often as they like, and at their own pace. Students can effortlessly control variables of a system which allows them to explore the causal role of individual parts of a system and receive real-time feedback that can be visualized in multiple ways of their choosing. In this way, students continuously renegotiate and reinforce their knowledge and understanding of a concept. The computational modeling component requires students to identify assumptions explicitly, helping to organize their learning. The ease of control over variables allows students to explore the causal role of different parts of a system and receive real-time feedback that can be visualized in many ways.

There are many considerations to engaging pedagogy effectively, with context and discipline-specific factors playing a dominant role. To evaluate the effectiveness of a pedagogical model, we need to consider the alignment and interdependence of pedagogy, content, and assessment.

We next describe, in the general case, considerations for implementing this pedagogical model within an educational learning module (ELM). Then we describe a discipline-specific design example of an ELM for engineering statics that targets an individual, difficult concept. For both of these cases we explain the pedagogy, content, and assessment aspects of the design of the learning environment.

ELM Design for the General Case and for Engineering Statics Example

ELM Design, General Case

The learning objectives of an individual ELM are first identified and then classified using Bloom's Revised Taxonomy; the taxonomy describes educational objectives, learning activities, and assessment processes.[20] The most important learning objectives are then analyzed using the assessment triangle of observation, interpretation, and cognition – three key elements that underlie any assessment.[21] This triangle conceptualizes assessment as a process of reasoning from evidence. In order for assessment to be effective, all three elements must be aligned. Last, we examined the overall alignment of the content of the ELM namely, its curricular priorities and assessment sections.

Grounded in a constructivist epistemology, each ELM focuses on a specific concept or restricted content area in the curriculum. The process of designing ELMs is largely influenced by our proposed pedagogical model and additionally draws upon approaches to human learning by Vygotsky[22, 23] and Bandura's social learning theory to scaffold student learning. Commonalities between them exist, due in part to the derivative nature of shared core theories.

When students receive an ELM, they also receive an assessment rubric. The rubric specifies how their performance will be assessed for each activity. Later in this report, we discuss in greater detail how students are evaluated.

Engineering Statics and Difficult Concepts

Engineering statics is the branch of engineering mechanics that is concerned with the analysis of forces on physical systems in static equilibrium. Engineering statics is a core course for secondyear undergraduate students majoring in mechanical engineering. It is often required for students in other engineering degree programs such as biomedical, civil, and aerospace engineering.

We wanted to design ELMs for engineering statics that improves students' knowledge and understanding of difficult concepts. We first describe the environment and how the ELM is assigned. The ELMs are targeted for implementation in an engineering statics course taught at a large Midwestern university that uses a blended approach to learning. Every week, students watch instructional lecture videos that introduce to a new concept. Students then come to class ready to actively engage (e.g., through discussion, individual or group problem-solving, watching in-class demonstrations) in applying the new concept. In a few days, students submit a homework assignment on the same material.

If a concept is particularly difficult for students, and the instructor wants students to continue thinking about this concept after homework is collected, then an ELM is assigned. Upon submission of the ELM assignment, students are provided access to solutions to check their work. Quality and timely feedback have an essential role in student learning.

To date, we have developed ELMs for three difficult concepts in engineering statics: *moment of a force*, *truss analysis*, and *second moment of area*. We next describe our ELM for *moment of a force*.

ELM Design for Moment of a Force

The ELM for moment of a force contains a set of activities that gradually increase in complexity. The first activity engages students to articulate responses to qualitative questions that by design, require no calculations, but require both convergent and divergent thinking. Subsequent activities contain both qualitative and quantitative components. The computational, simulation component is introduced about midway in the ELM with a rudimentary example. In the final activity, students use prior scaffolded knowledge to write their own MATLAB® code to solve engineering statics problems.

The ELM is assigned through the university's course's web management system (e.g., Blackboard, Moodle, Piazza). Students additionally have access to the MATLAB® software as part of a licensing agreement with the university. Students are first presented with the ELM's learning objectives and outcomes (see Table 2 and Table 3, respectively). At the end of the ELM, the student is provided with a copy of the rubric for reference. The rubric is discussed in greater detail later, in the evaluation section.

