Apply Deliberate Practice in Teaching Dynamics to Reinforce a Systematic Problem Solving Approach

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Abstract

In this paper we will share how we apply deliberate practice (DP) in introductory dynamics to help students improve problem solving skills. Solving dynamics problems in a systematic approach involves different knowledge and skills such as problem formulation and applying the concepts of dynamics, etc. Students often find it difficult in learning dynamics because they have not acquired skills needed for implementing such a systematic approach. This issue has been well studied in Cognitive Load Theory (CLT), which is a comprehensive and proven instructional theory for improving efficiency in learning. Aligned with CLT and redeemed as the cause for expert performance, DP refers to a highly structured activity designed with the specific goal of improving performance. When applying DP in teaching dynamics, we isolate elements of problem solving skills, design repetitive and successive refined exercises to improve each of the elements, and schedule the sequence of activities to achieve smoother transitions to more complex learning tasks. Since these focused practices can fully utilize students' working memory without causing cognitive overload, students will be able to acquire specific skills within a short period of time and stay motivated to practice and master more complex skills.

Keywords

Deliberate practice, cognitive load theory, dynamics

1. Introduction

Dynamics is one of the most difficult subjects for engineering students. It requires a solid math foundation, a good understanding of physical systems, and effective problem solving skills, all of which students are generally not well prepared for. Therefore, developing effective dynamics instruction strategies has been a central topic within the community of mechanics instructors[1-7].

However, few studies have tried to tackle one fundamental reason for this learning challenge: cognitive overload. Many training professionals have adopted the recommendation to design their instruction around the "magical number of 7 plus or minus 2" to avoid overloading their learners[8]. According to this guideline, our cognitive system can only process 7 ± 2 items at one time[9]. Once we exceed those limits, our thinking and learning processes will be hindered. Solving dynamics problems involves an accurate interpretation of what is given and what is to be found, a capability of drawing free-body diagrams (FBD), a familiarity with Newton-Euler equations and kinematics equations, and skills for solving a system of algebraic equations. Each single step may constitute of 7 ± 2 items depending on students' prior knowledge and how the contents are presented. No wonder why students often experience difficulty when learning dynamics. Based on the rule of 7 ± 2, a school of researchers have developed a comprehensive set of instructional principles called Cognitive Load Theory (CLT)[8]. CLT has seen great success in organizational training, but it seems unfamiliar to engineering educators and has had little impact on their instructional design. Since CLT is a scientific basis for efficiency in learning, introducing CLT to engineering education will definitely help enhance learning.

Similar to engineering educators' unfamiliarity with CLT, deliberate practice (DP) has not seen wide adoption in engineering education either. Aligned with CLT and redeemed as a cause for expert performance, deliberate practice (DP) is referred to a highly structured activity designed with the specific goal of improving performance[10]. This research has been popularized by the "10,000-hour rule" in the bestseller *Outlier* by Malcolm Gladwell[11]. Different from merely performing a skill a large number of times, DP focuses on breaking down the skill to small chunks and improving the skill chunks during practice paired with immediate coaching feedback. For example, instead of solving 10 different dynamics problems, DP applies a series of exercises with each set of exercises focusing on one specific weakness such as drawing FBD or applying the conservation of energy. Since these focused practices can fully utilize students' working memory without causing cognitive overload, students will be able to acquire specific skills within a short period of time and stay motivated to practice and master more complex skills.

In this paper we will share how we follow the guidelines from CLD to design DP activities in an undergraduate dynamics course to enhance students' learning experience and improve their problem solving skills. The paper is organized as follows. We will first explain CLT and DP in Section 2 Background to lay out the foundations for our instructional design. The next section Implementation will present the DP examples we used in the course, followed by Section 4 Discussions presenting student responses and the lessons we have learned. Finally, a summary and conclusions are presented in Section 5.

