# AC 2012-5015: SKILL AND CONTENT TRAJECTORY MAPPING IN A MECHANICAL ENGINEERING PROGRAM OF STUDY

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# Skill and Content Trajectory Mapping in a Mechanical Engineering Program of Study

## Abstract

In engineering education there are a number of central concepts and skills that form threads which connect one content area to another within a discipline. These threads form the core of an engineering education and are the scaffold upon which all future knowledge is built. An incomplete understanding in any of one of these concepts at an early stage in a student's education can lead to a cascade of failures or difficulties that resonate throughout their academic career. Although a program of study for a given discipline is designed so that students entering a given class have successfully completed all of the pre-requisite course material to attempt the class, student recall as well as student exposure to prior content can vary.

Current research has identified and mapped a number of central content and skill trajectories that are present in engineering education, focusing primarily on science and math content/skills essential to Mechanical Engineering. These content and skill areas have been assessed using a trajectory taxonomy to map and assess the intersection of the material with a program of study for a Mechanical Engineering program. Assessment of the trajectory is accomplished through an evaluation of the textbooks associated with each course and accounts for degree to which the subject relies on the pre-requisite knowledge and the level of re-instruction included within the text. This map of the content and skill trajectories permits the evaluation of a program of study/curriculum to identify critical points for the addition of remedial efforts and for instructional emphasis. It also provides a framework for assessing student capability and growth in these core content and skill areas and, from a larger vantage point, provides tools for examining curricular coherence.

## Introduction

In undergraduate education, and especially in STEM disciplines, there exist a number of central concepts and skills that form threads which connect one content area to another within a discipline. These threads form the core of a discipline-focused undergraduate education and are the scaffold upon which all future knowledge is built. Some of these concepts and skills may be viewed as 'basic' or 'tool oriented', like the ability to convert a quantity from one unit system to another, and are utilized at the same level of importance throughout a student's education, while others may be viewed as 'higher order' skills which may be essential for understanding in only a few advanced courses. Examples of 'higher order' skills include the ability to determine the dot product of two vectors or the ability to compute the partial derivative of a function with respect to one variable. Regardless of how these concepts and skills are ranked, they form the building blocks of the language of a discipline: they smooth introduction, facilitate deeper understanding and provide anchor points for extension in to unfamiliar or new territory.

An incomplete understanding in any of one of these concepts or skills at an early stage in a student's education can lead to a cascade of failures or difficulties that resonate throughout their academic career. Students who experience major gaps in their pre-requisite knowledge face difficult challenges in their upper level courses. In these classes these students find themselves in a position where they need to self-repair the gaps in their backgrounds while, at the same time, acquiring and synthesizing new knowledge. Since this new knowledge depends on students knowing, and often having fast recall, of the pre-requisite knowledge, this can be quite a challenge.

Gaps can have roots in student performance, such as inattention and lack of practice, or from an environmental mismatch (wrong school, incorrect placement, not prepared for the class), or even from prior instructional failure. To address this on the institutional side of the equation, programs of study are designed by departments to establish an instructional progression. These programs of study also incorporate considerations such as pre-requisite courses and GPA requirements to ensure that students are prepared for their future classes. The intent is to develop a structure that makes logical sense for the content of the discipline and which also includes needed skills and content understanding. Although a program of study for a given discipline is designed so that students entering a given class have successfully completed all of the pre-requisite course material prior to attempting the class, student recall as well as student exposure to prior content can vary.

Current research has focused on developing a 'small-footprint' tool which can be used by departments to identify and map a number of central content and skill trajectories that are present in engineering education, focusing primarily on science and math content/skills essential to Mechanical Engineering. A number of content and skill topics have been assessed using a trajectory-based taxonomy to map and assess the intersection of the material with a program of study. The instructional progression of these core components indicate numerous 'choke-points' which influence student preparedness for upper-level classes.