Learning Objectives
• Students will provide knowledge of mathematics, science, and engineering to solving moment of a force problems
• Students will perform accurate computer simulations using MathWorks® MATLAB® software tools in designing, analyzing, and troubleshooting moment of a force problems.
• Students will generate accurate results from solving problems in the module, relate those results to the appropriate theory, and submit their results and findings in the template provided.

Table 2. Learning objectives and outcomes for the *moment of a force* ELM

Learning Outcomes
• On successful completion of the module, students will be able to evaluate the theoretical and methodological foundation of the moment of a force.
• On successful completion of the module, students will be able to create rudimentary MATLAB® code to solve moment of a force problems.
• On successful completion of the module, students will be able to discuss how computational modeling incorporating MATLAB® software can build conceptual understanding and problem-solving skills in Statics.
• On successful completion of the module, students will be able to consider problems from a design perspective and model the solution of a problem in a series of sequential explanatory stages in advance of initiating a mathematical solution.

Table 3. Learning outcomes and outcomes for the *moment of a force* ELM

The students are first presented with a conceptual problem proposed to be one with which they can identify. The student reads and engages with a narrative of an electronic pet dog door design to then solve a set of qualitative questions. Through this inquiry-based activity, students examine their conceptual understanding of moments and articulate their understanding without the use of equations or computations.

A salient characteristic of this and all activities in the ELM is the use of examples with which the student can better identify, thus bringing content into context because a principle within CA is that all knowledge is situated and therefore context is important when relaying content[1]. For engineering statics, our ELMs offer more creative examples than what most textbooks of the last several decades provide – a predominance of construction-related equipment, and wrenches.

The second phase of the ELM summarizes the theoretical precepts of the moment of a force and is followed by its equivalent mathematical representation. Students can use this as a reference; it contains the organized set of all the salient points about this concept. This phase serves to reinforce and help organize what students understand about the concept as it was first introduced to them by way of lectures, in class activities, and a homework assignment.

The third phase of the ELM is a scaffolded problem that builds on the previous phase. Students are asked to consider the problem shown in Figure 1. The student is first stepped through the solution theoretically – meant to position the student to think of the conceptual principles that describe the problem. Following this, the student is guided step by step through a computational solution as justification for the theoretical explanation.

Example: Moments on a Beam

The beam below has the following loading: smart car = 1800 pounds and the Audi S4 = 3800 pounds. Determine the moment of each load on the beam using the reaction at **P** as the *center of the moments*.

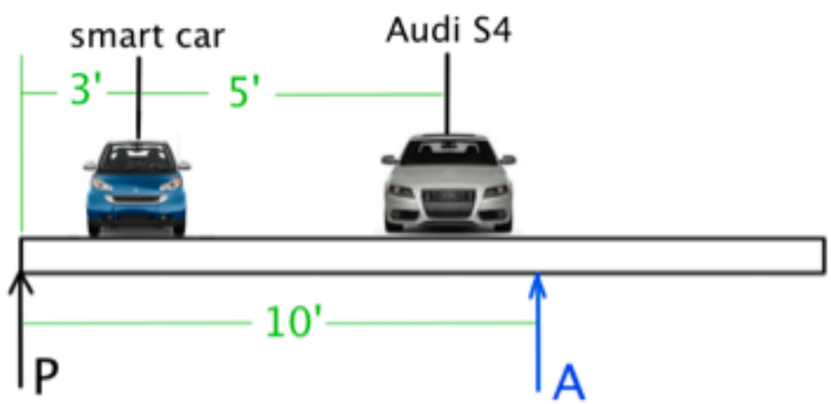

Figure 1: Second problem in *moment of a force* ELM

Students are then posed a set of qualitative questions intended to engage the student in reflective practice. Refer to Figure 2 for the set of questions.

Answer questions in full sentences omitting the inclusion of computations or equations.

