Applying a Lecture Structuring Method for Teaching Abstract Concepts in Engineering

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Abstract

Effectively teaching abstract concepts is a significant challenge in engineering education. Research on conceptual learning emphasizes the importance of building on prior knowledge and on active learning. Techniques described as active learning have gained much support. However, active learning techniques often require students to work in small groups which make the lecture difficult to manage. This study will describe efforts to apply a lecture structuring method called the “5 formal steps” to teach abstract engineering concepts. The method provides a structure to the lecture that encourages students to connect their relevant prior knowledge to new concepts by comparing and contrasting examples. The method has 5 steps and has been tried in a mechanical engineering course, system dynamics. This paper presents an application of the method and some observations.

Keywords

Teaching Method, Concepts, Pedagogy,

Introduction

Teaching abstract concepts is a particularly challenging aspect of engineering education. This challenge arises from the difficulty that students have with relating abstract concepts to their own experience and knowledge. Commonly, lectures are structured to begin with explanations of new concepts followed by examples illustrating the concepts. While this approach is time efficient, it is often ineffective. First of all, many students have little confidence in their ability to understand abstract concepts or theory, and so they simply disengage mentally until the examples are presented. When the examples are presented, however, the students may draw the wrong conclusions. They may learn the steps of the example but not actually understand the concepts necessary to solve a variety of conceptually similar problems.

Several researchers have sought to improve upon the acquisition of conceptual knowledge through study of and modifications to teaching methods. Based on cognitive research, Joseph Novak[1] stated that “meaningful learning results when the learner chooses to relate new information to ideas the learner already knows.” According to this statement, the first ingredient to meaningful learning is the student’s willingness to learn. The second ingredient is that the instructor must help the student build on their prior knowledge when teaching new concepts. Further support for this perspective is given by John Milton Gregory[2] who states that effective teachers, “excite and direct the activities of the learner, and tell him nothing that he can learn himself.”

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Research on active learning also emphasizes the importance of the student's own effort in learning. For example, Felder et al.[3] recommend a variety of active learning segments in engineering lectures that include peer-to-peer discussions among students followed by feedback discussions with the whole class. In addition to requiring student activity, the feedback discussions can reveal conceptual misunderstandings that can be corrected by the instructor. However, the active learning approach comes with the challenges of a much less structured learning environment. Switching between segments of lecture, peer discussion, and group discussion can be difficult to manage while maintaining order and making good progress.

Some effective instructors have sought ways to encourage students to learn actively without breaking into peer discussions. One example is found in a study done by Phillip Jackson[4] and his student Anne Kuehnle in which 150 survey respondent essays describing favorite teachers were analyzed for common characteristics. One of the three main characteristics found in effective teachers was an approach that Jackson called "soft-suasion". Following this approach, teachers use questions to lead students to discover concepts rather than simply explaining them.

Similarly, McMurray et. al[5] present a comprehensive approach to teaching called "the 5 formal steps" (5FS) of teaching. This approach has also recently been popularized by several organizations[6,7] in the classical education movement for K-12 private schools and homeschools. The 5 formal steps to teaching a concept are listed as: preparation (relevant prior knowledge remembered), presentation of examples, comparison of examples, explanation of concept, and application of concept. After presenting examples, the instructor directs the mental activities of the students to discover and state the related general concepts. This paper will give a detailed look at the use of the 5FS approach in a system dynamics course in the mechanical engineering department of the Mississippi State University. Some justification, observations, and best practices will also be presented.

An Illustration of Two Teaching Approaches

This section will present two approaches to teaching concepts related to the free response of first order systems. The first approach will be called the traditional approach which moves from generalizations to examples. The second approach will be called the 5 formal steps (5FS) approach and is more inductive in nature.

The Traditional Approach

The traditional approach begins with some general statements about the free response of first order systems:

- Free response applies for cases with non-zero initial conditions and no externally applied input to the system.
- Non-zero initial conditions means that the system has stored energy at the beginning of the simulation.
- This stored energy results in the system states changing with time as the system moves towards equilibrium (i.e. the states move to a zero value).
- The standard form for first order systems with no input is: $\tau\dot{x} + x = 0$, where $\boldsymbol{\tau}$ is defined as the time constant.

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Then, the instructor demonstrates using the Laplace transform that the solution to this first order differential equation in standard form is given as: $x(t) = x(0) * e^{-t/\tau}$. At this point a diagram is drawn as shown in Figure 1, and the instructor points out that the plot starts at the initial condition, moves to zero over time, and the rate at which this transition occurs depends on the time constant.

