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Dynamics in One Week

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Dynamics in One Week

Abstract

Introductory undergraduate dynamics in mechanical engineering covers a wide range of topics including kinematics, kinetics, and energy- and momentum-based analysis, for both particles and rigid bodies. Due to this breadth, students can complete a dynamics course and have only a rudimentary understanding of the how all of the topics are connected and, perhaps even more importantly, why they are important to the study of systems in motion. Students' lack of a "big picture" view of dynamics is often exacerbated by the way dynamics topics are typically arranged in textbooks. For example, many texts and courses begin with a focus on finding velocities and accelerations via kinematics without making an argument for why this is important and without making any connection to students' prior knowledge, such as the force balances they learned in statics.

Due to these concerns, the author has structured dynamics in a fundamentally different way: using a spiral curriculum. Central to this approach is teaching the most fundamental topics of dynamics in the first week: kinetics, kinematics, and computer simulation. This teaching takes place in the context of rectilinear motion using examples that extend across all three topic areas. This gives students an overview of the course, allowing them to make connections between what can seem like isolated topics. It also makes the course more robust; students learn the big ideas early on, and the rest of the course develops these ideas for cases of increasing complexity.

Exciting examples that students can relate to are used to teach the material which helps motivate student learning. The examples highlight how the major topics are tied together and why each could be important in solving a larger problem. By teaching kinetics before kinematics, students receive a more natural introduction to dynamics that ties back to their experience with statics. Kinematics then naturally follows as being necessary for determining how something moves. Computer simulation is likewise shown to be necessary if equations cannot be solved in closed form.

Students surveyed after taking the "dynamics in one week" curriculum indicated that the examples were appealing, that it was valuable for the examples to connect across the fundamental topics, and that the one-week format helped them to understand the relationship between kinetics, kinematics, and simulation. This demonstrates that this new arrangement for teaching dynamics is effective and worthy of further development.

Introduction

Dynamics is a fundamental part of the mechanical engineering curriculum. A typical introductory undergraduate course in dynamics will consider both particles and rigid bodies and develop methods of analysis encompassing kinematics, kinetics, and energy- and momentum-based approaches. To students seeing this material for the first time, how course topics are related is often unclear, as are criteria for choosing between analysis methods. In fact, students often see dynamics as a large, disjointed collection of topics or tools, despite the fact that a small, highly interconnected set of underlying principles undergird the course. This problem in the dynamics curriculum has been recognized for some time, as Ellis and Turner [1] considered the use of concept maps as a remedy to this problem as early as 2003.

However, the content of dynamics is not the only thing that can cause students to struggle to organize its ideas. The way it is taught may also be a part of the problem. Most textbooks (and hence most courses) first use kinematics to describe motion and later use kinetics to relate forces and accelerations. This organization makes perfect sense if you are designing a mechanism: a description of the motion is needed first, followed by a calculation of the forces that will act on different parts. However, little design work occurs in an introductory dynamics course, where the analysis of existing systems is central. For analysis, a progression from kinetics (to find accelerations) to kinematics (to find positions/velocities) is more logical. Because a first course in dynamics typically follows statics in the undergraduate curriculum, this ordering is also stronger pedagogically, since placing kinetics first allows students to begin dynamics by drawing free-body diagrams, directly linking the two courses. The topic of whether kinematics should follow statics has been investigated by Cornwell and collaborators [2,3] but the results were inconclusive regarding learning gains. Recktenwald, Bush, and Averill [4] also suggest this reordering.

Introductory dynamics also tends to omit one area critical to modern practice: simulation. Most textbooks focus on solving dynamics at a particular moment in time (so-called 'snapshot dynamics') rather than on developing differential equations valid for all time. See Hjelmstad and Baisley [5] for some discussion of this point. The reason behind this omission is that some students may not yet have received instruction in ordinary differential equations. Although this concern over mathematical background is valid, this often means that the use of computer software to numerically integrate equations of motion is omitted entirely from dynamics. This is a significant issue considering how often equations must be solved this way in practical engineering problems.