1. Answer by observation only. If you were to switch the two cars, what effect would this have on **A**, if at all? Explain your reasoning.
2. Answer by observation only. If you were free to move support **A**, where would you move it to so that the beam would remain stable but force **A** would become as small as possible? Explain your reasoning.
3. Luke states: "Adding a 2,000 pound force **B** pointing down at P from the top of the beam has absolutely zero effect on force **A** needed to center the moments." Do you agree with Luke? Justify your answer.
4. Answer by observation only. Pivot **P** is moved from its original location to the right by five feet, closer to force **A**. List the steps you would follow to solve the problem. Make sure to indicate whether the force contributes a positive or negative sense. (Tip: RHR)

Figure 2: Questions posed to students for the "Moments on a Beam" example of Figure 1.

Following this activity, students are presented with a set of common mistakes and trouble spots with this concept and tips to avoid them. It is believed that when students receive this information, students have solved several problems in this area, they are more attuned to relating and likely to understand and use than if the information was presented at the very beginning.[24, 25]

The fourth phase in the ELM is a computational modeling problem. To scaffold student learning about computational modeling, we first present a basic problem with only two member forces and students are shown how to solve for the cross product using MATLAB®. Due to varying levels of students' experience with MATLAB®, the problem is designed without any assumptions as to the student's prior programming experience. The student is shown, one step at a time, the solution of the problem as performed via calculation. At each step the corresponding set of MATLAB® command(s) are provided and the student is encouraged to copy and paste these at the command prompt. This problem concludes on a subsequent page showing the single script that contains all the individual commands that can be executed as one file. The code is appropriately commented to provide further guidance. Scaffolding students to learn MATLAB®

The fifth and last phase of the *moment of a force* ELM contains the last problem and builds off of the fourth phase. Maintaining the principle of using examples with which students can identify (i.e., content into context), students are provided the context of a storm shelter door they need to lift to get to safety. The door is shown to have three hinges and a force *F* created by the student pulling on the door to open it. Measurement locations and force components about all three axis are provided. The student is first asked to compute the moment of a force about each of the three hinge locations. The second part of this question asks students to solve the same for when there are only two hinges. Students are then guided to solving the problem using the instructional layout in Figure 3. All the steps in this layout build off of all the previous phases.

I. Using a bulleted list as your format, describe chronologically, each of the steps you will perform to arrive at your final solution. Each unique step is represented by a separate bullet. *Important*: Articulate each step without including or referring to mathematical equations.

II. Draw the free body diagram (FBD)
(*Tip!* This should also be a step you mentioned in I.)

III. Use MATLAB® to write the code that will calculate the cross product for the related steps outlined in I. Attach your self-authored code and the output from executing your code.

IV. Use the steps outlined in I. to solve using scalars. Attach your self-authored code and the output from executing your code.
(*Tip!* This is additionally useful as a method to cross-check your answers.)

Figure 3: Instructions for a representative problem containing a computational component in the *moment of a force* ELM

Evaluation

Pellegrino *et al.*'s principles of assessment [21] were used to guide the design of the grading rubric that contains attributes of cognitive apprenticeship and computational modeling. These rubric attributes are directly related to the six cognitive apprenticeship teaching methods selectively used to design the ELM: *modeling, coaching, scaffolding, articulation, reflection,* and *exploration*. The ELM's rubric four levels of student performance how well students acquired and integrated cognitive and metacognitive strategies since their first exposure to the particular concept about the different learning modalities (e.g., reading, lecture, homework problems, etc.).

The student may refer to the rubric at any time while completing the ELM. The rubric contains the overall grade weighting for each question or the set of questions that are collectively graded as one. Table 4 is the rubric for a representative problem that poses a set of qualitative questions. In the "Level of Practice" column, the labeled categories are assigned on a continuum from novice to expertise. Because the problems and questions focus on concepts that students have already seen, the novice level of practice is normalized with consideration to this. Under these conditions, a novice is defined as someone who lacks knowledge. The contents in the "Criteria" column were guided by principles of cognitive apprenticeship (and when applicable, computational modeling) and are problem-specific. Similarly Table 5 illustrates another rubric for a problem that incorporates a computational simulation.