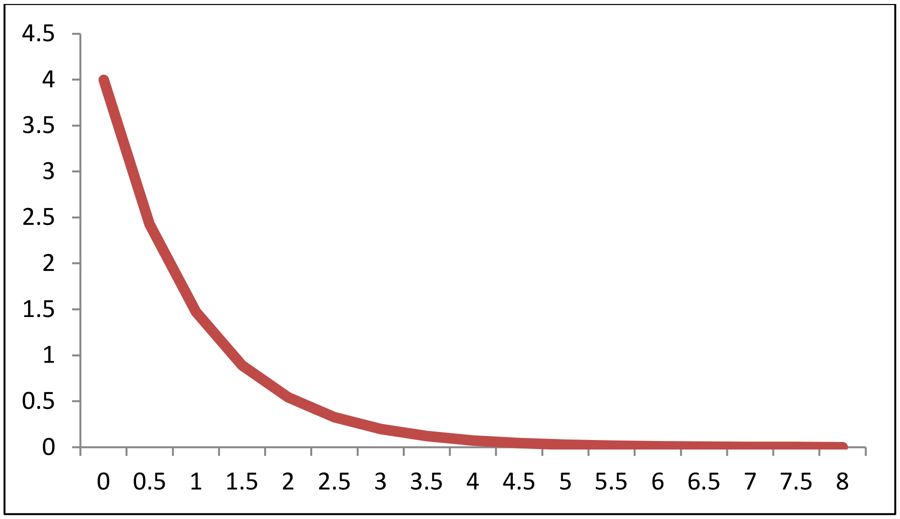

Figure 1. Free response of a first order system with an initial condition of 4.

Next, examples are given of the free response of first order systems. The system equation for a rotating mechanical system is given ($J\dot{\omega} + B\omega = 0$) and, then, put in standard form. The students are asked to relate the time constant to the mechanical system parameters, and it is shown that $\tau = J/B$ (Note: J and B represent inertia and damping, respectively). Then, the system equation for an electrical system is given ($C\dot{V} + \frac{1}{R}V = 0$) and put in standard form. The students are asked to relate the time constant to the electrical system parameters, and it is shown that $\tau = 1/RC$ (Note: R and C represent electrical resistance and capacitance, respectively). The concepts stated at the beginning are reinforced and expanded during the explanation of these examples. The lesson is then summarized by showing that the system parameters in these two examples impact the rate of decay of the free response of the system.

5 Formal Steps (5FS) Approach

The 5FS approach to this same lesson begins with the *preparation stage*. In this stage, the student's prior knowledge is brought to the surface to serve as a foundation for meaningful learning. The instructor presents a flashlight and leads the following dialogue with the class:

> Instructor: What happens when you use a flashlight over a long period of time?
>
> Students: The light starts out bright but slowly dims as the battery loses power.
>
> Instructor: How long does it take for the light to go out?
>
> Students: It depends on the type of bulb and the type of battery.
>
> Instructor: What is it about the battery and bulb that affects how long the flashlight lasts?

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Students: The size and type of battery affects the time it takes for the battery to go out. Perhaps, it is the resistance of the bulb that affects the same.

The dialogue will vary depending on the students and the instructor will likely be required to press students to refine their responses. However, senior engineering students almost uniformly have the prior knowledge necessary to answer these questions. The process of bringing prior knowledge to the surface continues as the instructor holds up a flywheel. The following dialogue occurs:

Instructor: What is the purpose of a flywheel in an engine system?

Students: The flywheel keeps the engine spinning when the engine isn't producing power.

Instructor: How is the flywheel able to do this?

Students: Through the kinetic energy stored in the flywheel.

Instructor: Why is the flywheel helpful in storing kinetic energy?

Students: It has a large mass or moment of inertia.

Again, this dialogue will take more prodding and iteration than is shown above. However, as seniors, most students taking this course should have had some exposure to flywheels and to kinetic energy. At this point several elements of relevant prior knowledge have been brought to the surface, and students are ready to build on this knowledge.

The instructor, then, moves to the second step of the 5FS by presenting examples which embody the concept(s) to be learned. The first example presented is a circuit diagram with a capacitor and a resistor. The students are shown how this could represent the flashlight with the capacitor being analogous to the flashlight battery and the resistor being analogous to the flashlight bulb. The system equation for the circuit is given: $\mathrm{C}\dot{\mathrm{V}} + \frac{1}{\mathrm{R}}\mathrm{V} = 0$. The students use the Laplace transform (taught in previous lectures) to show that the solution to this equation is $V(t) = V(0) * e^{-t/CR}$. This solution is graphed (see Figure 1), and the students are asked to describe the graph. The instructor asks questions to illumine graph details: Where does the response start? What value does the response settle to? What parameters dictate the rate of decay? Eventually, the students realize that the response starts at the initial capacitor voltage and decays to zero. The rate of decay is affected by both the capacitance and resistance parameters. The instructor asks the students to relate the response in the example to the dependency of flashlight life on the battery size/type and the resistance of the bulb.

Similarly, a second example is given for a free spinning flywheel with damping. The system differential equation is given as $\boldsymbol{J\dot{\omega}} + \boldsymbol{B\omega} = \mathbf{0}$. The response is shown to be: $\varpi(t) = \varpi(0)e^{-t*B/J}$. A series of questions are used to draw out the effect of the damping and inertia on the flywheel speed decay rate. This is also related back to the dialogue in the preparation step.

