A Software Suite for Self-Paced Learning

https://doi.org/10.3991/ijet.v17i19.34575

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Abstract—The faculty of engineering at McMaster University is very diverse with students coming from a variety of socio-economic backgrounds and nationalities. There is an expected level of prerequisite knowledge for courses in the program, especially for subjects in mathematics and physics. Yet, a significant number of students struggle to reach the same level of prior knowledge as their peers due to a lack of educational resources or due to language barriers. Entering lectures without the expected baseline understanding of the concepts increases the risk of cognitive overload because these students exert additional mental effort in retaining the pre-lecture information along with the lecture content. As a solution to this problem, we present a suite of web-based interactive programs that are accessible to the students outside the class. The Software Suite will provide supplementary material to assist with self-paced learning in a 3rd year undergraduate engineering course, i.e., Finite Element Analysis, at McMaster University's W Booth School of Engineering Practice and Technology. It will enable students design and analyze various engineering applications, namely, Spring System, Trusses, Beams, Frames, and Heat Transfer along one or two dimensions. The purpose of the interactive platform with several programs is to actively engage the students with this cognitive tool to cement their understanding of the concepts instead of passively perceiving it as a tutor or repository of information.

Keywords—Software Suite, self-paced learning, cognitive load, finite element analysis

1 Introduction

Amidst a global pandemic, rapid technological innovation, and rising interests in social pedagogy, there has been a fundamental shift in how educators approach teaching and learning [1]–[7]. Didactic lectures are one of the most common and traditional methods of teaching in higher education. There is an assumed transfer of knowledge from educator to student despite the method being a teacher-centred approach where students passively receive information [8]. This traditional approach is regarded as ineffective because it fails to engage students in active learning and does not foster critical thinking, which consequently impairs the students' ability to retain the information [1], [9], [10]. Researchers and educators who seek to fill this gap in traditional teaching methodologies have looked toward instructional design theories – pedagogical frameworks that offer guidelines on how to help people learn better [11]. One such theory that has garnered recent attention is the Cognitive Load Theory (CLT).

1.1 Cognitive load theory

At its core, CLT describes how the human brain has very limited processing and storage capacity for working memory [8], [12]. When new sensory information is received by the brain, one's working memory attempts to process that raw data into a meaningful schema which eventually is transformed into long-term memory [8]. These cognitive inputs can be categorized into three types: Germane Load, Intrinsic Load, and Extraneous Load [13]. Germane load is the mental effort devoted to the development of long-term memories through schema building – this facilitates learning. Intrinsic load is the mental effort that is inherently imposed by the learning task. Extraneous load is any additional mental effort imposed by factors that are not related to the learning task, such as the mode of learning. Generally, Cognitive Load (CL) refers to the mental effort used to process new inputs. In particular, it is the sum of the intrinsic load and the extraneous load of a task. By accounting for the function and architecture of human cognition, the principles of CLT help educators design instructional materials to optimize learning by increasing germane load, managing intrinsic load, and decreasing extraneous load [8].

1.2 Cognitive load in engineering education

While the issue of cognitive overload occurs in students from all disciplines, engineering students face a unique struggle for a number of reasons. Engineering is a discipline that relies heavily on the hands-on application of the studied subject matter [14]. Students are trained to undertake engineering work over a broad range of areas such as automotive simulations [15]–[19], process monitoring [20], engineering optimization [21], and subtle natural sciences phenomena such as thermodiffusion [22]–[27]. As a result, engineering professors make strong use of laboratories, maker spaces, or physical equipment to facilitate learning in class [28]. With this, the intrinsic load of engineering education is substantially high due to the complex engineering concepts being studied; as well as due to the emphasis on problem-solving [13], [29]. Additionally, the course load is also quite heavy and exhibits a stark contrast with the workload required in high school. The transition to online learning during the COVID-19 pandemic has exacerbated the issue of unnecessary extraneous load. The shift to distance learning has required students to rely solely on lecture notes, online simulations, and their imagination to understand abstract concepts. At the same time, professors often increase the number of assessments in classes to compensate for the removal of in-person components such as laboratories [29]. Collectively, these add to an already high cognitive load for engineering students. Extraneous load also increases when the lectures are disorganized, Learning Management Systems are difficult to navigate, and when internet access is unstable [2], [8]. To make matters worse, the heterogeneity of students' backgrounds gives rise to an unequal distribution of extraneous and germane load among the students.

