FOR SYSTEMATIC DEVELOPMENT OF CONCEPTESTS FOR ACTIVE LEARNING

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Abstract

We present a framework for developing instructional materials for the Concept Warehouse (CW), a technology-based tool to facilitate concept-based active learning, as it expands to include questions in the field of mechanics (i.e. statics and dynamics). High quality materials are critical for effective concept-based instruction. Question development in statics and dynamics is facilitated by explicitly identifying three goals: a content goal, a process goal, and an epistemological goal. For each subject area, we present questions with similar content goals but different process and epistemological goals. We use pairs of questions to illustrate the ways question design and intent of instruction interact. The Concept Warehouse is an open educational resource available to university instructors at http://cw.edudiv.org.

Keywords: active learning, technology, mechanics, engineering, conceptests

1 INTRODUCTION

Several consensus reports [1,2] cite that a change to evidence-based instructional practices, such as concept-based active learning, is needed to increase the number and diversity of STEM graduates over the next decade. C*oncept-based active learning* is the use of activity-based pedagogies whose primary objectives are to make students value deep conceptual understanding (instead of only factual knowledge) and then to facilitate their development of that understanding. It has been shown to increase academic engagement and student achievement [3], to significantly improve student retention [4], and to reduce the performance gap of underrepresented students [5]. Unfortunately, empirically proving that certain instructional practices are more effective than traditional methods in promoting student learning is not enough to ensure that desired systemic pedagogical change occurs. To significantly improve STEM education, evidence-based instruction must be widely adopted by faculty who are motivated by a host of factors to maintain the status quo [6]. Part of faculty reluctance stems from the fact that developing high-quality instructional materials is time-consuming and requires expertise. Even if instructional materials are developed, faculty need to first recognize that they are available, choose to implement them, and have support to develop the skills to implement them effectively.

In this paper we present a framework for developing educational materials for the Concept Warehouse, a community developed, technology-based tool to facilitate concept-based active learning [7], [8]. The Concept Warehouse was originally constructed for chemical engineering (ChE) courses. Based on its widespread adoption within that discipline, in our current project we are extending the tool to mechanics, including educational materials for statics and dynamics courses. Specifically, we address the development of *ConcepTests*, which are short questions that can rapidly be deployed to engage students in concept-oriented thinking and to assess their conceptual understanding [9]. The Concept Warehouse is an open educational resource available to university instructors at http://cw.edudiv.org.

The need for systematic development in this new subject area has led the project team to draw on design principles in the literature, as well as our extensive experience, to implement a framework for writing ConcepTests. The framework draws on work by Beatty and colleagues [10] to identify three explicit instructional goals for each ConcepTest: a content goal, a process goal, and an epistemological goal. Developing concept questions within a framework that recognizes distinct learning goals has several practical benefits. First, faculty are more likely to adopt instructional materials that align with their instructional goals, so questions targeted to specific learning outcomes are likely to increase intelligent adoption of materials. Second, instructional materials are more likely to promote the achievement of targeted learning goals if the developer explicitly identifies that goal and then thoughtfully designs questions to facilitate achieving that goal.

In the following sections, we first provide a brief background of the Concept Warehouse. Next we present the framework for developing new ConcepTests for courses in mechanics. We illustrate the framework with example question pairs for statics and mechanics. Each pair centers on the same content goal but illustrates different process and epistemological goals. We argue that the framework supports different types of pedagogical practices, instructional philosophies, and contextual realities. Importantly, it also forms a scaffold within the tool to help instructors recognize different ways to implement concept-based active learning and help them evolve their instruction practice.

2 THE CONCEPT WAREHOUSE

The Concept Warehouse has been developed to provide instructors and their students with a cyber-enabled infrastructure to deliver concept-based active learning [7], [8]. The overarching goals of the Concept Warehouse Community Project are to lower the barriers for instructors to adopt evidence-based pedagogies, to investigate student learning and engagement during concept-based instruction, and to study the conditions that promote adoption. The technology tool itself provides three distinct but complementary functions: (a) a repository of educational materials, (b) an audience response system to deliver them, and (c) learning analytics that provide data to instructors and researchers. Educational materials in the form of approximately 3,000 ConcepTests, 10 research-based Concept Inventories, and several Inquiry-Based Activities and Virtual Laboratories are now available for ChE. The design architecture of the Concept Warehouse is based on seven overarching principles [7], one of which is the Emergent Use Principle: Be versatile in how questions can be deployed in instruction so that instructors can use them in ways that best fit their philosophy and context.