To address these three concerns, the author has begun structuring a dynamics course using Brunner's idea of a spiral curriculum [6], in which topics are revisited several times, each time at a higher level of complexity. This allows the instructor to emphasize, and students to make and reinforce, connections between topics over a number of encounters. The spiral curriculum draws on the ideas of constructivism [7,8], in that students are assisted in developing connections between topics and methods through experience as opposed to direct instruction. Making connections this way has been shown to help students better learn and apply material. It also draws on the spacing effect [9-11] because revisiting a topic multiple times for instruction or practice has been shown to be more effective than spending the same amount of time as a single block.

As the starting point of this course, the author teaches the most fundamental topics of dynamics: kinetics, kinematics, and simulation, during the first week of class (i.e. three 52-minute classes). These topics are taught in the simplest possible context: rectilinear motion of a particle. The idea is to provide a broad overview of the course as early as possible, emphasizing how topics are related, in order to help students build connections. This is especially critical for learners who are more global than sequential [12-13] and need to see the big picture before they have a chance to understand the details. To further support these connections and address the concern regarding content order, the topics are sequenced as they would be for system analysis. Simulation is included in the first week to help students see how differential equations can (and often must) be solved numerically. Simulink is used for this purpose to avoid mathematical details to which students may not yet have been exposed.

A key component of this "dynamics in one week" curriculum is the use of example problems which extend across the week's topic areas. Since this is the beginning of the course and also students' first experience with dynamics, these problems need to be accessible, but also feel authentic, motivating, and (hopefully) fun. Student motivation is a known problem in dynamics, and many ways of motivating students have been proposed [14-17], but most of these involve larger projects or activities. During "dynamics in one week," students are engaged with examples associated with interesting videos of dynamic systems in action. Examples were adapted from the textbook by Gray, Costanzo, and Plesha [18], who revisit some systems several times in different contexts in their back-of-chapter problems.

The present paper includes a description of the "dynamics in one week" curriculum, presents and discusses student feedback collected via a survey instrument, and offers suggestions for future improvements as well as final conclusions.

Curriculum Description

Each of the 52-minute instructional sessions was organized around one of the three topics: kinetics, kinematics, and simulation. During a session, five major events occurred: (1) the instructor provided an introduction to the topic, defining the guiding principle and providing a brief procedure for applying it to problems (~20 min), (2) an example was worked by the instructor, showing the principle and process in action (~5 min), (3) a short video clip related to the subject matter of one of the example problems was shown, (~2 min) (4) students were given time to work on the problem exercises and ask questions (~20 min), and (5) a group question and answer period occurred with the exercise solutions posted (~5 min).

The two example problems which extended across the week's topics were skydiving and the human slingshot. Figure 1 shows the week's exercises for the skydiving example; the video used as the motivation component showed a variety of skydiving events set to uplifting music [19]. Figure 2 shows the week's exercises for the human slingshot example; the video used as the motivation component showed people enjoying a large, human slingshot from a variety of camera angles [20]. Students were presented with each exercise shown on the problem sheets separately; here they are presented together in the interests of space. Sessions involved interacting with one exercise for each of the problems. The kinetics session involved discussion of Exercise 1 for each problem, the kinematics session involved discussion of Exercise 2 for each problem, and the simulation session involved discussion of Exercise 3 for each problem.

To give some idea of what event (1) the introduction to the topic involved, consider the case of the first session on kinetics. For this session, instruction consisted of stating Newton's second law as an equation, discussing overdot notation for derivatives with respect to time, drawing out a free-body diagram (FBD) and a mass-acceleration diagram (MAD - also known as a kinetics

Skydiving

Exercise 1
A skydiver of mass m experiences air drag proportional to the square of their downward speed $\dot{x}$ and the drag coefficient C_d, so that the drag force $F_d = C_d\dot{x}^2$.