The faculty of engineering at McMaster University is very diverse with students coming from a variety of socio-economic backgrounds and nationalities. There is an expected level of prerequisite knowledge for courses in the program, especially for subjects in mathematics and physics [30]. Yet, a significant number of students struggle to reach the same level of prior knowledge as their peers due to a lack of educational resources (public school vs. private school) or due to language barriers (English as a foreign language vs. native speakers). Entering the lectures without the expected baseline understanding of the concepts increases the risk of cognitive overload because these students exert additional mental effort in retaining the pre-lecture information along with the lecture content [31].

1.3 Impacts of high cognitive load

There are significant negative effects of a classroom delivery designed with a high cognitive load. A high cognitive load directly impairs knowledge acquisition or long-term memory retention [12]. This significantly diminishes productivity and the ability to focus [32]. Students who experience cognitive overload may also experience learning anxiety, a lack of motivation, and feelings of being overwhelmed [29]. There are additional physiological symptoms associated with cognitive overload including dilating pupils, sweating, and a fast heart rate [33].

1.4 Strategies to alleviate cognitive load

Educators can minimize the extraneous load in their instructional material by avoiding common problems identified in CLT such as the split-attention effect, the redundancy effect, and the transient information effect [12]. The split attention effect occurs when textual and visual representations of the same information are presented in such a way that the learner must continually shift their attention between the two sources [34]. The redundancy effect occurs when the same information is unnecessarily repeated or presented in multiple formats such that the text or visual representation can be understood independently [12]. Finally, the transient information effect occurs when a dynamic visualization has too many elements rapidly entering and exiting the screen [35]. Each effect imparts a higher extraneous cognitive load on students because they interfere with the processing of essential information [36]. There are many solutions to overcome these issues, such as physically integrating text and visualizations close on the page [37], removing redundant or nonessential information from the material [38], and allowing learners to control the pace of visualizations via a scrollbar [39]. The strategy of interest in this paper is the use of a Software Suite as a supplementary material to assist with self-paced learning in a 3rd year undergraduate engineering course, i.e., Finite Element Analysis, at McMaster University's W Booth School of Engineering Practice and Technology.

1.5 Supplementary materials in engineering education

The benefits of self-paced supplementary materials in improving students' learning outcomes are well documented with studies covering a variety of disciplines. In the subset of those studies that focus on engineering or engineering-related topics, the researchers utilize vastly different strategies for providing supplementary material. For example, Aziz and Islam [1] employed a mixed-pedagogy approach by providing pre-recorded lectures, interactive videos, relevant webpages, and self-assessment quizzes for engineering students to use if they wanted to consolidate their knowledge outside of the classroom. Cruz-Madiclum and Mallari-Mistades [40] developed self-directed learning modules that covered topics in kinematics. Several self-directed learning tools were embedded in the modules, such as online simulations, self-assessment quizzes, and teacher-made video tutorials. Lam and Chan [41] developed short, animated videos on semiconductor devices for a Massive Online Open Course (MOOC) before distributing those videos as pre-lecture supplementary materials in three traditional electrical engineering courses. Moradi et al. [30] developed three online instructional modules on basic mathematics and physics concepts with the aim of equipping undergraduate students with the prerequisite skills for future engineering coursework. These modules were provided as out-of-class supplementary videos for students in a "Statics and Dynamics" course. Finally, Lijo et al. [42] assessed the pedagogical utility of an electrical engineering YouTube channel to enhance the education equality of engineering students through a 5-point Likert scale survey of the channel's audience. These studies have established that supplementary materials that promote self-paced learning significantly improve the learning outcomes of engineering students, with one study [42] specifically mentioning cognitive load.

Inspired by these studies, in this work, we present the development of a supplementary tool for the Finite Element Analysis (FEA) course offered in level 3 of the Automotive and Vehicle Engineering Technology program at McMaster. Specifically, we present a suite of software programs that will enable students to design and analyze various engineering applications, namely, Spring systems, Trusses, Beams, Frames, and Heat Transfer along one or two dimensions.