As shown in Fig. 1, the Concept Warehouse is now widely used by the ChE community [11]. After ~4 years of existence, almost 1,000 faculty members across the US and internationally at over 150 institutions are using it. While most of the educational materials are currently specific to ChE, the software design is general and there is opportunity to leverage the development work and apply this tool to any STEM discipline. A survey has shown that students generally connected the use of the CW to learning, with 155 of 179 students responding positively to the statement that its use helped them to understand the concepts behind the problems. Additionally, 145 of 181 students agreed that their conceptual understanding would increase in other courses if the tool were used in those classes [7].

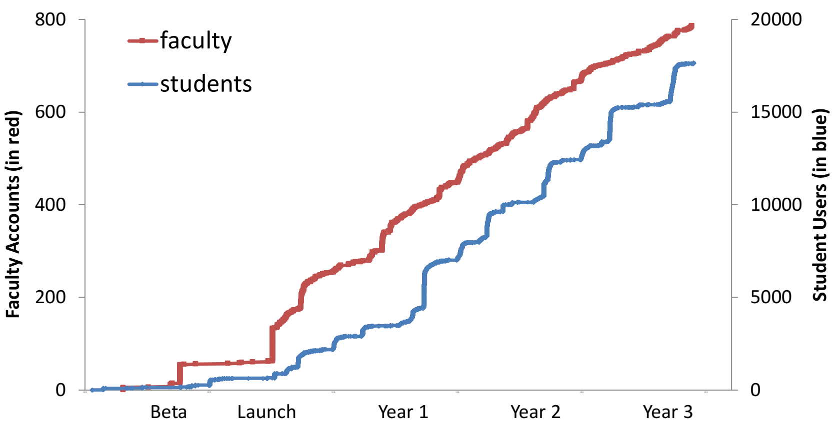

Figure 1. Growth of faculty and student users of the Concept Warehouse

In this paper, we report on a project to develop high-quality conceptual questions ConcepTests for two core engineering mechanics courses, statics and dynamics. Each course has a Course Lead and a corresponding Course Team consisting of 3-4 individuals. The Project Leaders and the Course Teams met for a two-day workshop to develop a shared understanding of how to construct high-quality questions for engineering faculty to use in statics and dynamics courses. This workshop was organized around the framework described next.

3 FRAMEWORK FOR QUESTION DEVELOPMENT

We approached the framework for the development of ConcepTests for mechanics by identifying a broad set of instructional goals for concept-based active learning. We draw on Heibert and Lefevre's [12] definition of conceptual knowledge as "characterized most clearly as knowledge that is rich in relationships. It can be thought of as a connected web of knowledge, a network in which the linking relationships are as prominent as the discrete pieces of information." (pp. 3–4).

However, science and engineering classes often orient activity towards problem solving algorithms with little explicit attention to connecting the foundational ideas needed to solve the problems to other ideas and concepts that the student is learning or has previously learned [13], [14]. This orientation may lead students to diligently memorize problem solving algorithms, and cause difficulty when they need to identify and use the underlying concepts in new situations [15]. While procedural fluency is important in engineering practice, so is the corresponding connected conceptual learning we seek to support.

Following the Emergent Use Principle, we aim to support instructors in using conceptual questions in ways that best fit their beliefs and context. For example, questions should enable faculty to intersperse formative assessment during more traditional lecture [13], but also support instructors who use questions as a central tool of instruction [10]. Concept Warehouse questions can be used to prompt discussion, arguing, and sense-making. The Concept Warehouse enables instructors to elicit written justifications for selected multiple-choice answers, preparing them to engage in discussion [16]. Because the uses of concept questions go beyond correct-answer assessment, the nature of effective questions can be quite different than those used in formal summative assessments (e.g., concept inventories, standardized tests).