(a) Using a FBD = MAD approach, determine an expression for the skydiver's acceleration $\ddot{x}$.

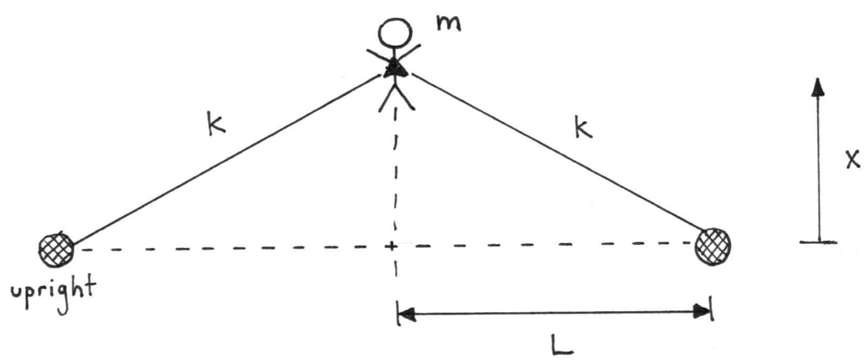
(b) After falling for awhile, the skydiver will approach *terminal velocity*: the velocity at which they are no longer accelerating. Starting with the expression from part (a), determine this terminal velocity $\dot{x}_*$.

Exercise 2
After free-falling near an initial terminal velocity $\dot{x}_{*0}$, the skydiver deploys a parachute which increases their drag coefficient C_d. Determine the distance travelled s until the skydiver is within 10% of the new terminal velocity x_* due to the parachute. Assume that $\dot{x}_{*0} = 55$ m/s, $C_d = 40$ kg/s, and that the skydiver has your mass.

Exercise 3
Express the differential equation for the skydiver's acceleration from exercise 1(a) as a block diagram in Simulink. Run a simulation for the conditions of exercise 2 and plot the skydiver's velocity versus time and position versus time. Is your answer from exercise 2 confirmed? How long does this process take? How much does the answer change if the skydiver is Tom Cruise?

Figure 1: The exercises used for the skydiving example problem.

Human Slingshot



Exercise 1
For the human slingshot, a person of mass m is attached to two elastic cords of equal length L having spring constant k. When the cords aren't stretched they have length L_0. To make the analysis simpler, consider the case of motion that occurs in a plane parallel to the ground, so that gravity can be neglected. Using a FBD = MAD approach, determine an expression for the acceleration $\ddot{x}$ of the human in the slingshot.

Exercise 2
If the human in the slingshot is released from rest after being pulled back a distance $x = x_0$, determine the speed of the human when they reach the location between the upright supports. You expression should be symbolic. By doing some research into the stiffness of a bungee cord and using estimates of the lengths shown on the video as well as your own mass, determine approximately how fast you might go on the human slingshot.

Exercise 3
Express the differential equation describing the acceleration of a human in the slingshot from exercise 1 as a block diagram in Simulink. Run a simulation for the conditions you assumed in Exercise 2. What happens to your maximum speed with different estimates of cord stiffness?

Figure 2: The exercises used for the human slingshot example problem.

diagram) to show Newton's second law for a crate being towed by a truck, and explaining how to assign directions for forces and accelerations that are dependent on a variable. This introduction will not address all student questions and confusion, but it will help them get started, and the question and answer periods (events 4 and 5) provide them opportunities to figure out details about which they are unsure ***within*** the context of problem-solving.

A weekly homework assignment provided additional opportunities for students to practice with problems that spanned the three topic areas.

Student Feedback – Data Collection

In order to assess students' experience with "dynamics in one week," students were surveyed during the second week and fourteenth (i.e. final) week of the semester-long course. Students received the same survey on both occasions. The survey consisted of five questions using a Likert scale running from "Strongly Disagree" to "Strongly Agree" as well as an open-ended prompt. The survey is reproduced in Figure 3. Twenty-five of twenty-seven students responded during the second week; nineteen of twenty-seven students responded during the final week.