Level of Practice	Criteria	Grade
Expertise	Answers articulate correct knowledge, reasoning, and an understanding of the problem-solving processes used. Examples provided are appropriate and clearly communicated. Demonstrates analytical decision-making and situated, self-identifying reflections.	**100**
Proficiency	Answers articulate some knowledge, reasoning, and an understanding of the problem-solving processes used. Demonstrates analytical decision-making and situated, self-identifying reflections.	**85**
Competence	Answers are rudimentary in scope. Some demonstration of analytical decision-making, and situated, self-identifying reflections.	**60**
Novice	Grasp of concept or material is not conveyed; answers are either missing or incorrect.	**0**

Table 4. Rubric for representative problem in the *moment of a force* ELM containing qualitative questions.

Level of Practice	Criteria	Grade
Expertise	Results are correct. Self-authored MATLAB® script is commented, compiles, and generates correct results. Demonstrates analytical decision-making and situated, self-identifying reflections.	**100**
Proficiency	Results are correct. Presence of 1-2 errors (e.g. absence of comments, algebraic, syntax) in self-authored MATLAB® script. Demonstrates analytical decision-making and situated, self-identifying reflections.	**85**
Competence	Submission demonstrates an understanding of concept and conveys understanding of the process steps needed. Presence of 3-4 errors (e.g. absence of comments, algebraic, syntax) in self-authored MATLAB® script. Demonstrates analytical decision-making and situated, self-identifying reflections.	**60**
Novice	MATLAB® code is significantly incomplete or not included.	**0**

Table 5. Rubric for a representative, scaffolded, computational simulation problem in the *moment of a force* ELM

Providing students with timely and appropriate feedback is directly related to how well they learn and improve.[26] ELM feedback is provided in two forms. The first are the solutions to the ELM. After the deadline to submit the ELM passes, students are given immediate access to the solutions of the ELM through a web-link assigned to them. For an open-ended problem, since a range of answers is possible, a set of representative parameters is chosen and only one solution is presented. The second form of feedback is the graded rubric returned to the student that may contain individualized problem-specific comments.

Prompt and appropriate feedback is an important part of the reflection and coaching processes of the cognitive apprenticeship model. When students compare their answers with the solutions and consider any additional feedback, they engage metacognitively: they self-assess what they have learned, and what they still need to know. They are self-directing their learning. According to Ambrose *et al.,* [27] the key metacognitive skills to becoming self-directed learners are "students must learn to assess the demands of the task, evaluate their own knowledge and skills, plan their approach, monitor their progress, and adjust their strategies as needed" (p. 191). When these metacognitive skills are nurtured, students' complex cognitive reasoning skills are enhanced which affect goal setting and improved performance.

Discussion

Discipline-based educational research seeks to understand impediments to student learning within a given discipline. We have applied findings from discipline-based education research to develop a pedagogical model for the design of ELMs. We showed an example of employing the model in the design of an ELM used to target difficult concepts in engineering statics. The ELM prototypes described herein were assignments in Adobe PDF. A second generation ELM prototype design we recommend is converting them to an online format and exploit social learning affordances. ELMs as used in statics can be generalizable to other subjects within and even beyond the engineering discipline.

Many previous pedagogical models that address ill-structured problems in authentic environments enhance student's overall quality of learning. However, within these models, not much is known about how well what students learn transfers to the workplace. Our research attempts to highlight the importance and necessity to effectively evaluate how and what students learn, transfers to real life work situations.

This project will illustrate how instructors can use technology judiciously to increase student learning. The MATLAB® modeling and simulation components of the engineering statics ELM reduces the time that students usually dedicate to computation. When students solve problems that have several equations and unknowns, they often commit manual errors. Introducing the MATLAB® component, as we do, after the students are exposed to the concept allows the students to spend more time reflecting on the theoretical aspects, setting up the problem correctly, and checking whether the final solution is within an expected range. Students can change parameters and increase dimensions in orders of magnitude quickly and without the burden of manual or calculator aided calculations. As a result, students' attention is directed to the underlying theory of the individual concept while the activity itself improves their complex cognitive processes on how they think about that concept – the original aim of the engineering statics ELMs.

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