2. Background

2.1 Cognitive Load Theory

Any instructional design not based on knowledge of human cognitive processes will fail[12]. The structures that constitute the framework of human cognitive architecture can provide essential guidelines for educators to deliver learning materials. CLT is one such theory for instructional design that was explicitly derived from knowledge of human cognitive architecture[12]. CLT provides essential information and tools that are relevant to instruction along with instructional consequences compatible with the architecture. CLT illustrates ways to reduce unproductive form of cognitive load and simultaneously maximize productive sources of cognitive load that result in efficient learning.

Learning relies on two memory systems, working memory and long-term memory, and the coordination between them. The relationship between working memory and long-term memory is similar to that of RAM and the hard drive in a computer. While in learning mode, working memory does the processing of new information to form knowledge structures called schemas which will be stored in long-term memory later on[8]. Schemas are memory structures that permit us to treat a large number of information elements as though they are a single element. The difference between experts and novices is that experts have effective schemas to engage greater information in working memory needed to solve complicated problems while novices have not developed schemas to hold more necessary information. The level of expertise derives from number and complexity of schemas stored in long-term memory.

The limits of working memory were first made explicit by George Miller's seminal paper published in 1956[9]. The phrase 7 ± 2 refers to limited working memory capacity as well as the duration of information held in working memory. This limitation implies that the information in working memory needs to be processed repetitively in order to be transferred to long-term memory which has massive capacity for information storage. Problem solving involves harmonic collaboration between working memory and long-term memory as all conscious processing only takes place in working memory which relies on schemas stored in long-term memory. More knowledge and skills stored in long-term memory will result in the greater virtual capacity of working memory.

Limited working memory are subject to three main types of cognitive load including intrinsic load, germane load, and extraneous load[13]. Intrinsic load is the mental work imposed by the complexity of the content. Germane cognitive load is mental work imposed by instructional activities that are beneficial for achieving instructional goals. In contrast to germane load which is relevant to learning goals, extraneous load is mental work imposed by inappropriate instruction strategies and consequently wastes limited working memory and hinders learning.

For a given subject, intrinsic load is determined by the subject complexity and the learner's prior knowledge which is beyond the instructor's control. What the instructor can control is to maximize germane load and minimize extraneous sources of load by segmenting and sequencing content in ways that optimize relevant information in working memory.

2.2 Deliberate Practice

Although breaking contents to chunks compatible with working memory capacity can avoid cognitive overload, the learning goals cannot be achieved without appropriate practice to process transient information in working memory and transfer it to long-term memory to be integrated with existing schemas or develop new schemas. Deliberate practice is one type of practice developed by the psychologist K. Anders Ericsson through his extensive research and theoretical development regarding elite performance[10,14]. Ericsson concludes that expert performance is the result of deliberate practice rather than innate talent. It is estimated that it takes about 10,000 hours for an individual to achieve highest levels of performance. For each course, students might work at most nine hours per week for 15 weeks, i,e,. only 135 hours per semester, far less than the time needed to develop elite performance. Even though we are unable to transform students to be experts within one semester, we could apply principles and guidelines of DP to maximize the impact of time spent in practice.

The rapid advancement of technology has imposed great challenges on engineering education[15,16]. Educational researchers have also started to relate key findings from studies of development of expertise to engineering education[17]. Deliberate practice has received attention from engineering scholars[17]. The two key processes in deliberate practice include identifying which knowledge and/or skills need to be improved and selecting a learning approach resulting in the desired improvements. The need for two types of practice, practice that develops component skills and practice that requires skills to be integrated to address more complex problems, has been discussed[18].

The research findings from CLT and DP have provided guidelines for us to design practices to enhance effective learning experiences.

3. Implementation

ES 204 Dynamics (three credit hours), the second mechanics course following ES 201 Statics, is required for students in aerospace, civil, and mechanical engineering at Embry-Riddle Aeronautical University (ERAU) in Daytona Beach, FL. Each semester, ES 204 is offered in five sections with approximately 30 students in each section. The textbook we have adopted is titled *Engineering Mechanics: Dynamics* by Anthony Bedford and Wallace Fowler (5th ed.). Each section meets either three times with one hour for each meeting or twice with one and a quarter hours for each meeting every week. We have started to develop and apply DP activities in one section every semester since the fall 2013 semester.

