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Board 327: Learning Map Framework to Align Instruction and Improve Student Learning in a Physics-Engineering Mechanics Course Sequence

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Learning Map Framework to Align Instruction and Improve Student Learning in a Physics-Engineering Mechanics Course Sequence

Motivation

Prerequisite course sequences are ubiquitous in post-secondary engineering education [1]. For undergraduate students to succeed in their degree, they must retain and transfer learning from their prerequisite coursework into new and more advanced learning contexts. If knowledge transfer is incomplete, students may struggle in subsequent courses or need to retake those courses. Further, engineering curricula are notoriously complex. Failure of key foundational courses (e.g., Calculus, Physics) in the first and second years, can lead to major setbacks ranging from course repeats, delayed graduation, change of degree, or stop-out [2], [3]. These challenges tend to be exacerbated for students historically in the margins and represent a major barrier to student success in engineering degrees [4].

Instructional design is one factor that is under the control of faculty and programs and can be leveraged to minimize barriers to student learning [5]. Faculty respond to students' incomplete prerequisite knowledge in a variety of ways. At the course level, faculty may provide additional support such as supplemental review materials, review sessions, office hours, self-paced modules, or opportunities to resubmit failed quizzes and assignments. At the program level, faculty may coordinate curricula and instruction across courses, either in response to observed deficiencies or proactively through the intentional design of whole curricula. The same can be done in the case of prerequisite course sequences that occur across different programs, though cross-program coordination may be more challenging than interventions at the course or program level.

Purpose

The purpose of this study is to develop and pilot an instructional design approach that faculty can use to align learning outcomes, assessments, and instruction in undergraduate STEM course sequences, across or within programs. The key research questions are as follows:

- Can an instructional design framework be developed that streamlines coordination among instructors and across a course sequence?
- How do we assess whether knowledge transfer has occurred for students in the course sequence?
- Will the alignment of learning outcomes, assessments, and instructional activities across the course sequence lead to improved knowledge transfer and academic outcomes for students?

Approach

The specific goals, outcomes, and timeline to address these questions are shown in Table 1. Year 1 goals include the development of a new framework to help instructors align instruction, referred to as the Learning Map (LMap) Framework. The Framework involves an in-depth analysis of the existing curricula by the research team and a series of summer workshops in which participating faculty build consensus around the key interdependent learning outcomes in the sequence and how they will teach them.

The effect of this “intervention” (alignment of instruction) on student and faculty outcomes will be assessed via a pilot study of a common Physics – Statics – Dynamics course sequence. This sequence encompasses required knowledge of engineering mechanics in many ABET- accredited programs across the country [6] and is typically completed in the first two years of study in preparation for upper-level and applied engineering coursework (mechanics of solids, fluid mechanics, materials engineering, system dynamics, and advanced structures). The rate of D, F, and Withdrawal grades (DFW) in these courses tends to be high at the authors’ institution. In Academic Year AY21-22 for example, the DFW rate for the Physics, Statics, and Dynamics courses averaged 5.2%, 8.2%, and 14.8%, respectively. The importance of this sequence to student progress and its relatively high failure rate, make it an ideal candidate for the proposed intervention.

Table 1. Project goals, outcomes, and timeline

Project Goals	**Outcomes**	**Timeline**
1. Develop framework to help instructors…		
1.1 Identify interdependent LOs in Physics – Statics - Dynamics	LMap curriculum analysis; Hierarchy of concepts and assessments	Fall 2023 – Spring 2024
1.2 Facilitate alignment of LOs, assessments, instruction across sequence	Faculty workshops; Resulting changes to curricula (“Intervention”)	June 2024
1.3 Assess students’ knowledge transfer between courses	Knowledge Transfer Inventories (KTI)	Spring 2024 - 2026
2. Test the framework		
2.1 Evaluate student learning and success outcomes before / after faculty intervention	Pre/Post-intervention Pilot Study	Spring 2024 - 2026
3. Dissemination and scaling		
3.1 Share approach and learning with other faculty	Web resources; KTI; LMap Workshop for VT educators	Spring 2026
3.2 Identify faculty partners / courses for future efficacy research	Next phase proposal	Spring 2026

