"It's Too Hard," to "I Get It!" – Engaging Developmental Science as a Tool to Transform First Year Engineering Education

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Her research in the cognitive development of science learning requires collaborations with faculty in psychology, psychometrics, big data statistics, education, as well as teachers from K-13. Since a sabbatical period in the laboratory of Dr. Kurt Fischer at the Harvard Graduate School of Education, she has spent the past several years developing a common language in order to bridge and translate the findings of developmental science to first year college engineering and science education.

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Abstract

According to a 2012 article in *The Chronicle of Higher Education*, “60% of students who enter college with the goal of majoring in a STEM subject end up graduating in a non-STEM field”. This exodus is a long-standing problem. For several decades students have been saying that they feel that getting a STEM degree is too “hard”. Engineering students indicate that they are working constantly and still struggle to *understand* basic STEM concepts. In order to address the first-year exodus, higher education must shift its attention to providing educational mechanisms that focus on helping students enhance their *understanding of basic STEM concepts*. By *understanding* we mean a deep-seated knowledge that has become deep-rooted in a student’s way of thinking and that they can comfortably use when solving problems.

The focus of our paper is to provide a new set of fundamental ideas from which one can *re-direct* the conversation about the educational needs of first-year STEM students. We are proposing a bold new direction that embraces a rich empirical theory from the field of cognitive development called, dynamic skill theory. Our objective is to transform the current *status quo* in first-year engineering education where students say, “It’s too hard,” to where they say, “I get it.”

The Hardness of STEM – An Old Problem

For several decades the engineering and science education communities has been trying to address the problem of:

Why do students leave STEM disciplines during their first year of college?

The exodus of students from the STEM disciplines contributes to what Shirley Jackson, president of Rensselaer Polytechnic University, calls the “quiet crisis.”¹ According to a 2012 article in *The Chronicle of Higher Education*, “60% of students who enter college with the goal of majoring in a STEM subject end up graduating in a non-STEM field”.² The fact that this has been a long-term problem suggests that we have not been able to address the heart of the matter.

This problem has been brought to the forefront due to recent economic needs of the United States and the rising demand for STEM talent in an increasingly technological world. The President’s Council of Advisors on Science and Technology issued a report in 2012 that states:

Economic projections point to a need for approximately 1 million more STEM professionals than the US will produce at the current rate over the next decade if the country is to retain its historical preeminence in science and technology.³

The conversation about how to address student attrition in STEM majors is finding it difficult to make much headway. People have been studying this problem for many years and various approaches have been tried with mixed success. The one factor that has remained constant over

this period of time is students communicating their impression and belief that STEM majors are “hard”. Parents and society express the same impression.

A recent New York Times article attributes some of this hardness to tough introductory math and science classes. The article included the following quote from a student (with 800 Math SAT and reading and writing scores in the 700’s) who switched from mechanical engineering to psychology during fall of their sophomore year:

“I was trying to memorize equations, and engineering’s all about the application, which they really didn’t teach too well,” he says. “It was just like, Do these practice problems, then you’re on your own”.⁵

Seymour and Hewitt⁴ published a landmark ethnographic study in 1997 titled, *Talking About Leaving: Why Undergraduates Leave the Sciences*. This study identified 23 factors that contributed to students’ decisions to switch from a STEM discipline to a non-STEM discipline. Most of the factors were associated with issues related to faculty teaching, pedagogy, assessment practices, curriculum design and conceptual difficulty.

However pedagogy, curriculum, assessment and conceptual understanding do not exist in isolation. They are inter-related components of an educational ecosystem that has a direct impact on the development of a student’s understanding of a concept. The students in Seymour and Hewitt’s study associated aspects of volume, pace, and difficulty of the curriculum under the umbrella term of “hardness.” A worrisome finding was a “belief” by some students that they would not be able to understand STEM concepts no matter their level of effort.