During the first week of MECH 252, we did "dynamics in one week" where we looked at the central topics of dynamics: kinetics, kinematics, and simulation in the context of rectilinear (straight-line) motion.

Thinking back to the examples (e.g. human slingshot, skydiver) in the first week, please respond to the following prompts. . .

Q1: It was motivating to have examples that were based on real-life situations (e.g. human slingshot, skydiver).

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

Q2: It was interesting to see videos that showed the example systems in action.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

Q3: It was valuable for the examples to connect across multiple sessions (e.g. kinetics one session, kinematics the next session, and simulation the final session) to show the relationship between topics.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

Now, thinking more broadly about the first week, please respond to the following prompts. . .

Q4: Overall, the first week did a good job *introducing* the central topics of dynamics: kinetics, kinematics, and simulation.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

Q5: I think I understand the relationship between kinetics, kinematics, and simulation well.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

Q6: Do you have any suggestions that might improve the first–week experience for future students?

Figure 3: The survey used to solicit student feedback in weeks two and fourteen.

Two questions on the survey (Q1 and Q2) sought information about how engaging the first week content was, asking about the motivation generated by the real-life examples and the appeal of the videos. One question (Q3) sought information about whether having examples that extended across topics and class sessions was valuable. Two additional questions sought information about the first week overall, specifically how well it introduced the major topics (Q4) and how well students felt they understood the relationship between these topics (Q5). Finally, a prompt was included to record any suggestions for improving the first-week experience for future students (Q6).

Student Feedback – Results

Figure 4 shows student responses to questions regarding how engaging they found the first week content (Q1 and Q2) for survey data collected during week two of the semester. Figure 5 shows responses to the same questions collected during the final week of the semester.

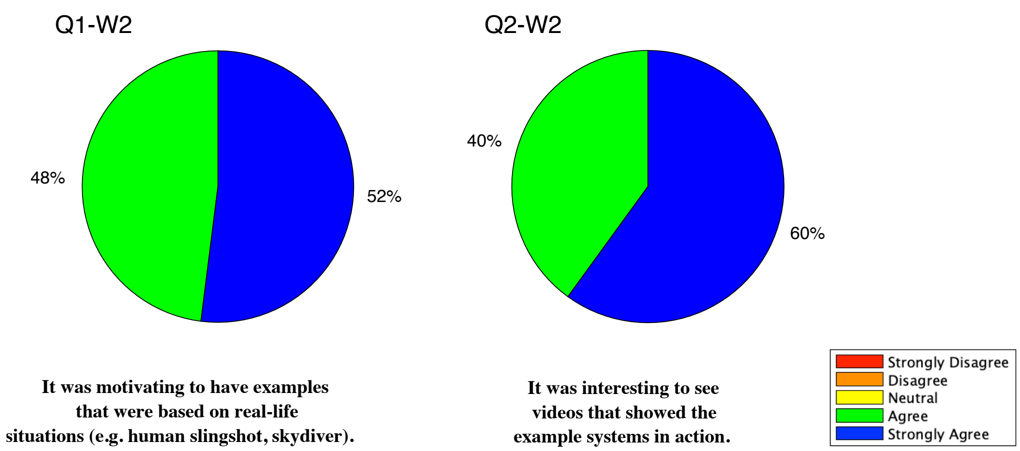


Figure 4: Student responses to questions regarding engagement with real-life examples (Q1-W2) and video content (Q2-W2) solicited during the second week of the course.