Progress

Learning Map Framework. The instructional design framework under development by the research team, specifically for *course sequences*, is based on the well-established fields of Analysis, Design, Development, Implementation, Evaluation (ADDIE) [7] and Backward Design [8], [9]. The ADDIE task-analysis model supports knowledge and skills transfer across learning contexts or modules, but sees limited application in academia. The application of ADDIE to engineering course sequences provides a systematic process for aligning and assessing learning outcomes *across courses*, in contrast to common instructional design frameworks, which focus on defining and assessing learning goals within a single course. For existing courses, as is the case in this study, course learning outcomes (CLOs) and assessments are analyzed to identify over-lapping or 'interdependent' learning outcomes (ILOs) between courses. For each ILO, specific subordinate skills, Bloom's cognitive levels, and example problems are identified for each course. Ultimately, the analysis produces a visual skills hierarchy or Learning Map (LMap) for the sequence (Appendix 1), which highlights the common learning outcomes, subordinate skills, and assessment examples. The products of the curriculum analysis serve as a focal point for faculty interested in aligning their course design and classroom activities (Figure 1).

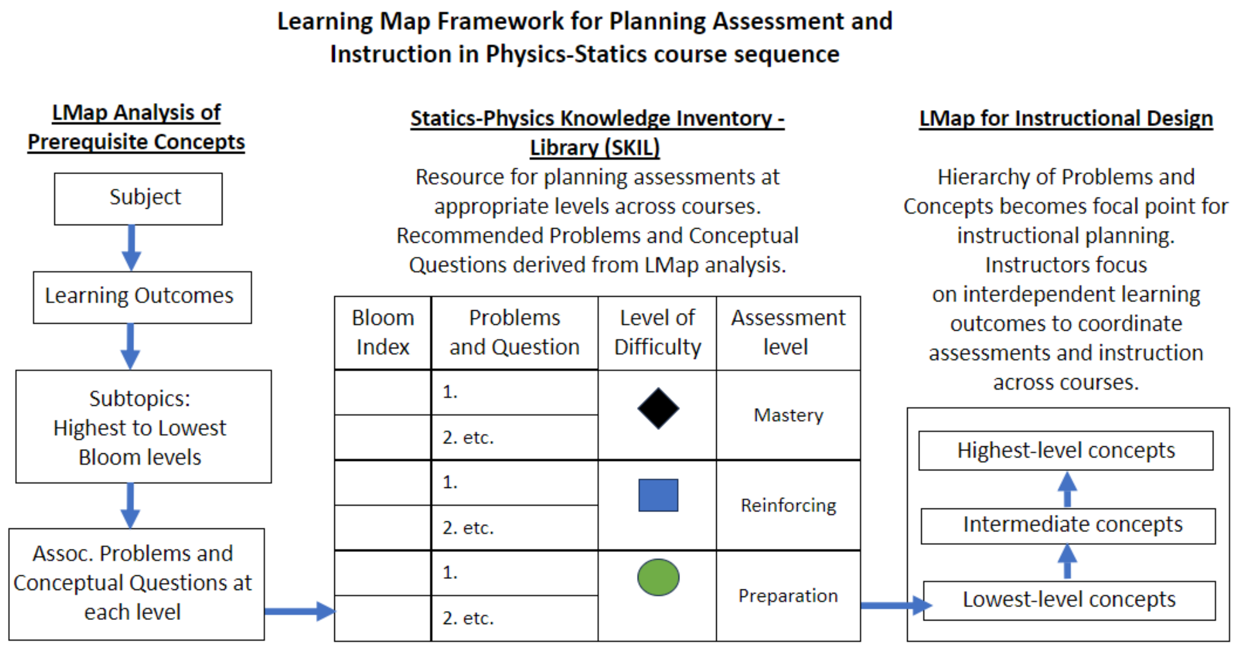

Figure 1. The Learning Map Framework begins with the analysis of learning outcomes in the terminal or intermediate course in a sequence. The hierarchy of concepts and problems that result serve as a focal point for faculty to coordinate assessment and instruction across levels in the sequence (preparatory – mastery), as shown in this example for the Physics-Statics course linkage.