A specific example of the hardness in STEM includes the first year, introductory “gatekeeper” courses, such as General Physics or General Chemistry. Significant efforts to improve and assist student performance in classes such as, Calculus, General Chemistry, are reported in the literature. Treisman’s hugely successful results in Calculus I emphasize the benefits of high expectations, community and group learning.⁶ Zare also extolled the benefits of a supportive learning community in institutions of higher learning.⁷ Other efforts include online preparation programs, extended recitations, and peer led mentoring and study groups.⁸⁻⁹ Additionally, active learning methods in lecture and interactive faculty result in increased student engagement in the learning process during these classes.¹⁰

Consistent with the students’ portrayal of this hardness in introductory STEM courses, there is a vast literature spanning several decades that documents difficulties in conceptual understanding in chemistry and physics from kindergarten through the college years. In fact, there is an entire bibliography with 8400 references dedicated to students’ and teachers’ alternate conceptions based on a collection of papers begun by Helga Pfundt in the late 1970’s.¹¹ These conceptual difficulties have been labeled as misconceptions, preconceptions, alternative conceptions, commonsense, intuitive or naïve beliefs; but they all describe the struggles exhibited by students to learn some of the most fundamental ideas of our physical world, such as the particulate nature of matter, Newtonian mechanics, or electricity and magnetism.

This paper attempts to shift the conversation related to *hardness* in a **bold** new direction that embraces long-standing empirical findings from the field of cognitive development. We use the word **bold** because most of us in the STEM education community are not accustomed to and likely uncomfortable with traversing the pathways and landscape of cognitive developmental science.

Why This Journey?

The purpose of this paper to begin moving the STEM education community in a direction that focuses on providing educational mechanisms that enhance a student's understanding of key STEM related concepts. In order to do so one must embrace the students' portrayal of hardness, and listen as they reveal their limited understanding through fragmented explanations and partially developed interpretations. One must engage the problem of hardness head on and figure out in detail what it means when students say, "I don't understand." Educators need to engage students in genuine conversations about their level of understanding. This requires the students to feel comfortable expressing their ideas and that someone listens to what they are saying.

It is useful to discuss what *genuine understanding* means, which is at the heart of the expression of *hardness*. Understanding is a significant underlying factor that dictates a student's performance. One cannot see how people think or the ideas that they bring to bear on the solution of a problem. One can only assess understanding when one solicits a student's ideas orally or in written form. Students are not directly asked enough, "Do you really understand?" or "Show me how." Often an unseen gap exists between the genuine understanding of a concept and a student's satisfactory performance on an assessment.

Genuine understanding is:

- permanent - It is deep-seated knowledge that has become part of the person's mind. This deep learning is anchored in highly varied experiences in formal or informal educational settings. It is robust and not easily fragmented. It is not fleeting or easily forgotten.
- flexible - If the context of the problem changes, one can bring relevant knowledge to the task and apply these ideas to changes in the problem.
- fluent - The ideas needed to solve a problem arrive quickly; they are coordinated or connected in the correct ways.

Deep understanding is **not**:

- rote or algorithmic.
- about repeating back facts or words that lack underpinning in experience.
- the accumulation of facts or acquisition of information. Tests of understanding do not involve repetition, or mastered practice; but rather, appropriate application of concepts to newly posed questions and problems.

Understanding is a process that requires risk-taking. An individual's understanding varies with subject and discipline. When learning something new everyone initially exhibits weak or fledgling understanding of the concepts being presented. The construction of genuine

understanding comes from repeated exposure to the ideas, which eventually, turn into knowledge.

This paper is the result of the concern that the authors have had about continued high rate of attrition for students in STEM majors as well as watching many *capable* students struggle with learning basic concepts. In order to help address our concerns it was necessary for us to develop a better understanding of how students achieve genuine understanding of concepts. The goal is to begin to change their statements from, “It’s too hard”, to “I get it.”

What is unusual is to have chemist/material scientist and a civil engineer in the College of Engineering and Physical Sciences at the University of New Hampshire delve into the terrain of cognitive developmental psychology and education. After doing so two things became clear:

- This is just the first step on an adventure that will attempt to elucidate the types of ideas, their inter-relationships, and temporal aspects that emerge as students construct a genuine understanding of STEM concepts and practices.
- What we have learned so far needs to be translated and presented in a form that can be used by most STEM educators to help their students develop the knowledge they need to be “successful” in STEM careers, if that is the direction they wish to pursue and not be sidelined by the feeling of *hardness*.