To facilitate ConcepTest development in mechanics to support conceptual understanding and emergent uses, we have delineated three kinds of instructional goals for the Course Teams to identify and apply:

- Content goals [10]: What disciplinary concept or big idea do we want to illuminate?
- Process goals [10]: How might the students use the concept/big idea? What cognitive skills do we want students to exercise?
- Epistemological goals: What ideas about learning and doing engineering do we wish to reinforce?

Content goals. When looking for instructional materials, instructors often focus first on the disciplinary content or topic they wish students to learn. To support content goals, we organize courses in terms of searchable major topics or big ideas. For example, in statics the topics include: centroids, frames and machines, friction, internal forces, etc.

Process goals. Process goals address the student thinking and sense-making processes that instructors intend to elicit. By sense-making, we follow Campbell, Schwarz, and Windschitl [17] to mean that learners are "working on and with ideas—both students' ideas (including experiences, language, and ways of knowing) and authoritative ideas in texts and other materials—in ways that help generate meaningful connections" (p. 19). For example, refs [10] and [18] describe the practice of identifying the core concepts from a situation and then applying those concepts to reason towards a prediction as an important process goal. Other examples of process goals include seeking alternative representations, explaining or justifying, contrasting situations, and making predictions and observing [10].

Epistemological goals. Epistemology refers to the study of knowledge and knowing and includes what it means to know, what one believes counts as knowledge, and how that knowledge is produced [19], [20]. Through their experiences in engineering school, students develop conceptions of the types of knowledge and knowing entailed in doing engineering work, and what knowledge is valued. For example, if the questions posed to students always have single answers that are clearly correct or incorrect, they may learn to view working knowledge in engineering as having one certain truth rather than viewing knowledge as fluid and incomplete [21]. Alternatively, if students are encouraged to grapple with open-ended problems, they might develop a better appreciation that the best engineering solution is often contextual rather than universal and absolute. Similarly, if instructors consistently and immediately provide that correct answer, students may view engineering phenomena as imbued with single authoritative interpretations which could lead them to memorize the "correct" interpretation rather than constructing their own interpretations and understanding. Alternatively, if students are asked to generate and evaluate different solutions from a variety of sources, they might better learn to value multiple perspectives and recognize the limits of authority or specific types of expertise.

Next we present a two pairs of ConcepTests for mechanics with the same content goal but different process and epistemological goals and illustrate the ways question design and intent of instruction interact.

4 EXAMPLES FROM MECHANICS

Introductory engineering mechanics students often bring deeply rooted ideas about how objects behave and move under the influence of forces [22]. For example, they may have observed that a heavy ball will fall faster than a sheet of paper leading to the idea that heavier objects fall faster than lighter objects under the influence of gravitational forces. Their observations of the ball and the sheet of paper lead them to the erroneous conclusion that the ball falls faster due to its weight rather than the effect of form drag on the piece of paper. However, such ideas often do not align with normative understandings of Newton's Second Law. Another issue that arises in mechanics is the ability to model and transform a real system into an appropriate model that includes both approximations and notational conventions [23]. The general goal of the educational materials being developed for mechanics is to provide instructors resources to develop normative conceptual understanding in ways that also develop corresponding thinking processes and ways of knowing of practicing engineers.

In this section, we illustrate the framework above as applied to a pair of ConcepTests in statics and a pair in dynamics. Finally we describe how an instructional sequence might play out.

4.1 Statics

Figs. 2 and 3 present two ConepTests for statics. Both questions address the same content goal, developing student conceptual understanding of rigid body equilibrium. The first question focuses specifically at translating a representation of loads and supports into a free body diagram. The second question is broader and asks students to translate between photos of a forklift into a qualitative representation of the relation between force, moment, and distance. Answering this question supports process goals and epistemological goals related to standard accepted representations. It reinforces the epistemological belief that qualitative predictions are part of engineering thinking and, importantly, that the engineering methods being learned in statics apply to real mechanical systems. The content, process, and epistemological goals for both questions are provided in Table 1.

Table 1. Summary of Content, Process, and Epistemological Goals of the Statics ConcepTests.