## Background

The decision to examine the undergraduate STEM learning experience from a skill and content trajectory basis, as opposed to a concept inventory or mindset perspective, is grounded in the cyclical nature and progressive growth themes that are present in a number of core education theories. The observations of student gaps and repair/remediation issues are the everyday, real life exemplars of what happens when there is a mismatch between principles of theory and practice.

The learning cycles approach, first articulated in the late 1950's and 1960's by Robert Karplus and J. Myron Atkin (physics/elementary science education) and independently developed by Chester Lawson (biology education) (Lawson, 1989), is one of these core philosophies which informs this research. Karplus and Atkin based their Learning Cycles approach on observation and Piaget's work on children's development and learning. In their approach, there are three elements in a Learning Cycle: Exploration, Concept Introduction and Concept Application. The methods used in each phase of the cycle are flexible but all phases are necessary for the Learning Cycle to be effective. Numerous studies support the effectiveness of using learning cycles particularly when one of the goals is to develop thinking skills in the students (examples as sited in Lawson, 1989: Abraham & Renner, 1984 [chemistry]; Renner, Abraham & Birnie, 1983 [physics]; Renner, Abraham & Birnie, 1985, 1988; Lott, 1983; Story & Brown, 1979; Renner & Paske, 1977). Learning Cycles support the current research in that the staging of learning and the view of student learning as an acquisition and integration process, this is further reinforced when the concept of a spiral curriculum is also considered.

Kolb (2000) in his Experiential Learning Theory (ELT) highlights the necessity of cyclical instruction. ELT divides the learning cycle in to four phases: experiencing, reflecting, thinking, and acting. As a model for education, this process is both planned (formatted) and responsive to the situation and content/skills being learned: activities are structured and planned but flexible to include individual. The cyclical nature of ELT supports this project in the necessity of revisiting concepts at various points, over time to solidify and deepen a learner's knowledge or concept acquisition and mastery.

While there are several prominent methods for dissecting and analyzing a program of study, in Mechanical Engineering two methods dominate the discipline. Accreditation driven efforts, such as ABET (Accreditation Board for Engineering and Technology), take a large scale approach addressing entire curricula and generating large amounts of data. The structure of the accreditation review imposes external drivers of interaction and investment and the focus in these efforts is often on outcomes rather than instructional delivery and process. Other structured efforts, such as SUCCEED (Southeastern University and College Coalition for Engineering Education), focus on staging student learning and developing connections and transitions between classes.

ABET's approach to curriculum mapping and assessment is both more proscribed than the SUCCEED outcomes and, at the same time, more dependent on the institution for the manner in which student learning is assessed. Within ABET the Program Outcomes (POs) set forth in Criterion 3 (ABET, 2007) address eleven student objectives, (a) through (k), in which an institution must demonstrate that students have attained success. These student objectives are gross skills such as "an ability to apply knowledge of mathematics, science, and engineering" or "an ability to function on multidisciplinary teams". Course Learning Outcomes (CLOs) are locally developed and used to enumerate class specific learning objectives. These outcomes are typically expressed in matrix form indicating the presence of a CLO or a PO within a course. While ABET requires that there must be an assessment and evaluation process that periodically documents and demonstrates the degree to which the program outcomes are attained, within the ABET structure the methods by which these are addressed is up to each department to develop and pursue. Studies by various researchers (Wagner, 1999; Wang, 2006) indicate that the tools and metrics used to assess students range considerably and vary from institution to institution.

Within the SUCCEED structure two methods of curriculum analysis were developed which provide structured and hierarchical views of the curriculum: the Knowledge/Skills Method and the Augmented Syllabus Method. These approaches take a much more structured view of the educational process, chaining outcomes and spiraling curriculum. The Knowledge/Skills Method (SUCCEED, 2009a) encourages the establishment of a sequential process in which the "big picture" is first sketched in broad strokes and then filled in by detail to look at where in the curriculum specific knowledge and skills are addressed. Within this structure, skills are defined as learned capacities (as opposed to content) that are fundamental to engineering and cover broad areas of application (engineering design skills, engineering control skills, problem solving skills, organizational skills). With the Knowledge/Skills Method, a matrix for a given curriculum is generated to track student growth and development where the rows consist of the courses offered and the skills or knowledge areas are represented in the columns. These matrices are used to analyze a curriculum to determine how requirements are being met, how the knowledge elements and skills are integrated, or how groups of courses are "time-phased".