An assessment of student readiness using the Mechanics Readiness Test[19] and the Dynamics Concept Inventory 1.0[20] indicated that students lack math foundations and key concepts that are required for learning dynamics. This situation motivated us to adopt effective instructional design strategies which address such deficiencies. Because their foundation is deeply rooted in human cognitive architecture, CLT and DP have been adopted and investigated through our teaching practices. By following guidelines of CLT, we have developed DP practices intended to systematically improve problem solving skills and achieve the learning goals for dynamics.

Research has indicated that a structured problem solving approach will help students develop a universal problem solving procedure which can be applied in any engineering course as well as in research and development[2]. We have adopted a five-step problem solving procedure consisting of Given/Find, Strategy, Governing Equations, Numerical Solutions, and Reflection, commonly used in advanced mechanics courses and upper-division engineering courses at ERAU. In Given/Find, students are required to use appropriate variables and notations to represent what is given and what is to be found. By relating given information to relevant principles, tentative strategies along with the associated rationale are presented in Strategy, followed by governing equations. When a system of independent equations for the equal number of unknowns is obtained, Matlab is used to find numerical solutions. Finally, the problem solving is concluded by students' reflection on the problem by verifying the correctness of the solution and discussing the solution's physical meaning.

However, our background survey results showed that few students had used this approach prior to taking Dynamics. It will produce extraneous (irrelevant) cognitive load for students who are not familiar with the approach if they are forced to adopt this approach without any training. By following the guidelines of CLT, we have developed DP activities to focus developing knowledge and skills for each step. When the majority has mastered the knowledge and skills for each step, we then require students to implement the complete procedure.

Since Steps One (Given/Find) and Four (Numerical Solution) are common for all learning modules and do not require content related knowledge, we designed DP activities to help

students develop good habits and skills required for formulating Given/Find and familiarize them with using the Symbolic Toolbox in Matlab. During the first two weeks, students were assigned with homework only requiring them to show Given/Find and represent Givens in Matlab. For each problem, students need to conduct self-assessment in Reflection to evaluate whether they meet the criteria for Given/Find: be accurate (use exact values and units), be thorough (include all given information), and be appropriate (use suitable variable names and subscripts to facilitate representation in Matlab). The learning goal of the Matlab part is to develop good habits in naming conventions and code readability.

Since students are only required to work on Steps One and Four, the simplicity and intensity of exercises can result in good learning outcomes. Here is an example of such assignment and the solution:

Engineers testing a vehicle drop the vehicle from the test rig shown at $h = 6\ \text{m}$.

1) What is its downward velocity 1 s after it is released?
2) What is its downward velocity just before it reaches the ground?

Given: $h = 6\ \text{m}$, $t_0 = 0$, $v_0 = 0$, $s_0 = 0$, $a = 9.81\ \text{m/s}^2$, $s_2 = h$, $t_1 = 1\ \text{s}$

Find: $v_1\ \text{m/s}$, $v_2\ \text{m/s}$.

Numerical Solutions:

```
clear all;clc;
syms t v vfcn s t2;
syms v1 v2 positive;
% Given
a = 9.81;       % [m/s^2]
t0 = 0;
s0 = 0;         % [m]
v0 = 0;         % [m/s]
H = 6;          % [m]
t1 = 1;         % [s]
s2 = H;
```

Steps Two (Strategy) and Three (Governing Equations) are related to learning modules. The DP activities were designed by identifying key component knowledge and skills essential for understanding each topic (particle kinematics, particle kinetics, rigid-body kinematics, and rigid-body kinetics). Table 1 summarizes our findings.

Table 1 Component Knowledge and Skills for Learning Dynamics.