It is worthwhile to emphasize that our work is a translational effort. We are using one well-established cognitive theory and *learning how* its results can be put into practice in the STEM classroom to improve student understanding, particularly in the first year engineering experience. Our focus, as educators, is on practice – or - the events happening in the STEM classroom. Our journey began when one of the authors spent a sabbatical engaged in conversations about the hardness of STEM with a cognitive psychologist, Dr. Kurt Fischer, and his colleagues. A long-standing and on-going collaboration has developed over the last few years in which we have strived to learn, understand, and finally begun to translate the language of one cognitive developmental science framework for use by STEM educators. This collaboration has required us to merge perspectives, language, and methods from the cognitive sciences, psychometrics, and STEM education.

There exist other boundary crossing efforts between cognitive scientists and STEM educators, For example, David Klahr espouses the synergies of collaboration between cognitive development and science education.¹² There exist a significant number of conversations between cognitive scientists and STEM educators of younger children.¹³ Recently, a entire novel conference was devoted to the findings of partnerships between cognitive science and STEM education.¹⁴ Such interdisciplinary collaborations between cognitive scientists and educators have been happening for a long time, and will continue to offer advantages to education.¹⁵⁻¹⁷ The work reported in this paper coincide with the first translational step suggested by Daniel in his framework for moving from the cognitive science laboratory to the classroom.¹⁸

Dynamic Skill Theory – Beginning the Translation

The interdisciplinary science of cognitive development constructs models that explain human thinking and how it changes as a function of a person’s age and their interactions with their

environment. It is a perspective that embraces learning as a transformation of a person due to the interactions among a person's brain, mind, and educational experiences. These educational moments occur everywhere (schools, homes, playgrounds, museums, jobs, etc.). Our engagement with the field of cognitive development was similar to the first step undertaken by engineers or scientists while applying the design process or scientific method to solve a particular problem. In our case we asked, "Do any models or empirical findings exist that explain how understanding happens?"

What came to light was that dynamic skill theory, developed by Dr. Kurt Fischer, is a comprehensive scientific model from the field of cognitive development that describes how a person's understanding about something transforms or develops over time and with experience.¹⁹⁻²⁰ The theory not only describes how a person's ideas transform as their understanding about something grows; but it also reveals several mechanisms for how these transitions occur, the importance of task and context on these transitions, as well as the temporal aspects of these transitions. The term comprehensive refers to the sheer breadth and depth encompassed by the model; the empirical and modeling studies on which it is grounded have been in the making over the last four decades, and in a variety of domains, such as: mathematics,²¹ reflective judgment,²² and conceptions of density.²³ Dynamic skill theory integrates over 100 years of research in cognitive development, extending from Baldwin's²⁴ pioneering theory that intellectual development happened in stages, to Piaget's²⁵ theory of constructivism, which has made an enormous impact on science education.²⁶ Fischer, known as a neo-Piagetian, advanced Piaget's theories by recognizing the hierarchical pattern of ideas that emerge as a person's understanding grows with time.

The central feature of dynamic skill theory is a scale that describes the progression of increasing complexity of ideas that a person uses to think about a concept as their understanding grows with time. Dynamic skill theory identifies a series of hierarchical steps or levels that emerge during the development of understanding. These levels are organized into four (4) tiers that occur in the following sequence: (1) sensory motor behaviors (actions), (2) representations (tangible characteristics of objects, event or people), and (3) abstractions (intangible characteristics of objects, events, or people), and (4) first principles. Abstract skills are at a higher level and are more complex than representational skills, which are more complex than sensory-motor skills. More complex in skill theory means that the understanding of the concept or behavior requires understanding more prerequisite ideas or behaviors, and that there are more inter-relationships among these multiple sets of ideas or behaviors.

Each tier, except first principles, is further subdivided into four levels:

- (1) single ideas,
- (2) mappings - a relationship between two single ideas,
- (3) systems (inter-relationships between two or more mappings), and

Figure 1. A tier and its sublevels according to dynamic skill theory.

(4) system of systems.