	Content Goal	Process Goal	Epistemological Goal
Statics 1 (Schematic representations of a beam)	Build understanding of rigid body equilibrium	Identify standard representations (translate loads and supports into a free body diagram) Recognize Cartesian vector notation and appropriate signs	Learn that working through engineering problems involves successive transformations of graphical representations
Statics 2 (Forklift)		Translate a photo of a real physical system to an appropriate model representation Reason through the qualitative response of the system to determine the relationships between force, moment, and distance	Recognize that engineering analysis applies to real systems (with some messiness) Learn that representational transformations are central to engineering modelling Learn that qualitative predictions are part of engineering thinking

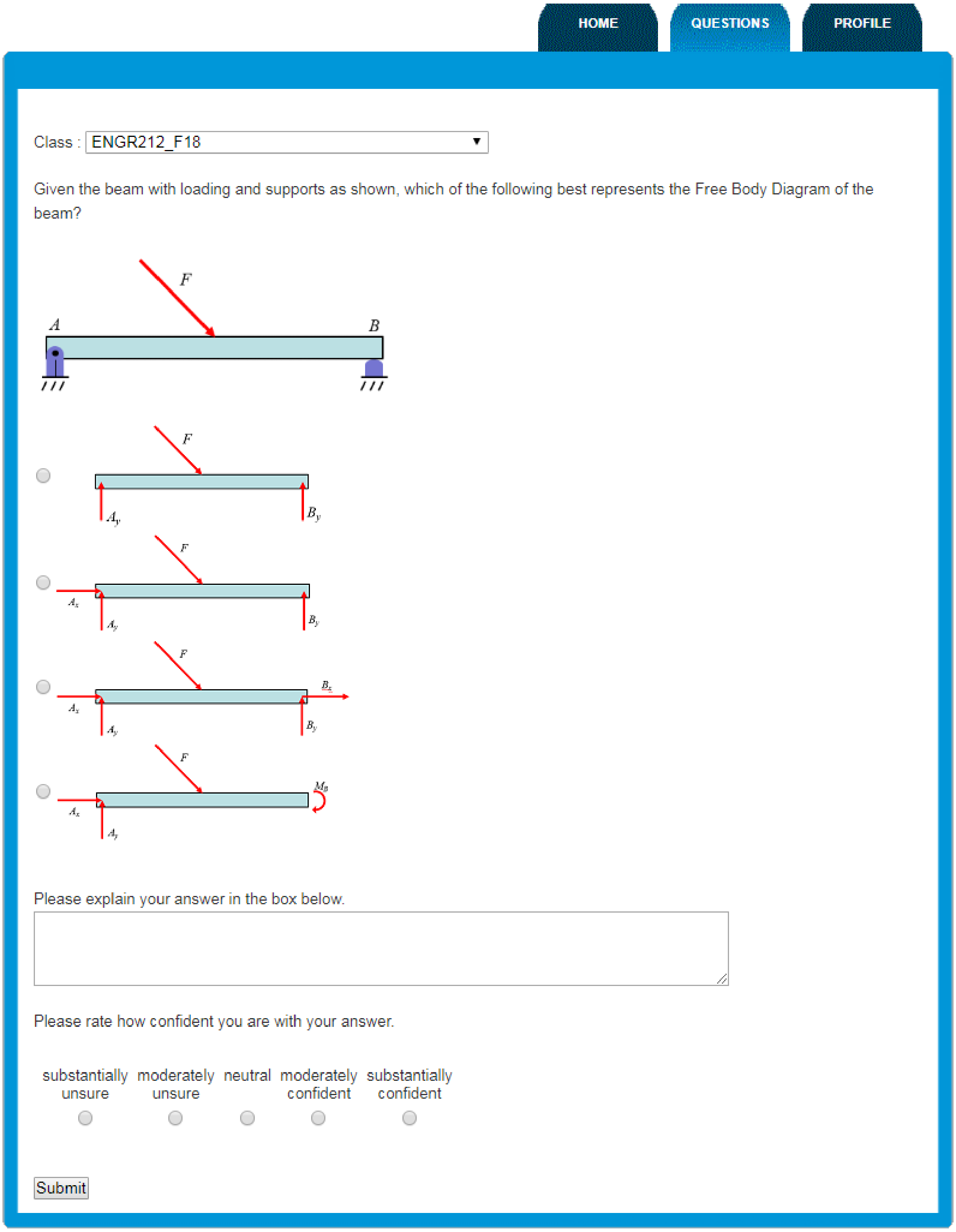

Figure 2. Question asking students to identify the correct representation of a free body diagram as viewed on the student interface in the Concept Warehouse.