2 The finite element analysis course at McMaster

The FEA course covers the following topics: (i) fundamentals of finite element analysis including the basic steps, generic solution approaches, and verification of solutions, (ii) structural analysis of trusses, beams, and frames, and (iii) thermal analysis. Students are taught to solve one- and two-dimensional problems using theoretical principles. These topics are covered over a period of 13 weeks. Each week, the class meets for a 3-hour session in which the theoretical principles are explained, and an example is solved to elucidate the concepts. Subsequently, students are also involved in a problem-solving session in which they are required to solve an additional problem of a similar type on their own. This active learning session is in a constructivist setting [43]–[48] that helps students interact with each other and understand the problem from the perspective of their peers as well. The enriching learning environment is aimed at maximizing the learning and reinforcing the concepts [49], [50].

Typically, the class time is primarily used to introduce new concepts and illustrate an engineering example requiring the application of extensive mathematical and finite element methods concepts. Needless to say, the instructor has to be mindful of the pace of the class to ensure that every student understands the concepts and their application. The intensity of the lectures, mainly due to the complexity of the topics, requires significant attention demands that usually exceed students' capacities, often leading to a poor performance [51], [52]. In such intense lectures, cognitive overload can prevent information from being adequately processed and can interfere with learning [53]. Put differently; this means that it is difficult to present numerous examples in the limited class time. Additionally, optimal utilization of class time to deliver all the material in the course means that it leaves little room for interaction on older material or taking up challenges pertaining to the earlier concepts during class time. While office hours are available, students often experience scheduling issues or have other concurrent commitments which require equally urgent attention. As a result, students often yearn for more examples in the classroom. In fact, in this course, it is normal for students to often request numerous practice questions with detailed solutions to see how the various concepts are applied. The availability of such a resource will significantly aid in their learning. Thus, the current situation could be summarized as the following optimization problem: *For each topic, prepare adequate illustrations, clearly describing how the various concepts are being applied to conduct finite element analysis, accessible to the students. The constraints in meeting this objective are: (i) Limited class time (3 hours per week), (ii) prevent cognitive overloading to enable adequate processing of the information, (iii) completing the syllabus in a timely manner.*

As a solution to the above problem, we present a suite of web-based interactive programs that are accessible to the students outside the class. The purpose of the interactive platform with several programs is to actively engage the students with this cognitive tool to cement their understanding of the concepts instead of passively perceiving it as a tutor or repository of information.

3 The Software Suite

The Finite Element Analysis Software developed in this work is a web application designed using ASP.NET, which can generate complete theoretical solutions to the following 6 different engineering applications taught in our FEA course: 1-D spring assembly, trusses, frames, beams, 1-D heat transfer and 2-D heat transfer. The software is built in C# using Microsoft .NET framework. The front end contains the User Interface where the user provides input and parameters, defining the problem completely. The back end processes the data and returns the complete theoretical solution to the user.

The software functions as follows: At the software index page, the user will be prompted to select an engineering application to start with. Typically, for any application, the user enters information pertaining to the geometry of the problem, assembly information, properties of the subsystems, and some constraints on the operating environment. With these inputs, the FEA suite solves the system to equilibrium and presents a detailed theoretical solution, including the result of each mathematical step. It must be noted that this is very different from the commercial software such as ANSYS or COMSOL which are also FEA solvers but are mainly used to determine the end results such as displacement of specific points, temperature at different points of the system, etc. and some additional parameters such as stress distribution in the assembly. In these commercial software, the results are often rendered via a graphical user interface. On the other hand, the main objective of the software suite presented in this work is to elucidate the mathematical formulations and the steps that need to be undertaken to obtain these results. Put differently, the software suit presents the background calculations that happen in these commercial software.

The functionality of the software suite is illustrated with the following two examples:

Analysis of a Spring Assembly: In the spring assembly, several springs are connected in a series as illustrated in Figure 1. We are interested in understanding the displacement of the specific points, called nodes, in this system (c.f. Figure 1). While some of the nodes in the assembly are fixed (example node 1 in Figure 1) others are free to move (example nodes 2 and 3 in Figure 1). As part of the question, students are required to determine the equilibrium position of the system, i.e., the position of the nodes, in the spring assembly, when a certain force is applied on the system.