The last level (system of systems) in each tier is the same as the first level (single ideas) in the next tier. The levels are hierarchical because the ideas or ways of thinking at one level are built from the ideas or ways of thinking at the level below. For example, representational mappings require multiple sets of single representations, and representational systems require multiple representational mappings (Figure 1). The development of understanding or the increased complexity of ideas about a concept is induced by interactions between a person and a learning environment. Once we determine the progression of ideas that students can use to develop an understanding of a concept, we can rationally modify the curriculum so that it enhances students' ability to progress through the various levels of understanding.

One can think of this pattern seen in the development of understanding as being similar to the developmental pattern seen in motor development as a baby learns to walk by starting from a lying down position, moving to a sitting position, then to crawling, standing, cruising and finally to walking. It would be considered quite unusual to see a baby go from sitting to walking without practicing these intermediate steps or milestones. Likewise, we cannot expect students to understand the concept of friction at an abstract level, without several experiences involving the interaction of surfaces with a various levels of roughness.

In the case of motor development, no two babies show the exact same sequence of behaviors in following the pattern. Similarly, no two students will inter-relate the exact same set of ideas and experiences in learning to understand friction. The steps in the pattern for motor development are visual and have been previously identified by collecting motor development data from many children over many years. This pattern and its visual cues enable parents and care providers to easily know how to help an infant bridge from one level to the next. For example, adults will often hold a crawling baby in a standing position in order to help them learn how to stand. In fact, stand up bouncers are pieces of baby equipment designed to let a child stand and bounce with support. Since it is known that a child develops from crawling to standing, bridging mechanisms to assist this development are easily implemented, either with bouncers or parents holding a baby to a standing position.

It is our vision that the translation of the cognitive developmental framework embodied in dynamic skill theory will enable us to design educational mechanisms to help students bridge from one level to the next in their understanding of STEM concepts. The following steps are necessary to achieve this vision:

- Collect the data that will reveal the ideas students use to think about STEM concepts, such as forces or static friction, at all grade levels including college.
- Analyze the data by determining the ideas, their tier, and how they inter-relate, according to dynamic skill theory.
- Determine the developmental pattern of understanding for a variety of STEM concepts.

While dynamic skill theory provides a powerful set of tools for educators it is currently described in a language most familiar to its historic audience – cognitive psychologists. A common language must be developed between the educators and the theory originators in order for the

tools to be put to use. The products of this alliance will be a set of tools that can be used by the engineering education community.

There are other findings in the STEM education literature consistent with the framework of levels of understanding described in dynamic skill theory. Liu has presented a synthesis of the research findings on students' conceptions of matter from grades one through twelve that revealed these misconceptions could be arranged into seven hierarchical categories, ranging from simplest to most complex.^{27,28} Since the late 1990's there has been a proliferation of learning progressions; these have been described as sequential descriptions of the successively more sophisticated ideas or concepts *within a topic* that follow one another as students learn.²⁹ For example, learning progression for forces and motion, as well as matter and atomic-molecular theory have been described in the literature.^{30,31} Much of this work is at the K-12 level, and our work will complement and intersect these efforts by providing information about grade 13 or first year college level data. The framework of dynamic skill theory builds on the work of learning progressions because it provides not only the expected levels of understanding, but also the defining characteristics of the understanding at each expected level. The student assessment data to be collected in subsequent work will provide examples of the ideas students use at each level.

Dynamic Skill Theory in Operation

The following is an example of a static friction problem that would be seen in a first-year engineering physics course or an engineering mechanics (statics) course. The focus of the example is to illustrate how one could apply the concepts of dynamic skill theory to the various engineering and physics concepts embedded in the problem.

<p>Problem Statement</p> <p>Determine if the sloping surface is at 32 degrees to the horizontal will the box of mass, M, slide down the sloping surface shown in the figure.</p>	<p><u>Problem image</u></p>
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Figure 2. Static friction problem statement

The following information is typically given for this problem:

- $M = 10.5$ kg (mass of the box)
- $\theta = 32$ degrees (angle of sloping surface)
- $\mu = 0.62$ (coefficient of static friction).