Intervention. To coordinate the alignment of the three pilot courses, faculty will participate in a two-day Learning Map Workshop series led by the research team in June 2024. The workshop will orient the faculty to the learning maps for their courses and guide them through five stages of course design, centering on the ILOs in the sequence. The research team will provide details on relevant learning theory, instructional design, and active learning approaches as well as individual or group prompts at each stage. By the end of the workshop, faculty participants will have a plan in place for modifying their courses beginning in the next academic year. The five stages of facilitation are summarized in Table 2. The effect of the intervention on course planning and faculty knowledge of instructional design methodologies will be assessed through faculty pre- and post-workshop surveys, a follow-up analysis of course materials in year 2, classroom observations before and after the intervention, and a final interview following the treatment term in which the aligned course materials and instructional plans are first piloted.

Table 2. Five stages of Learning Map Workshop facilitation (faculty intervention).

Facilitation Stage	**What faculty will be asked to do**
1. Identify interdependent learning outcomes (ILO)	Review provided learning map resources and curriculum analysis prepared by research team; Build consensus on the ILOs that will be the focus for the remainder of the session.
2. Choose Bloom cognitive levels for each course learning outcome (CLO)	For each ILO, identify associated CLOs in each course; Review learning theory, Bloom's Taxonomy cognitive levels; Build consensus on appropriate Bloom's levels for each CLO in the sequence.
3. Review/ revise individual Course Learning Outcomes (CLOs)	Review and revise the individual CLOs as needed; Review best practices for writing effective learning outcomes; Share revisions and discuss with the group.
4. Choose assessments	Review how CLOs are currently being assessed in each course; Consider the balance of formative and summative assessment in each course; Identify assessments appropriate to the identified CLOs and ILOs; Share and discuss with the group.
5. Align classroom activities	Consider best-practices for student engagement in the classroom; Discuss how each learning outcome is presented to students and associated classroom activities; Identify opportunities to improve student engagement in individual courses and throughout the sequence.

Pilot Study. To assess the efficacy of the intervention on student outcomes in the pilot courses, student cohorts will be assessed before (pre-intervention, control) and after (post-intervention, treatment) the summer 2024 faculty workshops (Figure 2). Measures of student outcomes include individual course grades (overall as well as on individual assessments), gains on concept inventories within individual courses, and scores on Knowledge Transfer Inventories between courses. Longer term measures of student success will be assessed by cohort, including DFW rate, 2-yr retention rate, and graduation. Cohort sizes

The Physics – Statics – Dynamics sequence typically enrolls students in the Mechanical Engineering B.S. (ME) and Civil Engineering B.S. (CE; those degrees requiring the three courses in sequence), as well as other engineering and STEM degrees that may require some but not all of the courses. Further, students that require all three courses in sequence may not complete them in sequence, therefore sub-cohorts of students in the control and treatment terms will be identified to ensure appropriate comparisons between control and treatment terms. Sub-cohorts include:

- Mechanical Engineering B.S. and Civil Engineering B.S. (In Sequence);

- Mechanical Engineering B.S. and Civil Engineering B.S. (Out of Sequence);
- All others (In Sequence); All others (Out of Sequence)

There were 88 Mechanical Engineering and 19 Civil Engineering students in the first year degree cohorts beginning Fall 2023. One-year retention rates for students in these programs range from 86-89% for ME and 72-100% for CE (Fall 2015 – Fall 2021 cohorts). In Spring 2024, the Physics for Engineers course enrolled 147 students; 56% were ME, 6% were CE, and 37% were in other STEM programs.