The second SUCCEED coalition method of evaluating a department's curriculum is the Augmented Syllabus Method (SUCCEED, 2009b). The Augmented Syllabus Method addresses the curriculum at the degree to which goals are being met at a course level. It focuses on topical coverage and maps the path to mastery of a student by defining the level of accomplishment necessary at each stage, the pre-requisite knowledge for each topic and the anticipated use of the topics studied. One tool for use in the Augmented Syllabus method is the use of temporal displays of a curriculum, phase diagrams (SUCCEED, 2009b), to map a pathway towards mastery and to identify a progression in the depth of instruction on a topic. This phase diagram approach ascribes a four level mastery scale to measure the expected level of student understanding for various topics. In evaluating a department's curriculum, levels of implementation progress from "no exposure" to qualitative exposure (e.g. concepts) and then to quantitative exposure (e.g. homework problem) and finally to use in design or analysis. For example, a phase diagram for the concept of conservation principles published for Clemson University (Leonard, 1998) indicates that students will be exposed to the concept (Level 1) in their Sophomore year and then brought to Level 2 by the end of that year.

In addition to large-scale curriculum methods, there are also a number of focused approaches to examining learning which attend to the cyclical and scaffolded structure of learning. These approaches are primarily focused on the cognitive processing involved in developing individual concepts and have received considerable attention in K-12 education. One model of interest to this research is the concept of a learning progression.

In science education research the concept of a learning progression is used describe theoretical pathways toward developing ideas consistent with scientific consensus models of physical phenomena (Duschl, 2007; Smith, 2006). These learning progressions are usually proposed based on research into common student ideas in a given content domain (Talanquer, 2009) and are then tested with empirical evidence (Johnson, 2005; Johnson, 2011; Stevens, 2010). For example, a recent study employed cross-sectional interview data from grade 7-14 students to construct a multi-dimensional learning progression for the concepts of atomic structure and inter-atomic interactions. The authors of this study describe four levels of sophistication in these two linked topics. The progressions ranged from level I, where the atom is modeled as a sphere the interactions between atoms which are governed by undefined forces, to level IV which includes quantum mechanical models of the atom that interact with each other via electrical forces (Stevens, 2010).

The trajectory concept is especially relevant to this emerging area of research in that Duncan & Hmelo-Silver (2009) argue against the existence of a single learning progression for a given content domain, arguing instead that "there may be several viable paths and the progress is likely more akin to ecological succession than to constrained lock-step developmental stages" (Duncan, 2009). As an approach to addressing curricular structures, the trajectories-based approach blends outcomes and objectives from the two main curriculum assessment approaches discussed. This approach contains the large-scale analysis promoted by ABET while at the same time examining the scaffolding structures present in the SUCCEED methods. In this respect, however, the level of detail in a trajectory-based approach is considerably higher than that accomplished by either the Augmented Syllabus or Knowledge/Skills method from SUCCEED. The model being developed within this research also differs from these methods because it does not presuppose that a student's first exposure to the material leads directly to the advancement to the next level of mastery and is more akin to Duncan's "ecological succession". Finally, the content and skill trajectory approach differs from the ABET approach because it is designed to operate from an assessment standpoint as opposed to evaluation. With each skill or content topic addressed the goal is the identification as to common reasons for students not achieving success on that given topic and the identification of locations where knowledge transfer breaks down within the curriculum.