The components of the problem that the student must identify and understand include the following:

- One must calculate the weight (W) of the box by multiplying the mass (M) by the acceleration of gravity (g).
 - $W = M \cdot g$
 - $g = 9.81 \text{ m/s}^2$
 - The student must know this value or be able to look it up
 - The student must be aware of the units in the problem.
- The weight (W) of the box is vertical because the acceleration of gravity (g) is vertical.
 - The weight (W) is not perpendicular to the sloping surface
- The student must be able to work with the geometry to recognize the relationship between the slope of the surface (θ) and the angles in the force triangle for W , F_N and $F_{\parallel}$.
- The weight (W) needs to be expressed as:
 - F_N - a force perpendicular to the sloping surface and
 - $F_N = W \cos \theta$
 - $F_{\parallel}$ - a force parallel to the sloping surface
 - $F_{\parallel} = W \sin \theta$.
- There is a force resisting (F_R) the sliding of the box due to the friction that exists between the box and the sloping surface. (Figure 3)
 - F_R acts in a direction opposite the force $F_{\parallel}$.
 - F_R is a function of F_N and the coefficient of static friction (μ),
 - $F_R = \mu F_N$.

Figure 3. Force diagram

In order to solve the problem, the student needs to calculate the magnitude of the frictional resisting force (F_R) and the force parallel to the sloping surface due the weight of the box ($F_{\parallel}$). If the magnitude of $F_{\parallel}$ is greater than the magnitude of F_R the box will slide down the sloping surface

We will use dynamic skill theory as a tool to reveal the characteristics of the understanding required to successfully solve this problem by analysis of the concepts used in the presentation of the problem and its solution. A student must work with several physics and math concepts in order to solve this problem.

Some of the terms or concepts: slope, box, sliding movement, weight, parallel, perpendicular and geometry, would be classified as representations because they refer to tangible characteristics of an object, event or person. The following concepts: mass, acceleration of gravity, coefficient of static friction, force triangle, and force equilibrium, would be classified as abstractions because they refer to intangible characteristics of an object, event, or person. It is the latter concepts that are typically used in the presentation of problems in the first year college engineering curriculum.

If a student has not reached the abstraction tier for all the concepts related to this problem, then the term coefficient of static friction could be a source of confusion. Before a student can apply the abstract concept of the coefficient of static friction, they would first need to understand the concept in representational terms. The coefficient of static friction is comprised of many representational ideas, including the material each surface is made from, the roughness of each surface, and the way the surfaces of the two materials interact. When all of these representational ideas are brought together they form a system of representational systems that is the first level of the abstraction tier, a single abstraction.

The material a surface is made from is a single representation because it is something tangible to the student. The roughness of each surface is a mapping of two ideas, the material and typical texture of the material. One would assume that a glass surface is smooth and a gravel surface is rough. The way two surfaces interact as one tries to move one of the objects over the other consists of two mappings that form a representational system. Therefore, two materials, their individual roughness, and then their surface interactions form a system of representational systems, such as that shown in Figure 4.

Figure 4. The static friction problem representational tier.

According to the dynamic skill theory model, diversity of examples and contexts develops a student's understanding within a level. Investigating multiple examples of each type of concept in a laboratory setting is a good way to do this. In order to familiarize a student with these representations they would be presented with a variety of hands-on activities that would expose them to how much weight would need to be applied in order to cause objects of different materials to slide along a surface. By varying the material of the object (steel, wood, concrete, plastic, etc.), but keeping the weight

and footprint of the object and the support surface constant for each trial, a student would be able to develop an understanding of how the interaction of two materials changes the resistance to movement. With enough exposure to a diversity of experiments at the representational level, a student could develop an understanding for the concept of the coefficient of static friction and thus apply this to future problems.

A similar approach could be used to convey the influence of mass on this problem. Mass is also a system of abstract concepts; whereas as weight is the tangible quantity. One could select a particular material and vary the weight of the object. Again keeping the footprint and the sliding surface the same, one could see how the weight and therefore the mass influences the amount of force that needs to be applied to the system to overcome the sliding (frictional) resistance of the object.

What dynamic skill theory has shown is that a student must progress along a pathway that engages ideas from the representational tier, through its levels, and then to the abstraction tier. The student's perception of *hardness* can be generated from not having developed a solid

understanding of the related representational concepts before moving forward and being asked to understand and use concepts that are in abstraction tier.