Learning Module	Component Knowledge and Skills

Particle Kinematics	Straight-line Motion		• Identify how the process is described. • Determine while tool to use depending how the process is described.
	Curvilinear Motion	Cartesian	• Apply knowledge and skills learned from straight-line motion in individual direction of the Cartesian coordinates.
		Normal-Tangential	• Understand when to analyze kinematics in terms of normal and tangential components. • Understand how to find velocity and acceleration in terms of normal and tangential components.
		Radial/Transverse	• Understand when to analyze kinematics in terms of radial and transverse components. • Understand how to analyze kinematics in terms of radial and transverse components.
Particle Kinetics	Newton Equations		• Draw the Free-body Diagram (FBD). • Set up Newton equations with an appropriate coordinate system.
	Energy Methods		• Draw the Free-body Diagram (FBD). • Apply the principle of work and energy or conservation of energy.
	Momentum Methods		• Draw the Free-body Diagram (FBD). • Apply the principle of linear/angular impulse and momentum or conservation of linear/angular momentum.
Rigid-body Kinematics	Rigid-body without Sliding Contacts		• Represent general velocities in planar motion. • Identify instantaneous center. • Represent general accelerations in planar motion.

	Rigid-body with Sliding Contacts	• Set up the body-fixed reference frame. • Represent general velocities in planar motion. • Represent general accelerations in planar motion.
Rigid-body Kinetics	Euler Equations	• Draw the Free-body Diagram (FBD). • Apply equations of motion (EOM). • Determine kinematic relationships to supplement the EOM.
	Energy Methods	• Draw the Free-body Diagram (FBD). • Apply the principle of work and energy or conservation of energy. • Determine kinematic relationships.
	Momentum Methods	• Draw the Free-body Diagram (FBD). • Apply the principle of linear/angular impulse and momentum or conservation of linear/angular momentum. • Determine kinematic relationships.

When students started a new unit, they were provided with assistance, often referred to as "scaffolding"[18], to learn how to develop appropriate strategies and set up governing equations. For example, in analyzing straight-line motion, differentiation and integral are two general tools for solving this type of problems. Depending on what information is given and how it is given, we may use different ways to take integrals such as using separation of variables or the chain rule. To help students develop effective strategies, instructions were provided as follows:

i. Describe the motion,
ii. Draw the coordinate system,
iii. Which information (position, velocity, and acceleration) is given about the process? How is it given (as a function of time or something else or a constant)? Which information at instants is given? Which tool (differentiation or integral) should you use?

Then students were given the same problems with additional requirements for completing Strategies and Governing Equations. Here is the example:

Given: $h = 6 \text{ m}$, $t_0 = 0$, $v_0 = 0$, $s_0 = 0$, $a = 9.81 \text{ m/s}^2$, $s_2 = h$, $t_1 = 1 \text{ s}$

Find: v_1 m/s , v_2 m/s .

Strategy:

1) It is a straight-line motion.
2) We can use the coordinate system as shown.
3) The process: a as a constant.

$t_0 \quad s_0 \quad v_0$

Instants: t_1

$\boxed{t_2} \quad s_2$

Tool: direct integral.

Governing Equations:

$$\int_{t_0}^{t} a dt = \int_{v_0}^{v} dv \left(1 \text{ eq. } 1 \text{ unknown } v\right),$$

$$\int_{t_0}^{t_1} a dt = \int_{v_0}^{v_1} dv \left(1 \text{ eq. } 1 \text{ unknown } v_1\right),$$

$$\int_{t_0}^{t_2} v dt = \int_{s_0}^{s_2} ds \left(1 \text{ eq. } 1 \text{ unknown } t_2\right),$$

$$\int_{t_0}^{t_2} a dt = \int_{v_0}^{v_2} dv \left(1 \text{ eq. } 1 \text{ unknown } v_2\right).$$

There are 4 equations and 4 unknowns, $v_1, v, t_2,$ and v_2.