## Trajectory Definition and Conceptual Development

In the context of curriculum or program of study assessment, a content or skill trajectory is defined as the path described by a content or skill through a program of study marking where the topic intersects with individual courses. This trajectory concept is not just a static map of occurrences, including only the courses which introduce, extend or rely upon the concept or skill. A trajectory can also be used to address the progression of instruction by indicating the degree to which a given course relies upon that concept or skill as well as the instructional approach used to instruct/re-instruct on the concept or skill. While there are a number of dimensions to a learning progression, current efforts are focused on reducing the number of variables in the analysis so that the trajectory may be used in conjunction with other assessments to assess curricular development from a student perspective. Current efforts have focused on mapping just two aspects of a content/skill trajectory: Reliance and Development.

Assessing the dependence of the course material on a given content or skill can be accomplished either by analysis of the course textbooks or by observation of instruction. While observation of instruction would be the ideal, it is often impractical considering the number of classes which a given trajectory may intersect. Textbook analysis is appropriate for assessing the development of a skill or concept since instructional development in STEM is progressive and classes in Mechanical Engineering often follow the assigned text.

The Reliance aspect for a trajectory analysis addresses how the content of a course depends on the content or skill being investigated. For a textbook analysis of a program of study, the Reliance aspect has the following dimensions:

| | | |
|---|---|---|
| 0 | None | Course contains no direct dependence on the content or skill. |
| 1 | Tangential | Content/skill is used to develop a secondary concept within the class. |
| | | Dependent concept understanding would be considered 'broken' if the core content or skill was not understood prior to introduction. |
| | | Students with major gaps would not be able to solve problems using the new concept, but their understanding of the core components of a course would not be hindered. |
| 2 | Multiple Paths | Content/skill is used to develop a central concept within the class for which different approaches are provided. |
| | | Concept understanding would be 'hampered' if the core content or skill was not understood prior to introduction. |
| | | Students with major gaps would be able to solve problems and use new concepts so long as |
| 3 | Essential | Proper understanding of the content/skill is necessary to scaffold a central concept of the course. |
| | | Concept understanding would be 'broken' if the core content or skill was not well understood before the concept was introduced. |
| | | Students with major gaps would not be able to solve problems using the new concept and their understanding of the core components of a course would be hindered. |

Table 1: Dimensions of Content Reliance for Trajectory Assessment

The Development aspect of the trajectory refers to the manner by which the concept or skill is introduced within the context of the course instruction or the textbook. For a textbook analysis of a program of study using the trajectory map as a basis for assessment, this aspect has the following dimensions:

| | | |
|---|---|---|
| 0 | N/A | No development in textbook, No reliance |
| 1 | Transferred Responsibility | Content or skill development is not contained in the textbook, but concept depends on understanding content or skill |
| | | Responsibility for education/re-education on the content or skill is transferred to another (undeclared) entity |
| 2 | Modeled | Content or skill development is not contained within textbook, but the usage is modeled through example. |
| | | Steps and usage are shown in examples relating to course content, but without explanation or discussion. Skills and content are used in an abbreviated form – scaffolding of the core skill and content is not included. |
| 3 | Deferred Responsibility | Content or skill development is contained outside of the context of instruction on the content |
| | | Responsibility for education/re-education is deferred to a separate (dedicated) section of the textbook such an appendix |
| 4 | Review | Education/Re-Education on content or skills that are necessary for development of new content is developed in a brief review format |
| | | Focus in re-education is on usage and for application to concept |
| 5 | Fully-Developed | Instruction on content or skills that are necessary for development of new content is developed in detail |
| | | Outcomes form instruction on content/skills extend beyond concept under consideration |

Table 2: Dimensions of Content Development for Trajectory Assessment

## Example: Dot Product Trajectory

The program of study proscribed for the Mechanical Engineering program investigated is indicated in Figure 1. This is a graphical depiction of the lists of courses and suggested order of education that are published in student handbooks. The program of study considered consists of three core tracks: liberal studies, physical sciences and mechanical engineering. A number of individual supplementary courses from industrial and manufacturing engineering and electrical engineering are also included. The mechanical engineering track can be further broken down in to tracks pertaining to design, thermo/fluids and vibrations/controls. The discipline specific electives may consist of specialized classes in one of these tracks or applied courses which are typically focused subject matter. The arrows within the program of study describe the system of pre-requisite and co-requisite classes which are built in to the program of study.