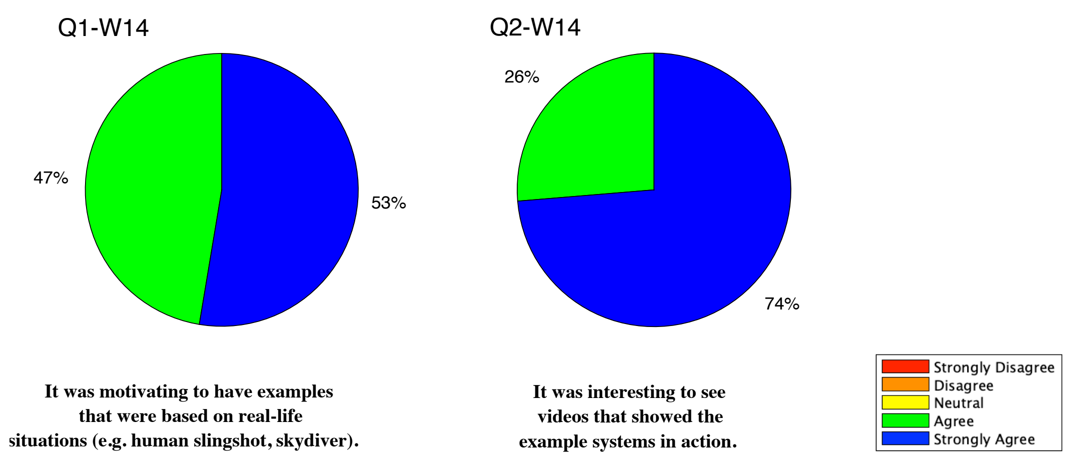


Figure 5: Student responses to questions regarding engagement with real-life examples (Q1-W14) and video content (Q2-W14) solicited during the final week of the course.

Figure 6 shows student responses to the question regarding how valuable it was to have problems that connected across multiple sessions and topics (Q3) during "dynamics in one week."

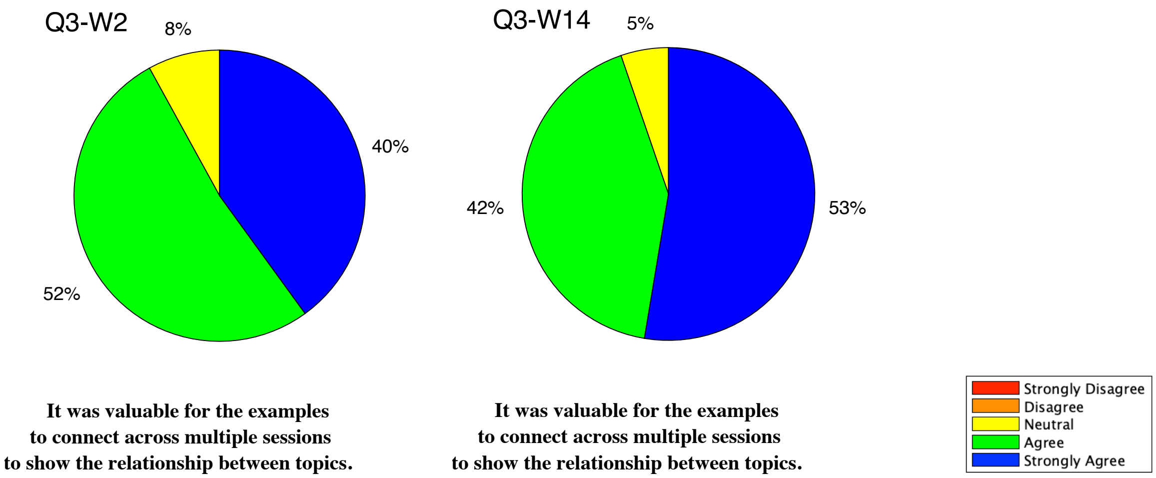


Figure 6: Student responses to the question regarding the value of problems that connected across sessions solicited during the second (Q3-W2) and final (Q3-W14) weeks of the course.