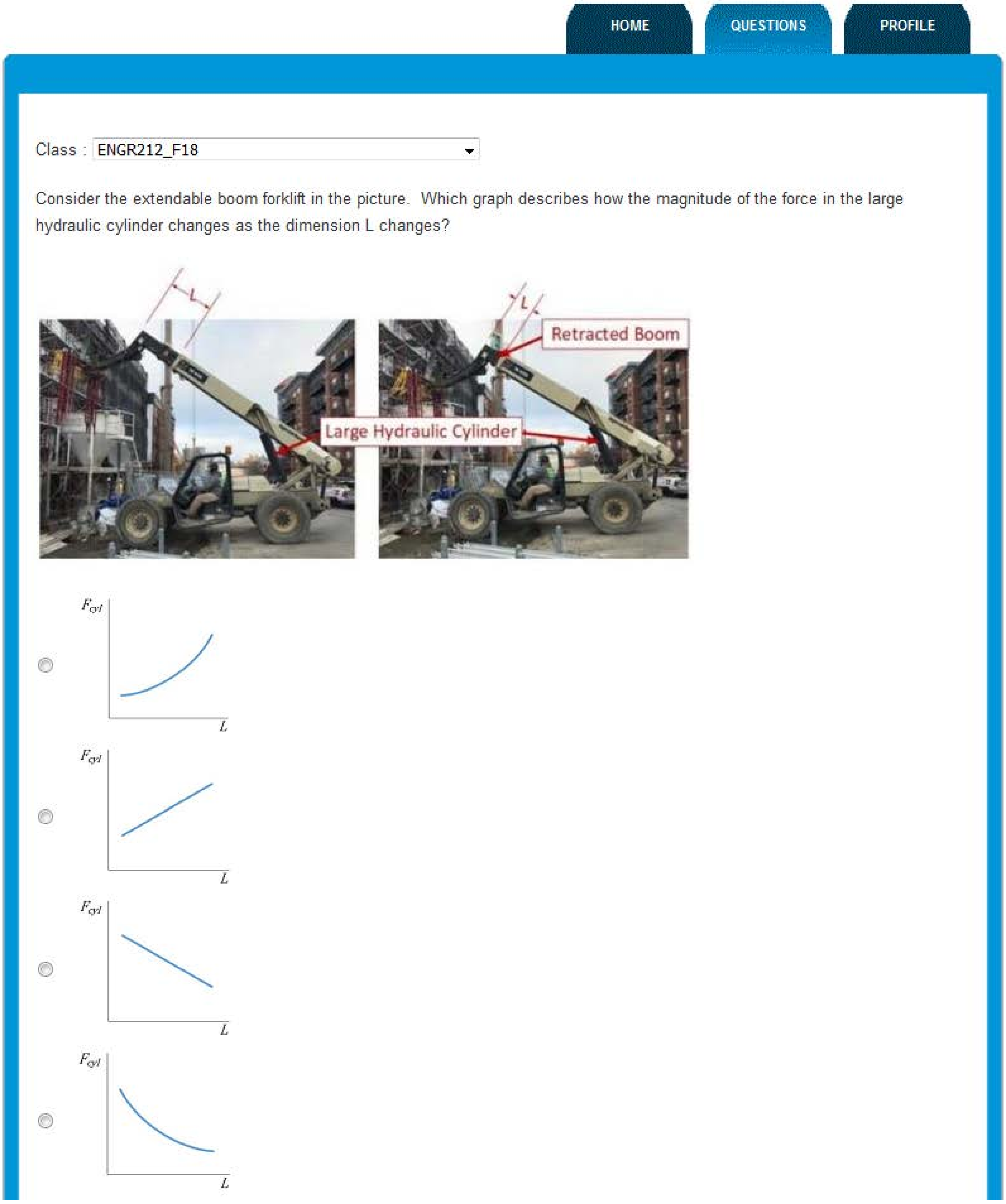

Figure 3. Question asking students to translate a photo of a real physical system to an appropriate model representation as viewed on the student interface in the Concept Warehouse. The bottom of the screenshot image has been cropped.