While the program of study does not require that students strictly adhere to the progression of courses, it serves as a template for advising/registration and the network of pre-requisites and co-requisites prevents extreme deviation from the program of study in each of the major tracks. An example of the static footprint of a trajectory is indicated by the dark boxes present around some of the classes listed in the program of study. This particular trajectory is the one describing how the concept of the dot product (scalar inner product) from calculus and vector algebra. For this particular trajectory, the dot product concept first intersects the program of study during the FR II term (second semester, freshman year) in both the Physics I and Calculus II courses. While some content and skills have their roots in K-12 education, these classes are the first time that the large majority of STEM undergraduates have ever come in to contact with the concept. Possible exceptions to this being students who have taken AP Calculus AB, although the dot product does not appear in the CollegeBoard's Course Description for AP Calculus (College Board, 2009). The topic is observed again in the JR I term and recurs in many upper level courses such as Fluid Mechanics and Heat Transfer. The topic does not, however, play a role in a number of classes. The classes Dynamic Systems I and Dynamic Systems II, which are equivalent to Vibrations and Feedback Control Systems, have no reliance on the dot product for this program of study.

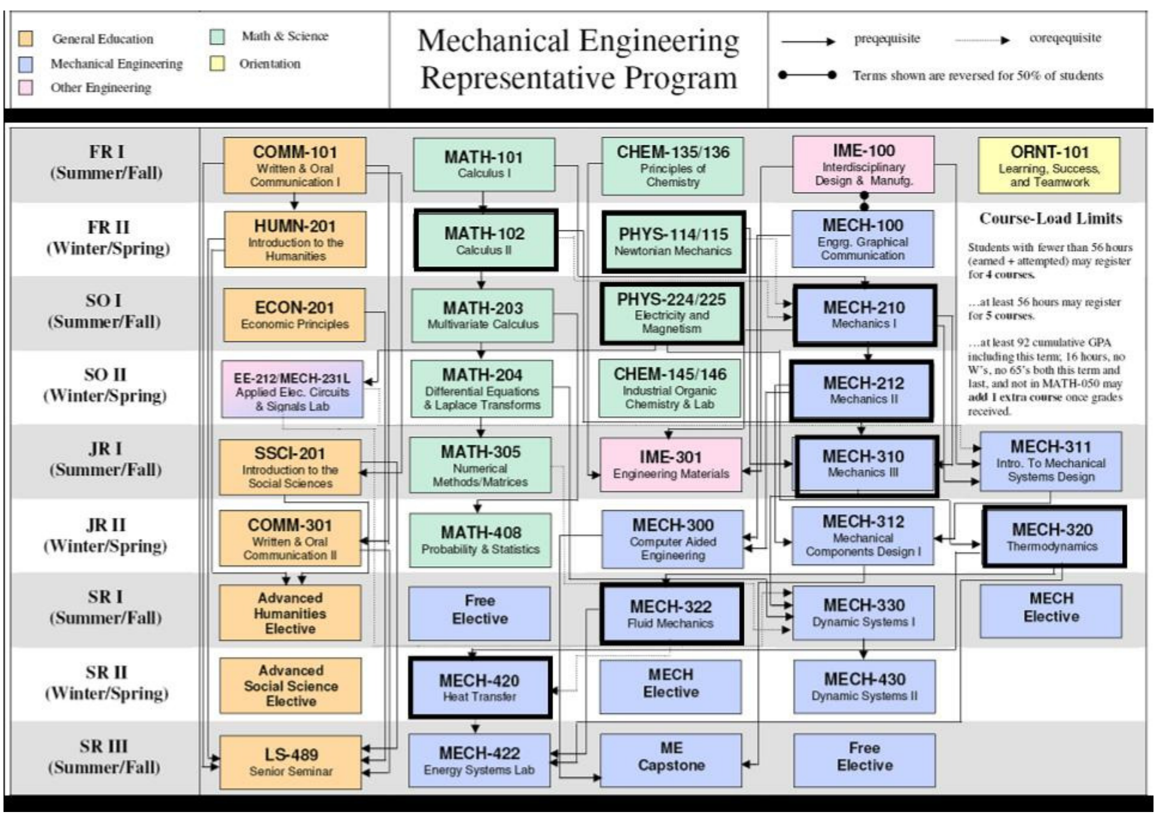


Figure 1: Representative Program of Study for Mechanical Engineering

Table 3 summarizes the results from a textbook analysis of the dot product. The entries indicate both how the topic is introduced in the textbook and the role that it plays in developing various concepts within the class. With this component it is noted that instruction on the topic is quickly transferred to the appendices for review/re-instruction and, in the advanced classes, the responsibility is placed upon the student to self-repair or for the faculty to develop re-instruction materials to better resolve student understanding and capability with the concept. For the current textbook choice, the topic does not play a role in the Heat Transfer text.