Figure 7 shows student responses to the questions regarding overall perception of the first week in terms of how well the central topics were introduced (Q4) and how well students felt they understood their connection (Q5) collected during week two. Figure 8 shows responses to the same questions collected during the final week of the semester.

All student comments to the open-ended question (Q6) are reproduced in Appendix A for both the second and final week surveys.

Discussion

The results show that overall "dynamics in one week" was well received by students. In particular, all students responded to the engagement-related prompts (see Figures 4 and 5) with "Agree" or "Strongly Agree" two and fourteen weeks into the course, establishing that the problems used for instruction are motivating and that the videos accompanying them are interesting. The only shift in student opinion was that during the second week, 60% of students strongly agreed that the videos were interesting, whereas during the fourteenth week 74% strongly agreed they were interesting. This is not a statistically significant change, and in general we see that student opinion on how engaging they found the content was solidified shortly following instruction. Clearly, this one-week structuring of material is able to catch and hold students' attention at the beginning of a dynamics course.

Students also saw value in the fact the problem-solving examples connected across class sessions in an effort to establish relationships between topics. Figure 6 shows that during the second week of class, 92% of students marked "Agree" or "Strongly Agree" in response to this question and during the fourteenth week 95% did the same. Again, the only shift came in the percentage of

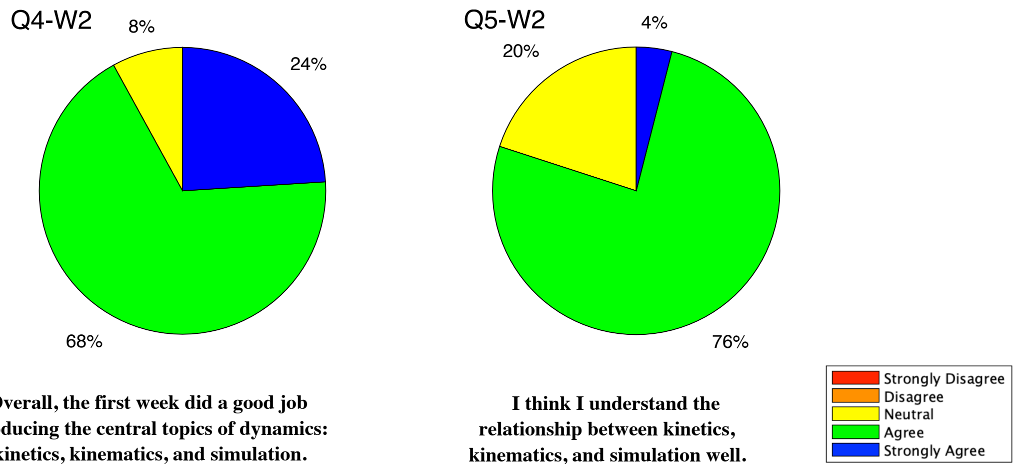


Figure 7: Student responses to questions regarding how well the first week introduced the topics (Q4-W2) and how well students could connect those topics (Q5-W2) solicited during the second week of the course.