4.2 Dynamics

Figs. 4 and 5 present two ConcepTests that can be used in sequence to help students construct conceptual understanding about how objects move and behave under the influence of forces. Both questions address the same content goal, to build understanding of the relationship between net force, total inertia and acceleration of particles as given by Newton's Second Law through exploring responses of a system with a cable and a pulley. Their content, process, and epistemological goals are provided in Table 2. The second epistemological goal for each question in Table 2 relates to the way the question might be used in class as described in Section 4.3.

Table 2. Summary of Content, Process, and Epistemological Goals of the Statics ConcepTests.

	Content Goal	Process Goal	Epistemological Goal
Dynamics 1 (Single system)	Build understanding of the relationship between net force, total mass and acceleration as given by Newton's Second Law	Draw a Free Body and Kinetic Diagram to represent the forces on a given mass Apply Newton's second law to a system with a cable and a pulley to reason to the correct answer	Learn that representational transformations are central to engineering modelling Discover which response aligns with the laws of mechanics through disagreement and debate with peers [Possible goal - see section 4.3]
Dynamics 2 (Two system)		Compare and contrast two systems to reason through the effect of total mass in a system in accordance with Newton's Second Law	Construct knowledge about systems without numerical calculations Observe real (or simulated) phenomena to verify or modify ideas about applying foundational knowledge to systems [Possible goal - see section 4.3]

The process goal for the first problem (Fig.4) is to have students draw a Free Body and Kinetic Diagram to successfully find the forces on the 1 Kg mass and apply Newton's second law to find the answer is D. Students who do not draw the Free Body Diagram may mistakenly forget the downward force on the 1 kg mass due to gravity and answer B. One epistemological goal of this question is for engineering students to learn that alternative representations to equations, such as Free Body and Kinetic diagrams, are a powerful method of understanding how forces interact with bodies to produce motion.

The second question (Fig. 5) uses a compare and contrast tactic [10] in a related question, again focusing on pulley and cable systems. Here students need to look at the two systems and notice differences in total mass and total net force that drive the system and understand their relation (acceleration is proportional to net force and inversely proportional to total mass) in order to make a correct prediction. Many students will focus only on the net force (which is the same for both systems) and erroneously predict that Mass A and B accelerate at the same rate, when in fact Mass B will accelerate faster due to a lower total mass. This approach would reinforce the epistemology of engineering dynamics that motion is predictable and follows naturally from Newton's second law and conclusions can be reached without analytical calculations as is often the impression many engineering homework assignments give (e.g. Question 1).

4.3 Instructional Sequence: Dynamics

From the perspective of creating a web-based resource, the questions themselves need to be independent entities available for instructors to use. However, it is useful to consider how they might sit within an active learning class to produce learning. In this section, we illustrate how the two dynamics questions together with a Virtual Laboratory can be used in class to address content, process and epistemological goals. We do not suggest that the questions posed in this sequence need to be used in this way, but we do advocate that instructors have clear content, process, and epistemological goals as they integrate these educational materials into their course. Conversely, as the project teams develop materials, it is useful to consider the different ways instructors might use them to support content, process and epistemological learning goals.