Numerical Solutions:

```
clear all;clc;
syms t v vfcn s t2;
syms v1 v2 positive;
% Given
a = 9.81;       % [m/s^2]
t0 = 0;
s0 = 0;         % [m]
v0 = 0;         % [m/s]
H = 6;          % [m]
t1 = 1;         % [s]
s2 = H;
% Solve
vfcn = solve(int(a,t,t0,t) == int(1,v,v0,vfcn),vfcn);
```

```
solns = solve(int(a,t,t0,t1) == int(1,v,v0,v1),...
              int(vfcn,t,t0,t2) == int(1,s,s0,s2),...
              int(a,t,t0,t2) == int(1,v,v0,v2),...
              v1,v2,t2);
% Convert
v1 = double(solns.v1);
v2 = double(solns.v2);
% Display
fprintf('The velocity at t1 is %3.2f m/s.\n',v1);
fprintf('The velocity of the truck before it reaches the ground is %3.2f m/s.\n',v2);
```

```
The velocity at t1 is 9.81 m/s.
The velocity of the truck before it reaches the ground is 10.85 m/s.
```

Similar assignments were given for each learning module to address specific learning difficulty. For example, when learning the principle of work and energy for rigid bodies, students had trouble representing the kinetic energy of rigid bodies. Instead of solving a couple of problems completely, students just needed to find kinetic energy of each rigid body at different instants in five to ten different problems, which could take the same time required for solving two complete problems. This strategy also helps maximize germane (relevant) load by exposing students to different contexts to improve their problem solving skills.

In summary, the key to applying DP is to provide targeted partial problems in order to transfer transient information in working memory to form schemas in long-term memory without causing cognitive overload. When students develop knowledge and skills required for each step of the problem solving procedure through DP activities, they will be more ready for applying the systematic problem solving approach.

4. Discussion

At the time of submitting the paper, the final assessment results were not available and we did not have sufficient time to conduct comprehensive data analysis. Here we only report some results obtained during the semester. The thorough analysis and results will be presented in [21].

Although it was reported in the literature that the structured approach was unfavorable for students[2], probably because of adopting CLT by providing scaffolding to avoid cognitive overload, 25 out of 26 students agreed that this approach helped them organize their thoughts and develop problem solving strategies.

We also observed the improved confidence in using Matlab after implementing DP. We started to use Matlab in the middle of the spring 2014 semester when solving a system of equations for rigid body kinematics. Most students have not used Matlab for almost a year since they completed their first course on Matlab. Over 50% students complained that using Matlab hindered their learning at the end of the semester. In the fall 2014 semester, we started to design DP activities to prepare students for using Matlab for finding numerical solutions. We surveyed students' confidence of using Matlab twice during the semester, one was one month into the semester and the other was at the end of the semester. As the results show, students' confidence was greatly enhanced.

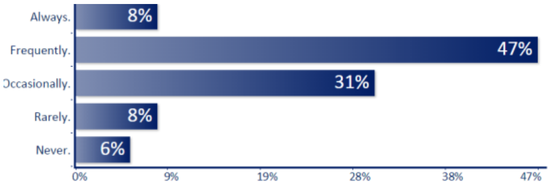

Figure 1 Results from 09/23/14

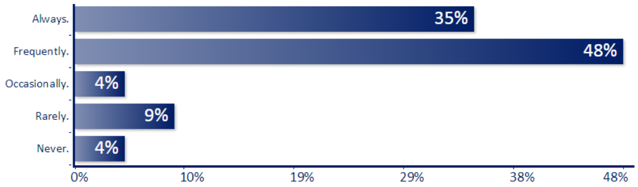

Figure 2 Results from 12/04/14

5. Summary and Conclusions

In this paper, we have shared our practice of applying CLT and DP in instructional design to help students develop a systematic problem solving approach in learning dynamics. Because of the intensity the DP activities could produce, it could be possible to optimize the usage of students' working memory by maximizing germane load and minimizing extraneous load. As a result, students' learning performance could be improved within a relatively short period of time.

References

1 Gray, G. L., and F. Constanzo. "A Problem-Centered Approach to Dynamics." In *Proc. ASEE Annual Conf.(Mech. Div. Best Pres. Award), Pittsburgh, PA, USA*. 2008.