| **Dot Product Trajectory** | | |
|---|---|---|
| FR II | Physics I: | re-instruction within text<br>components of vectors |
| FR II | Calculus II: | theory development<br>components of vectors, vector multiplication |
| SO I | Physics II: | re-instruction within text<br>flux concept |
| SO I | Statics: | method review in appendix<br>components of vectors |
| SO II | Materials: | not included |
| JR I | Dynamics: | method review in appendix<br>components of vectors |
| JR II | Thermodynamics: | not included |
| SR I | Fluid Mechanics: | no review<br>components of vectors, flux concept, divergence |
| SR II | Heat Transfer: | not included |

Table 3: Trajectory-Based Analysis of the Dot Product in the Representative Program of Study

Figure 2 indicates the trajectory-based map of the concept reliance and development for the dot product trajectory. Semesters towards graduation are listed on the horizontal axis with terms 1 to 8 corresponding to terms FR I to SR II in the representative program of study. The Dependence dimension is plotted on the y-axis while the diameter of each bubble is proportional to the Reliance dimensions. For this concept there are numerous terms where the content does not appear in the textbook.

Figure 3 is a limited trajectory-based map for the units conversion skill is presented to focus attention on a common issue with learning progressions in higher education. Data is plotted in a similar manner with the focus being on terms 5-8 (Junior and Senior years). In this case, two alternate textbooks were used to model MECH-330 and MECH-430 since both of those classes use an internally generated handbook rather than a text. Comparable texts in Vibrations and Feedback Control Systems were chosen using other local institutions of higher education as a guide.