A schematic of a question pertaining to such a spring assembly problem is shown in Figure 1. In this question, with node 1 fixed, node 2 experiencing a force (1000 N) that pulls it to the right, and node 3 moving by a fixed amount of 2mm to the right, the solution should determine the amount of horizontal displacement of node 2. In solving this question, the student would engage in detailed theoretical calculations and produce specific calculations such as the *local stiffness matrix*, *global stiffness matrix*, *displacements of all nodes,* and the reaction *force at* each node in response to the applied force of 1000N on node 2.

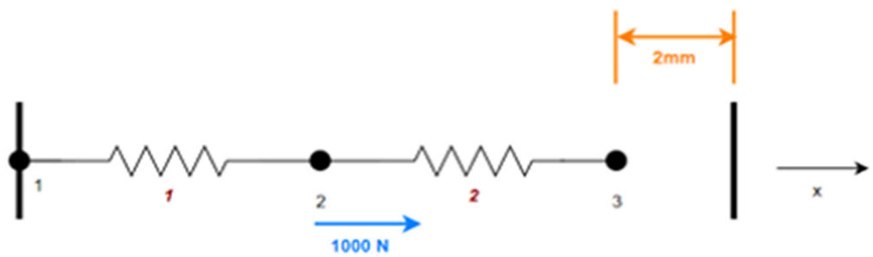

Fig. 1. Schematic of the spring assembly system to be studied. The system has two elements indicated by italic numbers and three nodes indicated by numbers right below the filled circles

To solve the above problem using the software developed in this work, the user defines the design of the assembly as well as the key property of each spring in the assembly, namely, the spring constant, i.e., the stiffness, via the graphical user interface shown in Figure 2. Subsequently, the user provides the operating conditions such as external applied force values on the nodes and the known displacement values of any node (c.f. Figure 3). Finally, with this comprehensive description of the problem, the software will present the detailed theoretical calculations at each step in a text file that can be saved by the user.

Fig. 2. Design of the spring assembly fed through the GUI

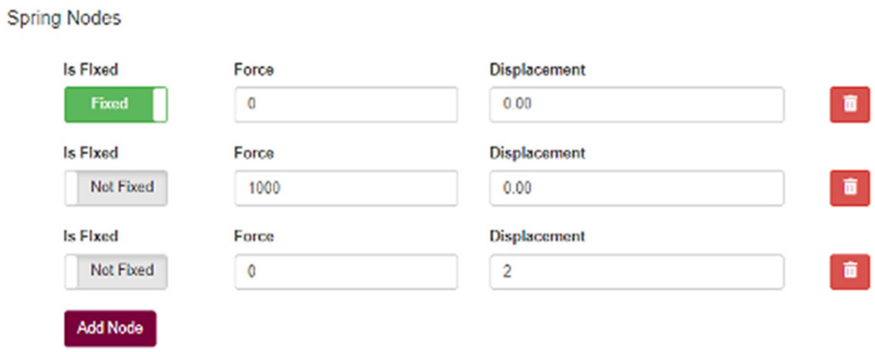

Fig. 3. Operating conditions such as applied forces and known displacement values of nodes

Analysis of heat transfer: The software suite can also analyze 1-D heat transfer, i.e, the transport of heat in a system in one direction. This is a more complex problem compared to the spring system. There are more variables to consider, such as Convective Heat Transfer Coefficient (h), Thermal Heat Transfer Coefficient (k), Ambient Air Temperature (Tfluid) and the Temperature at one particular point in the system (Tbase). In this application, the temperature distribution in a thin metallic fin is sought. One end of the fin is subject to a constant high temperature (say 100C) and the ambient air is at a much lower temperature (20C). The material characteristics and the dimensions of the fin are provided in the question to characterize the heat transfer process from the fin. A schematic of this problem is shown in Figure 4. In this schematic, we are interested in finding the temperature at five points (nodes) on the fin, labelled 1 through 5. Point 1 is subject to a constant temperature (say 100C) and the points are separated by a fixed distance (say 20mm). To determine the full theoretical solution, the user enters the details of the problem through a graphical user interface, a sample of which is shown in Figure 5. Upon submission of all the information pertaining to the problem, a detailed calculation at every step of the FEA solution is presented by the software, and this can be saved by the user in a text file.