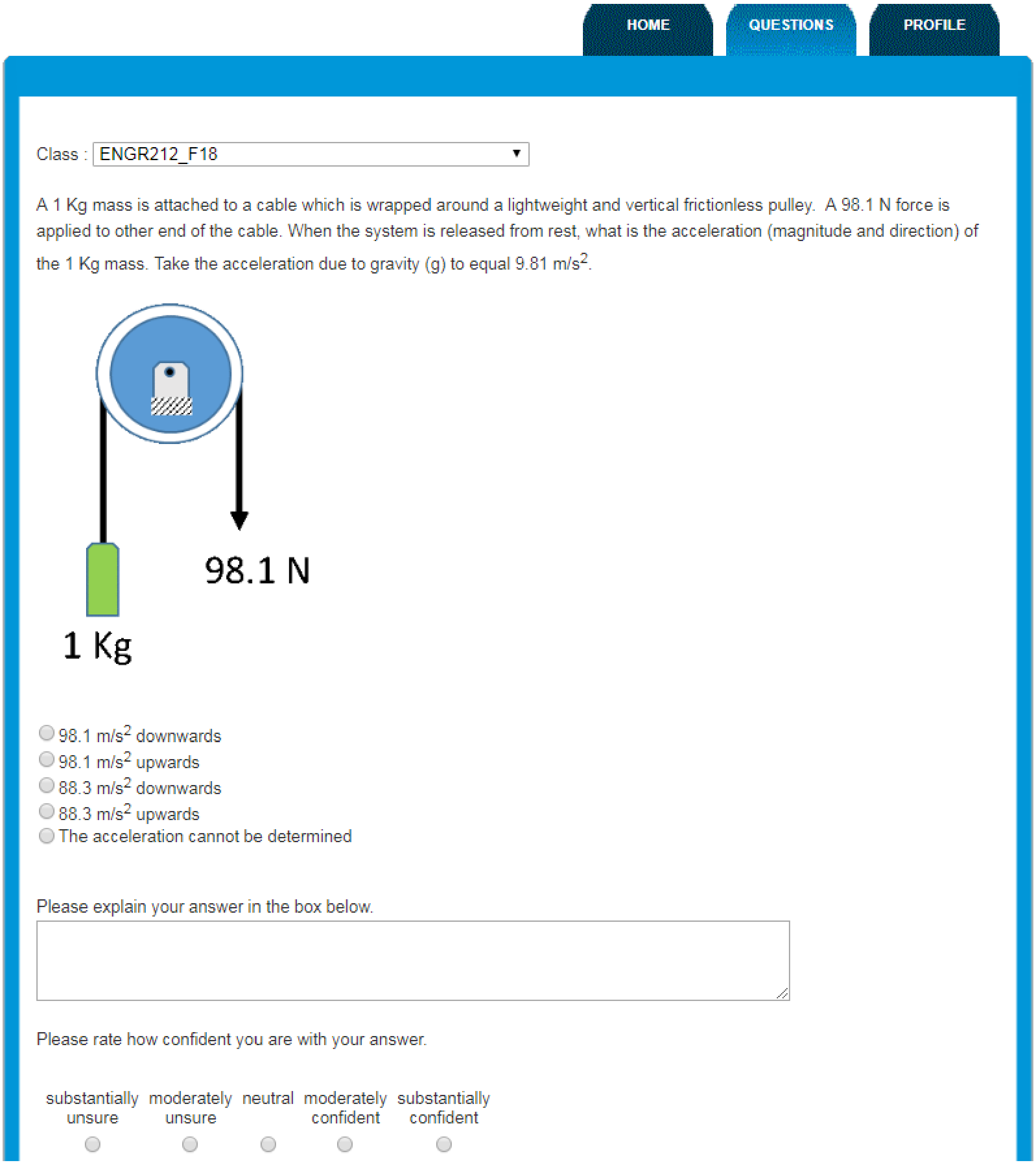

Figure 4. Single system question asking students to apply Newton's 2nd law as viewed on the student interface in the Concept Warehouse. The bottom of the screenshot image has been cropped.

The class sequence might begin with the question shown in Fig. 4.This question directs students to analyze a single pulley system and select the correct numerical response. When used, the instructor may choose the Peer Instruction pedagogy [9] where students first are asked to answer individually including providing a written justification as illustrated in the figure. They then form small groups of two or three students to discuss their answers, explore one another's reasoning, and come to consensus. Using this as a discussion question can lead to disagreement and argumentation among students as they seek to explain their answer. Such an approach can support the epistemological goal that disagreement and argumentation among peers can help students discover what response align with the laws of physics. The instructor might then ask the compare and contrast question pair shown in Fig. 5. If used in class, the instructor could use a simulation or physical demonstration to show an unexpected difference in acceleration between the two systems and then have students discuss why. This part of the activity would support the epistemological goal that observations of phenomena are a source to verify or modify ideas about applying foundational knowledge to systems.