At this point the students have been exposed to a pattern that is the foundation for the concepts to be taught. The instructor now guides the students into the comparison step (step 3 of the 5FS) with the following dialogue:

Instructor: How are the responses for these two systems similar?

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Students: The response equations have a similar form, and the graphs of both decay to zero exponentially from an initial condition.

Instructor: Compare the initial system model for each case.

Students: Both have a first order and zeroth order term, each multiplied by parameters.

Instructor: How do the parameters affect the response?

Students: They impact the rate of decay. For the electrical system higher C or R leads to slower decay. For the mechanical system higher J or lower B leads to slower decay.

Instructor: Is there a pattern to how the parameters affect the rate of decay?

Students: The rate of decay is proportional to the parameter on the zeroth order term and inversely proportional to the parameter on the first order term.

At this point the students have been led to discover the concepts to be learned and are ready for the instructor to summarize and clearly explain the concepts in the 4th step: explanation of the concept. It may also be helpful for the students to attempt this explanation. For this lesson the explanation would include the following:

- Free response applies for cases with non-zero initial conditions and no externally applied input to the system.
- As energy stored in the system through initial conditions is released, the system moves towards equilibrium (i.e. the states move to a zero value).
- The rate of decay is impacted by the system parameters through a new parameter called the time constant.
- The time constant is found by putting the system model in standard form: $\tau\dot{x} + x = 0$.
- Notice how in the examples above, $\tau = 1/CR$ for the first example and $\tau = J/B$ for the second example.
- The free response for first order systems can now be found by inspection simply by putting the model in standard form. Using the time constant the system response can be shown in general as: $\boldsymbol{x(t) = x(0) * e^{-t/\tau}}$.

The final step in both approaches is to apply the new concepts in an out of class assignment.

Justification and Observations of the 5FS Approach

This section includes some comparison of the two teaching approaches based on the author's observations and on some further points from the literature. The traditional approach began with generalizations about the free response of first order systems, and then used examples to illustrate the stated generalizations. On the other hand, the 5FS approach saves the succinct statement of new concepts for the end of the lesson and seeks to help students discover the desired concepts using examples and class dialogues. While the traditional approach can be more efficient, the 5FS approach provides a framework to help instructors produce lessons that are in line with research on meaningful learning. Specifically, the 5FS help instructors create lesson plans that include well designed examples, that encourage students to learn actively, and that maintain student interest.

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The first benefit of the 5FS approach is the design of examples that are conducive to conceptual knowledge acquisition. The 5FS approach requires that the examples chosen are useful in helping the student to discover an underlying concept rather than merely being illustrative of the concept. The author observed that this approach forces the instructor to consider the students prior knowledge and intentionally select examples that can build on that foundation. McMurray et al.[5] state that concrete examples serve the purpose of revealing the essential characteristics of a concept or category. The 5FS approach requires the instructor to design examples that eliminate non-critical steps and emphasize the essential elements of the concept to be taught.

Secondly, the 5FS approach encourages the students to learn actively. Rather than simply explaining the concept, the instructor leads the students to discover the concept through examples and dialogues about them. As discussed in the introduction, active learning has a strong research foundation. However, the 5FS is different from many active learning techniques discussed in the literature in that breaking into groups is not required. During implementation in the system dynamics course, the instructor observed that the students were actively thinking and trying to formulate explanations of the patterns observed in the preparation and example steps. Additionally, the students were much more able to continue building on the highly abstract material than was observed in previous semesters of the course.

A third essential element in effective teaching facilitated by the 5FS approach is maintaining student interest. Interest is first gained through the preparation step where students' prior knowledge is accessed, and its limits are explored. Then, the pattern to be discovered becomes a riddle that the students want to solve, and if done properly gives them confidence that they can solve it. Further, the approach maintains interest by calling the students to use a variety of human faculties such as observation, imagination, pattern recognition, analysis, etc. On the other hand, the traditional approach tends to require only listening and copying. The author observed that the students actually displayed a high level of confidence and interest in discovering the concept, and they were highly satisfied when the concept was explained. This left the students more open to future conceptual learning.

Summary and Future Work

This work has presented an application of the 5FS approach to teaching highly abstract and mathematical concepts a mechanical engineering course. The 5FS approach shows much promise to encourage students to learn meaningfully by actively building on prior knowledge. This approach also shows the potential to be an alternative to active learning approaches that require breaking up the lecture into group work segments. However, the approach still takes longer than the traditional lecture approach. It may be best to use the 5FS approach for more essential or difficult concepts and still use the traditional approach on others to maintain its efficiency benefits. Future work must be done to further quantify the benefits of the 5FS approach in an engineering environment and to explore the 5FS approach in other courses.

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