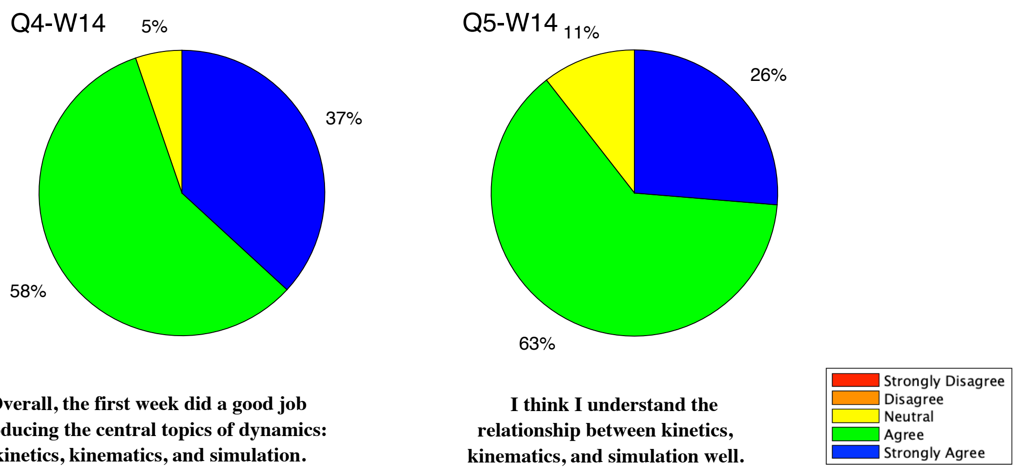


Figure 8: Student responses to questions regarding how well the first week introduced the topics (Q4-W14) and how well students could connect those topics (Q5-W14) solicited during the final week of the course.

students who indicated "Strongly Agree," which increased from 40% to 53% by the end of the course. This difference is again not statistically significant, but might indicate students could see more value to the instructional approach with the entirety of the course behind them.

Turning to overall impressions of "dynamics in one week," students felt the first week was successful in introducing the three major topics of the course as shown in Figures 7 and 8. During the second week, 92% of students expressed agreement that the curriculum did a good job of introducing these topics; during the fourteenth week 95% expressed agreement. Those who strongly agreed increased over the course of the semester from 24% at the second week to 37% by the fourteenth week. Again, this might suggest that impressions of the curriculum were slightly enhanced by more experience with the subject matter.

Finally, Figures 7 and 8 also show that student understanding of the relationship between the three major topics was rated highly as a result of "dynamics in one week." About 80% of students reported understanding the relationship between these topics during the second week, and this number improved to 89% by the end of the course. More importantly, those who strongly agreed increased from 4% to 26%. If responses are coded so that "Strongly Disagree" equals one and "Strongly Agree" equals five, with intermediate responses increasing proportionally, this change in understanding is on the cusp of being statistically significant ($p=0.056$). This increase is unlikely to do with the "dynamics in one week" curriculum, and probably reflects gains made by students over the course of the entire semester. However, one could argue that the fact that this change only verges on significance suggests students were in a relatively strong position after only the first week.

The student open-ended comments (see Appendix A) complement the quantitative results. Most of the second week comments focus on details of classroom management/topical coverage or indicate that the pace of instruction seemed fast (definitely true!). However, a few comments indicate that students appreciated the instructional approach even early on. One student wrote:

> *Honestly, the first week really helped lay the groundwork for this course. Now, do I understand kinematics? Maybe, but the disconnect is on my end, not the course instructor or class the first week.*

Another said:

> *I think zooming out in order to get the full picture of the course is very helpful and can make the course seem more manageable.*

These types of reflective comments grew to be a clear majority by the fourteenth week of the course (again, see Appendix A). Even better, students at the end of the semester also tended to identify relevant ways the first week curriculum could be improved. For instance, one student wrote:

> *It was helpful once I realized the relationship between kinetics, kinematics, and simulation, but it took me a little bit to realize their connection. So maybe make the relation between each topic more obvious/apparent at first.*

Another student made the comment:

> *Always clarify in the problem solutions when kinetics, kinematics, and simulation are brought back later on in the course because it is not always apparent.*

These types of comments show that not only do students value the approach of "dynamics in one week" but as they continue to wrestle with the connections they have started to make after the first week, they want to see reinforcement of these connections throughout the course. This strongly supports "dynamics in one week" as well as arranging course material in spiral curriculum more generally.

Future Improvements

The student comments, along with the instructor's experience, suggest a few ways in which "dynamics in one week" might be further improved.