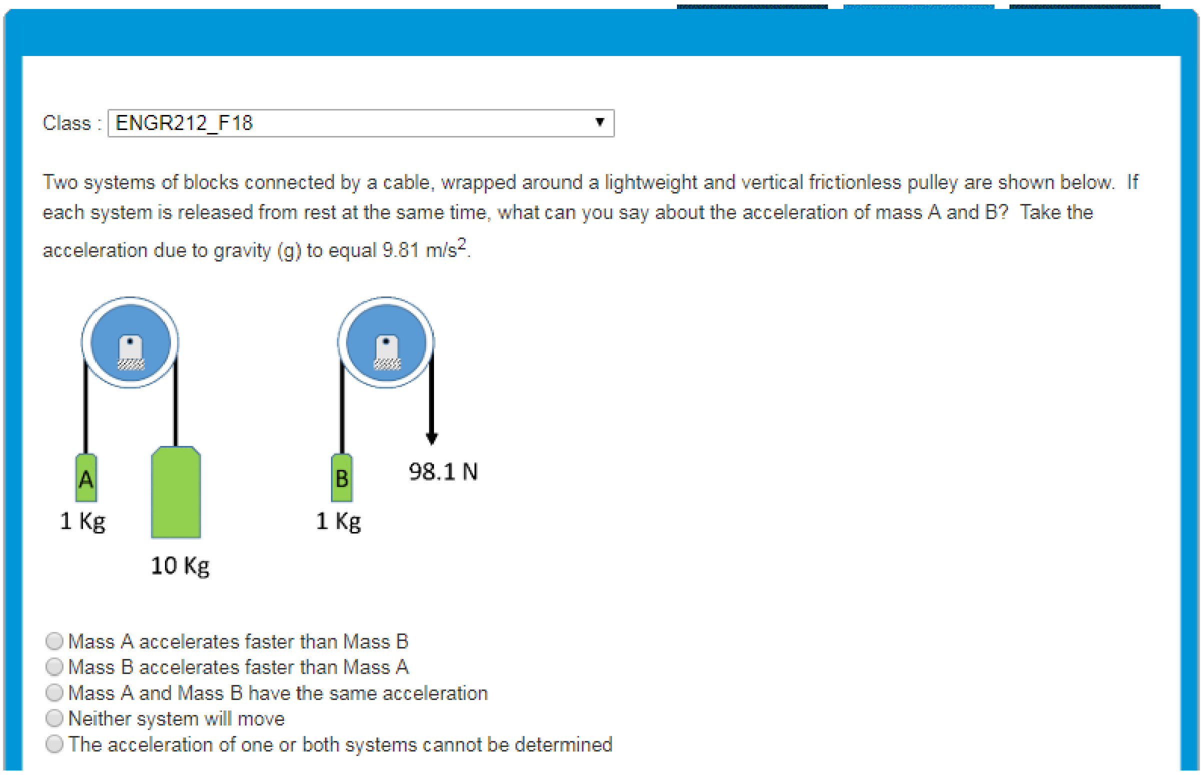

Figure 5. Two system question asking students to apply Newton's 2nd law as viewed on the student interface in the Concept Warehouse. The screenshot image has been cropped.

DISCUSSION

We argue that a framework for developing instructional materials that recognizes distinct content, process, and epistemological goals will better support different types of pedagogical practices, instructional philosophies, and contextual realities. Importantly, the framework also forms a scaffold within the tool to help instructors recognize different ways to implement concept-based active learning and help them evolve their instruction practice. In this approach, the question itself is not viewed as a sequestered tool to produce learning but rather as something to be used to support an instructional plan such as described in Section 4.3. For example, an effective strategy might be following up on the question shown in Fig. 4 by asking students to reflect on *incorrect* answers by asking "Many students mistakenly choose the second response. What error might lead a student to choose this option and what way of approaching the problem might minimize this from happening?". The instructor could then choose and present a set of written responses and ask students to pick the one that is most complete and well-reasoned. The idea is that it is not just the question itself, but how the question is embedded with other questions and how the instructor uses the question, that determines how that question facilitates the achievement of distinct learning goals.

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