What exists in much of the support material (textbooks, problem sets, etc.) for STEM related courses is a misalignment between the presentation of the material and a student's developmental level of understanding of the concepts. One often sees that the information presented to a student, who is often seeing the material for the first time, includes ideas presented at the abstraction tier. The student needs to first develop an understanding of the concepts at the representational tier. Look at the problem statement above. For a student that has not seen this material before, the perception of hardness could come from seeing the phrase "the coefficient of static friction". It is a big leap from the idea of surface roughness of a material to the coefficient of static friction for many students. Alternatively, if one views the understanding required to solve the static friction problem as a system of systems (either at the representational or abstract levels), the hardness may result from the student missing one or more of the ideas integrated in this level, or one or more of the links among the ideas.

Table 1 below presents the various ideas or concepts related to the static friction problem and their associated tier / level.

Table 1. Static friction problem - relevant concepts according to dynamic skill theory scale.

Representational Tier				Abstraction Tier
Single	Mappings	Systems	System of Systems	Single
Weight	Movement	Sliding interaction	Coefficient of Static Friction	Force
Footprint	Volume	Weight on Sliding interaction		Mass
Material	Roughness of surface	Relative movement		Gravity
Perpendicular	Geometry			Motion
Parallel				

Our Hypothesis

As shown by our dynamic skill theory analysis of the static friction problem, it is reasonable to ask if college-level STEM instruction of other topics also assumes a certain level of development of understanding of STEM concepts and practices. For the static friction problem, we showed that this level was at the abstract systems level within the abstraction tier. Similar analyses in other topic areas will be necessary to determine how much of the curriculum expects this level of understanding. A limitation of this paper is that it only analyzes one typical topic in the first year curriculum. Additionally, we will also still need to collect actual assessment data consisting of student responses to a typical static friction problem in order to determine if there is a difference between the level of understanding in first year students about static friction versus the level of understanding expected by the presentation in the curriculum.

This analysis of the presentation of the static friction problem led us to hypothesize that it is a potential gap between the level of development of understanding for STEM concepts of the first year student and the level of understanding required to succeed in first year STEM courses that is at the heart of the hardness of STEM courses. Our next step will be to collect assessment data, which will be actual student response data to the static friction problem.

Next Steps – Collection of Assessment Data and Network analysis of student generated open-ended responses

To determine how first year students understand STEM concepts through the lens of dynamic skill theory, we will gather student generated written responses to open-ended questions about typical first year STEM concepts, such as those incorporated in the sliding box problem discussed previously. These questions are designed to force the students to engage with the concepts and explain how they think about them. For the sliding box problem in the previous section, we would ask the following questions:

- How would you explain to someone else what you observe in the picture?
- What is meant by "equilibrium?"
- Can you explain what it means for the crate to have a mass of 20 kg?
- Would the mass change if the crate were placed on the moon?
- What is the weight of the object and how is that different than the mass of the object?
- Explain what is meant by the co-efficient of static friction?
- Where is friction in the problem?
- What is friction? And what causes friction?

From these short answer questions, we will extract all the types of ideas generated by the student, as well as which ideas are inter-related, and how they are inter-related. Each idea will be assigned to one of the three tiers: representational, abstraction, and principles. It will also be assigned to one of four levels: an isolated idea, a mapping between two ideas, a system relating three or more ideas, or a system of systems with multiple inter-relationships. The analysis of each student response will be recorded as a data set consisting of the individual ideas elicited, and their characteristics, including the tier understanding and its inter-relatedness, or level within a tier.

Traditional statistical analysis of educational data typically requires a spreadsheet type data consisting of cases (rows) and variables (columns). Our data set for one student could be represented in such a form, but this would entail multiple entries (rows) for each idea to accommodate the hierarchical structuring of tiers and several levels of inter-relationships. The spreadsheet would be highly unbalanced with a large number of missing entries, which would make traditional analyses impossible.

Instead an efficient representation of this data can be achieved via the construction of a "network" that consists of all the ideas as vertices and incorporates all the relationships as edges that connect vertices. The answers provided by one student are then represented by such a network, and the student's characteristics of the answers is embodied by the characteristics (or topology) of the network. Hierarchical structure would result in a network that is a tree.