2 Costanzo, Francesco, and Gary L. Gray. "A structured approach to problem solving in statics and dynamics: Assessment and evolution." In *Proceedings of the ASEE Annual Conference and Exposition. 2008 ASEE Annual Conference and Exposition*. 2008.

3 Mikesell, David R., and John-David S. Yoder. "Teaching Dynamics with a Design Project." In *American Society for Engineering Education*. American Society for Engineering Education, 2011.

4 Coller, Brianno. "First Look at a Video Game for Teaching Dynamics." In *American Society for Engineering Education*. American Society for Engineering Education, 2011.

5 Nissenson, Paul Morrow, Jaehoon Seong, and Chuan-Chiang Chen. "Developing Web-Assisted Learning Modules in Vector Dynamics." In *American Society for Engineering Education*. American Society for Engineering Education, 2014.

6 West, Matthew. "Sustainable Reform of" Introductory Dynamics" Driven by a Community of Practice." In *American Society for Engineering Education*. American Society for Engineering Education, 2014.

7 Lovell, Matthew D., Sean P. Brophy, and West Lafayette. "Transfer effects of challenge-based lessons in an undergraduate dynamics course." In *American Society for Engineering Education*. American Society for Engineering Education, 2014.

8 Clark, Ruth C., Frank Nguyen, and John Sweller. *Efficiency in learning: Evidence-based guidelines to manage cognitive load*. John Wiley & Sons, 2011.

9 Miller, George A. "The magical number seven, plus or minus two: some limits on our capacity for processing information." *Psychological review* 63, no. 2 (1956): 81.

10 Ericsson, K. Anders, Ralf T. Krampe, and Clemens Tesch-Römer. "The role of deliberate practice in the acquisition of expert performance." *Psychological review* 100, no. 3 (1993): 363.

11 Gladwell, Malcolm. *Outliers: The story of success*. Penguin UK, 2008.

12 Sweller, John, Paul Ayres, and Slava Kalyuga. *Cognitive load theory*. Vol. 1. Springer, 2011.

13 Sweller, John. "Cognitive load theory, learning difficulty, and instructional design." *Learning and instruction* 4, no. 4 (1994): 295-312.

14 Schneider, Walter, and Richard M. Shiffrin. "Controlled and automatic human information processing: I. Detection, search, and attention." *Psychological review* 84, no. 1 (1977): 1.

15 Jamieson, Leah H., and Jack R. Lohmann. "Creating a Culture for Scholarly and Systematic Innovation in Engineering Education: Ensuring US engineering has the right people with the right talent for a global society." *American Society of Engineering Educators (ASEE)* (2009).

16 Sheppard, Sheri, Kelly Macatangay, and Anne Colby. *Educating engineers: Designing for the future of the field*. Vol. 3. Jossey-Bass Inc Pub, 2008.

17 Litzinger, Thomas, Lisa R. Lattuca, Roger Hadgraft, and Wendy Newstetter. "Engineering education and the development of expertise." *Journal of Engineering Education* 100, no. 1 (2011): 123-150.

18 Ambrose, Susan A., Michael W. Bridges, Michele DiPietro, Marsha C. Lovett, and Marie K. Norman. *How learning works: Seven research-based principles for smart teaching*. John Wiley & Sons, 2010.

19 Snyder, V. W. "Mechanics readiness test: Revisited." In *Proceedings, ASEE Annual Conference and Exposition*. 1988.

20 Gray, Gary L., Francesco Costanzo, Don Evans, Phillip Cornwell, Brian Self, and Jill L. Lane. "The dynamics concept inventory assessment test: A progress report and some results." In *American Society for Engineering Education Annual Conference & Exposition*. 2005.

21 Tang, Yan and Bai, Haiyan, “Develop a Better Way to Practice to Enhance Students’ Learning Experience in Dynamics”, In *American Society for Engineering Education*, 2015 (in preparation).

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