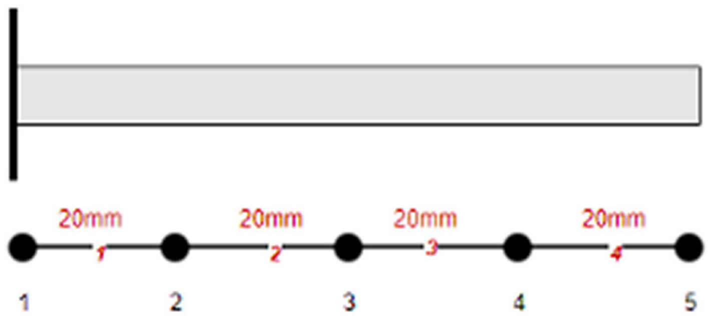

Fig. 4. 1D heat transfer analysis of a fin

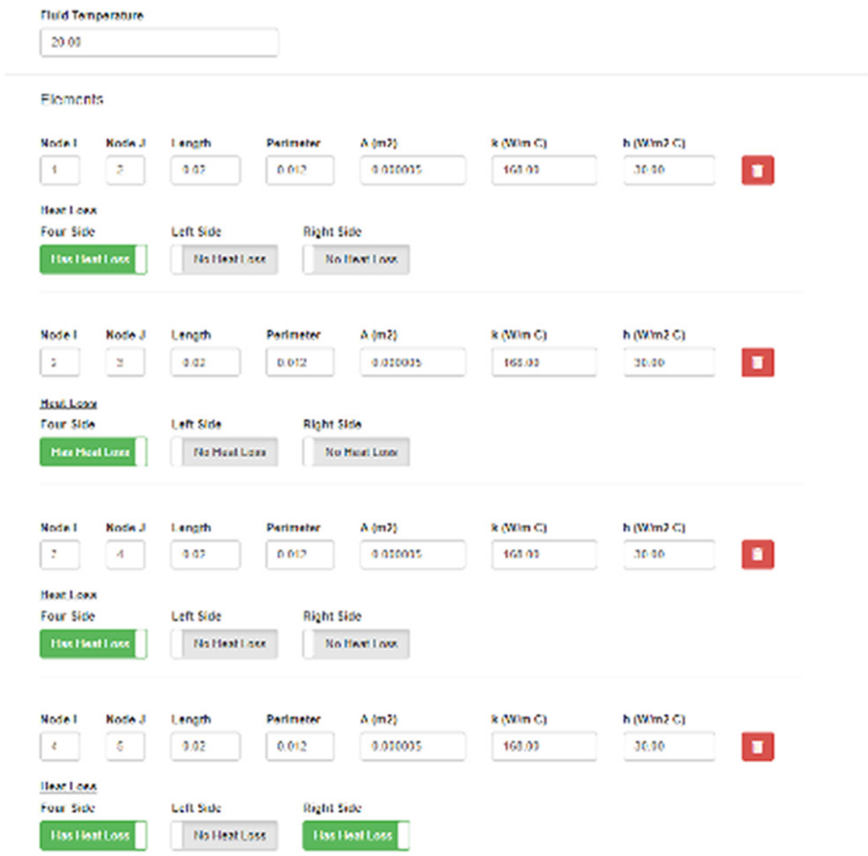

Fig. 5. Input screen to describe the 1D heat transfer problem

4 Operations and next steps

The software suite is loaded as an application on the server and is accessible through remote login. Thus, students can access the software at their convenience. Specifically, the in-class sessions could be used to elucidate the concept through just one or two examples in great detail while the students can use the software suite to analyze additional problems. This will not only minimize the cognitive loads within the classroom but also help allow students to study the material at a convenient time and at their own pace. Knowing that the time of the day when the student wants to study the material has an important bearing on their learning of the material, this self-paced convenient learning through this supplementary suite of algorithms is likely to boost learning.

The software suite will be launched in Fall 2022 and surveys will be undertaken to determine the student perception, feedback and suggestions to improve this suite. Additionally, the effectiveness of this assistive tool will be determined by assessing the performance of students in various assessments throughout the course, namely, quizzes, tests and the final exam. The performance of the students from this cohort will be compared to the performance of the students in the earlier cohorts.

5 Acknowledgment

Funding for this project was provided by the MacPherson Institute as part of the Leadership in Teaching & Learning Fellowship Program. The authors are grateful to the reviewers for their time in evaluating the manuscript and providing valuable suggestions to improve the quality of this work.

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Article submitted 2022-07-08. Resubmitted 2022-08-10. Final acceptance 2022-08-15. Final version published as submitted by the authors.