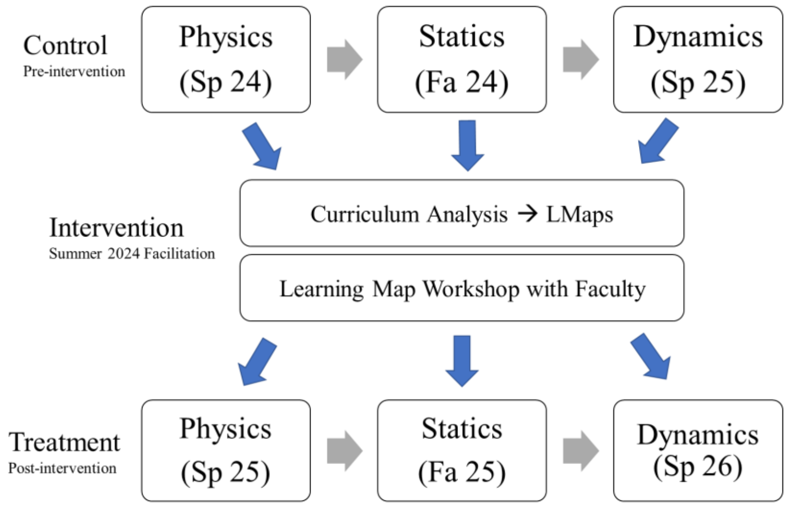

Figure 2. Pilot Study design. Student and faculty assessments will occur prior to the intervention during control terms (Spring 2024 – Spring 2025) and after the intervention during treatment terms (Spring 2025 – Spring 2026).

Measures of Student Conceptual Knowledge Within and Across Courses. Established concept inventories (CI) will be used to assess gains in students' conceptual knowledge *within individual courses*, both before and after the intervention: Force Concept Inventory (FCI) [10], Statics Concept Inventory (SCI) [11], and Dynamics Concept Inventory (DCI) [12] as available from the AIChE Concept Warehouse [13]. Established and novel concept inventories will be used to assess *knowledge transfer* between adjacent courses in the sequence. We refer to this category of assessments as Knowledge Transfer Inventories (KTI) in contrast to CI. KTIs will be deployed at the end of the prerequisite course term (e.g., end of Physics) and at the beginning of the subsequent course term (e.g., beginning of Statics) to assess retention of knowledge between courses. In contrast to a CI, which typically results in positive gains to student scores if learning is apparent, a KTI will assess knowledge retention (likely a flat score or no change in knowledge between terms) or loss (a declining score). It is expected that students with high and flat KTI scores will be prepared for the next course in the sequence, relative to students with greater declines on the KTI. The Statics Concept Inventory (SCI) is currently used this way for statics to dynamics knowledge assessment. To our knowledge, there is no established KTI for physics to statics, therefore a secondary goal of this research is to develop a new tool and supplemental resources for Statics, referred to here as the Statics-Physics Knowledge Inventory (SKI).

The SKI problem set consists of eight multiple choice problems, some conceptual and some requiring calculations, and seven short answer problems. No calculus-based questions are included. The problems assess knowledge of basic physics concepts needed by students entering the Statics course. Concepts include vector representation, static equilibrium, moment of a force, and static friction force. Most of the procedural problems in the SKI problem set were selected from the textbook by Randall Knight (Pearson)[14], the problem library in Pearson's Learning Catalytics [15], and the Statics textbook by Plesha, *et al.* (McGraw-Hill) [16] used in the Physics for Engineers course and the Statics course at the authors' institution. Conceptual problems were identified in existing ConcepTest questions on the Concept Warehouse [13] or created by the physics instructors on the research team. A library of potential SKI problems (SKIL) was created by the Physics and Statics course instructors on the research team, and a sub-set of fifteen questions was selected for the first inventory to be piloted in the spring 2024 Statics course.

The SKI pilot will be used to assess common student responses to the problems, completion time, student confidence, and thought process. The SKI will be modified for the Statics pre-treatment term (spring 2025) and used by the instructor to identify concepts and procedures that require additional attention and support for students. Results of the initial curriculum analysis and SKI pilot tests will be available at the time that this paper is presented.

Conclusions

The Learning Map Framework and resources developed during this project will be tested with faculty teaching in the Physics – Statics – Dynamics course sequence. The resulting alignment of learning outcomes, assessments, and instruction across the course sequence is expected to improve student outcomes in course-level learning assessments and overall success in the degree. Key outcomes include the development of resources to guide instructors through the Learning Map curriculum alignment process as well as a repository of conceptual and procedural problems specific to the interdependent learning outcomes of the sequence.

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Appendix 1. Example Learning Map of an interdependent learning outcome (ILO) related to vector operations as identified for the Physics-Statics course linkage. The skills hierarchy illustrates subordinate tasks that students must master in Physics in order to succeed in Statics. The learning map is provided to faculty as a focal point for coordinating assessment and instruction between courses.