First, in terms of implementation, it may be better to divide the content over slightly longer than one week. Teaching this material over the course of three, 52-minute class blocks ***is*** possible, but both the instructor and students feel the time constraints acutely. If four class periods instead of three are used, the additional time can be spent to consolidate learning. This consolidation could take a simple form, such as a student question and answer session and some additional practice. However, a better approach might be having student groups tackle a challenging, real-world, somewhat ill-structured problem that includes two or more of the major topic areas. One example of a problem that fits this description, authored by Heller and Hollabaugh [21], incorporates both rectilinear kinetics and kinematics and involves determining whether to fight a traffic ticket based on skid marks left on a hill. This type of group-solved example offers the advantage of review, but also forces students to bring the topics together once again in a slightly more challenging environment which should benefit learning and retention.

Second, as the student comments make clear, more actively supporting "dynamics in one week" through the rest of the course is likely to pay dividends for students. Making explicit when topics from the first week reappear in a different context or in a more complex form is likely to help students establish or reinforce their learning, particularly in connecting different topics. It seems likely to be important to leverage student memory in this regard by using language like "remember when we did X in the first week to solve the problem about Y, this draws on the same idea but now…"

Finally, one of the weaknesses of this study is that all of the data is student reported. In particular, although students indicated "dynamics in one week" is a good introduction to kinetics, kinematics, and simulation and credited it with helping them understand the connections between these topics, this paper provides no evidence that the curriculum improved student learning or performance on assessments. In the future, a tool such as the dynamics concept inventory should be used to assess students who go through the "dynamics in one week" curriculum vs a control group of students who do not. This would determine whether the strong positive response elicited in students translates to meaningful learning gains.

Conclusions

Teaching three major topics of dynamics in a simple form during the first week of an introductory-level dynamics class seems to be an effective way of helping students establish connections between these topics by giving them an overview and priming them for further learning. Exciting examples of rectilinear motion were selected and developed into problems in service of this approach. Students reported that these course materials were motivating and that they saw value in how examples extended across class periods and topic areas. They also indicated that overall the "dynamics in one week" curriculum was a good introduction to kinetics, kinematics, and simulation.

Acknowledgements

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Appendix A – Student Comments

Student responses during week two to "Q6: Do you have any suggestions that might improve the first-week experiences for future students?":

- Overall, slow down and maybe allow for short half- to one-minute discussions during class so students can talk.
- Doing a day of examples that are review kinematics problems from physics to remember where we left off.
- The simulation is, for me, hard to understand in a short time. Maybe consider spending more time to illustrate this.
- More Simulink/simulation setup examples.
- I think zooming out in order to get the full picture of the course is very helpful and can make the course seem more manageable.
- Do examples of more complex simulations.
- Physical examples (models).
- Maybe using the computer as a note-taking tool would be good so you could upload the notes on Moodle.
- More example problems.
- Honestly, the first week really helped lay the groundwork for this course. Now, do I understand kinematics? Maybe, but the disconnect is on my end, not the course instructor or class the first week.
- Some in-person/hands-on demos might be fun, like predicting a ball's motion out of a slingshot or something like that.
- It would be valuable to spend some more time on learning what to integrate with respect to.
- No, just a little confused on the difference between a_r and r_doubledot or a_theta and theta_doubledot.

Student responses during week fourteen to "Q6: Do you have any suggestions that might improve the first-week experiences for future students?":

- A differential equations review before starting problems would be helpful.
- Always clarify in the problem solutions when kinetics, kinematics, and simulation are brought back later on in the course because it is not always apparent.
- First week was done well.
- Go over using Simulink a bit more, I'm still confused by it.
- I feel like the first week was a fairly comprehensive intro to the course. I can't think of anything to improve it.
- It was helpful once I realized the relationship between kinetics, kinematics, and simulation, but it took me a little bit to realize their connection. So maybe make the relation between each topic more obvious/apparent at first.
- I believe that the example problems provided a great review for learning about and integrating mass-acceleration diagrams (MAD).
- I like being introduced to real-world applications early on in the course. I think its motivating as engineers to see that what we are learning is relevant to real life. I think the first week was engaging and I would not suggest a large change to what we did.