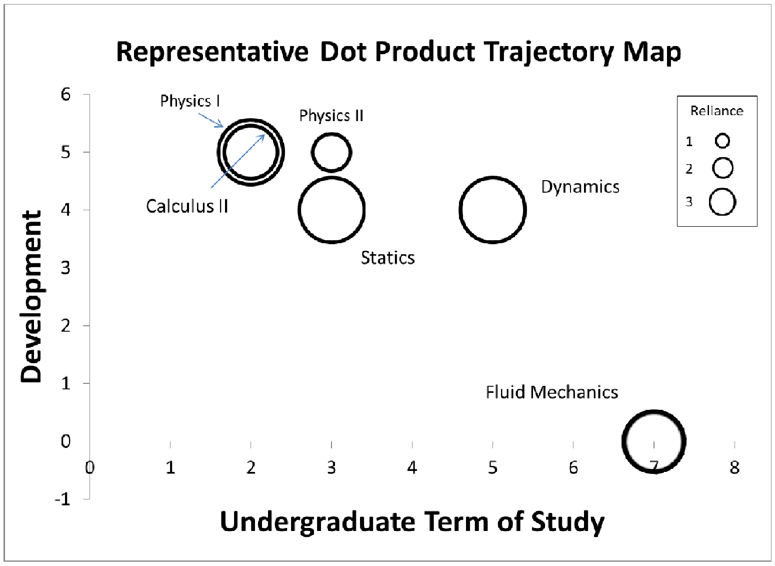


Figure 2: Reliance and Development Dimensions of the Dot Product Trajectory

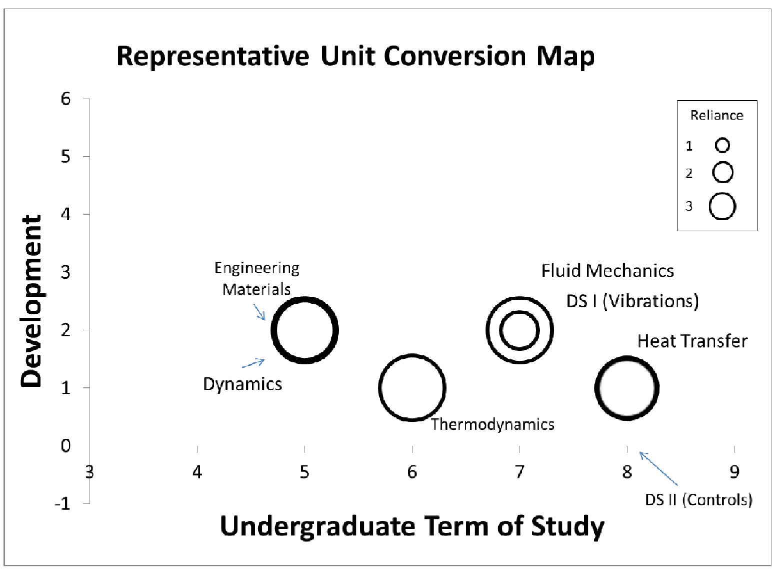


Figure 3: Reliance and Development Dimensions of the Units Conversion Trajectory

## Discussion

Results from the dot product trajectory indicate that this concept is developed in such a way that the reliance generally increases over the course of the program of study while the development of the concept drops sharply. In the early stages of this concept there are generally multiple paths present for the student to understand the dependent content. As a result it would be expected that student errors or difficulties with the dot product concept could go un-remediated as the student progresses towards degree and that considerable errors will interfere with content understanding in the later Fluid Mechanics course. In many respects, this is what would be considered an ideal progression for instruction on a core content or skill, where Reliance increases as Development decreases. If students at the SR I term were discovered to have issues with the concept, then the trajectory map would also indicate opportunities for more explicit re-instruction or usage of a concept.

Other trajectory-based analyses of core concepts and skills in Mechanical Engineering illustrate the variety present in the coherence of the curriculum and textbook choices. For example, concepts like "units conversion" demonstrate considerable development at the early stages of the program of study and can disappear completely from later classes. The focus in the early classes is especially interesting since the roots of the "units conversion" trajectory are deep in K-12 education. In later classes the ability is presumed and not even introduced except in examples. In some cases, such as Thermodynamics and Heat Transfer, units conversions are very minimally developed and the texts contain only limited examples: the units "magically" appear in the correct unit systems at the end of a problem.

## Conclusion

The decision to examine the undergraduate STEM learning experience from a skill and content trajectory or pre-requisite knowledge capability basis, as opposed to a concept inventory or mindset perspective, is grounded in the cyclical nature and progressive growth themes that are present in a number of core education theories. Trajectory-based assessments of core concepts and skills can be used to examine the logical progression of skill and content development in a program of study. Coupled with pre-term assessments and other assessments of student capability with these core concepts, a profile of student capability can be developed and remedial efforts can be targeted.

The number of assumptions as to student capability with basic or core concepts is extreme and evident by the textbook analysis of upper level classes. Future research will focus on building additional maps, adding dimensions to specific topics and assessing student performance along these trajectories to ascertain the degree to which student capability with pre-requisite material aligns with implicit assumptions as demonstrated by the textbook development and reliance dimensions.

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