Networks can be represented graphically in various ways.^{32,33} As an illustrative example we show a fictional network that represents one student's ideas. The network is represented in a radial layout. Ideas are labeled as $W_1, \dots, W_{25}$ (words). Each idea was assigned to one of, or several, of the three tiers, labeled as: R (representations) A, (abstractions), P, (principles). The tiers were organized in a hierarchical fashion. The network provides a visualization of the inter-relationships between ideas and the grouping of ideas into five clusters based on five principles.

Figure 5. A representational radial network of a student's ideas

Network models have been proposed since about the 1970's mostly for social networks, traffic flow, and in psychometrics. However rigorous statistical analysis of networks and the comparisons of multiple networks is in its infancy, because it requires considerable computing, and defining statistical models on trees is generally a challenge.

We expect that the networks derived from the answers of a sample of students will elucidate the students' conceptual understanding.

Student networks can be compared to networks derived from expert solutions to answer such questions as:

- At what level does a student understand the concept?
- Is a student engaging with all the requisite concepts?
- What concepts need to be understood prior to more advanced concepts?
- What concepts is a student, or a cohort of students, missing in order to further develop understanding?
- What necessary links between concepts are students missing?

Initially, statistical comparison of networks, as well as clustering of networks, will help to obtain a summary of the overall characteristics of understanding of a sample of students. Eventually, as more samples (networks) will be available, the information contained in the networks will lend itself to revise initial understanding of how ideas are tiered and connected within the framework of dynamic skill theory. Over the long term, one could envision development of educational tools that automate the construction of the network themselves, as well as their analyses and comparisons.

In turn, this data will enable the design of curriculum, instruction, or academic support methods to enable STEM students develop the requisite understanding to succeed in first year coursework. The novelty in our work will be that the design of all these tools and methods, and we expect them to be numerous and diverse, will be based on empirical findings guided by a cognitive developmental framework (dynamic skill theory) which describes how understanding (of STEM concepts) develops in students.

Conclusions

We have taken steps that begin to address the heart of the matter regarding the hardness of first year STEM courses:

- We have begun to translate for the STEM education community, the core concepts from dynamic skill theory - a model from the field of cognitive development that describes the characteristics of the ideas used to understand a concept, as that understanding develops and becomes increasingly complex.
- We have analyzed a typical first year static friction problem according to dynamic skill theory, dissected it into component ideas, and explained the type of understanding required to solve the problem as it is typically presented in the first year of an engineering curriculum. This presentation of a typical static friction problem in the first year curriculum is presented at the level of abstract systems, which requires coordination of multiple abstract concepts.

Based on our analyses, we hypothesize that there is a misalignment between the student's development of understanding of a concept and the development of understanding required by the presentation of first year coursework. If such a misalignment is found, one can then ask for how many topics is this case? Specifically, if many students engage with STEM concepts at the level of representations, but their coursework requires understanding at the higher end of the abstract tier, then they will find STEM "hard".

These steps lay some of the groundwork necessary to design educational tools and methods to address what to *do* about the hardness of STEM. First, the dynamic skill theory scale represents a scale that describes the milestone characteristics of the types of ideas people use as they develop understanding of a concept. We have begun the work of translating that scale for use by educators. This scale, together with statistical analyses of networks generated from student responses, will create a set of tools for mapping the diverse pathways students use to develop an understanding of many STEM concepts and practices. Eventually we can study how these pathways change as a function of curriculum, assigned activities, and instruction.

In turn, this data will enable the rational design of curriculum, instruction, or academic support methods to enable STEM students to develop the requisite understanding to succeed in first year coursework. A longer-term vision would extend this work to collecting data about key science concepts in subsequent college courses as well, such as those found in the second year. The novelty in our work will be that the design of all these tools and methods, and we expect them to be numerous and diverse, will be based on empirical findings guided by a cognitive

developmental framework (dynamic skill theory) which describes how understanding (of STEM concepts) develops in students.

The translation of the language of dynamic skill theory into a set of tools for educators is the realm of an educational engineer – someone who uses the science of cognitive development, or other learning sciences, as well as the engineering design process to solve problems in educational settings. The term, educational engineer, was suggested by Fischer³⁴ as one necessary component of an improved infrastructure for education in which research and practice are intertwined to inform one another, and lead to better ways to teach and enable learning. The groundwork underlying this paper represents the initial steps toward those goals.

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